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Book of Abstracts

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Flow-based density of states for complex actions

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Emerging sampling algorithms based on normalizing flows have the potential to solve ergodicity problems in lattice calculations. Furthermore, it has been noted that flows can be used to compute thermodynamic quantities which are difficult to access with traditional methods. This suggests that they are also applicable to the density-of-states approach to complex action problems. In particular, flow-based sampling may be used to compute the density directly, in contradistinction to the conventional strategy of reconstructing it via measuring and integrating the derivative of its logarithm. By circumventing this procedure, the accumulation of errors from the numerical integration is avoided completely and the overall normalization factor can be determined explicitly. In this proof-of-principle study, we demonstrate our method in the context of two-component scalar field theory where the O(2) symmetry is explicitly broken by an imaginary external field. First, we concentrate on the zero-dimensional case which can be solved exactly. We show that with our method, the Lee-Yang zeroes of the associated partition function can be successfully located. Subsequently, we confirm that the flow-based approach correctly reproduces the density computed with conventional methods in one- and two-dimensional models.

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Stochastic normalizing flows for lattice field theory

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Normalizing flows (NFs) are a class of machine-learning algorithms that can be used to efficiently evaluate posterior approximations of statistical distributions. NFs work by constructing invertible and differentiable transformations that map sufficiently simple distributions to the target distribution, and provide a new, promising route to study quantum field theories regularized on a lattice. In this contribution, based on our recent work [**arXiv:2201.08862**], I explain how to combine NFs with stochastic updates, demonstrating that this theoretical framework is the same that underlies Monte Carlo simulations based on Jarzynski's equality, and present examples of applications for the evaluation of free energies in lattice field theory.

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Kernel controlled real-time Complex Langevin simulation

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This study explores the utility of a kernel in complex Langevin simulations of quantum real-time dynamics on the Schwinger-Keldysh contour. We give several examples where we use a systematic scheme to find kernels that restore correct convergence of complex Langevin. The schemes combine prior information we know about the system and the correctness of convergence of complex Langevin to construct a kernel. This allows us to simulate up to 2β on the real-time Schwinger-Keldysh contour with the $0+1$ dimensional anharmonic oscillator using $m = 1,\ \lambda = 24$, which was previously unattainable using the complex Langevin equation.

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Gauge-equivariant flow models for sampling in lattice field theories with pseudofermions

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In this talk, we discuss gauge-equivariant architectures for flow-based sampling in fermionic lattice field theories with pseudofermions. We also discuss how flow-based sampling approaches can be improved by combination with standard techniques such as even/odd preconditioning and the Hasenbusch factorization. Numerical demonstrations in two-dimensional U(1) and SU(3) theories with $N_f = 2$ flavors are provided.

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Automatic differentiation for stochastic processes

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Automatic Differentiation (AD) techniques allows to determine the Taylor expansion of any deterministic function. The generalization of these techniques to stochastic problems is not trivial. In this work we explore two approaches to extend the ideas of AD to stochastic processes, one based on reweighting and another one based on the ideas of numerical stochastic perturbation theory using the Hamiltonian formalism. We show that, when convergence can be guaranteed, the approach based on NSPT is able to converge to the Taylor expansion with a much smaller variance.

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Applying the worldvolume tempered Lefschetz thimble method to lattice field theories

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The numerical sign problem has been a major obstacle to first-principles calculations of many important systems, including QCD at finite density. The worldvolume tempered Lefschetz thimble method is a HMC algorithm which solves both the sign problem and the ergodicity problems simultaneously. In this algorithm, configurations explore the extended configuration space (worldvolume) that includes a region where the sign problem disappears and also a region where the ergodicity problem is mild. The computational cost of the algorithm is expected to be much lower than other related algorithms based on Lefschetz thimbles, because one no longer needs to calculate the Jacobian of the gradient flow of Picard and Lefschetz when generating configurations. In this talk, after reviewing the basics of the method, we apply the method to various lattice field theories suffering from the sign problem, and report on the numerical results together with the computational cost scaling with the lattice volume.

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Status update on flow models for gauge field generation

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I will describe recent progress in the development of custom machine learning architectures based on flow models for the efficient sampling of gauge field configurations. I will present updates on the status of this program and outline the challenges and potential of the approach.

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Exploration of Efficient Neural Network for Path Optimization Method

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We present our attempts to control the sign problem by the path optimization method with emphasis on efficiency of the neural network. We found a gauge invariant neural network is successful in the 2-dimensional U(1) gauge theory with a complex coupling. We also investigate possibility of the improvement in the learning process.

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Reducing the Sign Problem using Line Integrals

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We present a novel strategy to strongly reduce the severity of the sign problem, using line integrals along paths of changing imaginary action. Highly oscillating regions along these paths cancel out, decreasing their contributions. As a result, sampling with standard Monte-Carlo techniques becomes possible in cases which otherwise requires methods taking advantage of complex analysis, such as Lefschetz-thimbles or Complex Langevin. We lay out how to write down an ordinary differential equation for the line integrals. As an example of its usage, we apply the results to a 1d quantum mechanical anharmonic oscillator with a x^4 potential in real time, finite temperature.

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Topology changing update algorithms for SU(3) gauge theory

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At fine lattice spacings, lattice simulations are plagued by slow (topological) modes that give rise to large autocorrelation times. These in turn lead to statistical and systematic errors that are difficult to estimate. We study the problem and possible algorithmic solutions in 4-dimensional SU(3) gauge theory, with special focus on instanton updates and metadynamics.

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Machine Learning Trivializing Maps

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A trivializing map is a field transformation whose Jacobian determinant exactly cancels the interaction terms in the action, providing a representation of the theory in terms of a deterministic transformation of a distribution from which sampling is trivial. A series of seminal studies have demonstrated that approximations of trivializing maps can be 'machine-learned' by a class of invertible neural models called *Normalizing Flows*, constructed such that the Jacobian determinant of the transformation can be efficiently computed. Asymptotically exact sampling from the theory of interest can be performed by drawing samples from a simple distribution, passing them through the network, and reweighting the resulting configurations (e.g. using a Metropolis test). From a theoretical perspective, this approach has the potential to become more efficient than traditional Markov Chain Monte Carlo sampling techniques, where autocorrelations severely diminish the sampling efficiency on the approach to the continuum limit. A major caveat is that it is not yet well-understood how the size of models and the cost of training them is expected to scale. In previous work, we conducted an exploratory scaling study using two-dimensional ϕ^4 theory with up to 20^2 lattice sites, which suggested that training costs grow very quickly indeed. We present updated results using a more scalable architecture utilising convolutional neural networks, and discuss various factors contributing to the scalability of these methods.

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Learning trivializing flows

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The recent introduction of machine learning tecniques, especially normalizing flows, for the sampling of lattice gauge theories has shed some hope on improving the sampling efficiency of the traditional HMC algorithm. However, naive usage of normalizing flows has been shown to lead to bad scaling with the volume. In this talk we propose using local normalizing flows at a scale given by the correlation length. Even if naively these transformations have a very small acceptance, when combined with the HMC lead to algorithms with high acceptance and reduced autocorrelation times compared with HMC. Several scaling tests are performed in the ϕ^4 theory in 2D.

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Overcoming exponential volume scaling in quantum simulations of lattice gauge theories

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The study of real-time evolution of quantum field theories is known to be an extremely challenging problem for classical computers. Due to a fundamentally different computational strategy, quantum computers hold the promise of allowing for detailed studies of these dynamics from first principles. However, much like with classical computations, it is important that quantum algorithms do not have a cost that scales exponentially with the volume. In this paper, we present an interesting test case: a formulation of a compact U(1) gauge theory in 2+1 dimensions. A naive implementation onto a quantum circuit has a gate count that scales exponentially with the volume. We discuss how to break this exponential scaling by performing an operator redefinition that reduces the non-locality of the Hamiltonian and also provide explicit implementations using the Walsh function formalism. While we study only one theory as a test case, we expect the exponential gate scaling to persist for formulations of other gauge theories, including non-Abelian theories in higher dimensions.

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Exploring the phase structure of the multi-flavor Schwinger model with quantum computing

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We propose a variational quantum eigensolver suitable for exploring the phase structure of the multi-flavor Schwinger model in the presence of a chemical potential. The parametric ansatz we design incorporates the symmetries of the model and can be implemented on both measurement-based and circuit-based quantum hardware. We numerically demonstrate that our ansatz is able to capture the phase structure of the model and allows for faithfully approximating the ground state. Our results show that our approach is suitable for current intermediate-scale quantum hardware and can be readily implemented on existing quantum devices.

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Digitizing $\mathrm{SU}(2)$ gauge fields and what to look out for when doing so

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With the long term perspective of using quantum computers for lattice gauge theory simulations, an efficient method of digitizing gauge group elements is needed. We thus present our results for a handful of discretization approaches for the non-trivial example of $\mathrm{SU}(2)$, such as its finite subgroups, as well as different classes of finite subsets. We focus our attention on a freezing transition observed towards weak couplings. A generalized version of the Fibonacci spiral appears to be particularly efficient and close to optimal.

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Defining Canonical Momenta for Discretised SU(2) Gauge Fields

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Simulating SU(N) gauge theories on a quantum computer requires some form of digitization of the gauge degrees of freedom. Recently, we have proposed discretisation schemes, which offer in contrast to finite subgroups the possibility to freely refine the discretisation. Here we present an approach to define the corresponding canonical momentum operators. We present results on the restoration of the fundamental commutation relations towards continuous gauge field degrees of freedom.

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Toward Quantum Computing Phase Diagrams of Gauge Theories with Thermal Pure Quantum States

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Sign problems in Monte Carlo simulations have long hindered studies of phase diagrams of lattice gauge theories (LGTs) at finite densities. Quantum computation of LGTs does not encounter sign problems, but preparing thermal states needed for a complete phase-diagram analysis on quantum devices is a difficult and resource-intensive process. Thermal Pure Quantum (TPQ) states have been proposed in recent years as an efficient method to reliably estimate thermal expectation values on a quantum computer. We propose a new form of TPQ states, called Physical Thermal Pure Quantum (PTPQ) states, to quantum compute thermal expectation values and non-equal time correlation functions of LGTs at finite temperature and density. We illustrate the approach by computing the chiral phase diagram of a toy theory accessible to near-term quantum hardware, 1+1 dimensional $\mathbb{Z}_2$ LGT coupled to staggered fermions, and analyze the resource requirement of the associated quantum algorithms. Our approach may open new paths forward in simulating the phase diagram of strong interactions in nature using the ever-improving quantum computers.

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Quantum state preparation algorithms for the Schwinger model with a theta term

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Quantum computing is a promising new computational paradigm which may allow one to address exponentially hard problems inaccessible in Euclidean lattice QCD. Those include real-time dynamics, matter at non-zero baryon density, field theories with non-trivial CP-violating terms and can often be traced to the sign problem that makes stochastic sampling methods inapplicable. As a prototypical example we consider a low-dimensional theory, Quantum Electrodynamics in 1+1 space-time dimensions with a theta term. Using staggered fermions, this model can be mapped to a quantum Ising-like model with nearest-neighbor interactions which is well-suited for digital gate-based quantum computers. We study and compare properties of three algorithms that can be employed for the initial state preparations: Quantum Adiabatic Evolution (QAE), Quantum Approximate Optimization Algorithm (QAOA) as well as recently proposed Rodeo Algorithm. Understanding their convergence properties may be helpful for designing optimal algorithms with minimal number of CNOT gates for near-term noisy intermediate scale quantum (NISQ) devices that are currently within technological reach.

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Real time evolution and a traveling excitation in SU(2) pure gauge theory on a quantum computer.

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The Hamiltonian approach can be used successfully to study the real time evolution of a non-Abelian lattice gauge theory on the available noisy quantum computers. In this talk, results from the real time evolution of SU(2) pure gauge theory on IBM hardware are presented. The long real time evolution spanning dozens of Trotter steps with hundreds of CNOT gates and the observation of a traveling excitation on the lattice were made possible by using a comprehensive set of error mitigation techniques. Self-mitigation is our novel tool, which consists of using the same physics circuit as a noise-mitigation circuit.

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Determining the Mass Renormalization of the Schwinger Model with Wilson Fermions using Tensor Networks

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Studies of the Schwinger model in the Hamiltonian formulation have hitherto used the Kogut-Susskind staggered approach. However, Wilson fermions offer an alternative approach and are often used in Monte Carlo simulations. Tensor networks allow the exploration of the Schwinger model even with a topological θ-term, where Monte Carlo methods would suffer from the sign problem. Here, we study the one-flavour Schwinger model with Wilson fermions and a topological θ-term using Matrix Product States (MPS) methods in the Hamiltonian formulation. The mass parameter in this model receives an additive renormalization shift from the Wilson term. In order to perform a continuum extrapolation, the knowledge of this shift is important. We present a method suitable for tensor networks that determines the mass renormalization using observables such as the electric field density, which vanish when the renormalized mass is zero. Using this shift, the continuum extrapolation is performed for various observables.

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Improving Quantum Simulations towards lattice SU(3)

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Quantum simulations of QCD require digitization of the infinite-dimensional gluon field. Schemes for doing this with the minimum amount of qubits are desirable. A practical digitization for SU(3) gauge theories via its discrete subgroup S(1080) has been shown to allow classical simulations down to a=0.08 fm and reproduce thermal and glueball spectrum using modified and improved actions. Together with primitive gates and improved Hamiltonians for non-abelian gauge theories, the time is approaching where more realistic quantum resource estimates will become possible.

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Quantum Computing for Open Systems

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Open quantum systems are good models of many interesting physical systems. Non-Hermitian Hamiltonians are known to describe, or at least approximate some of these open quantum systems well. Recently, there has been an increase in interest in quantum algorithms for simulating such Hamiltonians, such as the Quantum Imaginary Time Evolution algorithm, and other ones based on trace preserving quantum operations, using an enlarged Hilbert space. The focus of our work is on testing the near-term applicability of some of these NISQ-era algorithms on real, noisy quantum hardware. We will look at the 1D quantum Ising model in complex parameter space. Such models have a rich phase-structure in the complex plane and studying them would allow us to explore critical regions such as Lee-Yang edges and Fisher zeros. We will also discuss the applicability of these algorithms for ground-state preparation.

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D_n Lattice Gauge Theory on the Quantum Annealer

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Using D-Wave's quantum annealer as a computing platform, we study lattice gauge theory with discrete gauge groups. As digitization of continuous gauge groups necessarily involves an approximation of the symmetry, we extend the formalism of previous studies on the annealer to finite, simply reducible gauge groups. As an example we use the dihedral group D_n with $n = 3, 4$ on a two plaquette ladder for which we provide proof-of-principle calculations of the ground-state and employ the known time evolution formalism with Feynman clock states.

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Quantum computing for lattice supersymmetry

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Future quantum computers will enable the study of real-time dynamics of non-perturbative quantum field theories without the introduction of the sign problem. We present ongoing progress on low-dimensional lattice systems which will serve as suitable testbeds for near-term quantum devices. The two systems studied to date are 0+1 dimensional supersymmetric quantum mechanics and the Wess-Zumino model in 1+1 dimensions. In both we comment on whether supersymmetry is dynamically broken for various superpotentials.

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Grassmann tensor-network method for strong-coupling QCD

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We present a tensor-network method for strong-coupling QCD with staggered quarks at nonzero chemical potential. After integrating out the gauge fields at infinite coupling, the partition function can be written as a full contraction of a tensor network consisting of coupled local numeric and Grassmann tensors. To evaluate the partition function and to compute observables, we develop a Grassmann higher-order tensor renormalization group method, specifically tailored for this model. We apply the method to the two-dimensional case and validate it by comparing results for the partition function, the chiral condensate and the baryon density with exact analytical expressions on small lattices up to volumes of 4×4. For larger two-dimensional volumes, we present first tensor results for the chiral condensate as a function of the mass and volume, and observe that the chiral symmetry is not broken dynamically in two dimensions. We also present tensor results for the number density as a function of the chemical potential, which hint at a first-order phase transition.

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Toward tensor renormalization group study of three-dimensional non-Abelian gauge theory

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We propose a method to represent the path integral over gauge fields as a tensor network. We introduce a trial action with variational parameters and generate gauge field configurations with the weight defined by the trial action. We construct initial tensors with indices labelling these gauge field configurations. We perform the tensor renormalization group with the initial tensors and optimize the variational parameters. As a first step to the TRG study of non-Abelian gauge theory in more than two dimensions, we apply this method to three-dimensional pure SU(2) gauge theory. Our result for the free energy agrees with the analytical results in weak and strong coupling regimes.

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Entanglement filtering and improved coarse-graining on two dimensional tensor networks including fermions

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Tensor renormalization group (TRG) has attractive features like the absence of sign problems and the accessibility to the thermodynamic limit, and many applications to lattice field theories have been reported so far. However it is known that the TRG has a fictitious fixed point that is called the CDL tensor and that causes less accurate numerical results. There are improved coarse-graining methods that attempt to remove the CDL structure from tensor networks. Such approaches have been shown to be beneficial on two dimensional spin systems. We discuss how to adapt the removal of the CDL structure to tensor networks including fermions, and numerical results that contain some comparisons to the plain TRG, where significant differences are found, will be shown.

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Symmetry breaking in an extended-O(2) model

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Motivated by attempts to quantum simulate lattice models with continuous Abelian symmetries using discrete approximations, we consider an extended-O(2) model that differs from the ordinary O(2) model by an explicit symmetry breaking term. Its coupling allows to smoothly interpolate between the O(2) model (zero coupling) and a q-state clock model (infinite coupling). In the latter case, a q-state clock model can also be defined for non-integer values of q. Thus, such a limit can also be considered as an analytic continuation of an ordinary q-state clock model to non-integer q. The phase diagram of the extended-O(2) model in the infinite coupling limit was established in our previous work, where it was shown that for non-integer q, there is a second-order phase transition at low temperature and a crossover at high temperature. In this work, we investigate the model at finite values of the coupling using Monte Carlo and tensor methods. The results may be relevant for configurable Rydberg-atom arrays.

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Density of states techniques for fermion worldlines

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Worldline representations were established as a powerful tool for studying bosonic lattice field theories at finite density. For fermions, however, the worldlines still may carry signs that originate from the Dirac algebra and from the Grassmann nature of the fermion fields. We show that a density of states approach can be set up to deal with this remaining sign problem, where finite density is implemented by working with a fixed winding number of the fermion worldlines. We discuss the approach in detail and show first results of a numerical implementation in 2 dimensions.

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Improved lattice method for determining entanglement measures in SU(N) gauge theories

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The determination of entanglement measures in SU(N) gauge theories is a non-trivial task. With the so-called "replica trick", a family of entanglement measures, known as "Rényi entropies", can be determined with lattice Monte Carlo. Unfortunately, the standard implementation of the replica method for SU(N) lattice gauge theories suffers from a severe signal-to-noise ratio problem, rendering high-precision studies of Rényi entropies prohibitively expensive.
In this work, we propose a method to overcome the signal-to-noise ratio problem and show some first results for SU(N) in 3 and 4 dimensions.

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Error Reduction using Machine Learning on Ising Worm Simulation

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We develop a method to improve on the statistical errors for higher moments using machine learning techniques. We present here results for the dual representation of the Ising model with an external field, derived via the high temperature expansion.
We compare two ways of measuring the same set of observables via machine learning: the first gives any higher moments but has larger statistical errors, the second provides only two point function but with small statistical errors. We use the decision tree method to train the correlations between the higher moments and the two point function and use the accurate data of these observable as a input data.

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An ML approach to the classification of phase transitions in many flavor QCD

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Supervised machine learning with a decoder-only CNN architecture is used to interpolate the chiral condensate in QCD simulations with five degenerate quark flavors in the HISQ action. From this a model for the probability distribution of the chiral condensate as function of lattice volume, light quark mass and gauge coupling is obtained. Using the model, first order and crossover regions can be classified, and the boundary between these regions can be marked by a critical mass. An extension of this model to studies of phase transitions in QCD with variable number of flavors is expected to be possible.

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Generative models for scalar field theories: how to deal with poor scaling?

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Deep generative models such as normalizing flows are suggested as alternatives to standard methods for generating lattice gauge field configurations. Previous studies on normalizing flows demonstrate proof of principle for simple models in two dimensions. However, further studies indicate that the training cost can be, in general, very high for large lattices. The poor scaling traits of current models indicate that moderate-size networks cannot efficiently handle the inherently multi-scale aspects of the problem, especially around critical points. In this talk, we explore current models that lead to poor acceptance rates for large lattices and explain how to use effective field theories as a guide to design models with improved scaling costs. Finally, we discuss alternative ways of handling poor acceptance rates for large lattices.

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Mitigating the Hubbard Sign Problem. A Novel Application of Machine Learning

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Many fascinating systems suffer from a severe (complex action) sign problem preventing us from simulating them with Markov Chain Monte Carlo. One promising method to alleviate the sign problem is the transformation towards Lefschetz Thimbles. Unfortunately, this suffers from poor scaling originating in numerically integrating of flow equations and evaluation of an induced Jacobian. In this talk we present a new preliminary Neural Network architecture based on complex-valued affine coupling layers. This network performs such a transformation efficiently, ultimately allowing simulation of systems with a severe sign problem. We test this method within the Hubbard Model at finite chemical potential, modelling strongly correlated electrons on a spatial lattice of ions.

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Infinite Variance in Fermionic Systems

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In Monte Carlo simulations of lattice quantum field theories, if the variance of an estimator of a particular quantity is formally infinite, or very large compared to the square of the mean, then expectation of the estimator can not be reliably obtained using the given sampling procedure. A particularly simple example is given by the Gross-Neveu model where Monte Carlo calculations involve the introduction of auxiliary bosonic variables through a Hubbard-Stratonovich (HS) transformation. Here, it is shown that the variances of HS estimators for classes of operators involving fermion fields are divergent in this model. To correctly estimate these observables, an infinite sequence of discrete Hubbard-Stratonovich transformations and a reweighting procedure that can be applied to any non-negative observable are introduced.

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Oscillating Autocorrelation and the HMC Algorithm

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The study of autocorrelation times of various meson operators and the topological charge revealed the presence of hidden harmonic oscillations of the autocorrelations (for the HMC).
These modes can be extracted by smoothing the observables with respect to the Monte Carlo time. While this smoothing procedure removes the largest share of the operator's signal, it can not be excluded that physically relevant contributions remain coupled to the oscillations. Furthermore, common statistical error analysis relies on binning and, thus, is not suited to remove non-decaying forms of autocorrelation.
I present a new error analysis framework that is based on defining an effective number of independent measurements via the ratio of the entropy of the correlated data distribution excluding autocorrelation and the entropy of the distribution including autocorrelation.
This framework is used to show that the autocorrelation oscillations are significant. I argue that the oscillations could be understood in terms of a 5D theory involving the Molecular dynamics momenta and are manifestations of the theoretical modes used by the Fourier acceleration approach. FA might control the modes and suppress their impact on the simulated physics.

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Transfer matrices and temporal factorization of the Wilson fermion determinant

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When lattice QCD is formulated in sectors of fixed quark numbers, the canonical fermion determinants can be expressed explicitly in terms of transfer matrices. This in turn provides a complete factorization of the fermion determinants in temporal direction. Here we present this factorization for Wilson-type fermions and provide explicit constructions of the transfer matrices. Possible applications of the factorization include multi-level integration schemes and the construction of improved estimators for generic n-point correlation functions.

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MLMC++ as a variance reduction method

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The trace of a function $f(A)$, in our case matrix inverse A^{-1}, can be estimated stochastically using samples $\tau^* A^{-1}\tau$ if the components of the random vectors τ obey an appropriate probability distribution, for example when τ is an i.i.d random vector with each component taking the value

± 1 at equal probability 0.5, this is known as Hutchinson estimator. This Hutchinson Monte-Carlo sampling, however, suffers from the fact that its accuracy depends quadratically on the sample size, making higher precision estimation very expensive. Since the variance of that approach is depending roughly on $\|A^{-1}|_F$, the challenge is to reduce that variance in some way.

Recently, an enhancement of Hutchinson's method has been proposed, termed `Hutch++`, in which the sample space is enriched by several vectors of the form $A^{-1}x$, x a random vector as in Hutchinson's method. Theoretical analyses show that under certain circumstances the number of these added sample vectors can be chosen in a way to reduce the accuracy dependence from $\mathcal{O}(n^2)$ to $\mathcal{O}(n)$.

In this talk, we combine `Hutch++` with our recently suggested multigrid multilevel Monte Carlo approach. We will present results that show that the two approaches behave additively, resulting in an overall variance reduction that cannot be obtained by just one of the approaches.

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Deflation in multigrid multilevel Monte Carlo

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In lattice QCD, the trace of the inverse of the discretized Dirac operator appears in the disconnected fermion loop contribution to an observable. As simulation methods get more and more precise, these contributions become increasingly important. Hence, we consider here the problem of computing the trace $\mathrm{tr}(D^{-1})$, with D the Dirac operator.

The Hutchinson method, which is very frequently used to stochastically estimate the trace of the function of a matrix, approximates the trace as the average over estimates of the form $x^H D^{-1} x$, with the entries of the vector x following a certain probability distribution. For N samples, the accuracy is $\mathcal{O}(1/\sqrt{N})$.

In recent work, we have introduced multigrid multilevel Monte Carlo: having a multigrid hierarchy with operators A_ℓ, P_ℓ and R_ℓ, for level ℓ, we can rewrite the trace in the form $\mathrm{tr}(A_0)^{-1} = \sum_{\ell=0}^{L-1} \mathrm{tr}(A_\ell^{-1} - P_{\ell+1} A_{\ell+1}^{-1} R_{\ell+1}) + \mathrm{tr}(A_L^{-1})$ (this reduced expression is in the special case when $R_\ell P_\ell = I$). We have seen significant reductions in the variance and the total work with respect to exactly-deflated Hutchinson.

In this talk, we explore the use of exact deflation in combination with the multigrid multilevel Monte Carlo method, and demonstrate how this leads to both algorithmic and computational gains.

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Towards the Application of Skewed Detailed Balance in Lattice Gauge Theories

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Most Monte Carlo algorithms generally applied to lattice gauge theories, among other fields, satisfy the detailed balance condition (DBC) or break it in a very controlled way. While DBC is not essential to correctly simulate a given probability distribution, it ensures the proper convergence after the system has equilibrated. While being powerful from this perspective, it puts strong constraints on the algorithms.
In this talk, I will discuss how breaking DBC can accelerate equilibration and how it can be tailored to improve the sampling of specific observables. By focusing on the case of the so-called Skewed Detailed Balance Condition, I will discuss applications in lattice gauge theories and the perspective of improving sampling over topology, for theories with distinct topological sectors.

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Efficiently unquenching electromagnetism in QCD+QED

Author: Tim Harris[1]

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In this talk I will outline a strategy to include the effects of the electromagnetic interactions of the sea quarks in QCD+QED. When computing leading order corrections in the electromagnetic coupling, the sea-quark charges result in quark-line disconnected diagrams which are not easily computed using stochastic estimators. An analysis of their variance can help construct better estimators for the relevant traces of quark propagators. I will present preliminary numerical results for the corresponding contributions to the hadronic spectrum using ensembles of domain-wall fermions from the RBC/UKQCD collaboration.

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Circuitizing product formulas for (1+1)D SU(2) lattice gauge theories: Lessons from alternative formulations

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We develop digital quantum algorithms for simulating a 1+1 dimensional SU(2) lattice gauge theory in the Schwinger boson and loop-string-hadron (LSH) formulations. These algorithms complement and improve on the algorithm by Kan & Nam (arXiv:2107.12769) based on the angular momentum basis, which generalized an earlier algorithm for a U(1) gauge theory (the Schwinger model) [Quantum 4, 306 (2020)]. We share the lessons learned regarding the application of product formulas to time evolution in various formulations of this lattice gauge theory, especially the identification of individually-circuitizable Hamiltonian terms, how to circuitize the SU(2) interactions, and what factors make a given formulation more or less costly. Within this framework, the LSH formulation leads to the least resource-intensive algorithm to date for the model considered.

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On the determination of the strong QCD coupling at the Z-pole with new gradient-flow based beta-function

Authors: Chik Him (Ricky) Wong[None]; Julius Kuti[None]; Szabolcs Borsanyi[None]; Zoltan Fodor[None]

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Recently we introduced a new gradient flow based beta-function which is defined over infinite Euclidean space-time to calculate and integrate infinitesimal scale changes in RG flows. It can be applied in high-precision determination of the strong coupling at the Z-pole in QCD. In this talk we will discuss the results and challenges of the method applied to quenched QCD (pure Yang-Mill theory) as a pilot test for application to full QCD.

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T-mu phase diagram using classical-quantum hybrid algorithm

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We report results on the Schwinger model at finite temperature and density using a variational algorithm for near-term quantum devices. We adapt β-VQE, a classical-quantum hybrid algorithm with a neural network, to evaluate thermal and quantum expectation values and study the phase diagram for the massless Schwinger model along with the temperature and density. By comparing the exact variational free energy, we find that the variational algorithm works for the Schwinger model for T>0 and μ>0. As a result, we obtain a qualitative picture of the phase diagram for the massless Schwinger model. This talk is based on arXiv:2205.08860.

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Strategies for the Determination of the Running Coupling of $(2+1)$-dimensional QED with Quantum Computing (II): Numerical Setup on Quantum circuits and Results

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The Ansatz for studying 2+1-dimensional QED on a quantum computer is described. This comprises the transposition of the system onto a quantum circuit, and the Jordan-Wigner transformation for the numerical implementation of fermionic degrees of freedom. In order to find the low-lying eigenvalues of a given Hamiltonian and hence the mass-gap, we discuss an extension of the Variational Quantum Eigensolver algorithm, the so called Variational Quantum Deflation method. Instead of constructing the Ansatz such that only physical, i.e. gauge invariant states are expressed, we define penalty terms in the Hamiltonian that suppress unphysical contributions on the final states. Tests in the pure gauge system are presented and first results for the mass gap and the plaquette expectation value in the full theory, including fermionic matter are given.

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Strategies for the Determination of the Running Coupling of $(2+1)$-dimensional QED with Quantum Computing (I): Motivations and Theoretical Foundations

Authors: Arianna Crippa[None]; Giuseppe Clemente[1]; Karl Jansen[2]

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In our work we study lattice QED in 2+1 dimensions,
which serves as a toy model for 3+1-dimensional QCD due to similarities in the behaviour of running coupling.
Moreover, the theory exhibits a rich and interesting phenomenology in itself and can be extended by including a topological term, non-zero matter density and time evolution.
Our main goal is to match physical quantities, such as mass gap and static force, between results obtained via quantum computing and Monte Carlo (MC) methods.
As a first step, we describe the QED system on the lattice: we consider Kogut-Susskind fermions with periodic boundary conditions. A discretization and truncation of the gauge group $U(1)$ is then introduced,
discussing possible encoding in the quantum circuit paradigm. In the analysis, we consider exact diagonalization results for both the electric and magnetic basis,
commenting on the convergence properties in terms of the coupling and truncation level. We then present two ideas to compute the running coupling. The first proposal is to use a step scaling approach, based on measurements of the static potential, and a match with MC for physical units in the intermediate to large coupling regime. From those results it is possible to compute the renormalized coupling and the Λ parameter along with perturbation theory calculations. The second proposal is a boosted coupling approach, i.e. redefine the perturbative expansion of the coupling constant by including the expectation value of the plaquette operator. In addition, we describe the scale setting by determining the renormalization scale in physical units for which the lattice spacing needs to be calculated.

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Strategies for the Determination of the Running Coupling of $(2+1)$-dimensional QED with Quantum Computing (I): Motivations and Theoretical Foundations

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Quantum computations are presently restricted to only a small number of qubits. At the example of 2+1 dimensional QED
we will describe how this fact can still be utilized by quantum computing (QC) small distance quantities such as the running
coupling in regimes that are difficult to reach for classical Markov Chain Monte Carlo (MCMC) calculations. By matching results for, e.g., the mass gap from QC and MCMC simulations at intermediate coupling values it becomes possible to obtain the physical value of the lattice spacing and hence the physical renormalization scale. This would allow eventually to compute the important Lambda paramter.

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$pi^+pi^+K^+$ and $pi^+K^+K^+$ interactions from the lattice

Authors: Andrew Hanlon[1]; Ben Horz[None]; Colin Morningstar[2]; Fernando Romero-Lopez[3]; Stephen Sharpe[4]; Zack Draper[4]

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We present results for the energy levels for two pions and a kaon, and two kaons and a pion, all at maximal isospin, on CLS ensembles D200 and N203, with pion/kaon masses of 200/480 MeV and 340/440 MeV, respectively. We use multiple frames, and have determined many energy levels on each ensemble. We fit these levels, together with those for $2\pi^+$, $2K^+$ and π^+K^+, to the predictions of the 2+1 three-particle quantization condition, and thus determine two- and three-particle K matrices. We compare our results to the expectations of chiral perturbation theory. Issues that arise in the implementation of the 2+1 quantization condition are discussed.

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Multihadron resonances in a finite volume

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The quest of unraveling the nature of excited hadrons necessarily involves determination of universal (reaction independent) parameters of these states. Such determinations require input, either from experiment or theory.
Lattice gauge theory is the only tool available to us to tackle the non-perturbative dynamics of QCD encoded in the determined finite-volume interaction spectra. Many insights have been gained on resonant two-body systems in the past by studying such spectra. Now – with the advent of the three-body finite-volume methods – advances are being made towards more complex systems. This progress will be discussed in the talk, including theoretical developments and applications to phenomenologically interesting systems.

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Three particle resonance in lattice ϕ^4 theory

Authors: Marco Garofalo[1]; Maxim Mai[2]; Fernando Romero-Lopez[3]; Akaki Rusetsky[1]; Carsten Urbach[1]

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We study a three-particle resonance in Euclidean Lattice ϕ^4 theory with two fields, having different masses and an interaction that makes the heavy field decay into three light. We observe the avoided-level crossings characteristic of a resonance and analyse the data with two formalisms FVU and RFT with an aim to determine the mass and the width of the resonance.

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Relativistic invariance of the NREFT three-particle quantization condition

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Recent years have witnessed a rapid growth of interest to the three-body problem on the lattice. In this connection, the derivation of a relativistic-invariant three-particle quantization condition, which relates the finite-volume lattice spectrum to the infinite-volume observables in the three-particle sector, has become a major challenge. First and foremost, providing a manifestly relativistic-invariant framework is important because the typical momenta of light particles studied on the lattice are generally not small, as compared to their mass. Moreover, Lorentz invariance puts stringent constraints on the possible form of the two- and three-body interactions, reducing the number of effective couplings needed for their parameterization. These constraints are absent in the non-invariant formulations, leading to an inflation of the number of independent parameters.

In the literature, there exist three different but conceptually equivalent formulations of the three-particle quantization condition. In this talk, I shall put the issue of the relativistic covariance of these formulations under a renewed scrutiny. A novel formulation is suggested, which is devoid of some shortcomings of the existing approaches related to the explicit non-covariance of the three-particle propagator. The proposed approach is based on the "covariant" NREFT framework. We reformulate this framework, choosing the quantization axis along an arbitrary timelike unit vector νμ, demonstrate the explicit relativistic invariance of the infinite-volume Faddeev equations and derive the modified quantization condition. The relativistic invariance is tested numerically, producing synthetic data for the energy levels in different moving frames.

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Two- and three-particle scattering in the (1+1)-dimensional O(3) non-linear sigma model

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In this talk, I will present our recent results on two- and three-particle scattering in the O(3) non-linear sigma model in 1+1 dimensions. We focus on the isospin-1 and 2 channels for the two-particle case, and the isospin-2 and 3 channels for three particles. We perform numerical simulations at four values of the physical volume and three lattice spacings, using a three-cluster generalization of the cluster update algorithm. The lattice results for two particles are then compared against exact analytic predictions of the finite-volume energy levels obtained combining analytic results for the phase shifts and the (1+1)-dimensional two-particle scattering formalism. For the three-particle results, we use the relativistic field theory (RFT) approach to constrain the scheme-dependent three-body interaction.

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Towards the finite-volume spectrum of the Roper resonance

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We investigate the energy levels corresponding to the Roper resonance based on a two-flavor chiral effective Lagrangian at leading one-loop order. We show that the Roper mass can be extracted from these levels for not too large lattice volumes.
Further, to include three body dynamics, such as $N\pi\pi$, we introduce a non-relativistic effective field theory for the Roper resonance within a covariant particle-dimer picture. This particle-dimer approach is a suitable framework to investigate three particle scattering relevant for the Roper channel. We analyze the appearing dimer fields, calculate the energy levels of the Roper resonance in a finite volume and compare the obtained energy levels with the results from the fully relativistic chiral effective Lagrangian.

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Finite volume pionless effective field theory for nuclear systems

Authors: Di Luo[1]; Phiala Shanahan[1]; William Detmold[1]; Fernando Romero-Lopez[1]; Sun Xiangkai[1]

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Finite-volume pionless effective field theory is an efficient framework with which to perform the extrapolation of finite-volume lattice QCD calculations of multi-nucleon spectra and matrix elements to infinite volume and to nuclei with larger atomic number. In this contribution, a new implementation of this framework based on correlated Gaussian wavefunctions optimized using differentiable programming and using a solution of a generalised eigenvalue problem is discussed. This approach is found to be more efficient than previous stochastic implementations of the variational method, as it yields comparable representations of the wavefunctions of nuclei with atomic number $A \leq 6$ with an order of magnitude fewer terms. Future applications to infinite-volume extrapolations of nuclear matrix elements will also be discussed.

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6144 Pions in a Box

Authors: Fernando Romero-Lopez[1]; Ryan Abbott[1]; William Detmold[1]

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This talk presents a new method for computing correlators for systems of many identical mesons. The method allows the computation of every meson correlator up to N mesons from propagators using only a single N by N eigendecomposition. This pushes the frontier of many-meson calculations from dozens to thousands, and as a demonstration I will present the computation of the maximal-isospin pion correlator for systems from 1 up to 6144 pions on an ensemble of Wilson fermions with slightly heavier than physical pions ($m_\pi \sim 170\,\mathrm{MeV}$). In addition, I will cover some aspects of analyzing such correlators, a task complicated by the sheer scale of the correlators involved.

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Implementing the finite-volume scattering and decay formalism across all three-pion isospin channels

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The formalism for relating finite-volume energies and matrix elements to scattering and decay amplitudes has been established for three-pion states with all possible isospins in the so called RFT (relativistic field theory) method. This necessarily leads to coupled-channel systems. The three-pion I=1 channel, for example, includes all two-pion isospins as sub-channels. In this talk I describe issues and strategies in implementing both the scattering and decay formalism in practice and show examples of the relations between finite- and infinite-volume quantities. I also describe an open source python library that supports the practical implementation.

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The Lüscher scattering formalism on the t-channel cut

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The Lüscher scattering formalism, the standard approach for relating the discrete finite-volume energy spectrum to two-to-two scattering amplitudes, fails when analytically continued so far below the infinite-volume two-particle threshold that one encounters the t-channel cut. This is relevant, especially in baryon-baryon scattering applications, as finite-volume energies can be observed in this below-threshold regime, and it is not clear how to make use of them. In this talk we present a generalisation of the scattering formalism that resolves this issue, allowing one to also constrain scattering amplitudes on the t-channel cut.

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Formalism for studying $\gamma^*\gamma^* \to \pi\pi$ in a finite, Euclidean spacetime

The $\gamma^*\gamma^* \to \pi\pi$ scattering amplitude can help constrain hadronic contributions to the anomalous magnetic moment of the muon, as well as structural information of glueball and tetraquark candidates. To leading order in QED, this amplitude can be accessed from matrix elements from non-local products of electromagnetic currents evaluated in an infinitely large Minkowski spacetime. In this talk, we present a model-independent formalism to determine this amplitude from finite, Euclidean spacetime correlation functions.

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Finite volume corrections for form factors of two-nucleon systems

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Determining the internal structure of hadrons is a necessary step to advance our understanding of the dynamics of confined partons. Extracting form factors of resonances directly from lattice QCD requires a formal connection between the finite volume Euclidean correlation functions and the infinite volume Minkowski amplitudes. In this talk we describe a novel procedure to extract transitions that couple states with at most two nucleons by exploiting the finite volume of the lattice. Building on previous work pertaining to spinless systems, we describe how to achieve the description of the spin degrees-of-freedom given their non-trivial finite-volume interaction with an external local current of arbitrary Lorentz structure. We will present the main ingredients of our derivation, and an outlook for future calculations where we discuss a case study of the significance of the finite-volume corrections as a function of the binding energy of a deuteron-like state.

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Evidence for a doubly charm tetraquark in DD^* scattering

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Recently, a doubly charmed tetraquark T_{cc} with flavor $cc\bar{u}\bar{d}$ just $0.36(4)$ MeV below D^0D^{*+} threshold was discovered by the LHCb collaboration. We present the first lattice study of DD^* scattering in this channel, involving rigorous determination of pole singularities in the related scattering amplitudes that point to the existence of T_{cc}. Working with a heavier than physical light quark mass, we find evidence for a shallow virtual bound state pole in the DD^* scattering amplitude with $l = 0$, which is likely related to T_{cc}.

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Doubly charm tetraquark and its quark mass dependence

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The doubly charm tetraquark with exotic quark composition $cc\bar{u}\bar{d}$ is the longest-lived exotic hadron discovered in the experiment. Our lattice simulation establishes a virtual bound state pole in DD* scattering at $m_\pi \simeq 280$ MeV, which is likely related to this state. We discuss the expected dependence of this hadron on the light and heavy quark masses, and compare it to the lattice results.

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Lattice study on a tetra-quark state T_{bb} in the HALQCD method

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We study a doubly-bottomed tetra-quark state $(bb\bar{u}\bar{d})$ with quantum number $I(J^P) = 0(1^+)$, denoted by T_{bb}, in lattice QCD with the NRQCD quark action for b quarks.
Employing $(2+1)$-flavor gauge configurations at $a \approx 0.09$ {fm} on $32^3 \times 64$ lattices, we have extracted the coupled channel HAL QCD potential between $\bar{B}\bar{B}^*$ and $\bar{B}^*\bar{B}^*$, which predicts an existence of a bound T_{bb} below the $\bar{B}\bar{B}^*$ threshold.
By extrapolating results at $m_\pi \approx 410,\ 570,\ 700$ {MeV} to the physical pion mass $m_\pi \approx 140$ {MeV}, we obtain a biding energy with its statistical error as $E^{\rm (single)}_{\rm binding} = 155(17)$ MeV and $E^{\rm (coupled)}_{\rm binding} = 83(10)$ MeV, where "coupled" means that effects due to virtual $\bar{B}^*\bar{B}^*$ states are included through the coupled channel potential, while only a potential for a single $\bar{B}\bar{B}^*$ channel is used in the analysis for "single".
A comparison shows that the effect from virtual $\bar{B}^*\bar{B}^*$ states is quite sizable to the binding energy of T_{bb}. We estimate systematic errors to be ± 20 MeV at most, which are mainly caused by the NRQCD approximation for b quarks.

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D meson – pion scattering on CLS 2+1 flavor ensembles

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We report progress on finite-volume determinations of heavylight-meson – Goldstone boson scattering phase shifts using the Luescher method on CLS 2+1 flavor gauge field ensembles. In a first iteration we will focus on D-meson – pion scattering in the elastic scattering region at various pion masses using ensembles with three lattice spacings. We employ ensembles on the CLS quark-mass trajectory with a fixed trace of the quark-mass matrix as well as ensembles with a strange-quark mass fixed close to its physical value, which will allow us to study both the light- and the strange quark-mass dependence of positive parity heavy-light hadrons close to threshold.

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Charmonium-like states with $J^P = 1^+$ and isospin 1

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We present an investigation of the spectrum of exotic charmonium-like mesons using lattice QCD. The focus is on $\bar{c}c\bar{q}q$ $J^{PC} = 1^{+\pm}$ states with isospin 1. Many mesons with properties incompatible with a $\bar{c}c$ structure have already been discovered, e. g. the Z_c mesons with isospin 1. A lattice study of a four-quark system with two different total momenta and on two different lattice sizes is made. We extract the energy levels, use Lüscher's formalism, and determine the scattering length for the $D\bar{D}^*$ scattering close to the threshold. A comparison to results from the phenomenological approaches is made, and the constraints on the scattering length are given.

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Optimized meson operators for charmonium spectroscopy and mixing with glueballs

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Optimized meson operators in the distillation framework are used to study the charmonium spectrum in two ensembles with two heavy dynamical quarks at half the physical charm quark mass but different lattice spacings. The use of optimal meson distillation profiles is shown to increase the overlap with the ground state significantly, as well as grant access to excited states, for multiple quantum numbers including hybrid states with very little additional cost. These same operators are also employed for the calculation of meson-glueball mixing.

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A determination of the gradient flow scale on $N_f = 2 + 1$ CLS ensembles

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We determine the gradient flow scale t_0 at the physical point with an overall uncertainty of around 0.5% using the Ξ baryon mass as input. We utilise 47 CLS ensembles generated with $N_f = 2 + 1$ non-perturbatively $O(a)$ improved Wilson dynamical fermions comprising six lattice spacings in the range $a = 0.04 - 0.1$ fm, spatial volumes with $LM_\pi > 4$ and pion masses ranging from around 420 MeV down to the physical point. Combined quark mass, continuum limit, and finite volume fits are performed to the baryon octet masses along three trajectories in the quark mass plane, which tightly constrains the mass of the Ξ baryon at the physical point. The strange and light quark sigma terms are determined for all octet baryons from the dependence of the baryon masses on the renormalized quark masses.

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Benchmark Continuum Limit Results for Spectroscopy with Stabilized Wilson Fermions

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The OpenLat initiative presents its results of lattice QCD simulations using Stabilized Wilson Fermions (SWF) using 2+1 quark flavors. Focusing on the $SU(3)$ flavor symmetric point $m_\pi = m_K = 412$ MeV, four different lattice spacings ($a = 0.064, 0.077, 0.094, 0.12$ fm) are used to perform the continuum limit to study the cutoff effects.

We present the results of basic gauge observables and of hadron masses, and their statistical properties like the autocorrelation. For the determination of the hadron masses we used a Bayesian analysis framework with constraints and model averaging to obtain the most unbiased results as possible.

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The static energy of a quark-antiquark pair from Laplacian eigenmodes

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We compute the static energy of a quark-antiquark pair in lattice QCD using a method which is not based on Wilson loops, but where the trial states are formed by eigenvector components of the covariant lattice Laplace operator. The computational effort of this method is significantly lower than the standard Wilson loop calculation, when computing the static potential not only for on-axis, but also for many off-axis quark-antiquark separations, i.e., when a fine spatial resolution is required, e.g., for string breaking calculations. We further improve the signal by using multiple eigenvector pairs, weighted with Gaussian profile functions of the eigenvalues, providing a basis for a generalized eigenvalue problem (GEVP), as it was recently introduced to improve distillation in meson spectroscopy. We show results from the new method for the static potential with dynamical fermions and demonstrate its efficiency compared to traditional Wilson loop calculations.

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Lattice field theory results for hybrid static potentials at short quark-antiquark separations and their parametrization

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We present SU(3) lattice Yang-Mills data for hybrid static potentials from five ensembles with different small lattice spacings and the corresponding parametrizations for quark-antiquark separations $0.08\text{ fm} \leq r \leq 1.12\text{ fm}$. We remove lattice discretization errors at tree level of perturbation theory and at leading order in a^2 as well as the a-dependent self-energy. In particular the tree-level improvement of static potentials is discussed in detail and two approaches are compared. The resulting parametrizations are expected to represent continuum results for hybrid static potentials within statistical errors.

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Antiheavy-antiheavy-light-light four-quark bound states

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We study four-quark systems using lattice QCD, which consist of two heavy antiquarks (either $\bar{b}\bar{b}$ or $\bar{b}\bar{c}$) and two light quarks (either ud or us) and search for bound states in these channels. In addition

to commonly used local interpolating operators we also employ scattering interpolating operators, which seem to be very important for an accurate extraction of possibly existing bound states as well as low-lying scattering states.
Moreover, we study the overlaps of trial states generated by our interpolating operators and low-lying energy eigenstates to obtain insights regarding the composition of the latter.

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The continuum limit with various discretized fermion actions

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We present the leading order mixed-action effect $\Delta_{\rm mix} \equiv m^2_{\pi,\rm vs} - \frac{m^2_{\pi,\rm vv}+m^2_{\pi,\rm ss}}{2}$ using HISQ, clover or overlap valence fermion actions on the gauge ensembles with kinds of sea fermion actions among a widely used lattice spacing range $a \in [0.04, 0.19]$~fm. The results suggest that $\Delta_{\rm mix}$ decreases on the forth order of the lattice spacing on the gauge ensembles with the dynamical chiral sea fermion, likes the Domain wall or HISQ fermion. When the clover sea fermion action which has explicit chiral symmetry breaking is used in the ensemble, $\Delta_{\rm mix}$ can be much larger regardless of the valence fermion action used.

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The glueball spectrum with $N_f = 4$ light fermions

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We investigate the glueball spectrum for $N_f = 4$ fermions corresponding to low pion masses of $m_\pi \sim 260$MeV. We do so by making use of configurations produced with maximally twisted fermions within the framework of the Extended Twisted Mass Collaboration (ETMC). We extract states that belong to irreducible representations of the octagonal group of rotations R in combination with the quantum numbers of charge conjugation C and parity P, i.e. R^{PC}. We implement the Generalized Eigenvalue Problem (GEVP) using a basis consisting only of gluonic operators. The purpose of this work is to investigate the effect of light dynamical quarks on the glueball spectrum and how this compares to the statistically more accurate spectrum of pure gauge theory. We employed large ensembles of the order of $\sim calO(10\mathrm{K})$ configurations each for three different lattice spacings. Our results demonstrate that in the scalar channel A_1^{++} we obtain an additional state due to inclusion of the dynamical quarks while the mass of the tensor glueball $J^{PC} = 2^{++}$ appears to be insensitive to the inclusion of sea quarks. In addition we perform an investigation of the low lying spectrum of the representation A_1^{++} for $N_f = 2 + 1 + 1$ twisted mass quarks with low masses and demonstrate that the lowest mass depends strongly on the pion mass. This suggests that the ground state of the scalar glueball has a quark content.

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Lattice calculation of glueball masses using the renormalized energy-momentum tensor with gradient flow

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It is a fundamental question: what is the origin of the glueball masses? In the pure Yang-Mills theory, there is no mass scale in the classical level, while the breaking of scale invariance is induced by quantum effects. This is regarded as the trace anomaly, which is associated with the non-vanishing trace of the energy-momentum tensor (EMT) operator. In this context, the origin of the glueball masses can be attributed to the trace anomaly. Our purpose is to quantify how much the trace anomaly contributes to the glueball masses by using lattice simulations. Once one can have the renormalized EMT operator $T_{\mu\nu}$, the hadron matrix element of T_{00} directly provides the mass of hadron. Therefore, it is natural to consider the mass decomposition in terms of the trace and traceless part of the EMT operator. However, it is hard to construct the renormalized EMT operator on the lattice, where the loss of translational invariance is inevitable due to the discretization of the space-time. To overcome this problem, H. Suzuki proposed that the gradient Yang-Mills flow approach can be utilized to construct the renormalized EMT operator from the flowed fields. In this talk, we directly measure the glueball matrix element of T_{00} that is calculated by the gradient flow method, and then evaluate the contributions of the trace anomaly to the scalar glueball mass.

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Anisotropy from the Wilson flow in QED in 2+1 dimensions

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Lattice simulations of QED in 2+1 dimensions are done both in the Lagrangian and Hamiltonian formalism. Though equivalent in the continuum limit, at finite lattice spacing there is no trivial correspondence among the physical parameters, and a matching is required. This can be done non-perturbatively, finding the Hamiltonian parameters that reproduce the $a_t \to 0$ limit of asymmetric lattice actions. In this work we consider the pure gauge theory on a torus $L^2 \times T$ for several values of β and of the anisotropy ξ. We show how to extract the mass gap of the theory and how to compute the renormalized anisotropy using both the static potential and the Wilson flow evolution of gauge fields.

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Scale Setting for RBC-UKQCD 2+1 flavor Domain Wall Fermion Lattices

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The RBC and UKQCD Collaborations continue to generate 2+1 flavor domain wall fermion ensembles to support a variety of physics goals. With the current set of ensembles, which includes one with physical quark masses and an inverse lattice spacing of 2.7 GeV, we can revisit the scale setting approach we have previously used in Phys. Rev. D 93 (2016) 7, 074505. This global-fit approach involves a simultaneous fit to a number of observables on a collection of ensembles, using an expansion in light-quark masses and finite lattice spacing errors, along with an expansion about the physical strange quark mass. We report on our results to date, along with our estimates of the systematic errors in our procedure.

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Setting the Scale Using Baryon Masses with Isospin-Breaking Corrections

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We present first results from our effort to incorporate isospin-breaking effects stemming from the non-degeneracy of the light quark masses and electromagnetic interactions into the determination of the lattice scale. To this end we compute the masses of octet and decuplet baryons on isospin-symmetric ensembles generated by the CLS effort for $N_f = 2 + 1$ flavours and include isospin-breaking
effects perturbatively. We show leading-order results for baryon masses on two ensembles with $m_\pi \approx 290\,\mathrm{MeV}$ and $m_\pi \approx 215\,\mathrm{MeV}$ at a lattice spacing of $a \approx 0.076\,\mathrm{fm}$.

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Static Energy in (2+1+1)-Flavor Lattice QCD: Scale Setting and Charm Effects

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We present results for the static energy in (2+1+1)-flavor QCD over a wide range of lattice spacings and several quark masses, including the physical quark mass, with ensembles of lattice-gauge-field configurations made available by the MILC Collaboration. We obtain results for the static energy out to distances of nearly 1 fm, allowing us to perform a simultaneous determination of the scales r_1 and r_0 as well as the string tension, σ. For the smallest three lattice spacings we also determine the scale r_2. Our results for $\frac{r_0}{r_1}$ and $r_0\sqrt{\sigma}$ agree with published (2 + 1)-flavor results. However, our result for $\frac{r_1}{r_2}$ differs significantly from the value obtained in the (2 + 1)-flavor case, which is most likely due to the effect of the charm quark. We also report results for r_0, r_1, and r_2 in fm, with the former two being slightly lower than published (2 + 1)-flavor results. We study in detail the effect of the charm quark on the static energy by comparing our results on the finest two lattices with the previously published (2 + 1)-flavor QCD results at similar lattice spacing. We find that for $r > 0.2$~fm our results on the static energy agree with the (2 + 1)-flavor result, implying the decoupling of the charm quark for these distances. For smaller distances, on the other hand, we find that the effect of the dynamical charm quark is noticeable. The lattice results agree well with the two-loop perturbative expression of the static energy incorporating finite charm mass effects. This is the first time that the decoupling of the charm quark is observed and quantitatively analyzed on lattice data of the static energy.

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Two-baryon variational spectroscopy

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Variational methods can be used to provide robust upper bounds on the energy spectra of hadrons and nuclei, but the presence of small energy gaps for multi-hadron states makes it difficult to ensure that the ground- and lowest-energy excited-states have been identified. I will discuss recent calculations of two-baryon systems using large and varied sets of interpolating operators, including non-local products of plane-wave baryons as well as operators spanning the full Hilbert space of local six-quark operators, to probe for the existence of two-baryon bound states at unphysically large quark masses. Results for baryon-baryon scattering phase shifts and their implications for understanding the quark mass dependence of baryon-baryon interactions will also be discussed.

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Hadronic observables from master-field simulations

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Substantial progress has been made recently in the generation of master-field ensembles.
This has to be paired with efficient techniques to compute observables on gauge field configurations with a large volume.
Here we present the results of the computation of hadronic observables, including hadron masses and meson decay constants, on large-volume and master-field ensembles with physical volumes of up to $(18\,\mathrm{fm})^4$ and $m_\pi L$ up to 25, simulated using $N_\mathrm{f} = 2 + 1$ stabilized Wilson fermions.
We obtain sub-percent determinations from single gauge configurations with the combined use of position-space techniques, volume averages and master-field error estimation.

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Non-perturbative heavy quark action tuning using machine learning

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We present a fully non-perturbative determination of a relativistic heavy quark action's parameters on the CLS ensembles using neural networks, with a particular focus on the charm sector. We then further illustrate the applicability of such an approach for lattice NRQCD bottom quarks.

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Exploring distillation at the SU(3) flavour symmetric point

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In this talk we present an exact distillation setup with stabilised Wilson fermions at the SU(3) flavour symmetric point utilising the flexibility of the Grid and Hadrons software libraries. This work is a stepping stone towards the non-perturbative investigation of hadronic D-decays where we need to control the multi-hadron final states. As a first step we study two-to-two s-wave scattering of pseudoscalar mesons. In particular we examine the reliability of the extraction of finite volume energies as a function of the number of eigenvectors of the gauge-covariant Laplacian entering our distillation setup.

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Resolving the NN controversy: a direct comparison of methods used for Luscher and the potential

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An understanding of the nearly decades-long controversy between calculations of nucleon-nucleon interactions using the Luscher spectroscopy method and the HALQCD potential method has seen significant advancement in recent years due to the efforts of several groups. In particular, the use of improved operator methods has shed light on possible issues related to excited state contamination, while the first study of the lattice spacing dependence in a baryon-baryon system has shown large potential discretization systematics. In this talk, I will present a new study which compares the use of all methods in the literature for computing NN interactions on a single ensemble, in order to discriminate between excited state contamination and discretization effects, and discuss conclusions that this controversy has finally brought to light.

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Investigating Unitarity Violation With Chiral Perturbation Theory

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Partial quenching can be used to avoid isospin mixing in a theory incorporating a mass twist, but comes at the cost of introducing unitarity violation. This talk will examine pion-pion scattering in partially-quenched twisted-mass lattice QCD using chiral perturbation theory. The specific partially-quenched setup corresponds to that used in numerical lattice QCD calculations of the $I = 0$ scattering length. We study previously unquantified discretization errors proportional to a^2, with a the lattice spacing, and newly identified errors that arise due to the use of Lüscher's two-particle quantization condition in a theory that is not unitary. The discretization errors may be as large as $\sim 100\%$ but can be systematically subtracted using a calculation of the $I = 2$ scattering amplitude in the same partially-quenched framework. The error from the violation of unitarity is $\sim 25\%$ and will be difficult to reduce in practice.

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Long-range matrix elements with three-body intermediate states

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Several outstanding puzzles involve electroweak interactions of low-energy nuclear systems. Observables such as long-range matrix elements can be used to study processes such as neutral meson mixing or the substructure of hadrons. Contributions from multi-hadron states to these matrix elements are central to many of these puzzles. In this talk, we present a framework for studying long-range matrix elements from lattice QCD, which extends previous work to include three-hadron on-shell effects. We show the relevant finite-volume scaling relations for connecting correlation functions from lattice QCD to the infinite-volume transition amplitudes.

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The long-distance behavior of the vector correlator from pi-pi scattering at the physical point.

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We present the finite volume contributions to the long distance behavior of the vector correlator, which is dominated by the two-pion scattering states in the I = 1 channel. The finite volume spectroscopy calculations have been performed using the (stochastic) distillation framework on the physical point Nf = 2 + 1 CLS ensemble. We also compute the timelike pion form factor to reconstruct the long distance part of the vector correlator. The reconstructions improve the lattice estimates of hadronic vacuum polarization contribution to the muon anomalous magnetic moment.

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Precise determination of decay rates for $J/\Psi \to \gamma\eta_c$, $J/\Psi \to \eta_c e^+e^-$ and $\eta_c \to \gamma\gamma$

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We calculate the decay rates for $J/\Psi \to \gamma\eta_c$, $J/\Psi \to \eta_c e^+e^-$ and $\eta_c \to \gamma\gamma$ in lattice QCD with the effect of u, d, s and c quarks in the sea for the first time. Our calculations are carried out on gluon field configurations generated by the MILC collaboration that include 2+1+1 flavours of Highly

Improved Staggered sea quarks. Valence c quarks also use the Highly Improved Staggered Quark action. Extrapolation to the continuum and to physical quark masses is controlled through the use of four different lattice spacings that range from 0.015 fm to 0.045 fm and u/d sea quarks with two masses: one-fifth that of the s quark mass; and the physical u/d mass. Our results are more accurate than those from previous lattice QCD calculations.

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Hadronic Parity Violation from Twisted Mass Lattice QCD

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We present results for an exploratory lattice calculation of the leading parity-violating pion-nucleon coupling h^1_π. Based on the PCAC relation we use a parity-conserving Lagrangian and focus on the techniques to determine the nucleon matrix elements of the effective four-quark operators. For our study we employ an ensemble of Twisted Mass fermions with 260 MeV pion mass. Barring mixing with lower-dimensional operators and renormalization at this stage, we discuss our estimate h^1_π.

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An update on QCD+QED simulations with C* boundary conditions

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We give an update on the ongoing effort of the RC* collaboration to generate fully dynamical QCD+QED configurations with C* boundary conditions using the openQ*D code. The simulations are tuned to the U-symmetric point ($m_d = m_s$) with pions at $m_{\pi^\pm} \approx 400$ MeV. The splitting of the light mesons is used as one of three tuning observables and fixed to $m_{K^0} - m_{K^\pm} \approx 5$ MeV and $m_{K^0} - m_{K^\pm} \approx 25$ MeV on ensembles with renormalized electromagnetic coupling $\alpha_R \approx \alpha_{\text{phys.}}$ and $\alpha_R \approx 5.5\alpha_{\text{phys.}}$ respectively. In this talk we will discuss some details concerning our tuning strategy, we will present our calculation of the meson and baryon masses, and we will comment on finite-volume effects comparing meson masses on two different volumes with $m_{\pi^\pm}L \approx 3.2$ and $m_{\pi^\pm}L \approx 5.1$. Finally, we will also present a cost analysis for our simulations. More technical details will be discussed in the companion poster presented by A. Cotellucci.

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The σ resonance as a bound, virtual bound and resonant estate.

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We determine, from Lattice QCD, the elastic $\pi\pi$ scattering amplitude in the isoscalar $I = 0$ channel, and the σ resonance. We extract its lineshape for two different quark masses corresponding with $m_\pi \sim 283$ and 330 MeV; where it is predicted that this state transitions from bound to virtual bound. In order to provide an accurate picture we use a high statistics volume for the heavier pion mass, and two for the lighter. The comparison between the two masses showcases very different lineshapes for the phase shifts. This is related to the different behavior of the σ resonance for these values of its quark mass dependence.

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The I=1/2 and 3/2 K-pi scattering length with domain wall fermions at physical pion mass with all-to-all propagators

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We present our calculations for the I=1/2,3/2 K-pi scattering length, extracted from the interaction energy of Euclidean two-point functions. We use the domain wall fermion action with physical quark masses at a single lattice spacing. We are specifically interested in the systematic effects due to around-the-world terms on the overall determination of the scattering length. We present our progress and discuss the various systematic effects in our preliminary results.

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Towards $K\pi$ scattering with domain-wall fermions at the physical point using distillation

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Resonances play an important role in Standard Model phenomenology. In particular, hadronic resonances are found in flavour-physics processes, such as B and D decays, which can be central for New Physics searches. Lattice QCD simulations combined with the finite-volume method can nowadays be used to reliably study strongly coupled scattering processes such as $K\pi$ and thus the hadronic

resonance K^*. In this work, we approach $K\pi$ scattering on a domain-wall $N_f = 2+1$ RBC-UKQCD ensemble at the physical point. We use the distillation method within Grid and Hadrons software to compute sets of operator basis. That allows solving an eigenvalue problem to extract the low-energy finite-volume spectra, which is then translated into scattering information. We update the state of the calculation by reviewing the smearing process and displaying consistency checks and conclude by showing preliminary data.

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Electromagnetic form factors of the proton and neutron from $N_\mathrm{f} = 2 + 1$ lattice QCD

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We present results for the electromagnetic form factors of the proton and neutron computed on the Coordinated Lattice Simulations (CLS) ensembles with $N_\mathrm{f} = 2 + 1$ flavors of $\mathcal{O}(a)$-improved Wilson fermions and an $\mathcal{O}(a)$-improved conserved vector current. In order to estimate the excited-state contamination, we employ several source-sink separations and apply the summation method. The quark-disconnected diagrams entering the isoscalar quantities are computed explicitly. For this purpose, a stochastic estimation based on the one-end trick is performed, in combination with a frequency-splitting technique and the hopping parameter expansion. By these means, we obtain a clear signal for the form factors including the quark-disconnected contributions, which have a statistically significant effect on our results. From the Q^2-dependence of the form factors, we determine the electric and magnetic charge radii and the magnetic moment of the proton and neutron. The chiral interpolation is carried out by simultaneously fitting the pion mass and Q^2-dependence of our form factor data directly to the expressions resulting from covariant chiral perturbation theory including vector mesons. To assess the influence of systematic effects, we average over various cuts in the pion mass and the momentum transfer, as well as over different models for the lattice spacing dependence, using weights derived from the Akaike Information Criterion (AIC).

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Nucleon electromagnetic form factors using N_f=2+1+1 twisted mass fermion ensembles at the physical mass point

Authors: Constantia Alexandrou[None]; Giannis Koutsou[1]; Gregoris Spanoudes[1]; Jacob Finkenrath[None]; Karl Jansen[2]; Kyriakos Hadjiyiannakou[3]; Martha Constantinou[4]; Martha Constantinou[4]; Simone Bacchio[1]

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We present results for the nucleon electromagnetic form factors using N_f=2+1+1 twisted mass lattice QCD with clover improvement and with quarks with masses tuned to their physical values. Our preliminary analysis includes three ensembles at similar physical volume and lattice spacings a ∼0.08 fm, ∼0.07 fm, and ∼0.06 fm allowing us to take the continuum limit directly at the physical mass point. For each ensemble we assess excited state effects using several sink-source time separations in the range 0.8 fm - 1.6 fm, exponentially increasing statistics with the separation.

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Gravitational structure of the proton and pion

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We present the results of a complete lattice calculation of the gravitational form factors (GFFs) of the proton and pion, including glue as well as connected and disconnected quark contributions, on an ensemble with 2+1 flavors of Wilson fermions with close-to-physical pion mass of 170 MeV. We use these results to predict full, physical densities of energy, pressure, and shear forces inside the proton and pion via the relation of GFFs with the energy-momentum tensor.

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Nucleon isovector form factors from 2+1-flavor domain-wall QCD at physical mass

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Nucleon isovector form factors calculated on a 2+1-flavor domain-wall-fermions ensemble with strange and degenerate up and down quarks at physical mass and lattice cut off, a^{-1}, of about 1.730(4) GeV, will be presented. The ensemble was generated jointly by RBC and UKQCD collaborations with a spatial extent of $48a$ or about 5.5 fm. The form factors are calculated in collaboration with LHP as well. The resulting shape parameters of the form factors such as vector-charge mean squared radius, $\langle r_1^2 \rangle$, or anomalous magnetic moment, $F_2(0)$ appear less dependent on possible excited-state contaminations than the corresponding charges. This is likely because of larger statistical fluctuations at finite momentum transfer. For example, preliminary estimates are $\langle r_1^2 \rangle \sim 0.142(13)\,\mathrm{fm}^2$ and $F_2(0) \sim 3.22(8)$.

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Nucleon form factors with sLapH OR nucleon-pion sigma term from MDWF on HISQ

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I will discuss progress on computing nucleon elastic form factors with the stochastic LapH method.

OR, if results these results are not yet ready,

I will discuss preliminary results on the nucleon-pion sigma term determined with O(30) HISQ ensembles with MDWF valence fermions. The nucleon spectrum results are determined at 7 pion masses in the range 130 < Mpi < 400 MeV, four lattice spacings in the range 0.06 < a < 0.15 fm, and several volumes. The nucleon-pion sigma term is determined through a derivative of the extrapolation of the nucleon mass to the physical point.

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Isovector Axial Form Factor of the Nucleon from Lattice QCD

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We present results for the isovector axial form factor of the nucleon computed on a set of $N_f = 2+1$ CLS ensembles with $\mathcal{O}(a)$-improved Wilson fermions and the Lüscher-Weisz gauge action. The set of ensembles covers a range of pion masses from 353 MeV down to the physical pion mass, and lattice spacings between 0.05 fm and 0.09 fm.

We use the summed operator insertion method (summation method) to suppress the contamination from excited states, and use the z-expansion to parametrise the Q^2-behaviour of the form factor. Systematic effects are taken into account by performing a number of fits with cuts for the pion mass and lattice spacing and with different ansätze for the chiral and infinite-volume extrapolations. Our final result for the z-expansion coefficients is provided by an Akaike-information-criterion based model average.

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Mass and isovector matrix elements of the nucleon at zero-momentum transfer

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We present the current status of our analyis of nucleon structure observables including isovector charges and twist-2 matrix elements as well as the nucleon mass. Results are computed on a large

set of CLS $N_f = 2 + 1$ gauge ensembles with $M_\pi \approx 0.130\text{MeV} \ldots 350\text{MeV}$, four values of the lattice spacing $a \approx 0.05\text{fm} \ldots 0.09\text{fm}$ and covering a large range of physical volumes. Compared to the results presented at last year's conference we have added data on a very fine and large box at small light quark mass ($T \times L^3 = 192 \times 96^3$, $M_\pi = 172\text{MeV}$, $a = 0.05\text{fm}$). Besides, additional (intermediate) source-sink separations have been computed on the coarser ensembles, further increasing effective statistics and allowing for a more fine-grained control in the treatment of the excited state contamination. Excited states in the nucleon matrix elements are tamed by a simultaneous, two-state fit ansatz using the summation method. The physical extrapolation for all observables including the nucleon mass can be carried out in a global fit.

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Resonance form factors from finite-volume correlation functions with the external field method

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The study of resonance form factors in lattice QCD is a challenging endeavor. Namely, the infinite-volume limit, $L \to \infty$, is not well defined in the matrix element (here, L is the spacial extension of a rectangular lattice). This irregular behavior persists even after multiplying each external leg with the pertinent Lellouch-Lüscher factor and stems from the so-called triangle diagram.

In this talk, I shall discuss a novel method to tackle this problem in which the difficulty, related to the presence of the triangle diagram, never emerges. The approach is based on the study of two-particle scattering in a static, spatially periodic external field by using a generalization of the Lüscher method in the presence of such a field. In addition, I shall demonstrate that the resonance form factor in the Breit frame is given by the derivative of a resonance pole position in the complex plane with respect to the coupling constant of the external field. This result is a generalization of the well-known Feynman-Hellmann theorem for the form factor of a stable particle.

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Towards the continuum limit of nucleon form factors at the physical point using lattice QCD

Author: Ryutaro Tsuji[1]

Co-authors: Ken-Ichi Ishikawa [2]; Eigo Shintani [3]; Yasumichi Aoki [4]; Yoshinobu Kuramashi [5]; Shoichi Sasaki [1]; Takeshi Yamazaki [3]

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We present results of nucleon structure studies measured in 2+1 flavor QCD with the physical light quarks (m_π = 135 MeV) in a large spatial extent of about 10 fm. Our calculations are carried out with the PACS10 gauge configurations generated by the PACS Collaboration with the stout-smeared $O(a)$ improved Wilson fermions and Iwasaki gauge action at β=1.82 and 2.00 corresponding to the lattice spacings of 0.085 fm (coarser) and 0.063 fm (finer) respectively. When we compute nucleon two-point and three-point functions, the all-mode-averaging technique is employed in order to reduce the statistical errors significantly without increasing computational costs. At both lattice spacings, we evaluate nucleon form factors associated with lepton-nucleon elastic scattering measurements.

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Sigma Terms and Nucleon Charges from $N_f = 2 + 1$ Lattice Simulations

Author: Daniel Jenkins[1]

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We report on the recent progress of our analysis into nucleon sigma terms, as well as the singlet axial and tensor nucleon charges.
These are extracted from the CLS gauge configurations, which utilise the Lüscher-Weisz gluon action and the Sheikholeslami-Wohlert fermion action with $N_f = 2 + 1$ fermions, with pion masses ranging from the physical value up to 410 MeV, and lattice spacings covering a range between 0.09fm and 0.04fm.
We have employed a variety of methods to determine the necessary correlation functions, including the sequential source method for connected contributions, and the truncated solver method for disconnected contributions.
Extrapolation to the physical point involves leading order discretisation, chiral and finite-volume effects.

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The pion-nucleon sigma term with $N_f = 2+1$ O(a)-improved Wilson fermions

Authors: Andria Agadjanov[1]; Dalibor Djukanovic[None]; Georg von Hippel[2]; Harvey B. Meyer[1]; Konstantin Ottnad[3]; Hartmut Wittig[None]

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We present an analysis of the pion-nucleon sigma term on the CLS ensembles with $N_f = 2+1$ flavors of $calO(a)$-improved Wilson fermions. We perform a chiral interpolation based on ensembles with pion masses ranging from 130 MeV to roughly 350 MeV. The analysis covers four lattice spacings between $a \approx 0.05\text{fm} \ldots 0.09\text{fm}$, allowing for an estimate of systematics associated with lattice artefacts.

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Sigma terms of the baryon octet in $N_\mathrm{f} = 2 + 1$ QCD with Wilson quarks

Author: Pia Leonie Jones Petrak[1]

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A lot of progress has been made in the direct determination of nucleon sigma terms. Using similar methods we consider the sigma terms of the other octet baryons as well. These are determined on CLS gauge field ensembles employing the Lüscher-Weisz gluon action and the Sheikholeslami-Wohlert fermion action with $N_\mathrm{f} = 2 + 1$. The ensembles have pion masses ranging from $410\,\mathrm{MeV}$ down to the physical value and lattice spacings covering a range between $0.039\,\mathrm{fm}$ and $0.098\,\mathrm{fm}$. We present a preliminary chiral extrapolation for $a \approx 0.06$ fm along a trajectory where the sum of the sea quark masses is kept constant. We discuss multi-state fits to tackle the well-known problem of excited state contamination comparing ratio and summation method.

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Transverse momentum-dependent parton distributions for longitudinally polarized nucleons from domain wall fermion calculations at the physical pion mass

Authors: Andrew Pochinsky[1]; Christos Kallidonis[2]; Giorgio Silvi[3]; Jeremy R Green[4]; John Negele[1]; Michael Engelhardt[5]; Nesreen Hasan[3]; Sergey Syritsyn[6]; Stefan Krieg[7]; Stefan Meinel[8]; Taku Izubuchi[9]

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Previous Lattice QCD calculations of nucleon transverse momentum-dependent parton distributions (TMDs) focused on the case of transversely polarized nucleons, and thus did not encompass two leading-twist TMDs associated with longitudinal polarization, namely, the helicity TMD and the worm-gear TMD corresponding to transversely polarized quarks in a longitudinally polarized nucleon. Based on a definition of TMDs via hadronic matrix elements of quark bilocal operators containing staple-shaped gauge connections, TMD observables characterizing the aforementioned two TMDs are evaluated, utilizing a RBC/UKQCD domain wall fermion ensemble at the physical pion mass.

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Lattice QCD Determination of the Bjorken-� Dependence of PDFs at Next-to-next-to-leading Order

Authors: Andrew Hanlon[1]; Xiang Gao[2]; Peter Petreczky[1]; Philipp Scior[1]; Sergey Syritsyn[3]; Swagato Mukherjee[1]; Yong Zhao[2]

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We report the first lattice QCD calculation of pion valence quark distribution with next-to-next-to-leading order perturbative matching correction, which is done using two fine lattices with spacings $a = 0.04$ fm and 0.06 fm and valence pion mass $m_\pi = 300$ MeV, at boost momentum as large as 2.42 GeV. As a crucial step to control the systematics, we renormalize the pion valence quasi distribution in the recently proposed hybrid scheme, which features a Wilson-line mass subtraction at large distances in coordinate space, and develop a procedure to match it to the $\overline{\mathrm{MS}}$ scheme. We demonstrate that the renormalization and the perturbative matching in Bjorken-x space yield a reliable determination of the valence quark distribution for x in range of 0.03 $\sim$ 0.80 with 5–20 % uncertainties.

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Quark Transversity Distributions in the Nucleon using the LaMET approach

Authors: Fei Yao[1]; Lisa Walter[2]

Co-authors: Andreas Schäfer [2]; Hai-Tao Shu [2]; Jian-Hui Zhang [1]; Jiunn-Wei Chen [3]; Jun Hua [4]; Lingquan Ma [1]; Luchang Jin [5]; Peng Sun [6]; Sebastian Lahrtz [2]; Wolfgang Söldner [2]; Xiangdong Ji [7]; Xiaonu Xiong [8]; Yi-Bo Yang [9]; Yong Zhao [10]; Yu-Sheng Liu [11]; Yushan Su [7]

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We report a state-of-the-art lattice QCD calculation of the isovector quark transversity distribution of the proton in the continuum and physical limit using large-momentum effective theory. The calculation is done at three lattice spacings $a \approx$ {0.085, 0.064, 0.049} fm and various pion masses $m_\pi \approx$ {350, 280, 220} MeV, with the proton momenta up to 2.8 GeV. The result is non-perturbatively renormalized in the hybrid scheme with self renormalization which is the only infrared-free approach known so far, and extrapolated to the continuum, physical and infinite momentum limit. We also

make a comparison with recent global analyses for the nucleon isovector quark transversity distribution.

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Study of quasi-beam function in twisted mass lattice QCD

Authors: Aniket Sen[1]; Aurora Scapellato[2]; Carsten Urbach[1]; Constantia Alexandrou[None]; Fernanda Steffens[1]; Gregoris Spanoudes[3]; Jacopo Tarello[3]; Karl Jansen[4]; Krzysztof Cichy[5]; Kyriakos Hadjiyiannakou[6]; Martha Constantinou[2]; Shi-Cheng Xia[7]; Xu Feng[7]; Yuan Li[7]

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We present an exploratory study of the quasi-beam function on a $N_f = 2 + 1 + 1$ twisted mass lattice of size $24^3 \times 48$, with a pion mass of 350 MeV and of lattice spacing 0.093 fm. We show preliminary results for longitudinal momentum of up to 1.7 GeV and transverse separation of up to 0.28 fm. We also discuss the possible renormalization of the bare matrix element using RI/MOM scheme and outline the next steps in extracting the continuum TMDPDF.

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Collins-Soper kernel and soft function from lattice QCD

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In this talk I will show our calculations of Collins-Soper kernel and soft function on a newly generated 2+1 flavor clover fermion CLS ensemble of size 48^4 with $a = 0.098$ fm. The light sea quark mass corresponds to a pion mass of 333 MeV for this ensemble and the valence quark mass to 662 MeV. We measure the large-momentum-transfer meson form factors and its transverse-momentum-depdent wave functions at momenta up to $P^z = 12\frac{2\pi}{L}$. The Collins-Soper kernel and soft function are extracted from them using next-to-leading-order factorization based on large-momentum effective theory. Our results are in good agreement with literature.

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Nucleon PDFs at the physical point from lattice QCD using NNLO matching

Authors: Andrew Hanlon[1]; Xiang Gao[2]; Jack Holligan[3]; Nikhil Karthik[4]; Peter Petreczky[5]; Philipp Scior[5]; Sergey Syritsyn[6]; Swagato Mukherjee[5]; Yong Zhao[2]

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We present results for the parton distribution functions (PDFs) of the nucleon at the physical point from lattice QCD utilizing a next-to-next-to-leading order (NNLO) matching. We consider two different strategies in our calculation. The first makes use of the short-distance factorization formalism to extract the first few Mellin moments in a model-independent way. In the second approach, we consider a matching in Bjorken-x space using the recently developed hybrid renormalization scheme.

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Unpolarized gluon PDF for the proton using the twisted mass formulation

Author: Joseph Delmar[1]

Co-authors: Constantia Alexandrou ; Krzysztof Cichy [2]; Martha Constantinou [1]; Kyriakos Hadjiyiannakou [3]

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We present results of the x-dependence of the unpolarized gluon PDF for the proton. We use an $N_f = 2 + 1 + 1$ ensemble of maximally twisted mass fermions with clover improvement and the Iwasaki improved gluon action. The quark masses are tuned so that the pion mass is 260 MeV. We use a $32^3 \times 64$ lattice size with a lattice spacing $a = 0.093$ fm giving a spatial extent of 3 fm. We employ the pseudo-distribution approach and obtain the light-cone Ioffe time distribution (ITD) combining data for nucleon momentum boosts up to 1.67 GeV and Wilson line length, z, up to 0.56 fm. We explore systematic effects such as the dependence on the maximum value of z entering the fits to obtain the ITD. We also study various options to reconstruct the x-dependence of the gluon PDF.

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Continuum limit of parton distribution functions from the pseudo-distribution approach on the lattice

Authors: Aurora Scapellato[1]; Jeremy R Green[2]; Krzysztof Cichy[3]; Manjunath Bhat[4]; Martha Constantinou[1]; Wojciech Chomicki[3]

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Precise exploration of the partonic structure of the nucleon is one of the most important aims of high-energy physics. In recent years, it has become possible to address this topic with first-principle Lattice QCD investigations. In this talk, we focus on the so-called pseudo-distribution approach to determine the isovector unpolarized PDFs. In particular, we employ three lattice spacings to study discretization effects and extract the distributions in the continuum limit, at a pion mass of around 370 MeV. Also, for the first time with pseudo-PDFs, we explore effects of the 2-loop matching from pseudo- to light-cone distributions.

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Chiral-even twist-3 GPDs for the proton

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"We present results on the chiral-even twist-3 quark GPDs for the proton using one ensemble of two degenerate light, a strange and a charm quark ($N_f = 2+1+1$) of maximally twisted mass fermions with a clover term, corresponding to a pion mass of 260 MeV. We employ the quasi-distribution method which relates lattice matrix elements of non-local operators defined in coordinate space to the light-cone distributions in the momentum (x) space. The approach requires momentum-boosted proton states and a matching formalism computed in Large Momentum Effective Theory (LaMET). In our calculation, we use three values of the momentum boost, namely 0.83, 1.25, 1.67 GeV. The GPDs are defined in the symmetric (Breit) frame, which we implement here with 4-vector momentum transfer squared of 0, 0.69, and 1.39 GeV^2, all at zero skewness."

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Leading-twist Quark PDFs of the Nucleon from Ioffe-time Pseudo-distributions

Authors: Anatoly Radyushkin[1]; Christopher Monahan[2]; Colin Egerer[3]; David Richards[4]; Eloy Romero[5]; Joseph Karpie[None]; Kostas Orginos[6]; Nikhil Karthik[4]; Raza Sufian[7]; Robert Edwards[3]; Savvas Zafeiropoulos[8]; Wayne Morris[9]

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The Parton Distribution Functions (PDFs) encode the non-perturbative collinear dynamics of a hadron probed in inclusive and semi-inclusive scattering processes, and hence provide an avenue to address a number of key questions surrounding the structure of hadrons. This talk will summarize recent efforts of the HadStruc Collaboration to map out the leading-twist quark PDFs of the nucleon using Lattice QCD. This effort hinges on the computation of matrix elements of space-like parton bilinears, which factorize, akin to the QCD collinear factorization of hadronic cross sections, in a short-distance regime into the desired PDFs - ideas codified within the pseudo-distribution formalism. By exploiting the distillation spatial smearing paradigm, matrix elements of sufficient statistical quality are obtained such that the leading-twist PDFs and various systematic effects can be simultaneously quantified. Consistency of our obtained PDFs with phenomenological expectations is also explored.

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Towards determining gluon helicity distribution in the nucleon from lattice QCD

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We present a lattice QCD calculation towards determining gluon helicity distribution and how much of the proton's spin budget is contributed by gluons. We consider matrix elements of bilocal operators composed of two gluon fields that can be used to determine the polarized gluon Ioffe-time distribution and the corresponding parton distribution function. We employ a high-statistics computation using a $32^3 \times 64$ lattice ensemble with 358 MeV pion mass and 0.094 fm lattice spacing using a combination of numerical techniques previously proven successful for the case of unpolarized gluon distribution. An important outcome of this work is that we find a hint for a nonzero gluon spin contribution to the proton spin from the model-independent extraction of gluon helicity Ioffe-time distribution over a range of Ioffe-time, $\nu \leq 9$.

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A lattice QCD calculation of the off-forward Compton amplitude and generalised parton distributions

Authors: Alec Hannaford Gunn[1]; Gerrit Schierholz[2]; Hinnerk Stuben[3]; James Zanotti[4]; K. Utku Can[1]; Paul E. L. Rakow[5]; Roger Horsley[6]; Ross Young[1]

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A major focus of the new Electron-Ion Collider will be the experimental determination of generalised parton distributions (GPDs). I will give an outline of the CSSM/QCDSF collaboration's determination of GPD properties from a lattice calculation of the off-forward Compton amplitude (OFCA). By determining the OFCA, we can access phenomenologically important properties such as scaling and non-leading-twist contributions, and the subtraction function. We calculated the OFCA for soft momentum transfer $t \in [0.3, 1.2]$, and determine moments of the helicity-conserving and -flipping amplitudes, which reduce to their respective GPD moments at leading-twist.

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Nucleon transverse quark spin densities

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The nucleon transverse quark spin densities are presented. The densities are extracted from the unpolarized and transversity generalized form factors using three Nf = 2 + 1 + 1 twisted mass fermion ensembles simulated with physical quark masses. The results obtained for three lattice spacings are extrapolated to the continuum limit directly at the physical pion mass. The isovector tensor anomalous magnetic moment is determined to be κT = 1.051(94), which confirms a negative and large Boer-Mulders function, h⊥1 , in the nucleon.

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GPDs in non-symmetric frames

Authors: Andreas Metz[1]; Aurora Scapellato[1]; Fernanda Steffens[2]; Jack Dodson[1]; Krzysztof Cichy[3]; Martha Constantinou[1]; Shohini Bhattacharya[4]; Swagato Mukherjee[4]; Xiang Gao[None]; Yong Zhao[5]

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It is often taken for granted that Generalized Parton Distributions (GPDs) are defined in the "symmetric" frame, where the transferred momentum is symmetrically distributed between the incoming/outgoing hadrons. However, such frames pose more computational challenges for the lattice QCD practitioners. In this talk, we lay the foundation for lattice QCD calculations of GPDs in non-symmetric frames, where the transferred momentum is not symmetrically distributed between the incoming/outgoing hadrons. The novelty of our approach relies on the parameterization of the matrix elements in terms of the so-called Generalized Ioffe-time Distributions (ITD), which helps in not only isolating but also reducing part of the higher-twist contaminations as a byproduct. This work opens possibilities for faster and more effective computations of GPDs.

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Accessing proton GPDs in lattice QCD using a non-symmetric frame

Authors: Martha Constantinou[1]; Shohini Bhattacharya[2]; Krzysztof Cichy[3]; Jack Dodson[1]; Xiang Gao[None]; Andreas Metz[1]; Aurora Scapellato[1]; Fernanda Steffens[4]; Swagato Mukherjee[5]; Yong Zhao[6]

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We present a numerical investigation of a novel Lorentz covariant parametrization to extract x-dependent GPDs using off-forward matrix elements of momentum-boosted hadrons coupled to non-local operators. The novelty of the method is the implementation of a non-symmetric frame for the momentum transfer between the initial and final hadron state and the parametrization of the matrix elements into generalized Ioffe-time distributions (ITD), which are frame independent. The generalized ITD can then be related to the standard light-cone GPDs, which are frame-dependent. GPDs are defined in the symmetric (Breit) frame, which requires a separate calculation for each momentum transfer value, increasing the computational cost significantly. The proposed method is powerful, as one can extract the GPDs at more than one momentum transfer value within the same computational cost. For this proof-of-concept calculation, we use one ensemble of $N_f = 2+1+1$ twisted mass fermions and a clover improvement with a pion mass of 260 MeV to calculate proton GPDs.

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Calculation of Distribution Amplitudes in Quantum Chromodynamics using Large-Momentum Effective Theory up to power accuracy

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Distribution amplitudes (DAs) describe the momentum of a meson's constituent partons and are of great importance in quantum chromodynamics (QCD) experiments and phenomenology. The advent of large-momentum effective theory (LaMET) in 2013 made the determination of DAs amenable to lattice calculations. Parton physics is described in the limit of infinite momentum and corrections to LaMET calculations are quadratic in Λ_{QCD}/P. However, contamination from renormalons results in corrections linear in Λ_{QCD}/P. A new and more robust method for removing the effects of renormalons in linear divergence is presented, applied to the calculation of meson distribution amplitudes in QCD and preliminary results are shown.

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Double parton distributions in the nucleon on the lattice: Flavor interference effects

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Information about double parton distributions (DPDs) can be obtained by calculating four-point functions on the lattice. We continue our study on the first DPD Mellin moment of the unpolarized proton by considering interference effects w.r.t. the quark flavor. In our simulation we employ an $n_f = 2 + 1$ ensemble with inverse coupling $\beta = 3.4$, and pseudoscalar masses of $m_\pi = 355$ MeV and $m_K = 441$ MeV. The results are converted to the $\overline{\text{MS}}$-scheme at the scale $\mu = 2$ GeV. We analyze the dependence of the considered Mellin moments on the quark polarization and compare our results with quark model predictions.

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Quark mass dependence of hadron resonances

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We study the dependence of hadronic resonances on the mass of quarks through the analysis of data from QCD lattice simulations form various collaborations. Using Machine Learning techniques as the LASSO algorithm we fit lattice data in order to extrapolate them to the physical point and extract the results for the quark mass dependence for exotic resonances like Ds0 and Ds1.

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Pion nucleon excited state effects in nucleon observables

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Calculations of nucleon charges and form factors have reached a level of precision requiring a more precise accounting of the contribution of excited states in both the two and three point functions. Recently, it was suggested that the excited states that are suppressed in two-point function maybe enhanced in certain three point functions. Such an enhancement increases when using lattice simulations at the physical point where πN states form a dense spectrum . In this work we include two hadron interpolating fields and perform a variatonal analysis to obtain the first few energy levels in the $I = 1/2, I_3 = +1/2$ channel at physical pion mass.

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Non-perturbative renormalization of quark and gluon operators using a gauge-invariant scheme

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We present preliminary results of the renormalization functions (RFs) for a number of quark and gluon operators studied in lattice QCD using a gauge-invariant renormalization scheme (GIRS). GIRS is a variant of the coordinate-space renormalization prescription, in which Green's functions of gauge-invariant operators are calculated in position space. A novel aspect is that summations over different time slices of the operators' positions are employed in order to reduce the statistical noise in lattice simulations. We test the reliability of this scheme by calculating RFs for the vector one-derivative quark bilinear operator, which enters the average momentum fraction of the nucleon. We use $N_f = 4$ degenerate twisted mass/clover fermion ensembles of different volumes and lattice spacings. We also present first results of applying GIRS when operator mixing occurs: the mixing coefficients of the gluon and quark singlet energy-momentum tensor operators are evaluated by imposing appropriate renormalization conditions on the lattice.

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Pion polarizability from four-point functions in lattice QCD

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We study the electric polarizability of a charged pion from four-point functions in lattice QCD as an alternative to the background field method. We show how to evaluate the correlation functions under special kinematics to access the polarizability. The elastic form factor (charge radius) is needed in the method which can be obtained from the same four-point functions at large current separations. Preliminary results from the connected quark-line diagrams will be presented.

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Calculation of the pion charge radius from an improved model-independent method

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We investigate an improved analysis method of the recently-proposed model-independent method to obtain the pion charge radius from the electromagnetic pion three-point function. We discuss

a systematic error of the original method in small volume, and propose an improvement to reduce it. Using the $N_f = 2 + 1$ lattice QCD data at $m_\pi = 0.51$ GeV, we compare the result of the pion charge radius from our improved method with the ones from the original method, and also from a traditional model-dependent method.

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Nucleon charges, moments, and form factors from 2+1-flavor lattice QCD

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I will give a status report on our calculations of matrix elements of quark bilinear operators between nucleon states. Summary of results for isovector charges, moments, and axial, electric and magnetic form factors will be presented.

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Removing the $N\pi$ contamination from axial matrix elements at non-vanishing momentum

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Excited state contamination is one of the most challenging sources of systematics to tackle in the determination of nucleon matrix elements and form factors. The signal-to-noise problem prevents one from considering large source-sink time separations. Instead, state-of-the-art analyses consider multi-state fits. Excited state contributions to the correlation functions are particularly significant in the axial channel. In this work, we confront the problem directly. Since the major source of contamination is understood to be related to pion production, we consider three-point correlators with a N operator at the source and a $N\pi$ interpolating operator at the sink, which allows studies of $N \to N\pi$ matrix elements. After discussing the challenges that arise when using a two-particle interpolating operator, like the projection onto the proper irreducible representation and on the isospin components, we present solutions of the Generalised Eigenvalue Problem for a matrix of two-point functions
constructed using different bases of N and $N\pi$ operators. We adopt the GEVP results to present improved $N \to N$ axial and pseudoscalar matrix elements, where we remove directly the contamination from $N\pi$ states, on a $m_\pi \approx 420$ MeV ensemble.

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The momentum sum rule via the Feynman Hellmann theorem

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Determining the quark and gluon contributions to the momentum of a hadron is a difficult and computationally expensive problem. This difficulty mainly arises from the calculation of the gluon matrix element which involves a quark-line disconnected gluon operator, which suffers from noisy ultra-violet fluctuations. Furthermore, a complete calculation also requires a determination of the non-perturbative renormalisation of this operator. In this work, we performed a quenched QCD study of the fully-renormalised quark and gluon contributions to the pion and nucleon momenta via an adaption of the Feynman-Hellmann technique. We find the momentum sum rules are satisfied within our uncertainties for both the pion and nucleon for 3 different values of the quark masses. We also discuss some recent progress on extending this procedure to a dynamical simulations.

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Progress in calculation of the fourth Mellin moment of the pion light-cone distribution amplitude using the HOPE method

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The light-cone distribution amplitude (LCDA) of the pion carries information about the parton momentum distribution and is an important theoretical input into various predictions of exclusive measurements at high energy, including the pion electromagnetic form factor. We present progress towards a lattice calculation of the fourth Mellin moment of the LCDA using the heavy quark operator product expansion (HOPE) method.

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Update on flavor diagonal nucleon charges

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We present an update on the calculation of flavor diagonal nucleon axial, scalar and tensor charges on eight 2+1+1-flavor MILC HISQ ensembles using Wilson-clover fermions. We discuss the excited state contributions (ESC) in the connected and disconnected diagrams, nonperturbative calculation of the renormalization constants and flavor mixing in the RI-sMOM scheme. These data are extrapolated to the physical point using a simultaneous chiral-continuum-finite-volume fit.

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Inverse Problems in PDF determinations

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The determination of a function from a finite set of points is notoriously an ill-defined problem, which clearly affects the determination of PDFs. As high-energy physics moves into the era of precision, it is mandatory to find a robust way of quantifying the uncertainties affecting the determination of PDFs, which play a central role in the analysis of experimental data at hadronic colliders. We discuss a Bayesian approach to inverse problems and its application to the case of PDFs.

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Lattice Data / 464

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Lattice Data / 467

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Multi-point Padè for the study of phase transitions: from the Ising model to lattice QCD.

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The Bielefeld Parma collaboration has recently put forward a method to investigate the QCD phase diagram based on the computation of Taylor series coefficients at both zero and imaginary values of the baryonic chemical potential. The method is based on the computation of multi-point Padè approximants. We review the methodological aspects of the computation and, in order to gain confidence in the approach, we report on the application of the method to the two-dimensional Ising model (probably the most popular arena for testing tools in the study of phase transitions). Besides showing the effectiveness of the multi-point Padè approach, we discuss what these results can suggest in view of further progress in the study of the QCD phase diagram.

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Determination of Lee-Yang edge singularities in QCD by rational approximations

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We report updated results on the determination of Lee-Yang edge (LYE) singularities in $N_f = 2 + 1$ QCD using highly improved staggered quarks (HISQ) with physical masses on $N_\tau = 4$, 6, 8 lattices. The singularity structure of QCD in the complex μ_B plane is probed using conserved charges calculated at imaginary μ_B. The location of the singularities is determined by studying the (uncancelled) poles of multi-point Padé approximants. We show that close to the Roberge-Weiss (RW) transition, the location of the LYE singularities scales according to the 3-d $\mathbb{Z}_2$ universality class. By combining the new $N_\tau = 6$ data with the $N_\tau = 4$ data from our previous analysis we extract a rough estimate for the RW temperature in the continuum limit. We also discuss some preliminary results for the singularities close to the chiral phase transition obtained from simulations on $N_\tau = 6$, 8 lattices.

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Fourier coefficients of the net-baryon number density

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We calculate Fourier coefficients of the net-baryon number as a function of a purely imaginary chemical potential. The asymptotic behavior of these coefficients is governed by the singularity structure of the QCD partition function and thus encodes information on phase transitions. Although it is not easy to obtain a high number of Fourier coefficients from lattice QCD data directly, models for these coefficients have been constructed in the past. We investigate to what extent our data is consistent with those models and estimate the position of the nearest singularities in the complex chemical potential plane. Our lattice data has been obtained from simulations with (2+1)-flavors of highly improved staggered quarks (HISQ) at imaginary chemical potential on $N_\tau = 4$, 6 and 8 lattices at physical quark masses. For the calculation of the Fourier coefficients we apply asymptotic numerical quadrature designed for highly oscillatory integrals.

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Meson screening mass at finite chemical potential

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Knowledge of the screening masses at finite chemical potential can provide insight into the nature of the QCD phase diagram. However, lattice studies at finite chemical potential suffer from the well-known issue of the sign problem, which has made the calculation of observables such as screening correlators and screening masses at finite chemical potential quite challenging. One way to proceed is by expanding the observable in a Taylor series in the chemical potential and hence calculating the finite-density corrections to the observable. In this talk, we will use this approach to calculate the screening mass of the pseudoscalar meson at finite temperatures and chemical potential by expanding the screening correlator in a Taylor series in the chemical potential. We will present our results for the second derivative of the screening mass w.r.t. the chemical potential. Our calculation was done on $64^3 \times 8$ lattices generated using the (2+1) HISQ action.

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Electromagnetic conductivity of quark-gluon plasma at finite baryon chemical potential

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In this talk we present our study of the electromagnetic conductivity in dense quark-gluon plasma obtained within lattice simulations with $= 2 + 1$ dynamical quarks. We employ stout improved rooted staggered quarks at the physical point and the tree-level Symanzik improved gauge action. The simulations are performed at imaginary chemical potential. To reconstruct electromagnetic conductivity from current-current correlators, we employ the Tikhonov regularisation method as well as the modified Backus-Gilbert method, computing the convolution of the spectral density with the target function. Our study indicates that electromagnetic conductivity of quark-gluon plasma rapidly grows with the real baryon density.

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Magnetic catalysis in the (2+1)-dimensional Gross-Neveu model

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We study the (2+1)-dimensional Gross-Neveu model in an external magnetic field. The model, which serves as a toy model for QCD, has been predicted by mean-field studies to exhibit a very rich phase structure in the plane spanned by temperature and chemical potential as the external field is varied. We investigate what remains of this phase structure beyond the mean-field approximation. Our lattice results are consistent with the magnetic catalysis scenario, i.e. an increase of the chiral condensate with the magnetic field, both at finite temperature and chemical potential.

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Pion condensation at lower than physical quark masses

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In QCD at large enough isospin chemical potential Bose-Einstein Condensation (BEC) takes place, separated from the normal phase by a phase transition. From previous studies the location of the BEC line at the physical point is known. In the chiral limit the condensation happens already at infinitesimally small isospin chemical potential for zero temperature. The zero-density chiral transition might then be affected, depending on the shape of the BEC boundary, by its proximity. As a first step towards the chiral limit, we perform simulations of 2+1 flavors QCD at half the physical quark masses. The position of the BEC transition is then extracted and compared with the results at physical masses.

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Nuclear Transition in the Strong Coupling Limit.

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At finite baryon chemical potential, the sign problem hinders Monte Carlo simulations which is remedied by a Dual Representation that makes the sign problem mild. At the strong coupling limit, the dual formulation with staggered quarks is well established. We have used this formulation to look at the quark mass dependence of the baryon mass and the nuclear transition which allows us to quantify the nuclear interaction. The results obtained are also compared with the mean field theory.

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Towards Quantum Monte Carlo Simulations at non-zero Baryon and Isospin Density in the Strong Coupling Regime

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The Hamiltonian formulation of Lattice QCD with staggered fermions in the strong coupling limit has no sign problem at non-zero baryon density and allows for Quantum Monte Carlo simulations.

We have extended this formalism to two flavors, and after a resummation, there is no sign problem both for non-zero baryon and isospin chemical potential. We report on recent progress on the implementation of the Quantum Monte Carlo simulations and present results on the baryon and isospin densities in the chiral limit. These will be compared with Meanfield theory.

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Towards the phase diagram of cold and dense heavy QCD

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The thermodynamics of QCD with sufficiently heavy dynamical quarks can be described by a three-dimensional Polyakov loop effective theory, after a truncated character and hopping expansion. We investigate the resulting phase diagram for low temperatures by mean field methods. Taking into account chemical potentials both for baryon number and isospin, we obtain clear signals for a liquid-gas type transition to baryon matter at $\mu_I = 0$ and a Bose-Einstein condensation transition at $\mu_B = 0$, as well as for their connection as a function of both chemical potentials.

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Inhomogeneous phases in the 3+1-dimensional mean-field Nambu-Jona-Lasinio model on the lattice

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At low temperature and large chemical potential QCD might exhibit a chiral inhomogeneous phase, as indicated by various simple low-energy models. One of these models is the 3+1-dimensional Nambu-Jona-Lasinio model, which is non-renormalizable – rendering the results possibly dependent on the employed regularization scheme. While most previously published results regarding the inhomogeneous phase in this model were obtained with the Pauli-Villars or similar regularizations, this talk explores the dependence of this phase on different lattice regularizations. Furthermore, the lattice approach allows us to determine the energetically preferred shape of the condensate without a specific ansatz.

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Exponential improvement of the sign problem via contour deformations in the 2+1D XY model at nonzero density

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We studied the 2+1 dimensional XY model at nonzero chemical potential on deformed integration manifolds with the aim of alleviating its sign problem. We investigated several proposals for the deformations and managed to considerably improve on the severity of the sign problem with respect to

standard reweighting approaches. In this talk I present numerical evidence that a significant reduction of the sign problem can be achieved which is exponential in both the squared chemical potential and the spatial volume. Furthermore, I discuss a new approach to the optimizaiton procedure, based on reweighting, that sensibly reduces its computational cost.

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Equation of state and Taylor expansions at nonzero isospin chemical potential

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We compute the equation of state of isospin asymmetric QCD at zero and non-zero temperatures using direct simulations of lattice QCD with three dynamical flavors at physical quark masses. In addition to the pressure, the trace anomaly and the approach to the continuum, we will particularly discuss the extraction of the speed of sound. Furthermore, we will discuss first steps towards the extension of the EoS to small non-zero baryon chemical potentials via Taylor expansion.

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Isothermal and isentropic speed of sound in (2+1)-flavor QCD at non-zero baryon chemical potential

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Recently interest in calculations of the speed of sound in QCD under conditions like constant temperature c_T^2 or constant entropy per net baryon number c_s^2 arose in the discussion of experimental results coming from heavy ion experiments. It has been stressed that the former in particular is closely related to higher order cumulants of conserved charge fluctuations that are calculated in lattice QCD.

We present here results on c_T^2 and c_s^2 and compare results at vanishing strangeness chemical potential and vanishing net strangeness number with hadron resonance gas model calculations. We stress the difference of both observables at low temperature arising from the light meson sector, which does not contribute to c_T^2.

Using the scaling functions corresponding to the 3-d, O(N) universality class, we discuss the imprint of the chiral transition on the speed of sound. Here we stress the energy-like behavior of net baryon-number fluctuations, which in the chiral limit has as a consequence that c_T^2 as well as c_s^2 will be sensitive to a peak in the specific heat that is characteristic for critical behavior of theories in 3-d, O(N) spin models. Using data obtained on lattices with temporal extent $N_\tau = 8$ and lighter-than-physical up and down quark masses, we conclude that this universal feature will show up in QCD only for very small values of the pion mass.

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The isentropic equation of state of (2+1)-flavor QCD: An update based on high precision Taylor expansion and Pade-resummed expansion at finite chemical potentials

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We update the pressure, energy density and entropy density calculations at non-zero checmial potentials based on Taylor expansion up to 6th order performed by the HotQCD Collaboration in 2017.
The HotQCD collaboration has now accumulated an order of magnitude larger statistics for lattices with temporal extent
Nt=8 and 12 and added results for Nt=16 that were not available previously.
For Nt=8 we also calculated the 8th order expansion coefficients.
Furthermore, we showed that the straightforward Taylor series expansion for the pressure provides a well controlled description of the pressure upto $\mu_B/T \leq 2.5$.

In this talk, we will use the high statistics results on Taylor expansion coefficients, calculated with HISQ fermions and extrapolated to the continuum limit, for a determination of the QCD equation of state under conditions relevant for the description of hot and dense matter created in heavy ion collisions. We determine energy density and pressure along lines of constant entropy per net baryon-number.

We furthermore use the eighth order Taylor series for the pressure to construct Pade-resummed thermodynamic observables along lines of fixed entropy per baryon number-density and comment on the location of singularities in the complex chemical potential plane that influence the convergence of the Taylor series for bulk thermodynamic observables.
At low temperature we compare our results with hadron resonance gas (HRG) model calculations based on the recently constructed QMHRG2020 hadron list, which in addition to the hadronic resonances listed by the Particle Data Group, also includes resonances calculated in relativistic quark models.

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A new way to calculate equation of state at finite chemical potential

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We present a new way of calculating the QCD equation of state(EoS) at finite chemical potential. Our method derives from the previously published method of exponential resummation. While exponential resummation does resum Taylor coefficients to all orders in μ; on expansion of the series itself, it becomes evident that in addition to genuine higher order contributions, the contribution of a stochastic bias is also present.

In this talk, we consider only isospin chemical potential (density) and perform a cumulant expansion of the exponential resummation formula, in which each of the terms is carefully evaluated using the unbiased powers of the operators. We compare our results with both exponential resummation as well as Taylor series expansion, and find that our formalism has the potential to manifest the actual fluctuations of the different-ordered operators

Non-zero Density / 123

Direct results for the hot and dense quark gluon plasma in the physical point vs extrapolations

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I will present recent results on the lattice QCD equation of state from the direct reweighting approach advocated recently in 2004.10800 and 2108.09213. I will present direct results up to a baryochemical potential-to-temperature ratio of $\mu_B/T = 3$. I will concentrate on the plasma phase at non-zero baryochemical potential and compare the results with those obtained from different extrapolation procedures: the Taylor expansion around zero chemical potential and some of its resummations. Our results are based on simulations 2-stout improved staggered lattices with 8 time-slices and phyical quark masses.

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Resummed lattice QCD equation of state at finite baryon density: strangeness neutrality and beyond

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We calculate a resummed equation of state with lattice QCD simulations at imaginary chemical potentials. This talk presents a generalization of the scheme introduced in our previous work to the case of non-zero μ_S, focusing on the line of strangeness neutrality.
We present results up to $\mu_B/T \leq 3.5$ on the strangeness neutral line $\langle S\rangle = 0$ in the temperature range 130 MeV $\leq T \leq$ 280~MeV. We also extrapolate the finite baryon density equation of state to small non-zero values of the strangeness-to-baryon ratio $R = \langle S\rangle / \langle B\rangle$.
We perform a continuum extrapolation using lattice simulations of the 4stout-improved staggered action with 8, 10, 12 and 16 timeslices.

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QCD equation of state via the complex Langevin method

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We present results on the phase diagram of Quantum Chromodynamics (QCD) with two light quark flavours at finite chemical potential from first principle lattice simulations. To circumvent the sign problem we use the complex Langevin method. The pion mass is of approximately 480 MeV. We report on the pressure, energy and entropy equations of state. A particular emphasis is put on the "cold" regions of the phase diagram and the observation of the Silver Blaze phenomenon.

Non-zero Density / 416

Boundary terms in Complex Langevin simulations of full QCD

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Lattice simulations of non-zero density QCD introduce the so-called sign problem (complex or negative probabilities), which invalidates importance sampling methods. We use the Complex Langevin equation (CLE) to circumvent the sign problem, measure boundary terms and use reweighting to test the reliability of the boundary term observable, confirming expectations from previous studies. We also investigate boundary terms in simulations using CLE with dynamic stabilization and compare this, to results calculated with reweighting.

Non-zero Density / 138

Bump of sound velocity in dense 2-color QCD

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We obtain the equation of state (p vs. e) and the sound velocity ($c_s^2/c^2 = \partial p/\partial e$) for two-color QCD at low temperature and high density and find that in the superfluid phase, c_s^2/c^2 becomes larger than $1/3$, which is the value at the relativistic limit. Several independent Monte Carlo studies on 2-color QCD have been conducted intensively in recent years, and have found clear evidence of phase transition between hadronic and superfluid phases.

Our result is consistent with several recent works based on effective models which have shown the peak of sound velocity.

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Measurement of hadron masses in 2-color finite density QCD

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We investigate hadron masses in two-color QCD with $N_f = 2$ at low temperature and finite density using lattice simulation. We calculate π and ρ meson masses and find the flipping of the spectral ordering of these two mesons near the transition between the hadronic and superfluid phases. Furthermore, we measure hadron masses with isospin $I = 0$ and $J^P = 0^{\pm}$. According to the analysis of the linear sigma model of finite-density two-color QCD with a diquark gap, the meson, diquark, and antidiquark states in such channels are mixed due to the $U(1)_B$ symmetry breaking in the superfluid phase. Our lattice study provides the two-point functions, which are consistent with the above prediction.

Non-zero Temperature / 417

Chiral spin symmetry and the QCD phase diagram

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Recently an approximate SU(4) chiral spin-flavour symmetry was discovered in multiplet patterns of QCD meson correlation functions, in a temperature range above the chiral crossover. This symmetry is larger than the full chiral symmetry of QCD with massless u,d-quarks. It can only arise effectively when color-electric quark gluon interactions dominate the effective Dirac action of QCD, which suggests that quarks remain bound in such a regime.
At temperatures about two to three times the crossover temperature, this pattern disappears again, and the usual chiral symmetry is recovered.
We present additional evidence for this phenomenon based on meson screening masses, and discuss how this chiral spin symmetric band continues into the QCD phase diagram.

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Finite temperature QCD phase transition with 3 flavors of Mobius domain wall fermions

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We investigate the phase structure of QCD with three degenerate quark flavors at finite temperature using Mobius domain wall fermions. To locate the critical endpoint and explore the order of phase transition on the diagonal line of the Columbia plot, we performed simulations at temperatures 131 and 196 MeV with lattice spacing $a \sim 0.12$ fm corresponding to temporal lattice extent $N_\tau = 8, 12$ with varying quark mass for two different volumes with aspect ratios N_σ/N_τ ranging from 2 to 3. By analyzing the volume and mass dependence of the chiral condensate, disconnected chiral susceptibility and Binder cumulant we find that there is a crossover at $m_q^{\overline{\rm MS}}(2\,{\rm GeV}) \sim 40\,{\rm MeV}$ for $\rm T_{pc}$ $\sim$ 196 MeV and a transition point at $m_q^{\overline{\rm MS}}(2\,{\rm GeV}) \sim 4\,{\rm MeV}$ for $\rm T$ $\sim$131 MeV on $24^3 \times 12$ lattices. The $36^3 \times 12$ lattices are being investigated for the finite size scaling, we will present its result and discuss the nature of transition for $\rm T$ $\sim$131 MeV.

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Progress on the QCD Deconfinement Critical Point for $N_{\rm f} = 2$ Staggered Fermions

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The global center symmetry of quenched QCD at zero baryonic chemical potential is broken spontaneously at a critical temperature T_c leading to a first-order phase transition. Including heavy dynamical quarks breaks the center symmetry explicitly and weakens the first-order phase transition for decreasing quark masses until it turns into a smooth crossover at a Z_2-critical point. We investigate the Z_2-critical quark mass value towards the continuum limit for $N_{\rm f} = 2$ flavors using lattice QCD in the staggered formulation. As part of a continued study, we present results from Monte-Carlo simulations on $N_\tau = 8, 10$ lattices. Several aspect ratios and quark mass values were simulated in order to obtain the critical mass from a fit of the Polyakov loop to a kurtosis finite size scaling formula. Moreover, the possibility to develop a Ginzburg-Landau effective theory around the Z_2-critical point is explored. The coefficients of the Landau functional can be determined from fits of the Polyakov loop to the data as a function of the bare parameters.

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The chiral phase transition at nonzero imaginary baryon chemical potential for different numbers of quark flavours

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The so called Columbia Plot summarises the order of the QCD thermal transition as a function of the number of quark flavours and their masses. Recently, it was demonstrated that the first-order chiral transition region, as seen for $N_f = 3 - 6$ on coarse lattices, exhibits tricritical scaling while extrapolating to zero on sufficiently fine lattices. Here we extend these studies to imaginary baryon chemical potentials, using $N_f = 4, 5$. A similar shrinking of the first-order region is observed with decreasing lattice spacing, which is so far entirely similar to the situation at zero density.

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Parallel tempering algorithm applied for the deconfinement transition of quenched QCD

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QCD with infinite heavy quark masses exhibits a first-order thermal transition which is driven by the spontaneous breaking of the global $\mathcal{Z}_3$ center symmetry. We analyze the corresponding order parameter, namely the Polyakov loop and its moments, and show, with a rigorous finite size scaling, that in the continuum limit the transition is of first order. We show that the use of a parallel tempering algorithm can significantly reduce the large auto-correlation times, which are mainly caused by supercritical slowing down for first order phase transitions. As a result, we calculate the transition temperature $w_0 T_c$ with per-mill precision, and the latent heat, carrying out controlled continuum and infinite volume extrapolations.
Decreasing the quark masses weakens the transition until the latent heat vanishes at the critical mass. We give an update on our exploration of the heavy mass region with three flavors of staggered quarks.

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Topological features of the deconfinement transition in quenched QCD

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The QCD crossover is marked by the rapid change in various observables such as the chiral condensate, the Polyakov loop or the topological susceptibility. We studied the topological properties in pure SU(3) gauge theory where the transition is first order.

Our study focused on the topological susceptibility and the b_2 coefficient of the expansion of the free energy density around $\theta = 0$. There was already some evidence for the discontinuity in the topological susceptibility at the transition temperature in SU(N) Yang-Mills theories. We determined the continuum extrapolated value of this discontinuity for $N = 3$ in the infinite volume limit. We also determined the temperature dependence of the b_2 coefficient directly at $\theta = 0$ and by using information from imaginary θ simulations.

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Charm fluctuations in (2+1)-flavor QCD at high temperature

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Using the high statistics datasets of the HotQCD Collaboration, generated with the HISQ (2+1)-flavor action for light and strange quarks, and treating the charm sector in the quenched approximation, we analyze the second and fourth order cumulants of charm fluctuations and the correlations of charm with lighter conserved flavor quantum numbers. We can make use of a factor 100 larger statistics on $N_\tau = 8$ lattices and datasets on lattices with temporal extent $N_\tau = 12$ and 16, which never have been used in studies of the charm fluctuations. This allows us to perform the continuum limit for charm fluctuations in the quenched approximation.

Analyzing correlations of charm fluctuations with baryon number and electric charge fluctuations we can project onto charmed baryon and meson correlations and compare results with quark model extended hadron resonance gas model calculations. We aim at a precise determination of the dissociation temperature of charmed hadrons and will probe the sensitivity of the fluctuations observables to the presence of multiple-charmed baryons.

Non-zero Temperature / 219

Absence of inhomogeneous phases in 2+1-dimensional Four-fermion and Yukawa models

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We discuss results about inhomogeneous chiral phases, i.e. phases where in addition to chiral symmetry also translational symmetry is broken, in the $2+1$-dimensional Gross-Neveu model using the mean-field approximation. The phase diagram of the GN model is presented and the existence of inhomogeneous phases is ruled out. The non-existence of inhomogeneous phases will then be shown for a variety of Four-fermion and Yukawa models in 2+1 dimensions. Numerical minimizations of the effective action using two variants of naive fermions support our results.

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Euclidean correlators at imaginary spatial momentum in thermal QCD

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The thermal photon emission rate is determined by the spatially transverse, in-medium spectral function of the electromagnetic current. Accessing the spectral function using Euclidean data is, however, a challenging problem due to the ill-posed nature of inverting the Laplace transform. In this contribution, we present the first results about testing the proposal of directly computing the analytic continuation of the retarded correlator at fixed, vanishing virtuality of the photon via the calculation of the appropriate Euclidean correlator at imaginary spatial momentum. We employ two-flavors of dynamical Wilson fermions at a temperature of 250 MeV.

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Complex potential at T>0 from fine lattices

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We study the Wilson line correlation function in Coulomb gauge on $96^3\times$ Nt lattices in 2+1 flavor QCD with physical strange quark and light quark masses corresponding to pion mass of 310 MeV, with the aim to determine the complex potential at non-zero temperature. In our calculation we use HISQ action in fixed scale approach with lattice spacing 1/a=7.1 GeV and Nt=56,36,32,28,24,20, corresponding to temperatures T=127, 197, 221, 253, 296, 354 MeV, respectively. To reduce the noise in the correlator calculations we apply gradient flow. From the analysis of the Wilson line correlation function we conclude that the corresponding spectral function is well described by a dominant peak. The peak position corresponds to the real part of the potential, while the effective width of the peak gives the imaginary part of the potential. We find that the real part of the potential is temperature independent and shows no sign of screening, while the imaginary part shows a strong temperature dependence.

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Phase structure and critical point in heavy-quark QCD at finite temperature

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We study phase structure and critical point of finite-temperature QCD with heavy quarks applying the hopping parameter expansion (HPE). We first study finite-size effects on the critical point on $N_t = 4$ lattices with large spatial volumes taking the LO and NLO effects of the HPE, and find that the critical scaling of the Z(2) universality class expected around the critical point of two-flavor QCD is realized when the aspect ratio of the lattice is larger than about 9. This enables us to determine the critical point in the thermodynamic limit with high precisions. By a study of the convergence of the HPE, we confirm that the result of the critical point with the low orders of the HPE is reliable for $N_t = 4$, while we need to incorporate higher order effects for $N_t \geq 6$. To extend the study to $N_t \geq 6$ lattices, we then develop a method to take the effects of higher-order terms of the HPE up to a sufficiently high order. We report on the status of our simulations on $N_t \geq 6$ lattices adopting the new method.

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Novel bottomonium spectral results

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We present the latest results from the use of the Backus-Gilbert method for reconstructing the spectra of NRQCD bottomonium mesons using anisotropic FASTSUM ensembles at non-zero temperature. We focus in particular on results from the η_b, Υ and χ_{b1} generated from Tikhonov-regularized Backus-Gilbert coefficient sets. We extend previous work on the Laplace shifting theorem as a means of resolution improvement and present new results from its use. We conclude with a discussion of the limitations of the improvement routine and elucidate a connection with Parisi-Lepage statistical scaling.

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New results for thermal interquark bottomonium potentials using NRQCD from the HAL QCD method

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We report preliminary progress in the calculation of the thermal interquark potential of bottomonium using the HAL QCD method with NRQCD quarks. We exploit the fast Fourier transform algorithm, using a momentum space representation, to efficiently calculate NRQCD correlation functions of non-local mesonic S-wave states, and thus obtain the central potential for various temperatures. This work was performed on our anisotropic 2+1 flavour "Generation 2" FASTSUM ensembles.

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Heavy quark diffusion coefficient with gradient flow

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The heavy quark diffusion coefficient is encoded in the spectral functions of the chromo-electric and the chromo-magnetic correlators, of which the latter describes the T/M contribution. We study these correlators at two different temperatures T=1.5Tc and T=10^4Tc in the deconfined phase of SU(3) gauge theory. We use gradient flow for noise reduction. We perform both continuum and zero flow time limits to extract the heavy quark diffusion coefficient. Our results imply that the mass suppressed effects in the heavy quark diffusion coefficient are 20% for bottom quarks and 34% for charm quark at T=1.5Tc.

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The heavy quark diffusion coefficient from 2+1 flavor lattice QCD

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We present a novel approach to nonperturbatively estimate the heavy quark momentum diffusion coefficient, which is a key input for the theoretical description of heavy quarkonium production in heavy ion collisions, and is important for the understanding of the elliptic flow and nuclear suppression factor of heavy flavor hadrons. In the heavy quark limit, this coefficient is encoded in the spectral functions of color-electric and color-magnetic correlators that we calculate on the lattice to high precision by applying gradient flow. For the first time we apply the method to 2+1 flavor ensembles with temperatures between 200-350 MeV. Using our experience from quenched QCD, where we performed a detailed study of the lattice spacing and flow time dependence, we estimate the heavy quark diffusion coefficient using theoretically well-established model fits for the spectral reconstruction.

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Study of charm and beauty in QGP from unquenched lattice QCD

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We present full QCD correlator data and corresponding reconstructed spectral functions in the pseudoscalar channel. Correlators are obtained using clover-improved Wilson fermions on $N_f = 2 + 1$ HISQ lattices. We use gradient flow to check whether it reduces cut-off and mixed action effects. Valence quark masses are tuned to their physical values by comparing the mass spectrum obtained from the lattice QCD with experimental values at each flow time. For the spectral reconstruction, we use models based on perturbative spectral functions from different frequency regions like resummed thermal contributions around the threshold from pNRQCD and vacuum contributions well above the threshold. We show preliminary results of the reconstructed spectral function obtained for the first time in our study for full QCD. In addition, we compare the results with the previous continuum extrapolated results in the quenched approximation.

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Recent results from the FASTSUM Collaboration

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The FASTSUM collaboration has developed a comprehensive research programme in thermal QCD using 2+1 flavour, anisotropic ensembles. In this talk, we summarise our recent results including

hadron spectrum calculations using our "Generation 2L" ensembles. We will also report on our progress in obtaining anisotropic lattices with a temporal spacing of 17am, half that of our Generation 2L data, which we will use in future studies to reduce systematic effects.

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Charm baryons at finite temperature on anisotropic lattices

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Singly, doubly and triply charmed baryons are investigated at multiple temperatures using the anisotropic FASTSUM 'Generation 2L' ensemble. We discuss the temperature dependence of these baryons' spectrum in both parity channels with a focus on the confining phase. To further qualify the behaviour of these states around the pseudocritical temperature, the parity doubling due to the restoration of chiral symmetry is examined. The addition of heavier 'heavy' quarks and lighter 'light' quarks compared to our previous studies improves our understanding.

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QCD mesonic screening masses and restoration of chiral symmetry at high T

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We present a strategy to study QCD non-perturbatively on the lattice at very high temperatures. This strategy exploits a non-perturbative, finite-volume, definition of the strong coupling constant to renormalize the theory. As a first application we compute the flavour non-singlet meson screening masses in a wide range of temperature, from $T \sim 1$ GeV up to ~ 160 GeV with three flavours in the chiral limit of QCD. Our results show very interesting features of the screening spectrum at very high temperatures. On the one hand the mass splitting between the vector and the pseudoscalar screening masses is clearly visible up to the electroweak scale and cannot be explained by the known NLO perturbative result. On the other hand the restoration of chiral symmetry manifests itself through the degeneracy of the pseudoscalar and the scalar channels and of the vector and the axial ones. This degeneracy pattern is the one expected by Ward identities associated with the presence of chiral symmetry.

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Topology and the Dirac spectrum in hot QCD

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It is known that contrary to expectations, the order parameter of chiral symmetry breaking, the Dirac spectral density at zero virtuality, does not vanish above the critical temperature of QCD. Instead, the spectral density develops a pronounced peak at zero. We show that the spectral density in the peak has large violations of the expected volume scaling. This anomalous scaling and the statistics of these eigenmodes is consistent with them being produced by mixing instanton and antiinstanton zero modes. Consequently, we show that a nonvanishing topological susceptibility implies a finite density of eigenvalues around zero, which can have implications on the restoration of chiral symmetry above the critical temperature.

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Anomalous transport phenomena on the lattice

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The interrelation between quantum anomalies and electromagnetic fields leads to a series of non-dissipative transport effects in QCD. In this work we study anomalous transport phenomena with lattice QCD simulations using improved staggered quarks in the presence of a background magnetic field. In particular, we calculate the conductivities both in the free case and in the interacting case, analysing the dependence of these coefficients with several parameters, such as the temperature and the quark mass.

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Lattice QCD with an inhomogeneous magnetic field background

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The magnetic fields generated in non-central heavy-ion collisions are among the strongest fields produced in the universe, reaching magnitudes comparable to the scale of strong interactions. Backed by model simulations, we expect the resulting field to be spatially modulated, deviating significantly from the commonly considered uniform profile. In this work, we present the next step to improve our understanding of the physics of quarks and gluons in heavy-ion collisions by adding an inhomogeneous magnetic background to our lattice QCD simulations. We simulate 2+1 staggered fermions with physical quark masses for a range of temperatures covering the QCD phase transition. We assume a $1/\cosh(x)^2$ function to model the field profile and vary its strength to analyze the impact on the chiral condensate and the Polyakov loop. These order parameters show non-trivial spatial features due to the interplay between the sea and the valence effects as the system approaches the crossover temperature. We extrapolate these quantities to the continuum limit, draw the phase diagram in the T-B plane and interpret the implications of an inhomogeneous B to QCD physics. We also find that in this set-up, the system develops steady electric currents which flow in equilibrium. We use these currents to present our new method of obtaining the magnetic susceptibility of the QCD medium and compare it to previously established techniques.

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QCD phase diagram in a magnetic background

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We discuss the QCD phase diagram in the presence of a strong magnetic background field. We provide numerical evidence, based on lattice simulations of QCD with 2+1 flavours and physical quark masses, for a crossover transition at $eB = 4$ GeV^2 (with a pseudo-critical temperature $T_c =$ $(98{\pm}3)$ MeV) and for a first order phase transition at $eB = 9$ GeV^2 (where the measured critical temperature is $T_c = (63{\pm}5)$ MeV). We conclude that the critical endpoint is located at $eB = eB_{CEP}$ and $T = T_{CEP}$, where 4 GeV^2 $< eB_{CEP} <$ 9 GeV^2 and 63 MeV$< T_{CEP} <$ 98 MeV.

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Topology in electromagnetic fields and the axion-photon coupling

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The introduction of parallel electric and magnetic fields in the QCD vacuum enhances the weight of topological sectors with a non-zero topological charge. For weak fields, there is a linear response for the topological charge. We study this linear response which can be interpreted as the axion-photon coupling. In this work we use lattice simulations with improved staggered quarks including background electric and magnetic fields.

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Photon and dilepton production rate in the quark-gluon plasma from lattice QCD

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The photon emissivity of the quark-gluon plasma (QGP) is an important input to predict the photon yield in heavy-ion collisions, particularly for transverse momenta in the range of 1 to 2 GeV. Photon production in the QGP can be probed non-perturbatively in lattice QCD via (Euclidean) time-dependent correlators. Analyzing the spatially transverse channel, as well as the difference of the transverse and longitudinal channels as a consistency check, we determine the photon emissivity based on continuum-extrapolated correlators in two-flavour QCD. Estimates of the lepton-pair production rate can be derived by combining the two aforementioned channels.

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Photon production rate from Transverse-Longitudinal (T-L) mesonic correlator on the lattice.

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Thermal photons from the QGP provide important information about the interaction among the plasma constituents. The photon production rate from a thermally equilibrated plasma is proportional to the transverse spectral function $\rho_T(k_0 = |\vec{k}|, \vec{k})$. One can calculate the photon production rate also from the difference between ρ_T(transverse) and ρ_L(longitudinal) correlator as ρ_L vanishes on the photon point. The UV part of $\rho_T - \rho_L$ is suppressed, and therefore the corresponding Euclidean correlator receives most of its contribution from the IR part of $\rho_T - \rho_L$. We calculate the continuum extrapolated T-L correlator using Clover Improved Wilson fermion on the quenched lattices at temperatures 1.1 T_c and $1.5T_c$. We also calculate the same correlator on $N_f = 2 + 1$ flavor HISQ configurations with $m_l = m_s/5$ at temperature $\sim 1.15T_c$ and $\sim 1.3T_c$. We have used two ansätze of the spectral function, which are 1) Polynomial ansatz of the spectral function connected to the UV perturbative region and 2) Hydro-inspired spectral function. We have also used the Backus-Gilbert method to estimate the spectral function. We will compare the photon production rate estimated from all these different methods.

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A $(2+1)$-flavor lattice study of the pion quasiparticle in the thermal hadronic phase at physical quark masses

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We investigate the properties of the pion quasiparticle in the thermal hadronic phase of $(2+1)$-flavor QCD on the lattice at physical quark masses at a temperature $T = 128\,\text{MeV}$. We find that the pion quasiparticle mass $\omega_{\mathbf{0}} = 111(3)\,\text{MeV}$ is significantly reduced relative to the zero-temperature pion mass $m_\pi(T = 0) = 130(1)\,\text{MeV}$, by contrast with the static screening mass $m_\pi = 143(3)\,\text{MeV}$, which increases with temperature. On the other hand the pion quasiparticle decay constant does not change much compared to the corresponding zero-temperature decay constant. The difference of the vector- and axialvector spectral functions serves as an order parameter of chiral symmetry restoration. By analyzing this quantity we conclude that chiral symmetry restoration is already at an advanced stage in the spectral function.

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Thermodynamics with Möbius domain wall fermions near physical point (I)

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Investigation of QCD thermodynamics for $N_f = 2 + 1$ along the lines of constant physics with Möbius domain wall fermions is underway. At our coarsest lattice $N_t = 12$, reweighting to overlap fermions is not successful. To use domain wall fermions with the residual mass larger than average physical ud quarks, careful treatments of the residual chiral symmetry breaking are necessary. One of the examples is the chiral condensate where a UV power divergence associated with the residual chiral symmetry breaking emerges with a coefficient not known a priori. In this talk we present first the setup of the computations and then discuss methodologies to overcome potential problems towards the continuum limit in this setup.

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Thermodynamics with Möbius domain wall fermions near physical point (II)

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We perform finite temperature 2+1-flavor lattice QCD simulation employing the Möbius domain-wall fermion near the (pseudo-)critical point with Nt=12 and 16. The simulation points are chosen along the lines of constant physics, where the quark mass is fixed near physical point. The input quark mass for Möbius domain wall fermion with Ls=12 are tuned by taking into account the residual mass. In this talk, we focus on simulation details and present some preliminary results.

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Thermal phase transition in rotating QCD with dynamical quarks

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The relativistic rotation causes a change in QCD critical temperature. Various phenomenological and effective models predict a decrease in the critical temperature in rotating QCD. Nevertheless, it follows from lattice simulations that the critical temperature in gluodynamics increases due to rotation. But in QCD the rotation acts on both gluons and fermions, and combination of these effects may lead to unexpected results. In this report the first lattice results for a rotating QCD with dynamical $N_f = 2$ Wilson quarks will be presented. It is shown that the rotation of gluons and fermions has an opposite effect on the critical temperature. Dependence of the results on the pion mass is also discussed.

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Non-perturbative determination of couplings in Polyakov loop effective theories

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Polyakov loop effective theories have been shown to successfully describe the thermodynamics of QCD. Furthermore, due to the sign problem, they represent an alternative avenue to investigate the physics at non-zero chemical potential. However, when working with these effective theories, a new set of couplings appear whose expressions in terms of the gauge coupling and N_τ are only known from strong-coupling expansions. Using the finite-cluster method, we can show how one can efficiently compute high-order expressions for correlators of Polyakov loops in the effective theory which are directly mapped to those in full lattice QCD. These can then be in turn be used to determine the effective couplings as a function of temperature. Furthermore, the inclusion of heavy quarks allows one to investigate the cold and dense regime.

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Mean-field approximation of effective theories of lattice QCD

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For the exploration of the phase diagram of lattice QCD effective Polyakov loop theories provide a valuable tool in the strong coupling and heavy quark mass regime. In practice, the evaluation of these theories is limited by the appearance of long-range and multi-point interaction terms. It is well known that for theories with such kind of interactions mean-field approximations can be expected to yield reliable results. Here, those approximations are applied to such effective theories. Using this framework the critical endpoint of the deconfinement transition is determined and results are compared to the literature. This treatment can also be used to investigate the phase diagram at non-zero baryon and iso-spin chemical potential.

Non-zero Temperature / 375

Electric charge fluctuations using 4HEX quarks

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Fluctuations of conserved charges in a grand canonical ensemble can be computed on the lattice and, thus, provide theoretical input for freeze-out phenomenology in heavy ion collisions. Electric charge fluctuations and the corresponding higher order correlators are extremely difficult, suffering form the most severe lattice artefacts. We present new simulation data with a novel discretization where these effects are strongly suppressed and provide continuum extrapolated results in the temperature region of the chemical freeze-out.

Nuclear Physics / 368

Structure Factors of Neutron Matter

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Accurate modeling of the many-body properties of the neutrinosphere appears important for a correct description of core-collapse supernovae. The neutrinosphere is within the region of validity of pionless effective field theory.

We leverage techniques from lattice field theory to do a direct calculation of the many-body physics from leading-order pionless EFT. We present a calculation of thermodynamic observables and the static structure factors of the neutrinosphere accounting for all sources of uncertainty.

Nuclear Physics / 424

Symanzik Improvement of Non-Relativistic Field Theories

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I will describe a method to reduce spatial discretization errors in lattice formulations of pionless effective field theory. All $O(\Delta x)$ errors are cancelled, and generalizing to higher orders is simple. The method relies on set of renormalization conditions fixed by finite-volume energy levels, and may be useful for supernova phenomenology and cold-atomic physics, where spatial discretization errors are large.

Nuclear Physics / 215

Nucleon-nucleon scattering from distillation

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In published work, we reported a study of the H dibaryon in the continuum limit of SU(3)-flavor-symmetric lattice QCD with a pion/kaon/eta mass of roughly 420 MeV, employing finite-volume quantization conditions and distillation. The data were affected by large discretization effects, leading to a small binding energy in the continuum. In this talk, I will present results for nucleon-nucleon scattering based on the same dataset. In the S wave, we find that nucleon-nucleon systems with both isospin zero and one are unbound. We also obtain a nonzero signal for some higher partial waves as well as the mixing between spin-1 coupled S and D waves.

Nuclear Physics / 163

Extracting the chiral nuclear force from the finite volume energy levels using the plane wave basis and eigenvector continuation

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In this talk, I will illustrate an alternative approach to Luscher formulas for extracting the nuclear force from finite volume energy levels using the plane wave basis and eigenvector continuation. We adopt the formalism of semilocal momentum-space regularized chiral nuclear force up to fifth order to investigate the two-nucleon energy levels in the finite volumes using plane wave basis with no reliance on the partial wave expansion. In the chiral EFT framework, the long-range one-pion-exchange interaction is included nonperturbatively and the low energy constants are determined by fitting lattice QCD data at mpi=450 MeV from NPLQCD Collaboration. The pion mass dependence is incorporated self-consistently in the EFT framework. In the calculation, the eigenvector continuation is used to accelerate the fitting and uncertainty quantification, which also generates an interface to fitting the upcoming lattice QCD results in the future.

Opening / 472

Welcome and Announcements

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Particle physics beyond the Standard Model / 137

Towards a beyond the Standard Model model with elementary particle non-perturbative mass generation

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We show that a recently discovered non-perturbative field-theoretical mechanism giving mass to elementary fermions, is also capable of generating a mass for the electro-weak bosons and can thus be used as a viable alternative to the Higgs scenario. A detailed analysis of this remarkable feature shows that the non-perturbatively generated fermion and W masses have the parametric form $m_f \sim C_f(\alpha)\Lambda_{RGI}$ and $M_W \sim g_w c_w(\alpha)\Lambda_{RGI}$, respectively, where the coefficients $C_f(\alpha)$ and $c_w(\alpha)$ are functions of the gauge couplings, g_w is the weak coupling and Λ_{RGI} is the RGI scale of the theory. In view of these expressions, we see that to match the experimental value of the top quark and W masses, we need to conjecture the existence of a yet unobserved sector of massive fermions subjected, besides ordinary Standard Model interactions, to some kind of super-strong gauge interaction, so as to have the RGI scale of the whole theory in the TeV region. Though limited in its scope (in this talk we ignore hypercharge and leptons and discuss only the case of one family, neglecting weak isospin splitting), this approach opens the way to a solution of the mass naturalness problem and an understanding of the fermion mass hierarchy.

Particle physics beyond the Standard Model / 101

Non-perturbative study of Yang-Mills theory with four supercharges in two dimensions

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We present an update of our results for the ongoing work on the four-supercharge two-dimensional Yang–Mills theory discretized on a Euclidean torus using thermal boundary conditions. Although the theory under consideration does not have a gravity dual, we investigate whether it has features qualitatively similar to its sixteen-supercharge counterpart. Our investigation hints at a possible 'spatial deconfinement' transition in this theory similar to the maximal one with sixteen supercharges. We also analyse the behaviour of the scalars, Wilson lines, and the absence of supersymmetry breaking with a relatively large-N setup and various lattice sizes in different coupling (temperature) regimes and draw comparisons with the two-dimensional maximally supersymmetric Yang–Mills theory.

Particle physics beyond the Standard Model / 106

Update on SU(2) with one adjoint Dirac flavor

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We present an update of our ongoing study of the SU(2) gauge theory with one flavor of Dirac fermion in the adjoint representation. Compared to our previous results we now have data at larger lattice volumes, smaller values of the fermion mass, and also larger values of β. We present data for the spectrum of mesons, baryons, glueballs, and the hybrid fermion-glue state, as well as new estimates of the mass anomalous dimension from both finite-size hyperscaling and the Dirac mode number, and discuss the implications of these data for the presence or otherwise of chiral symmetry breaking in this theory.

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Noether supercurrent operator mixing from lattice perturbation theory

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In this work we present perturbative results for the renormalization of the supercurrent operator, S_μ, in $calN = 1$ Supersymmetric Yang-Mills theory. At the quantum level, this operator mixes with both gauge invariant and noninvariant operators, which have the same global transformation properties. In total, there are 13 linearly independent mixing operators of the same and lower dimensionality. We determine, via lattice perturbation theory, the first two rows of the mixing matrix, which refer to the renormalizations of S_μ, and of the gauge invariant mixing operator, T_μ. To extract these mixing coefficients in the $\overline{MS}$ renormalization scheme and at one-loop order, we compute the relevant two-point and three-point Green's functions of S_μ and T_μ in two regularizations: dimensional and lattice. On the lattice, we employ the plaquette gluonic action and for the gluinos we use the fermionic Wilson action with clover improvement.

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Supercurrent renormalization in $calN = 1$ supersymmetric Yang-Mills theory on the lattice in GIRS scheme

Authors: Georg Bergner[None]; Ivan Soler[1]; Gregoris Spanoudes[2]; Haralambos Panagopoulos[3]; Marios Costa[3]

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Supersymmetry on the lattice is explicitly broken by the gluino mass and lattice artifacts. However, it can be restored in the continuum limit by fine tuning the parameters based on the renormalized Ward identities. On the renormalization step not only the mass but also the renormalization of the supercurrent needs to be addressed. Here we present a lattice investigation to obtain the renormalization factors of the supercurrent for
$calN = 1$ SYM in a gauge invariant renormalization scheme (GIRS). We also provide the conversion factors which are necessary in order to translate our results to the continuum $\overline{MS}$ scheme.

Particle physics beyond the Standard Model / 126

Investigating Vector Boson Scattering: A Lattice study

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Vector Boson scattering (VBS) is a central process in the search for physics beyond the SM at collider experiments. To correctly identify SM and BSM physics, such as composite Higgs scenarios, at these experiments, it is crucial to gain a clear picture of VBS-like processes.
In our study we therefore analyse this process in a reduced SM-setup for different physical scenarios. To this end we apply a Lüscher-type analysis to extract scattering properties and compare the results with (augmented) perturbative tree-level predictions.
We show that the nonperturbative approach suggests a composite structure for the scalar degree of

freedom, being in line with previous investigations. Furthermore we present an alternative way of extracting resonance-like states from the spectrum by using the perturbative prediction as a tool.

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Exploring the large Nc limit with one quark flavour

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We use one-flavour QCD ($N_c = 3$) as a proxy to understand $\mathcal{N} = 1$ SYM. For our simulations, we use tree-level improved Wilson fermions and Symmanzik improved gauge action. The hadron spectrum is obtained using LapH for different masses and simulation volumes. We find that the ratio of pseudo-scalar over scalar is smaller than one, which is in line with expectations from theory. We also report on our efforts to increase the number of colours in our simulations.

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Reconstruction of spectral densities in a composite-Higgs model

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Composite Higgs models are a popular solution to the Naturalness problem in the Higgs sector, where the mass of the Higgs bosons is explained in terms of Goldstone dynamics. We address a composite model described by a $SU(4)$ gauge group with fermions in the fundamental and two index anti-symmetric representations of the gauge group. We will show results from lattice simulations investigating the chiral limit of this theory with a focus on the multi-representation dynamics and the reconstruction of spectral densities from lattice correlators.

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Lattice Studies of 3D Maximally Supersymmetric Yang–Mills

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We present ongoing investigations of maximally supersymmetric Yang–Mills ($Q = 16$ SYM) theory in three space-time dimensions. This theory is conjectured to be holographically dual to higher-dimensional quantum gravity. Previous results focused on the homogeneous “D2” phase. The work in progress concerns phase transitions between this “D2” phase and a localized “D0” phase.

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Exploring conformality in lattice N=4 supersymmetric Yang–Mills

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Maximally supersymmetric Yang–Mills theory ($\mathcal{N} = 4$ SYM) is conformal for any value of the coupling. Lattice regularization breaks conformality through the introduction of a non-zero lattice spacing and a finite lattice volume. I will present ongoing computations of conformal scaling dimensions in lattice $\mathcal{N} = 4$ SYM, based on a lattice formulation that exactly preserves a supersymmetry sub-algebra at non-zero lattice spacing. The main targets are the non-trivial anomalous dimension of the Konishi operator, as well as a mass anomalous dimension extracted from the eigenvalue mode number of the fermion operator. The latter is expected to vanish in the conformal continuum theory, providing insight into the interplay of lattice discretization and conformality.

Particle physics beyond the Standard Model / 196

Progress Towards Stealth Dark Matter Scattering

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On behalf of the Lattice Strong Dynamics (LSD) collaboration, we present first results of the SU(4) Gauge theory Stealth Dark Matter hadron spectrum using stochastic Laplacian Heaviside (sLapH) smearing. We compare our results to previous work in the context of our Stealth Dark Matter baryon scattering project.

Particle physics beyond the Standard Model / 144

Dark Isosinglet Mesons in $Sp(4)$ gauge theory

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In the context of Strongly Interacting Dark Matter theories dark isosinglet mesons might play an important role in the low-energy dynamics and might provide crucial signatures in collider and direct detection searches. We present first results in $Sp(4)$ gauge theory with $N_f = 2$ fundamental Dirac flavours on the dark isosinglet pseudoscalar η' and the isosinglet contribution to the dark π^0 meson in the case of strong isospin breaking. A preliminary investigation of the pion scattering lengths shows that the parameter space studied so far appears to be phenomenologically viable. Additionally, these results can be relevant to other BSM models such as composite Higgs scenarios.

Particle physics beyond the Standard Model / 247

Renormalization Group beta function for SU(3) gauge-fermion systems

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The renormalization group (RG) β function describes the running of the renormalized coupling and connects the ultraviolet and infrared regimes of quantum field theories. Focusing at systems with SU(3) gauge group and fermions in the fundamental representation, we study how the RG β function changes from a QCD-like system with $N_f = 2$ flavors to a conformal system with $N_f = 12$ flavors. Specifically we report on new results for simulations with $N_f = 4$, 6, and 8 flavors and compare our findings to existing lattice determinations in the literature as well as perturbative predictions.

Our results are based on gradient flow measurements performed on dynamical gauge field configurations generated using Möbius domain wall fermions and Symanzik gauge action. In the case of $N_f = 4$ and 6 flavor our investigations are limited by the emergence of confinement at stronger gauge couplings, whereas $N_f = 8$ simulations run into an unphysical bulk phase transition.

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Spectroscopy of $Sp(4)$ lattice gauge theory with $n_f = 3$ antisymmetric fermions

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We report on numerical results of masses and decay constants of the lightest pseudoscalar, vector and axial vector mesons in $Sp(4)$ lattice gauge theory with three Dirac flavours of fermions in the antisymmetric representation. In addition, we measure the masses of other flavoured mesons in the spin-0 and spin-1 channels, as well as the first excited state of the vector meson. Using the gradient flow method to set a common scale, we attempt to carry out the continuum extrapolation. In this setup, we also compute the masses of the chimera baryons composed of two fundamental and one antisymmetric fermion constituents.

Particle physics beyond the Standard Model / 245

Spectroscopy of chimera baryons on Sp(4) lattice gauge theory

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Chimera baryons are an important feature of composite Higgs models, since they play role of top partner in partial top compositeness. In the realisation of the mechanism provided by $Sp(4)$ gauge theory, such exotic objects are composed of two fundamental and one antisymmetric fermion constituents. We perform lattice computations for the chimera baryon spectrum both in the quenched approximation and with three dynamical antisymmetric Dirac fermions. Masses of various chimera baryons with different quantum number will be presented, including the one known as the top partner.

Particle physics beyond the Standard Model / 305

Density of states for gravitational waves

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Many models of composite dark matter feature a first-order confinement transition in the early universe, which would produce a stochastic background of gravitational waves that will be searched for by future gravitational-wave observatories. I will present work in progress using lattice field theory to predict the properties of such first-order transitions and the resulting spectrum of gravitational waves. Targeting both the thermal as well as the bulk phase transitions of SU(N) Yang-Mills theories, this work employs the Logarithmic Linear Relaxation (LLR) density of states algorithm to avoid long autocorrelations.

Particle physics beyond the Standard Model / 283

Position-Space Renormalisation of the Energy-Momentum Tensor Two-Point Function

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In the Holographic Model, the two-point function of Energy-Momentum Tensor (EMT) of the dual QFT can be mapped into the power spectrum of the Cosmic Microwave Background in the gravitational theory. However, the presence of divergent contact terms poses challenges in extracting a renormalized EMT two-point function on the lattice. Using a ϕ^4 theory of adjoint scalars valued in the su(N) Lie Algebra as a proof-of-concept motivated by Holographic Cosmology, we apply a novel method for filtering out such contact terms by making use of infinitely differentiable "bump" functions which enforce a smooth window that excludes contributions at zero spatial separation. The process effectively removes the local contact terms and allows us to extract the continuum limit behaviour of the renormalized EMT two-point function.

Particle physics beyond the Standard Model / 206

One flavour adjoint QCD with overlap fermions

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The infrared effective theory of adjoint QCD with one Dirac flavour is still under debate. The theory could be confining, conformal, or fermionic fields could become the lightest fields in the IR. Chiral symmetry seems to be important to answer this question. Previous investigations have considered Wilson fermions breaking chiral symmetry. We present here the first results for this theory based on overlap fermions. These indicate a chiral symmetry breaking and formation of a fermion condensate. We have also investigated the running coupling of the theory, which indicates no IR conformality in the energy region we have explored.

Particle physics beyond the Standard Model / 369

Gradient flow anomalous dimensions for ten-flavor SU(3) gauge theory

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Gradient flow can be used to describe a Wilsonian renormalization group transformation. In this talk, we use gradient flow to extract running mesonic and baryonic anomalous dimensions for an SU(3) gauge system with $N_f = 10$ fundamental flavors. Our results are important for constructing theories beyond the Standard Model describing fermion mass generation either by partial compositeness or 4-fermion interactions.

Particle physics beyond the Standard Model / 427

Complex Langevin Study of Spontaneous Symmetry Breaking in IKKT Matrix Model

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The IKKT matrix model in the large-N limit is conjectured to be a non-perturbative definition of the ten-dimensional type IIB superstring theory. Due to the Pfaffian's inherently complex nature upon Euclideanization, the model has a severe sign problem. The phase of the Pfaffian plays a critical role in determining the correct vacuum of the model. In recent years, the complex Langevin method has been proved to tackle the sign problem successfully. In this talk, we discuss our results from the complex Langevin simulations of the Euclidean version of the IKKT model. We investigate the possibility of spontaneous breaking of $SO(10)$ rotational symmetry. The model must be deformed to evade the singular drift problem during complex Langevin simulations. We recover the original model in the vanishing deformation parameters limit. In addition to mass deformations that explicitly break supersymmetry, we introduce supersymmetry-preserving deformations with a Myers term. We conclude that the phase of the Pfaffian indeed induces the spontaneous breaking of the $SO(10)$ rotational symmetry in the Euclidean IKKT matrix model.

Particle physics beyond the Standard Model / 400

The spectrum of GUT-like gauge-scalar models

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Past lattice simulations tentatively suggested that the spectrum of observable particles in BSM theories is qualitatively different than perturbatively expected. We expand on this using a GUT-like toy theory, SU(3) Yang-Mills coupled to a scalar 'Higgs' in the fundamental representation. We show the most comprehensive spectroscopy to date, including all channels up to spin 2., and find it indeed in disagreement with perturbative expectations.

The discrepancy can be traced back to nontrivial field-theoretical effects arising from the requirement of gauge invariance. These results still appear to be consistent with a mechanism proposed by Fröhlich, Morchio and Strocchi, giving a possible analytical approach.

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The density of state method in Yang-Mills theories and first-order phase transitions

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Beyond the standard model theories involving early universe first order phase transitions can lead to a gravitational wave background that may be measurable with improved detectors. Thermodynamic observables of the transition, such as the latent heat, determined through lattice simulations can be used to predict the expected signatures from a given theory and constrain physical models. Metastable dynamics around the phase transition make precise determination of these observables difficult and often lead to large uncontrolled numerical errors. In this talk, I will discuss a prototype lattice calculation in which the first order deconfinement transition in the strong Yang-Mills sector of the standard model is analysed using a novel lattice method, the logarithmic linear relaxation method. This method provides a determination of the density of states of the system with exponential error suppression. From this, thermodynamic observables can be reconstructed with a controlled error, providing a promising direction for accurate model predictions.

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Operator Mixing under the Gradient Flow: The Gluon CEDM

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Computing *CP*-violating nucleonic matrix elements on the lattice allows one to place theoretical constraints on the couplings of effective interactions related to BSM sources of *CP*-violation. These interactions are related to local operators that mix under renormalization. Typically, this mixing is parametrized by the only scale available, the lattice spacing, and induces local divergences in the coefficients of lower-dimensional operators, obscuring the continuum limit. The gradient flow has become an attractive method to circumvent this problem. In adopting the flow to define renormalized operators, the renormalization and mixing scales are disentangled, allowing for a clean computation of the corresponding matching (Wilson) coefficients. Perturbative calculations within the gradient flow formalism can be used to fix the high-energy behavior of the matching coefficients, so that the matrix elements are renormalized across a wide range of energy scales. We present results on the renormalization and mixing of the gluon chromoelectric dipole moment (gCEDM) operator to one-loop order in perturbation theory. These include the power-divergent mixing of the gCEDM with the topological charge density and the logarithmic mixing with various dimension-six operators. We also discuss the construction of a basis compatible with the chiral anomaly.

Plenaries / 405

QCD thermodynamics: an overview of recent progress

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Recent results from lattice simulations of QCD at nonzero temperature and/or density and/or in presence of magnetic fields will be reviewed. Progress in our understanding of the phases and boundaries in the phase diagram, as well as on the calculation of thermodynamic quantities with relevant phenomenological consequences will be discussed.

Plenaries / **52**

Use of Schwinger-Dyson equation in constructing an approximate trivializing map

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As the precision test of the standard model has become accurate, the need for fine lattices has been increasing. However, as we approach the continuum limit, we get into the critical region of the theory and encounter critical slowing down. Among many studies tackling this problem, we develop the idea of trivializing map, whose use in lattice calculation was proposed by Luscher. With this field transformation, the theory of interest will be mapped to the strong coupling limit. Luscher gave an analytic formula to construct the trivializing map in the form of t-expansion, where t is the trivializing-flow time. In this work, we alternatively use the Schwinger-Dyson equation to obtain the trivializing map approximately. In this method, we choose a set of Wilson loops to include in the flow kernel by hand and determine their coefficients from the expectation values of the Wilson loops. The advantages of this method over the t-expansion are two-fold: (1) We can circumvent the rapid increase of necessary Wilson loops which we have in increasing the order of t-expansion because the basis can be chosen arbitrarily. (2) We can expect to obtain a reasonable approximation of the trivializing map also for large beta because the coefficients are determined from a non-perturbative evaluation of the expectation values. In this talk, we show preliminary results applying our method to pure Yang-Mills theory.

Plenaries / **46**

Review on Quantum Computing for Lattice Field Theory

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In this talk, we review recent advances in applying quantum computing to lattice field theory. Quantum technology offers the prospect to efficiently simulate sign-problem afflicted regimes in lattice field theory, such as the presence of topological terms, chemical potentials, and out-of-equilibrium dynamics. First proof-of-concept simulations of Abelian and non-Abelian gauge theories in (1+1)D and (2+1)D have been accomplished, and resource efficient formulations of gauge theories for quantum computations have been proposed. The path towards quantum simulations of (3+1)D particle physics requires many incremental steps, including algorithmic development, hardware improvement, methods for circuit design, as well as error mitigation and correction techniques. After reviewing these requirements and recent advances, we discuss the main challenges and future directions.

Plenaries / 50

Modular Supercomputing and its Role in Europe's Exascale Computing Strategy

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Reaching Exascale compute performance at an affordable budget requires increasingly heterogeneous HPC systems, which combine general purpose processing units (CPUs) with acceleration devices such as graphics processing units (GPUs) or many-core processors. The Modular Supercomputing Architecture (MSA) developed within the EU-funded DEEP project series breaks with traditional HPC system architectures by orchestrating these heterogeneous computing resources at system-level, organizing them in compute modules with different hardware and performance characteristics. Modules with disruptive technologies, such as quantum devices, can also be included in a modular supercomputer to satisfy the needs of specific user communities. The goal is to provide cost-effective computing at extreme performance scales fitting the needs of a wide range of Computational Sciences.

This approach brings substantial benefits for heterogeneous applications and workflows. In a modular supercomputer, each application can dynamically decide which kinds and how many nodes to use, mapping its intrinsic requirements and concurrency patterns onto the hardware. Codes that perform multi-physics or multi-scale simulations can run across compute modules due to a global system-software and programming environment. Application workflows that execute different actions after (or in parallel) to each other can also be distributed in order to run each workflow-component on the best suited hardware, and exchange data either directly (via message-passing communication) or via the filesystem. A modular supercomputing system can supply any combination or ratio of resources across modules and is not bound to fixed associations between, for instance, CPUs and accelerators as will be found in clusters of heterogeneous nodes. It is therefore ideal for supercomputer centers running a heterogeneous mix of applications (higher throughput and energy efficiency).

This talk will describe the Modular Supercomputing Architecture – which constitutes the central element in Europe's roadmap to Exascale computing –, including its history, its role in Europe's Exascale computing strategy, its hardware and software elements, and experiences from mapping applications and workflows to MSA systems.

Plenaries / 58

Topical plenary on emergent geometry and duality in the carbon nucleus

Authors: Shihang Shen[None]; Timo A. Lähde[1]; Dean Lee[2]; Ulf-G. Meißner[3]

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Title: Structure and geometry of 12C from a Wigner SU(4) symmetric interaction

The carbon-12 nucleus, one of the most crucial elements for life, is full of interesting structures and multifaceted complexity. One famous example is the first excited 0+ state, the so called Hoyle state. It can not be described by most of the ab initio calculations. Moreover, a lack of model-independent description for the shape also hinders an understanding of its geometric properties. Here we present calculations of 12C by nuclear lattice effective field theory using a simple nucleon–nucleon interaction that is independent of spin and isospin and therefore invariant under Wigner's SU(4) symmetry. Despite the simplicity of the interaction, the agreement with experiment is impressive, not only for all the low-lying levels including the Hoyle state, but also properties such as the charge radius, density profiles, and BE2 transitions. Furthermore, we provide the first model-independent tomographic scan of the three-dimensional geometry for those nuclear states, which show many interesting shapes and features.

Plenaries / **278**

The spectral reconstruction of inclusive rates

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A recently re-discovered variant of the Backus-Gilbert algorithm for spectral reconstruction enables the controlled determination of smeared spectral densities from lattice field theory correlation functions. The particular advantage of this model-independent approach is the *a priori* specification of the kernel with which the underlying spectral density is smeared, allowing for variation of its peak position, smearing width, and functional form. If the unsmeared spectral density is sufficiently smooth in the neighborhood of a particular energy, it can be obtained from an extrapolation to zero smearing kernel width at fixed peak position.

The determination of scattering amplitudes is a natural application. As a proof-of-principle test, an inclusive rate is computed in the two-dimensional O(3) sigma model from a two-point correlation function of conserved currents. The results at finite and zero smearing radius are in good agreement with the known analytic form up to energies at which 40-particle states contribute, and are sensitive to the 4-particle contribution to the inclusive rate. The straight-forward adaptation to compute the R-ratio in lattice QCD from two-point functions of the electromagnetic current is briefly discussed.

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$B \to D^{(*)}\ell\nu$ semileptonic decays at non-zero recoil

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A very rich place to look for phenomena to challenge our current understanding of physics is the flavor sector of the Standard Model (SM). In particular, the $|V_{cb}|$ matrix element of the CKM matrix is the subject of a long standing tension, depending on whether it is determined using inclusive or exclusive methods. On top of that, the SM theoretical calculations of some universality ratios $R(X)$ show large, unexplained tensions with experimental measurements.
Recently, there have been interesting efforts in Lattice QCD (LQCD) trying to cast some light onto the current situation. Calculations of the form factors of the gold-plated channels $B \to D^{(*)}\ell\nu$ at non-zero recoil are becoming the
norm, and when combined with the latest data coming from B factories, they offer promising prospects of settling the matter.
In this talk, I will review the current status of the form factor LQCD calculations at non-zero recoil of the $B \to D^{(*)}\ell\nu$ channels, and their impact in the determination of $|V_{cb}|$ and $R(D^{(*)})$.

Plenaries / **49**

Heavy flavor physics from lattice QCD

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We review recent progress on heavy flavor physics from lattice QCD.

Plenaries / **63**

A review on Glueball hunting

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One of the most direct predictions of QCD is the existence of color-singlet states
called Glueballs, which emerge as a consequence of the gluon field self-interactions.

Despite the outstanding success of QCD as a theory of the strong interaction
and decades of experimental and theoretical efforts, all but the most basic properties of Glueballs are still being debated.

In this talk, I will review efforts aimed to understanding Glueballs and the current status of Glueball searches, including recent experimental results and lattice calculations.

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The Compton amplitude and nucleon structure functions

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The structure of hadrons relevant for deep-inelastic scattering are completely characterised by the Compton amplitude. The standard approach in structure function calculations is to utilise the operator product expansion where one computes the local matrix elements. However, it is well established that tackling anything beyond leading-twist presents additional challenges that are not easily overcome; complicating the investigations of hadron structure at a deeper level. Alternatively, it is possible to directly calculate the Compton amplitude by taking advantage of the Feynman-Hellmann approach. By working with the physical amplitude, the intricacies of operator mixing and renormalisation are circumvented. Additionally, higher-twist contributions become more accessible given precise enough data.

In this talk, we focus on the QCDSF/UKQCD Collaboration's advances in calculating the forward Compton amplitude via an implementation of the second-order Feynman-Hellmann theorem. We highlight our progress on investigating the low moments of unpolarised structure functions of the nucleon. We also have a glance at our progress on the polarised and off-forward cases.

Plenaries / **402**

Neutrino Oscillation and Lattice QCD

Author: Aaron Meyer[1]

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Next generation high-precision neutrino scattering experiments have the goal of measuring the as-of-yet unknown parameters governing neutrino oscillation. This effort is hampered by the use of large nuclear targets: secondary interactions within a nucleus can confuse the interpretation of experimental data, leading to ambiguities about the initial neutrino interaction in scattering events. The distribution of energies for neutrino events must instead be inferred from the responses of a sum of dissimilar event topologies. For this reason, precise neutrino cross sections on nucleon targets are of vital importance to the neutrino oscillation experimental program. On the other hand, the necessary experimental data for neutrino scattering with elementary targets are scarce because of the weak interaction cross section, which leads to poorly-constrained nucleon and nuclear cross sections.

Lattice QCD is uniquely positioned to provide the requisite nucleon amplitudes needed to enable high-precision oscillation experiments. In particular, LQCD has the ability to probe axial matrix elements that are challenging to isolate or completely inaccessible to experiments. In this talk, I will discuss some of my work to quantify neutrino cross sections with realistic uncertainty estimates, primarily focusing on neutrino quasielastic scattering and the nucleon axial form factor. I will also outline how the needs of next-generation neutrino oscillation experimental programs can be met with modern dedicated LQCD computations.

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Gluon Structure from Lattice QCD

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We review progress on the lattice QCD calculation of parton structure in the nucleon, specifically that of the gluon. The structure of a hadron is typically described by x dependent distributions, most notably the simplest case of the parton distribution function (PDF). Boosted hadronic matrix elements of operators, which are calculable in lattice QCD, can be related to the PDF indirectly. This relationship is not uniquely defined, both theoretically from how one organizes power corrections and practically due to limitations of lattice QCD calculations. I will present the latest lattice QCD calculations of these matrix elements and describe the practical approaches for relating that data to PDFs.

Plenaries / **56**

Topical plenary on multi-particle interactions from lattice QCD

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First-principles calculations of multi-hadron dynamics are a crucial goal for lattice QCD calculations. Significant progress has been achieved in developing, implementing and applying theoretical tools that connect finite-volume quantities to their infinite-volume counterparts. In this talk, I will review some recent theoretical developments and numerical results regarding multi-particle quantities in a finite volume. The focus will be laid on properties of resonances and observables involving nucleons.

Plenaries / **47**

Hadron Spectroscopy and Interactions from Lattice QCD

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I review the recent progresses on lattice calculations of hadron spectroscopy and interactions. The methods to precisely determine the energy eigenstates on lattice and subsequently extract the scattering information have been matured in the last years. After briefly introduce the methodology, I present the new results in the last couple of years, focus will be the results on the exotic hadrons beyond the conventional quark model, such as multi-quark states and glueballs. I will also discuss the existing challenges and future paths.

Plenaries / **457**

Update on the International Lattice Data Grid

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The International Lattice Data Grid (ILDG) started almost 20 years ago as a global community initiative to enable and coordinate sharing of gauge configurations within the lattice QCD community. We outline the basic ideas of ILDG and explain the urgent need to fully support the meanwhile established FAIR data management practices. We will report on recent activities within the ILDG and on ongoing efforts in migrating to modern technologies.

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Emergent strongly coupled ultraviolet fixed point with 8 fundamental flavors

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The emergence of a strongly coupled ultraviolet fixed point as 4-dimensional fermion-gauge systems cross into the conformal window has long been hypothesized. Using an improved lattice actions that include heavy Pauli-Villars (PV) type bosons I show that an SU(3) system with 8 fundamental flavors described by two sets of staggered fermions has a smooth phase transition from the weak coupling to a strongly coupled phase.
I investigate the critical behavior of this phase transition using finite size scaling of the renormalized gradient flow coupling. The result of the scaling analysis is not consistent with a first order phase transition, but it is well described by Berezinsky-Kosterlitz-Thouless or BKT scaling. BKT scaling could imply that the 8-flavor system is the opening of the conformal window, an exciting possibility that I study by investigating the renormalization group β function in the weak coupling regime.

The strongly coupled phase exhibits symmetric mass generation (SMG), so the associated fixed point must be related to t'Hooft anomaly cancellation. The existence of a non-perturbative fixed point and SMG phase could lead to many novel phenomena, justifying future detailed studies of both.

Plenaries / **66**

Quantum chaos in supersymmetric Yang-Mills-like model from exact diagonalization

Author: Pavel Buividovich[1]

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We use exact diagonalization to study quantum chaos in a simple model with two bosonic and one fermionic degree of freedom. Our model has a structure similar to the BFSS matrix model (compactified supersymmetric Yang-Mills theory), and is known to have a continuous energy spectrum. To diagnose quantum chaos, we consider energy level statistics and the out-of-time-order correlators

(OTOCs). We find that OTOCs exhibit monotonous growth down to the lowest temperatures, thus indicating Lyapunov instability at all temperatures. This is in contrast to the purely bosonic models like pure Yang-Mills theory, which are non-chaotic at low temperatures because of their gapped energy spectrum. Despite the apparently chaotic behavior at all temperatures, we find that the energy level statistics undergoes a sharp transition between non-chaotic, one-dimensional low-energy states and delocalized high-energy states with random-matrix-type statistics of energy levels.

Plenaries / **452**

KWA ceremony and presentation

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Plenaries / **450**

Exotic hadrons from an EFT perspective

Author: Feng-Kun Guo[None]

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The last two decades witness the discovery of tens of hadronic structures beyond the expectations of the traditional quark model. They are candidates of exotic hadrons. Many of these structures are close to the thresholds of a pair of hadrons, and thus allow for an EFT treatment. In this talk, I will give an overview of the understanding of such resonances, covering positive-parity heavy meson, hidden-charm and double-charm near-threshold hadrons.

Plenaries / **454**

Probing new horizons with flavour at the LHCb experiment

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The past decade has seen rapid developments in flavour physics, in particular driven by the LHCb experiment. A wealth of heavy-hadron states have been discovered, with some of them not fitting in the conventional meson-baryon classification scheme. Precision studies of beauty and charm hadron decays have not only improved our understanding of the flavour structure of the Standard Model, but also revealed a number of intriguing anomalies. This talk will present highlights from the LHCb experiment, focusing on the recent results in hadron spectroscopy and heavy-flavour decays.

Plenaries / **53**

Asymptotic lattice spacing dependence of spectral quantities in lattice QCD with Wilson or Ginsparg-Wilson quarks

Author: Nikolai Husung[1]

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One major systematic uncertainty of lattice QCD results is due to the continuum extrapolation to extract the continuum limit at lattice spacing $a \searrow 0$. For an asymptotically free theory like QCD one finds corrections of the form $a^{n_{\min}}[2b_0\bar{g}^2(1/a)]^{\hat{\Gamma}_i}$, where n_{min} is a positive integer and $\bar{g}(1/a)$ is the running coupling at renormalisation scale $\mu = 1/a$. $\hat{\Gamma}_i$ can take any positive or negative value, which will impact convergence towards the continuum limit. How problematic such corrections can be has been first pointed out by Balog, Niedermayer and Weisz in their seminal work for the O(3) model.

I will present an analysis based on Symanzik Effective Theory for lattice QCD actions with Ginsparg-Wilson and Wilson quarks. This analysis yields various powers $\hat{\Gamma}_i$ due to lattice artifacts from the discretised lattice action. Those powers are sufficient when describing lattice artifacts of spectral quantities, while non-spectral quantities will require additional powers originating from corrections to each of the discretised local fields involved. This new input should be incorporated into ansätze used for the continuum extrapolation.

Plenaries / **54**

Master-field simulations of QCD and the exponential clover action

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Simulating QCD in the traditional way on very large lattices leads to conceptual and technical issues with impact on performance and reliability. In view of master-field simulations, introduced at Lattice 2017, simulations with dynamical fermions are particularly challenging and require additional stabilising measures to reach physical point lattices without compromising the quality of the simulation. The proposed stabilising measures comprise algorithmic changes as well as a new O(a)-improved Wilson action with exponential clover term.
In this talk, the motivation for stabilising measures and its effects are reviewed as both, standard-sized and master-field simulations, profit from its implementation. Furthermore, the current status and prospects of QCD master-field simulations are presented.

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Stochastic and Tensor Network simulations of the Hubbard Model

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The Hubbard model is an important tool to understand the electrical properties of various materials. More specifically, on the honeycomb lattice it is used to describe graphene predicting a quantum phase transition from a semimetal to a Mott insulating state. In this talk I am going to explain two different numerical techniques we employed for simulations of the Hubbard model: The Hybrid Monte Carlo algorithm on the one hand allowed us to simulate unprecedentedly large lattices, whereas Tensor Networks can be used to completely avoid the sign problem. Respective strengths and weaknesses of the methods will be discussed.

Plenaries / **48**

Review on Algorithms for dynamical fermions

Author: Jacob Finkenrath[None]

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The talk will review recent algorithms that are enabling state-of-the-art lattice QCD simulations. We will begin with an overview of the developments that have been crucial in simulating fermions at physical quark masses and fine lattice spacings. This will include an overview on iterative linear solver methods, such as multi-grid methods, and challenges arising from large scale Markov-chain Monte Carlo simulations on state-of-the-art HPC machines.

We will also discuss promising methods that could potentially alleviate topological freezing, to enable simulations at very fine lattice spacings close to the continuum.

Plenaries / **64**

Matching lattice QC+ED to Nature

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The first step in any QFT calculation of a phenomenological observable is the matching of the theory to Nature. The matching procedure fixes the parameters of the theory in terms of an equal number of external inputs that, if the theory is expected to reproduce observations, must be experimentally measured physical quantities. At the (sub)percent level of accuracy QED radiative corrections become important and it is QCD+QED that is expected to describe the hadronic Universe. At this level of precision phenomenological predictions deriving from lattice QCD calculations do depend on the choice of the external inputs used to match/define the approximate theory.
In the first part of this talk I will concentrate on the theoretical aspects of the matching procedure of lattice QCD and of the lattice calculation of strong-isospin and QED radiative corrections to hadronic observables. In the second part I will concentrate on the so called theory scales. By heavily relying on the work recently done by the scale setting working group in the last edition of the FLAG review, I will discuss the numerical results obtained by the different collaborations for these useful auxiliary quantities.

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Nonperturbative matching of Hamiltonian and Lagrangian Simulations

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When comparing the Lagrangian and Hamiltonian formulations of lattice gauge theories, a matching procedure is required to match the parameters and observables between these two formulations. For this, we take the continuum limit in time direction on the Lagrangian side, while keeping the spatial lattice spacing fixed. We study several observables for this nonperturbative matching and compare different ways to take the temporal continuum limit. We apply our approach to the pure U(1) lattice gauge theory in 2+1 dimensions.

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Varying momentum cutoffs in lattice effective theories

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Low energy effective models are a useful tool to understand the mechanisms behind physical processes in QCD. They additionally provide ways to probe into regions of the QCD phase diagram that are harder to simulate on the lattice, e.g., small temperature, due to their lower UV cutoff, as well as more direct comparison with functional methods such as fRG. We present here lattice simulations of such an effective model: the quark-meson model. We simulate the theory via Stochastic Quantisation and report on the effects of employing coloured noise, a method that allows control over the momentum scale of the simulation.

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NLO perturbative effects in QCD sum-rule analyses of light tetraquark systems: \\A Case Study in the Scalar-Isoscalar Channel

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QCD sum-rule mass predictions for tetraquark states provide insights on the interpretations and internal structure of experimentally-observed exotic mesons. However, the overwhelming majority of tetraquark QCD sum-rule analyses have been performed at leading order (LO), which raises questions about the underlying theoretical uncertainties from higher-loop corrections. The impact of next-to-leading order (NLO) perturbative effects are systematically examined in scalar ($J^{PC} = 0^{++}$) isoscalar light-quark tetraquark systems where comprehensive LO sum-rule analyses have been performed and NLO perturbative corrections to the correlators have previously been calculated.

Using the scalar-isoscalar state as a detailed case study to illustrate the differences between LO and NLO analyses, it is shown that NLO effects in individual Laplace sum-rules are numerically significant and have an important role in improving the reliability of the sum-rule analyses by widening the Borel window. However, ratios of sum-rules are found to be less sensitive to NLO effects with the additional advantage of cancelling the anomalous dimension that emerges from the NLO corrections. NLO mass predictions based on these sum-rule ratios are thus remarkably robust despite the slow perturbative convergence of the underlying correlator. The mass prediction $0.52\,\mathrm{GeV} < m_\sigma < 0.69\,\mathrm{GeV}$ for the lightest scalar-isoscalar σ state are in good agreement with the four-quark interpretation of the $f_0(500)$, and the relative coupling strengths of the $f_0(980)$ and $f_0(500)$ to the tetraquark current agree with the pattern found in chiral Lagrangian analyses. Effects of the σ resonance width are studied for a different models, including resonance shapes inspired by chiral Lagranians.

Poster / **13**

The Second Love Number of Dark Compact Planets and Neutron Stars with Dark Matter

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In this study, we calculated the effect of self-interacting dark matter on neutron stars. Properties like the mass, radius and the tidal deformability are affected by the presence of dark matter in neutron stars. We show that the Love number can be used to probe the presence and the properties of dark matter inside of neutron stars in future gravitational wave measurements.

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Contrasting low-mode noise reduction techniques for light HISQ meson propagators

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The dominant contribution to the long distance region of any meson correlation function comes from the quark propagator's eigenmodes with the smallest eigenvalues. As precision demands for this region increase, methods that offer an exact determination of these low modes have become widely adopted as an effective tool for noise reduction. This work explores the effect of exact low modes on noise reduction for all-to-all as well as traditional wall-to-all propagator techniques. We focus on the connected light quark vector current two-point correlation function, a key observable for the hadronic vacuum polarization contribution to the muon's anomalous magnetic moment. For this analysis we use MILC's 2+1+1 Highly Improved Staggered Quark (HISQ) ensembles at lattice spacings as small as ~0.06 fm at physical mass.

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Distribution of energy-momentum tensor around static quarks in SU(3) gauge theory at high temperature

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In this study, we explore the distribution of energy-momentum tensor around the static quark and antiquark in SU(3) pure gauge theory at finite temperature. Double extrapolated transverse distributions on mid-plane of the flux tube have been presented for the first time at nonzero temperature. Also, we investigate the spatial distributions of the flux tube on the source plane obtaining from the stress tensor for several $q\bar{q}$ separations and temperatures above and below the critical temperature. The resultant distributions show the detailed structure of the flux tube. Finally, we show the dependence of F_{stress} that is computed from the integral of the stress tensor on the distance between the quark and antiquark on a finer lattice.

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MRHS multigrid solver for Wilson clover fermions

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We describe our implementation of a multigrid solver for Wilson clover fermions, which increases parallelism by solving for multiple right-hand sides (MRHS) simultaneously. The solver is based on Grid and thus runs on all computing architectures supported by the Grid framework. We present detailed benchmarks of the relevant kernels, such as hopping and clover term on the various multigrid levels, intergrid operators, and reductions. The benchmarks were performed on the JUWELS Booster system at FZ Jülich, which is based on Nvidia A100 GPUs. For example, solving a 48^4 lattice on 16 GPUs, the overall speedup obtained solely from MRHS is about 7x.

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Perturbative determination of c_{SW} to one-loop order for Brillouin fermions

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Wilson-like Dirac operators can be written in the form $D = \gamma_\mu \nabla_\mu - \frac{1}{2}\Delta$. For Wilson fermions the standard two-point derivative $\nabla_\mu^{\mathrm{std}}$ and 9-point Laplacian Δ^{std} are used. For Brillouin fermions these are replaced by improved discretizations $\nabla_\mu^{\mathrm{iso}}$ and Δ^{bri} which have 54- and 81-point stencils respectively. We derive the Feynman rules in lattice perturbation theory for the Brillouin action and apply them to the calculation of the improvement coefficient c_{SW}, which, similar to the Wilson case, has a perturbative expansion of the form $c_{\mathrm{SW}} = 1 + {c_{\mathrm{SW}}}^{(1)} g_0^2 + \mathcal{O}(g_0^4)$.
We find ${c_{\mathrm{SW}}}^{(1)}_{\mathrm{Brillouin}} = 0.16182118(1)$ compared to ${c_{\mathrm{SW}}}^{(1)}_{\mathrm{Wilson}} = 0.26858825(1)$.

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Study of $I = 0$ bottomonium bound states and resonances based on lattice QCD static potentials

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We investigate $I = 0$ bottomonium bound states and resonances in S, P, D and F waves using lattice QCD static-static-light-light potentials. We consider five coupled channels, one confined quarkonium and four open $B^{(*)}\bar{B}^{(*)}$ and $B_s^{(*)}\bar{B}_s^{(*)}$ meson-meson channels and use the Born-Oppenheimer approximation and the emergent wave method to compute poles of the \box{T} matrix. We discuss results for masses and decay widths and compare them to existing experimental results. Moreover, we determine the quarkonium and meson-meson composition of these states to clarify, whether they are ordinary quarkonium or should rather be interpreted as tetraquarks.

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Meson mass spectrum with HYP-smeared staggered fermions using sequential bayesian fitting method

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We report recent progress in data analysis on two-point correlation functions with HYP-smeared staggered fermions using a sequential bayesian fitting method. We present details on data analysis and preliminary results for the meson spectrum.

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Eight spectra of very excited flux tubes in SU(3) gauge theory

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We compute the spectra of flux tubes formed between a static quark antiquark pair up to a significant number of excitations and for eight symmetries of the flux tubes, up to Δ_u, using pure gauge $SU(3)$ lattice QCD in 3+1 dimensions. To accomplish this goal, we employ a large set of appropriate operators, an anisotropic tadpole improved action, smearing techniques, and solve a generalized

eigenvalue problem. Moreover, we compare our results with the Nambu-Goto string model to evaluate possible tensions which could be a signal for novel phenomena.

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Recent progress on data analysis on correlation functions of semileptonic decays $B_{(s)}$ →D_{(s)}^{(\ast)} \ell\nu$ form factors

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We report recent progress in data analysis on the correlation functions

of the semileptonic decays $B_{(s)} \to D_{(s)}\ell\nu$ form factors.

The data set of measurement is MILC HISQ ensemble for the light quarks

and Oktay-Kronfeld (OK) action for the heavy quarks: a12m310 ($N_f = 2+1+1$ flavor)

We used sequential Bayesian method for the analysis and adopted Newton

method to find better initial guess.

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Padé and Padé-Laplace methods for masses and matrix elements

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The problem of having to reconstruct the decay rates and corresponding amplitudes of the single-exponential components of a noisy multi-exponential signal is common in many other areas of physics and engineering besides lattice field theory, and it can be helpful to study the methods devised and used for that purpose in those contexts in order to get a better handle on the problem of extracting masses and matrix elements from lattice correlators. Here we consider the use of Padé and Padé-Laplace methods, which have found wide use in laser fluorescence spectroscopy and beyond, emphasizing the importance of using robust Padé approximants to avoid spurious poles. To facilitate the accurate evaluation of the Laplace transform required for the Padé-Laplace method, we also present a novel approach to the numerical quadrature of multi-exponential functions.

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Excited and Exotic B, B_s and B_c mesons

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A study of heavy-light meson spectroscopy, specifically the excited and exotic spectra of B, B_s and B_c is presented. This work was done on an anisotropic lattice of volume $20^3 \times 128$, with (2+1) flavours of dynamical quarks. A large basis of suitable operators was used in a variational analysis to determine finite volume spectra grouped by lattice irrep for each meson. Spin-identified spectra were produced by assigning continuum quantum numbers J^P to each energy level based on the distribution of dominant operator overlaps, up to spin $J = 4$. By examining the operator-state overlaps for each energy level in the lattice irreps, candidate states for a lightest hybrid supermultiplet with $J^P = (0, 1, 2)^-$ were identified in B, B_s and B_c.

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Ab-initio study of dibaryons with highest bottom number

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We present the first lattice study of dibaryons with highest bottom number. Utilizing a set of state-of-the-art lattice QCD ensembles and methodologies, we determine ground state of the dibaryon composed of two Ω_{bbb} baryons. We extract the related scattering amplitude in the $^1S_0$ channel and find a sub threshold pole, which is an unambiguous evidence for a deeply bound Ω_{bbb}-Ω_{bbb} dibaryon. The binding energy of such a state as dictated by this pole singularity is $-89(^{+16}_{-12})$ MeV. We quantify various systematic uncertainties involved in this determination, including those related to the Coulomb repulsion between the bottom quarks.

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Inclusion of heavy quark spin effects in the $I(J^P)$=$0(1^-)$ $ud\bar{b}\bar{b}$ four-quark channel in the Born-Oppenheimer approximation

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We refine our previous study of a $\bar{b}\bar{b}ud$ tetraquark resonance with quantum numbers $I(J^P) = 0(1^-)$ which is based on antistatic-antistatic-light-light lattice QCD potentials by including heavy quark spin effects via the mass difference of the B and B^* meson.
This leads to a coupled channel Schroedinger equation where the two channels correspond to BB and B^*B^* respectively. We explore the existence of a tetraquark resonance by searching for T matrix poles in the complex energy plane and find that the heavy quark spins have a significant impact. We

also provide an outlook on a possible future finite volume scattering analysis of the same system carried out in full lattice QCD.

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Interpolation as a means of shift selection in multilevel Monte Carlo with lattice displacements

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The calculation of disconnected diagram contributions to physical signals is a computationally expensive task in Lattice QCD. To extract the physical signal, the trace of the inverse Lattice Dirac operator, a large sparse matrix, must be stochastically estimated. Because the variance of the stochastic estimator is typically large, variance reduction techniques must be employed. Multilevel Monte Carlo (MLMC) methods reduce the variance of the trace estimator by utilizing a telescoping sequence of estimators. Frequency Splitting is one such method that uses a sequence of inverses of shifted operators to estimate the trace of the inverse lattice Dirac operator, however there is no a priori way to select the shifts that minimize the cost of the multilevel trace estimation. We present a sampling and interpolation scheme that is able to predict the variances associated with Frequency Splitting under displacements of the underlying space time lattice. The interpolation scheme is able to predict the variances to high accuracy and therefore choose shifts that correspond to an approximate minimum of the cost for the trace estimation. We show that Frequency Splitting with the chosen shifts displays significant speedups over multigrid deflation.

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Heavy Quarks in a Can and the QCD Coupling

Authors: Alberto Ramos[1]; Alessandro Nada[2]; Mattia Dalla Brida[3]; Francesco Knechtli[4]; Rainer Sommer[5]; Roman Höllwieser[None]; Stefan Sint[6]; Tomasz Korzec[7]

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The Lambda parameter of three flavor QCD is obtained by computing the running of a renormalized finite volume coupling from hadronic to very high energies where connection with perturbation theory can safely be made. The theory of decoupling allows us to perform the bulk of the computation in pure gauge theory. The missing piece is then an accurate matching of a massive three flavor coupling with the pure gauge one, in the continuum limit of both theories. A big challenge is to control the simultaneous continuum and decoupling limits, especially when chiral symmetry is broken by the discretization.

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Gradient flow scale setting with tree-level improvement

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Lattice scales defined using gradient flow are typically very precise, while also easy to calculate. However, different definitions of flows and operators can differ, suggesting possible systematical effects. Using the set of RBC-UKQCD 2+1 flavor domain wall fermion and Iwasaki gauge action ensembles, we explore differences between $\sqrt{t_0}$ and w_0 gradient flow scales, compare the impact of different operators to define the energy density, and study the effect of using tree-level improvement for the gradient flow. We find that tree level improvement, traditionally used in step-scaling studies, significantly reduces cut-off effects of the t_0 scale. Our findings should be generally applicable to any gauge action.

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Intra-taste eigenvalue splittings of staggered, KW and BC fermions in 2D

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Staggered fermions, Karsten-Wilczek (KW) fermions and Borici-Creutz (BC) fermions all retain a remnant chiral symmetry. The price to be payed is that they are doubled, and the resulting taste symmetry is broken by cut-off effects. We measure the size of the taste symmetry violation by determining the low-lying eigenvalues of these fermion operators in the two-dimensional Schwinger model which admits, like QCD, a global topological charge of a given gauge configuration. A first result is that it matters whether the pertinent eigenmode is a would-be zero-mode or a non-topological mode. The intra-pair splittings of the fermion formulations mentioned are found to depend sensitively on the gauge coupling β. Still, it turns out that it is surprisingly difficult to verify standard Symanzik scaling for these taste-breaking effects.

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Data analysis on 2pt and 3pt correlation functions with the OK action

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We report recent progress in data analysis on two-point and three-point correlation functions. The data set of measurement is obtained using the Oktay-Kronfeld (OK) action for the heavy quarks (valence quarks) and the HISQ action for the light quarks on MILC HISQ a12m220 ensemble ($N_f = 2 + 1 + 1$ flavors).

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Fine-Tuning of the Yukawa and Quartic Couplings in Supersymmetric QCD

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In this work, we calculate the fine tuning of parameters in N = 1 Super- symmetric QCD, discretized on a Euclidean lattice. Specifically, we study the renormalization of the Yukawa (gluino-quark-squark interactions) and the quar- tic (four-squark interactions) couplings. At the quantum level, these interactions suffer from mixing with other operators which have the same transformation properties. We exploit the symmetries of the action, such as charge conjuga- tion and parity, in order to reduce the list of the mixing patterns. To deduce the renormalizations and the mixing coefficients we compute, perturbatively to one-loop and to the lowest order in the lattice spacing, the relevant three-point and four-point Green's functions using both dimensional and lattice regularizations. Our lattice formulation involves the Wilson discretization for the gluino and quark fields; for gluons we employ the Wilson gauge action; for scalar fields (squarks) we use naive discretization. We obtain analytic expressions for the renormalization and mixing coefficients of the Yukawa couplings; they are func- tions of the number of colors Nc, the gauge parameter α, and the gauge coupling g. Furthermore, preliminary results on the quartic couplings are also presented.

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2022 update of ε_K with lattice QCD inputs

Authors: Chanju Park[1]; Jeehun Kim[2]; Jon Bailey[3]; Weonjong Lee[1]; Jaehoon Leem[4]; Sungwoo Park[5]; Sunkyu Lee[1]; Yong-Chull Jang[6]

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We report recent progress in determining ε_K, the indirect CP violation parameter in the neutral kaon system, calculated using lattice QCD inputs such as $\hat{B}_K$, ξ_0, ξ_2, $|V_{us}|$, $|V_{cb}|$, and $m_c(m_c)$.

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Direct lattice calculation of inclusive hadronic tau decay rates

Authors: Antonio Evangelista[None]; Francesco Sanfilippo[1]; Giuseppe Gagliardi[2]; Nazario Tantalo[3]; Roberto Frezzotti[4]; Silvano Simula[1]; Vittorio Lubicz[5]

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Inclusive hadronic τ decays are particularly interesting from the phenomenological since they give access to V_{ud} and V_{us}. A long-standing issue is the tension between the V_{us} determinations coming from leptonic and semileptonic kaon decays and the ones obtained from inclusive hadronic τ decays. To date (as far as we know) the problem has been addressed indirectly by using sum-rule techniques and non-perturbative lattice inputs complemented with perturbative calculations. In this talk we discuss how a recent method for the extraction of smeared spectral densities from euclidean lattice correlators can profitably be used to obtain a direct lattice calculation of inclusive hadronic τ decay rates. No perturbative inputs are used in our approach as the decay rate is extracted directly from euclidean correlators with two insertions of the relevant hadronic weak current. We also present preliminary numerical results obtained by applying our method to the correlators produced by ETMC with $N_f = 2 + 1 + 1$ dynamical flavours at $a = 0.08\,\mathrm{fm}$ and physical pion masses.

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Isospin Breaking Effects in the 2-Flavor Schwinger Model

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The automatic fine-tuning of isospin breaking effects by conformal coalescence found by Howard Georgi in the 2-flavor Schwinger model is studied. Numerical investigation of meson mass splitting confirms the exponential suppression of symmetry breaking effects.

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Semileptonic $b \to u$ and $b \to s$ decays of the B_c meson

Authors: Laurence Cooper[1]; Christine Davies[1]; Matthew Wingate[2]

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This poster reviews the recent HPQCD calcuation of $B_c^+ \to D^0\ell^+\nu$ and $B_c^+ \to D_s^+\ell^+\ell^-(\nu\bar{\nu})$ form factors [Phys. Rev. D 105, 014503 (2022), arXiv:2108.11242]. We comment on prospects for experimental measurement of $B_c^+ \to D^0\ell^+\nu$ and implications for CKM matrix elements.

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Metadynamics Surfing on Topology Barriers in the Schwinger Model

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Topological freezing is a well known problem in lattice simulations: with shrinking lattice spacing, a transition between topological sectors becomes increasingly improbable, leading to a problematic increase of the autocorrelation time. We present our investigation of metadynamics as a solution for topological freezing in the Schwinger model. Specifically, we take a closer look at the collective variable used in this process and its scaling behaviour. We visualize the effects of topological freezing and how metadynamics helps in that respect. Possible implications for and differences to four-dimensional SU(3) are briefly discussed.

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Strange and charm contribution to the HVP from C* boundary conditions

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We present preliminary results for the leading strange and charm connected contributions to the hadronic vacuum polarization contribution to the muon's g-2. Measurements are performed on the RC*collaboration's QCD ensembles, with $N_f = 3+1$ $O(a)$ improved Wilson fermions and C* boundary conditions. The HVP is computed on a single value of the lattice spacing and two lattice volumes. In addition, we compare the signal-to-noise ratio for different lattice discretizations of the vector current.

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The Quark-Gluon Vertex from Lattice QCD at Finite Temperature

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The quark-gluon vertex is an important object of QCD. Studies have shown that this quantity can be relevant for the dynamical chiral symmetry breaking pattern in the vacuum. The goal of our project is to obtain the quark-gluon vertex at finite temperature around the deconfinement/chiral transition using the tools provided by lattice QCD. It will be the first time that the quark-gluon vertex at finite temperature is determined using lattice QCD. The propagators, which are a by-product of this project, are also of interest in themselves. In this poster, we will describe our motivations and goals, some details of the determination and report on the status of the calculation.

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QCD Thermodynamics with stabilized Wilson fermions

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Stabilized Wilson fermions are a reformulation of Wilson clover fermions that incorporates several numerical stabilizing techniques, but also a local change of the fermion action - the original clover term being replaced with an exponentiated version of it. We intend to apply the stabilized Wilson fermions toolbox to the thermodynamics of QCD, starting on the Nf=3 symmetric line on the Columbia plot, and to compare the results with those obtained with other fermion discretizations.

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Bridge++ 2.0: Benchmark results on supercomputer Fugaku

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Bridge++ is a general-purpose code set for lattice QCD simulations aiming at a readable, extensible, and portable code while keeping practically high performance. The new version 2.0 employs machine-dependent optimization,extended from a fixed data layout in double precision only to a flexible data layout in float/double precision. In this talk, we report the performance on supercomputer Fugaku with Arm A64FX-SVE by Fujitsu.

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Two-link Staggered Quark Smearing in QUDA

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Gauge covariant smearing based on the 3D lattice Laplacian can be used to create extended operators that have better overlap with hadronic ground states. This is often done iteratively. For staggered quarks using two-link parallel transport preserves taste properties. We found that such iterative smearing was taking an inordinate amount of time when done on the CPU, so we have implemented the procedure in QUDA.
Instead of carrying out two consecutive parallel transports between nearest neighbor sites on each smearing iteration, we calculate the product of the two links joining next-to-nearest-neighbor sites once and reuse it for all iterations. This reduces both required floating point operations and communications.
We present the performance of this code on some recent GPUs.

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SIMULATeQCD - a SImple MUlti-GPU LATtice code for QCD calculations

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Increasing GPU power across a competitive market of various GPU manufacturers and GPU based supercomputers pushes lattice programmers to develop code usable for multiple APIs. In this poster we showcase SIMULATeQCD, a SImple MUlti-GPU LATtice code for QCD calculations, developed and used by the HotQCD collaboration for large-scale projects on both NVIDIA and AMD GPUs. Our code has been made publicly available on GitHub. We explain our design strategy, give a list of available features and modules, and provide our most recent benchmarks on state-of-the-art supercomputers.

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Isospin breaking corrections from massive QED

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Isospin breaking corrections become relevant when aiming to quantify hadronic observables with uncertainties below the percent level. Discretising QED on the lattice is a non-trivial task and several suggested methodologies are available in the literature. Our work uses massive QED, which provides a fully local prescription of QED on the lattice. We present a status update of our ongoing computation of isospin breaking corrections to the spectrum and provide an outlook on future computations.

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Improving Lattice QCD calculation of the Collin-Soper Kernel

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Collins-Soper (CS) evolution kernel is critical to relate transverse-momentum-dependent parton distribution functions (TMDPDFs) at different scales. When the parton transverse momentum is small, $q_T \sim \Lambda_{\rm QCD}$, the CS kernel is non-perturbative; the determination of the CS kernel in the non-perturbative regime can only be done through experiment or first-principles calculations. Here, preliminary results are presented for a new calculation of the non-perturbative CS kernel using lattice QCD and Large-Momentum Effective Theory. This work improves the control over and reduces the systematic uncertainties compared to previous lattice QCD calculations, and is the first computation at close-to-physical valence and sea pion masses $m_\pi \approx 140$ MeV.

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The nucleon-pion scattering lengths on a single CLS ensemble with m_{\pi} = 200MeV

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The I=1/2 and I=3/2 nucleon-pion scattering lengths are determined from a high-statistics computation on a single ensemble of gauge field configurations from the CLS consortium with dynamical up, down, and strange quarks and a pion mass $m_\pi = 200\mathrm{MeV}$. The stochastic-LapH approach to quark propagation enables the efficient computation of all required correlation functions, and a statistical precision is achieved which suggests that controlled computations at the physical point are possible. The I=3/2 p-wave scattering amplitude is also precisely determined, and is consistent with the presence of the narrow $\Delta(1232)$ resonance. Systematic errors due to excited states and the reduced symmetry of the finite volume are addressed, but the extrapolation to the continuum and physical quark masses is left to future work.

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Details of RQCD analyses on CLS ensembles

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High statistics results for quantities like the gradient flow scale, the quark masses, the lower lying baryon spectrum and the baryon octet sigma terms determined on CLS ensembles with $N_f = 2 + 1$ non-perturbatively $O(a)$ improved Wilson dynamical fermions are presented at this conference by the RQCD collaboration. In this contribution, we provide further details of the analysis focusing on systematics associated with the extraction of the lattice data including autocorrelations and the continuum, quark mass and finite volume extrapolations, including the fit forms employed.

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Lattice QCD study of antiheavy-antiheavy-light-light tetraquarks based on correlation functions with scattering interpolating operators both at the source and at the sink

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We present first results of a recently started lattice QCD investigation of antiheavy-antiheavy-light-light tetraquark systems including scattering interpolating operators in correlation functions both at the source and at the sink. In particular, we discuss the importance of such scattering interpolating operators for a precise computation of the low-lying energy levels in $\bar{b}\bar{b}ud$ and $\bar{b}\bar{b}us$ four-quark systems and corresponding scattering analyses.

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LapH interpolating fields with open boundary conditions

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The stochastic LapH method has proven to be successful in hadronic calculations. In this work, with charm light spectroscopy in mind, we set up and optimise the LapH procedure limiting ourselves to the evaluation of 2-point mesonic functions. The calculations are performed on CLS ensembles with $N_F = 2+1$ Wilson-Clover fermions on a $32^3 \times 64$ lattice with open boundary conditions. The results showed are obtained with two software packages, namely Grid/Hadrons and Chroma-laph, and a brief comparison between the two is drawn.

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Tuning of QCD+QED simulations with C* boundary conditions

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We give an update on the ongoing effort of the RC* collaboration to generate fully dynamical QCD+QED ensembles with C* boundary conditions using the openQ*D code. The simulations were tuned to the U-symmetric point ($m_d = m_s$) with pions at $m_{\pi^\pm} \approx 400$ MeV. The splitting of the light mesons is used as one of three tuning observables and fixed to $m_{K^0} - m_{K^\pm} \approx 5$ MeV and $m_{K^0} - m_{K^\pm} \approx 25$ MeV on ensembles with renormalized electromagnetic coupling $\alpha_R \approx \alpha_{\text{phys.}}$ and $\alpha_R \approx 5.5\alpha_{\text{phys.}}$ respectively. The tuning of the three independent quark masses to the desired line of constant physics is particularly challenging. In this poster we will define the chosen hadronic renormalization scheme, and we will present a tuning strategy based on a combination of mass reweighting and linear interpolation to explore the parameter space. We will comment on finite-volume effects comparing meson masses on two different volumes with $m_{\pi^\pm} L \approx 3.2$ and $m_{\pi^\pm} L \approx 5.1$. We will also provide some technical details on our updated strategy to calculate the sign of the fermionic Pfaffian, which arises in presence of C* boundary conditions in place of the standard fermionic determinant. An overview of the QCD+QED configurations generated by the RC* collaboration will be given in the companion talk presented by J. Lücke.

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Direct access to hadronic decay parameters with twisted boundary conditions

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Our exploratory study looks for direct access to the hadronic transition amplitude at the resonance without resorting to the Lüscher formalism.
We study the decay $\Psi(3770) \to D\bar{D}$ by applying partially twisted boundary conditions to the quenched charm quark, circumventing possible problems with final state interactions.
If successful, we could compute the dependence of the transition amplitude on the charm-quark mass, and test the predictions made by phenomenological quark pair creation models.
Finally, we investigate if and to what extent an explicit extraction of the excited state $\Psi(3770)$ with help of the GEVP is necessary for this analysis.

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Recent developments on real-time simulations of non-abelian gauge theories using complex Langevin

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Computations within theories with complex actions are generally inaccessible by standard numerical techniques as they typically suffer from the numerical sign problem. The complex Langevin (CL) method aims to resolve this problem. In recent years CL has been successfully applied to various problems, e.g. the QCD equation of state for finite chemical potential, and therefore also may represent a promising method in other applications with similar numerical issues. However, CL in its original formulation is numerically unstable and therefore needs to be artificially stabilised to avoid wrong attractors of the distribution function as well as runaway instabilities.
In this work, we study the application of modern stabilisation techniques such as dynamical stabilisation and gauge cooling to CL simulations of real-time SU(2) Yang-Mills theory. We present preliminary numerical results demonstrating that stabilisation techniques may extend the applicability of CL in real-time gauge theories.

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Update on light composite scalar in eight-flavor SU(3) gauge theory

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We give an update on our ongoing studies of the light composite scalar in eight-flavor SU(3) gauge theory. The chiral limit of this theory can serve as the strong dynamics input to a number of composite Higgs models. Composite Higgs models of this type naturally produce S and T parameters of the

size required to explain the new CDF W mass measurement. We present our improved subtraction scheme for scalar correlators at zero spatial momentum. We compare this scheme with results from moving frames at non-zero spatial momentum where no subtraction is required but an assumption must be made regarding the dispersion relation. We also perform an infinite volume extrapolation. Our analysis includes full implementation of the Bayesian model averaging procedure of Jay-Neil which substantially reduces the systematic uncertainties of our previous published results. We will also present first results for the flavor-singlet scalar decay constant and the flavor non-singlet scalar meson mass and decay constant. Finally, we will present two competing EFT analyses: one assuming the light scalar is a pseudo-dilaton and another assuming the massless theory has a strongly-coupled IR fixed point.

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On improvement and renormalisation of quark currents with stabilised Wilson fermions

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We report on the non-perturbative determination of the improvement coefficient c_A of the axial vector current $A^\mu(x)$ in three-flavour lattice QCD with stabilised Wilson-Clover fermions.
Our computational method exploits the PCAC relation for two different pseudo-scalar states within the Schrödinger functional, which are modelled by altering the spatial structures at the boundaries via properly chosen wavefunctions.
The lattice spacings considered span a range that matches the gauge field ensembles with the stabilised Wilson-Clover action being generated by the OPEN LATtice initiative.
In the same framework and using chiral Ward identities, we also present preliminary results on the renormalisation constants Z_V and Z_A of the vector and axial vector current, respectively.

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Fourier acceleration in strongly-interacting linear sigma models

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Fourier acceleration is a technique used in Hybrid Monte Carlo (HMC) simulations to decrease the autocorrelation length. In the weak interaction limit, Fourier acceleration eliminates the problem of critical slowing down. In this work, we show that by properly tuning the kinetic term in HMC simulations, Fourier acceleration can be applied effectively to a strongly interacting ϕ^4 theory. We use this algorithm to study the linear sigma model with a large coupling constant and in the spontaneous symmetry breaking phase. We find that Fourier acceleration leads to a reduced autocorrelation length and faster thermalization. In addition, we find a method to make use of the tuned kinetic term in the Fourier-accelerated HMC to further reduce the statistical error of many observables. There are several on-going efforts that try to apply Fourier acceleration to non-Abelian gauge theories like QCD. We think some techniques developed in this work can help the application of Fourier acceleration to QCD.

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A study of the pion and the kaon TMDPDFs in twisted mass lattice QCD

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We compute the pion and kaon matrix elements with non-local staple-shaped operators using an $N_f = 2 + 1 + 1$ twisted mass fermion ensemble. The lattice has volume $24^3 * 48$, lattice spacing $a = 0.093\ fm$ and a pion mass of $350\ MeV$. We employ momentum smearing to improve the signal as we increase the momentum. We explore momenta corresponding to $1.11\ GeV$ and $2.78\ GeV$. We also study the mixing pattern of the operators under renormalization and implement an RI/MOM scheme for the non-perturbative renormalization.

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Calculating B-meson Decay Constants, via SU (3)f Symmetry Breaking and Weighted Averaging Methods

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Modern B-factory experiments, such as Belle II, are able to investigate physics anomalies with some of the largest datasets ever produced. High luminosity datasets allow for precision measurements of exclusive B-decays, such as in B ⟶ ℓν, which in turn reduce error in calculations of the correponding CKM matrix element, Vub. This is especially important given the current tension between calculations
of Vub via exclusive decays and inclusive ones, the latter of which could hint towards the presence of
beyond Standard Model processes. While experimental error in Vub can be constrained with larger datasets, controlling the error contributions from the relevant theory parameters, such as the B(s) meson decay constant fB(s) , requires novel analysis.
This work will present the continuing efforts from the UKQCD/QCDSF/CSSM groups towards improving calculations of fB(s) with lattice QCD techniques. This is performed on 2+1 flavour gauge ensembles, where SU (3)f symmetry is broken in a controlled way. The heavy b-quark is treated with an anisotropic clover-improved action and tuned to the physical properties of B and Bs mesons. Such a tuning requires fitting approximately 1600 correlation functions, where individually optimising the bounds of each fit is no longer feasible, and may lead to systematic fit uncertainties that are difficult to

quantify. A weighted-average across multiple fitting regions is implemented so as to improve practicality
and reduce the potential for bias in the final derivation of fB(s)

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The Dispersion Matrix approach to semileptonic heavy-to-heavy and heavy-to-light B decays

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Semileptonic heavy-to-heavy and heavy-to-light B decays are very intriguing transitions since a long-standing tension affects the inclusive and the exclusive determinations of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$. In the former case, another discrepancy exists between the SM expectations and the measurements of the ratios $R(D^{(*)})$, which are a test of Lepton Flavour Universality (LFU). In both cases, a central role is played by the hadronic Form Factors (FFs) describing these decays. Our goal is to re-examine the $b \to c$ and $b \to u$ quark transitions through the Dispersive Matrix (DM) approach, which is based on the non-perturbative determination of the dispersive bounds. It describes in a model-independent way the FFs in the full kinematical range, starting from existing Lattice QCD data at large momentum transfer. From the DM bands we obtain the new SM expectations $R(D) = 0.296(8)$ and $R(D^*) = 0.275(8)$, each of which is compatible with the corresponding average of measurements at the 1.3σ level. The value of $R(D^*)$ corresponds to the use of the recent FNAL LQCD results for the FFs as input for the DM approach. Then, by comparing the DM bands of the FFs with the experiments we obtain $|V_{ub}| = (3.85 \pm 0.27) \cdot 10^{-3}$ from $B \to \pi$ and $B_s \to K$ decays and $|V_{cb}| = (41.2 \pm 0.8) \cdot 10^{-3}$ from $B \to D^{(*)}$ and $B_s \to D_s^{(*)}$ decays. These values are compatible with the inclusive ones and with the indirect determinations from the Unitarity Triangle within the 1σ level.

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nEDM from the theta-term and chromoEDM operators

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In our previous work, we showed that unresolved excited state contaminations provide a major source of systematic uncertainty in the calculation of the nucleon electric dipole moment due to the QCD topological term theta. Here we extend this result to the calculation of the nucleon electric dipole moment due to the quark chromo-electric dipole moment operator. We also show quantitatively the impact of mixing of the latter with lower-dimensional operators on the lattice. Finally, we present preliminary results from a unitary clover-on-clover calculation for the QCD topological term.

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Neutron Electric Dipole Moment from the Theta Term with Overlap Fermions

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We report our calculation of the neutron electric dipole moment (EDM) induced by the theta term. We use overlap fermions on three 2+1-flavor RBC/UKQCD domain wall lattices with pion mass ranging from ~300 to ~500 MeV. The use of lattice chiral fermions guarantees a correct chiral limit even at finite lattice spacings and enables us to reliably extrapolate our result from heavy pion masses to the physical point. Furthermore, by utilizing the partially-quenched chiral extrapolation formula, several valence pion points are added to better constrain the chiral extrapolation. With the help of the cluster decomposition error reduction (CDER) technique and a large amount of statistics accumulated, the statistical uncertainty is effectively controlled. We also carefully check the systematic uncertainties from the two-state fits, the momentum extrapolation, the chiral extrapolation and the CDER technique.

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Constraining Beyond The Standard Model Nucleon Isovector Charges

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At the TeV scale, low-energy precision observations of neutron characteristics provide unique probes of novel physics. Precision studies of neutron decay observables are susceptible to beyond the Standard Model (BSM) tensor and scalar interactions. The neutron electric dipole moment also has high sensitivity to new BSM CP-violating interactions. To fully utilise the potential of future experimental neutron physics programs, matrix elements of appropriate low-energy effective operators within neutron states must be precisely calculated. We present results from the QCDSF/UKQCD/CSSM collaboration for the isovector charges g_T, g_A and g_S using lattice QCD methods and the Feynman-Hellmann theorem. We use a flavour symmetry breaking method to systematically approach the physical quark mass using ensembles that span five lattice spacings and three volumes. We extend this existing flavour breaking expansion to also account for lattice spacing and finite volume effects in order to quantify all systematic uncertainties.

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Chiral extrapolation of hadronic vacuum polarization and isospin-breaking corrections

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By far the biggest contribution to hadronic vacuum polarization (HVP) arises from the two-pion channel. Its quark-mass dependence can be evaluated by combining dispersion relations with chiral perturbation theory, providing guidance on the functional form of chiral extrapolations, or even interpolations around the physical point. In addition, the approach allows one to estimate in a controlled way the isospin-breaking corrections that arise from the pion mass difference. As an application, I will present an updated estimate of phenomenological expectations for electromagnetic and strong isospin-breaking corrections to the HVP contribution in the anomalous magnetic moment of the muon.

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Isospin breaking corrections to the vector-vector correlator in QCD: the muon g-2 and tau decays.

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In this contribution we report on progress in the determination of the isospin breaking corrections to the vector-vector correlator in QCD from the RBC/UKQCD collaborations. They are relevant to estimate the hadronic contributions to the muon anomalous magnetic moment directly from first-principles lattice QCD simulations, and indirectly from cross sections measured in tau decay experiments.

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The (g-2) intermediate window quantity from a coordinate-space method

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We present a calculation of the intermediate window quantity of the hadronic vacuum polarization contribution to the muon g-2 using a Lorentz-covariant coordinate-space method at a fixed pion mass of ~350 MeV. This method is more flexible in the choice of the integration kernel than the time-momentum representation and gives a different perspective on the systematic errors of the g-2 calculation. It furthermore serves as a check for the recent results of the Mainz group.

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Disconnected contribution to the LO HVP term of muon g-2 from ETMC

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We present a lattice determination of the disconnected contributions to the leading-order hadronic vacuum polarization (HVP) to the muon anomalous magnetic moment in the so-called short and intermediate time-distance windows. We employ gauge ensembles produced by the Extended Twisted Mass Collaboration (ETMC) with $N_f = 2 + 1 + 1$ flavors of Wilson twisted-mass clover-improved quarks with masses approximately tuned to their physical value. We take the continuum limit employing three lattice spacings at about 0.08, 0.07 and 0.06 fm.

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Time windows of the muon HVP from twisted mass lattice QCD

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We present new lattice results of the ETM Collaboration for the SM prediction of the so-called intermediate window (W) and short-distance (SD) contributions to the leading-order hadronic vacuum polarization (HVP) term of the muon anomalous magnetic moment, a_μ^{HVP}.
Our results are obtained from extensive simulations of twisted mass lattice QCD with dynamical up, down, strange and charm quarks at physical mass values, different volumes, and lattice spacings down to $a \sim 0.057$ fm. Our determinations of $a_\mu^{HVP}(W)$ and $a_\mu^{HVP}(SD)$ are compared with existing lattice results and with their dispersive counterparts based on experimental data for e^+e^- annihilation into hadrons. The comparison with dispersive data confirms the tension in $a_\mu^{HVP}(W)$ while showing no significant tension in $a_\mu^{HVP}(SD)$.

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Intermediate window observable for the hadronic vacuum polarization contribution to the muon $g - 2$ from O(a) improved Wilson quarks

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With the publication of the new measurement of the anomalous magnetic moment of the muon, the discrepancy between experiment and the data-driven theory prediction has increased to 4.2σ. Recent lattice QCD calculations predict values for the hadronic vacuum polarization contribution that are larger than the data-driven estimates, bringing the Standard Model prediction closer to the experimental measurement. Euclidean time windows in the time-momentum representation of the hadronic vacuum polarization contribution to the muon $g-2$ can help clarify the discrepancy between the phenomenological and lattice predictions.
We present our calculation of the intermediate distance window contribution using $N_\mathrm{f} = 2+1$ flavors of $\mathrm{O}(a)$ improved Wilson quarks. We employ ensembles at six lattice spacings below 0.1 fm and pion masses down to the physical value. We present a detailed study of the continuum limit, using two discretizations of the vector current and two independent sets of improvement coefficients. Our result at the physical point displays a tension of 3.8σ with a recent evaluation of the intermediate window based on the data-driven method.

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The hadronic running of the electromagnetic coupling and electroweak mixing angle (Part I)

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We employ $N_\mathrm{f} = 2+1$ flavours of $O(a)$ improved Wilson fermions to determine the hadronic vacuum polarisation functions $\bar{\Pi}^{\gamma\gamma}$ and $\bar{\Pi}^{\gamma Z}$ for Euclidean squared momenta $Q^2 \leq 7\ \mathrm{GeV}^2$. We extrapolate the results to the physical point using ensembles at four lattice spacings and several pion masses, including its physical value. We observe a tension of up to 3.5 standard deviations between our lattice results for $\Delta\alpha^{(5)}_{\mathrm{had}}(-Q^2)$ and estimates based on the R-ratio for space-like momenta in the range $3-7\ \mathrm{GeV}^2$.

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The hadronic running of the electromagnetic coupling and electroweak mixing angle (Part II)

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We discuss the conversion of our lattice result for the hadronic running of the electromagnetic coupling, $\Delta\alpha(-Q^2)$, computed for Euclidean momenta into an estimate for $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$ using the Euclidean split technique (Adler function approach). We focus specifically on the running in the spacelike regime from momentum scales below $7\,\mathrm{GeV}^2$ up to M_Z^2, which can be determined either in perturbative QCD or by using dispersion theory and experimentally determined hadronic cross sections. A detailed comparison with results from other lattice calculations and phenomenology is performed. We present an in-depth discussion of the relation to lattice estimates of the hadronic vacuum polarisation contribution to the muon $g-2$ and the implications for global electroweak fits.

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A first look at the HVP from QCD and QCD+QED with C* boundary conditions

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Co-authors: Agostino Patella [2]; Alessandro Cotellucci [2]; Isabel Campos Plasencia [3]; Javad Komijani [4]; Jens Lücke [2]; Joao C. Pinto Barros [1]; Lucius Bushnaq ; Madeleine Dale ; Marco Catillo ; Marina Krstic Marinkovic [4]; Nazario Tantalo [5]; Paola Tavella [6]; Patrick Fritzsch [7]; Sofie Martins [8]

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We present an update on including isospin breaking effects in the determination of HVP using C* boundary conditions. We use QCD+QED configurations with 1+2+1 flavors of Wilson-Clover fermions produced by RC* collaboration, where the action parameters are chosen to highlight isospin breaking effects. In this series of two talks, we show preliminary results for three $32^3 \times 64$ gauge ensembles with varying values of the fine structure constant, and compare them with the results on the QCD-only ensemble, discussed in the poster presentation by Paola Tavella.

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A first look at the HVP from QCD and QCD+QED with C⋆ boundary conditions II

Authors: Anian Altherr[1]; Roman Gruber[1]

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We present an update on including isospin breaking effects in the determination of HVP using C⋆ boundary conditions. We use QCD+QED configurations with $1+2+1$ flavors of Wilson clover fermions produced by the RC⋆ collaboration, where the action parameters are chosen to highlight isospin breaking effects. In this series of two talks, we show preliminary results for three $32^3 \times 64$ gauge ensembles with varying values of the fine structure constant, and compare them with the results on the QCD-only ensemble, discussed in the poster presentation by Paola Tavella.

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Finite-Size Effects of the Hadronic Vacuum Polarization Contribution to the Muon $(g-2)$ with C⋆ Boundary Conditions

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The muon $(g-2)$ is a compelling quantity due to the current standing tensions among the experimental average, data-driven theoretical results, and lattice results. Matching the final target accuracy of the experiments at Fermilab and J-PARC will constitute a major challenge for the lattice community in the coming years. For this reason, it is worthwhile to consider different options to keep the systematic errors under control. In this talk, we discuss finite-volume effects of the leading Hadron Vacuum Polarization (HVP) contribution to the muon $(g-2)$ in the presence of C⋆ boundary conditions. When considering isospin-breaking corrections to the HVP, C⋆ boundary conditions provide a possible consistent formulation of QCD+QED in finite volume. Even though these boundary conditions can be avoided in the calculation of the leading HVP contribution, we find the interesting result that they remove the leading exponential finite-volume correction. In practice, compared to the periodic case, C⋆ boundary conditions cut the finite-size effects in half on a lattice of physical size $M_\pi L = 4$ and by a factor of almost ten for $M_\pi L = 8$. The origin of this reduction will be the focus of this talk.

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Probing the R-ratio on the lattice

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The ratio of the cross sections for $e^+e^- \to hadrons$ and $e^+e^- \to \mu^+\mu^-$ at c.o.m energy E, i.e. $R(E)$, is an extremely interesting observable. Its measurements are used in dispersive analyses of the leading hadronic vacuum polarization (HVP) contributing to the muon $g-2$, and the results of these analyses for a certain window observable are in significant tension with those coming from recent accurate lattice computations. It is thus very important to determine $R(E)$ from first-principles and compare it with experiment. In this talk we study $R(E)$ through a smearing in energy with different kernels $f(E)$. Indeed, by changing the shape of the smearing kernel one obtains an infinite number of observables, $R[f]$, that probe $R(E)$ in different ways. In particular, choosing $f(E) = \exp(-Et)$ yields the Euclidean lattice correlator of two electromagnetic hadronic currents. This is a primary quantity from the lattice viewpoint, which we compare with its experimental counterpart directly obtained from the measured $R(E)$. We also use a recently proposed method for extracting smeared spectral densities from Euclidean lattice correlators in order to compute $R[f]$ for smearing kernels f chosen as Gaussians of different width and central energy. Our still preliminary numerical results are obtained using state-of-the-art ETMC ensembles with $N = 2+1+1$ dynamical quark flavours at three values of the lattice spacing ($\geq$ 0.06 fm), large volumes and physical pion mass.

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Renormalization of the quark chromomagnetic dipole operators in the gradient flow scheme at next-to-next-to-leading order QCD

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Quark chromomagnetic dipole operators encode low-energy effects of heavy particles on flavor observables related to neutral Kaon mixing or Kaon decays, for example. However, their renormalization on the lattice is complicated by the power-divergent mixing with lower-dimensional operators. The gradient flow provides a promising scheme to circumvent this problem. The matching to the MSbar scheme can be obtained by a perturbative calculation. In this talk, we report on the results for the matching coefficients through NNLO QCD and discuss the impact of these corrections on the theoretical precision.

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Pion pole contributions to HLbL at the physical point

Authors: Gurtej Kanwar[1]; Sebastian Andreas Burri[1]; Marcus Petschlies[2]; Urs Wenger[1]

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Pseudoscalar pole diagrams provide the bulk of the contribution – as well as a large fraction of the error budget – of dispersive estimates of the hadronic light-by-light (HLbL) piece of the muon g-2. We report on a calculation of the pion transition form factor $F_{P\to\gamma\gamma}$ over a range of kinematics, including broad regions which are inaccessible from experimental data, which directly leads to an estimate of the pion pole contribution to the muon g-2. The results are evaluated using physical quark masses and are extrapolated to the continuum using twisted mass ensembles at several lattice spacings. Our result for the g-2 contribution is comparable with previous lattice and data-driven determinations, with combined uncertainties achieving sub-10% precision.

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Eta pole contributions to HLbL at the physical point

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We report on our computation of the eta transition form factor $\mathcal{F}_{\eta\to\gamma^*\gamma^*}$ from twisted mass lattice QCD at physical quark masses and at a single lattice spacing. On the lattice, we have access to a broad range of (space-like) photon momenta and can therefore produce data complementary to the experimentally accessible singly virtual case. We use the form factor to determine the eta pole contribution to the hadronic light-by-light scattering in the muon $g-2$, leading to a first lattice QCD estimate. Our estimate of $a_\mu^{\eta-pole}$ obtained at a single lattice spacing achieves an accuracy of below 40%. Since so far there are no determinations of this contribution from first principles, even such a crude determination is interesting from a phenomenological point of view.

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Rare $K^+ \to \pi^+\ell^+\ell^-$ decays with physical mass light-quarks

Author: Ryan Hill[1]

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$K^+ \to \pi^+\ell^+\ell^-$ is a highly suppressed decay mode in the Standard Model, and is therefore expected to be sensitive to new physics. In this talk, we present the first lattice calculation of the long-distance electromagnetic form factor V at physical light-quark masses for this decay. Our calculation features an explicit GIM subtraction, with dynamical zMöbius quarks and Möbius domain-wall fermion sea-quarks. In order to improve upon the obtained result, we identify the particular challenges to

overcome on the road towards a competitive physical-point lattice calculation and suggest routes forward.

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Progress on the exploratory calculation of the rare Hyperon decay $\Sigma^+ \to p\ell^+\ell^-$

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The rare Hyperon decay $\Sigma^+ \to p\ell^+\ell^-$ is an $s \to d$ flavour changing neutral current process, which is highly suppressed within the Standard Model, and is therefore sensitive to new physics. Due to recent improvements in experimental measurements of this decay, the Standard Model theory prediction must also be improved in order to identify any new physics in this channel. We present updates on our progress towards the first exploratory lattice calculation of the long-distance part of the form factors of this decay on a 340MeV pion mass ensemble using domain-wall fermions as part of the RBC-UKQCD collaboration.

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Finite-volume effects in a calculation of the rare Hyperon decay $\Sigma^+ \to p\ell^+\ell^-$

Author: Felix Erben[1]

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The rare Hyperon decay $\Sigma^+ \to p\ell^+\ell^-$, potentially sensitive to new physics beyond the Standard Model, is currently being pursued in an exploratory calculation by the RBC/UKQCD collaboration. At the physical pion mass, intermediate $N\pi$ states lead to poles in lattice quantities, which need to be removed to extract the physical amplitude. We present the formalism to achieve this and comment on the role of tuning lattice volumes specifically to account for these intermediate states.

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Hadronic contribution to the running of the electromagnetic coupling constant

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The electromagnetic coupling constant, α, is one of the fundamental parameters of the Standard Model (SM). Its value at the Z boson mass, $\alpha(M_Z)$, is of particular interest as it enters electroweak

precision tests. When running α from low energies up to the Z mass, five orders of magnitude in precision are lost. This makes it one of the least well determined parameters of the SM at that scale. The largest source of error comes from non-perturbative hadronic effects in the low energy region.

These non-perturbative effects can be determined from ab initio calculations on the lattice. We present preliminary lattice results for the leading order hadronic contribution to this running at different values of Q^2, the four-momentum transfer squared. These are obtained using simulations with 2+1+1 flavors of staggered fermions at physical values of the quark masses.

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Hadronic vacuum polarization from step scaling

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It is well known that the electromagnetic coupling constant alpha is an energy scale dependent quantity. Some of these dependencies originate from hadrons and can therefore be computed using Lattice QCD. The value at the mass of the Z boson is of particular interest. The large energy range makes a direct simulation unfeasible, so it has to be split up into several ranges. Setting the scale of the smaller and finer lattices, which cover the higher energies, is a challenging task. We present a general method to handle this issue in lattice gauge theories. A test of this strategy in two-dimensional QED is done and the hadronic vacuum polarization is computed on an energy range that spans two orders of magnitude.

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Neutrinoless Double Beta Decay from Lattice QCD: The Short-Distance $\pi^- \to \pi^+ e^- e^-$ Amplitude

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This talk presents a determination of the short-distance contributions to the unphysical $\pi^- \to \pi^+ e^- e^-$ decay through lattice QCD calculations. The hadronic contributions to the transition amplitude are described by the pion matrix elements of five Standard Model Effective Field Theory operators, which are computed on five ensembles of domain-wall fermions with $N_f = 2 + 1$ quark flavors with a range of heavier-than-physical values of the light quark mass. The matrix elements are extrapolated to the continuum limit and to the physical light quark mass and infinite volume limit using a functional form derived in chiral perturbation theory. This extrapolation also yields the pion-pion low-energy constants of chiral Effective Field Theory (χEFT), which are necessary input for χEFT calculations of neutrinoless double beta decay in nuclei.

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Preliminary Lattice QCD Study of nn → ppee Matrix Elements for Neutrinoless Double-Beta Decay

Authors: Anthony Grebe[1]; David Murphy[None]; Patrick Oare[1]; William Detmold[1]; Zhenghao Fu[1]

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Experimental searches for neutrinoless double-beta decay aim to determine whether the neutrinos are Dirac or Majorana fermions. Interpreting double-beta half-lives or experimental exclusions in terms of neutrino physics requires knowledge of the nuclear matrix elements, which are currently estimated from various nuclear models and carry a large model uncertainty. This talk will present preliminary results from a first-principles lattice QCD calculation of the short-distance (from a heavy intermediate Majorana neutrino) and long-distance (from a light Majorana neutrino) nuclear matrix elements for the simple $nn \to ppee$ transition at an artificially heavy quark mass, where the dineutron is a bound state. Such results can provide input for nuclear EFTs that can be extrapolated to nuclei of interest to reduce model uncertainties.

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Intermediate window observable for the muon g-2 from overlap valence quarks on staggered ensembles

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The Budapest-Marseille-Wuppertal collaboration computed the leading hadronic vacuum polarization contribution to the anomalous muon magnetic moment with unprecedented accuracy on the lattice. The result was obtained using staggered fermions. Here we present an improved crosscheck of the staggered result for the intermediate window observable using a mixed action setup: overlap valence quarks on staggered sea ensembles. We focus on the light connected contribution. Details of the overlap fermion formulation and of the methods used for the measurements of the hadronic vacuum polarization are described. We present first results for two different setups on lattices with a spatial extent of 3 fm.

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Pseudoscalar transition form factors and the hadronic light-by-light contribution to the muon g-2

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We present preliminary results toward the extraction of the transition form factors $\mathcal{F}_{p\to\gamma^*\gamma^*}$ ($p = \pi^0, \eta, \eta'$) using lattice QCD with staggered fermions on $N_f = 2+1+1$ gauge ensembles generated by the Budapest-Marseille-Wuppertal collaboration. These form factors are essential ingredients for the computation of the light pseudoscalar pole contributions to the hadronic light-by-light scattering in the muon $g-2$. In the first part of this talk we focus on the π^0 and compare it to previous results; in the second part we report the status of the analysis for the η, η'.

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Hadronic Vacuum Polarization: A Window on the muon g-2 mystery

Authors: Aida El-Khadra[1]; Carleton DeTar[2]; Steven Gottlieb[3]; Andreas Kronfeld[4]; Curtis Peterson[5]; Elvira Gámiz[6]; Ethan Neil[7]; Ruth Van de Water[4]; Shaun Lahert[8]

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The Fermilab Lattice, HPQCD, and MILC collaborations are engaged in multi-year projects to compute the hadronic vacuum polarization (HVP) contribution to the anomalous magnetic moment of the muon with high precision. In this talk, we present the status of our calculation of the light-quark connected contributions to HVP. The calculation relies on four ensembles of gauge configurations generated by the MILC collaboration. These ensembles have 2+1+1 flavors of dynamical highly-improved staggered quarks (HISQ) with the common up and down quark masses tuned to give a pion mass very close to its physical value. Lattice spacings range from approximately 0.15 fm to 0.06 fm. For most ensembles, the statistics have been increased from our last publication. We have results for various window regions that restrict the contribution to time ranges for which the vector-current correlation is precisely determined.

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Updates on the HVP computation from the BWM collaboration

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We discuss ongoing improvements to the hadronic vacuum polarization computation by the Budapest-Marseille-Wuppertal collaboration.

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Calculating the QED correction to the hadronic vacuum polarisation on the lattice

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Co-authors: Aida El-Khadra [2]; Alejandro Vaquero Avilés-Casco [3]; Alexei Bazavov [4]; Andreas Kronfeld [5]; Carleton DeTar [3]; Christine Davies [6]; Daniel Hatton [6]; Hwancheol Jeong [7]; James Simone [5]; Steven Gottlieb [7]

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Isospin-breaking corrections to the HVP component of the anomalous magnetic moment of the muon are needed to ensure the theoretical precision of $g_\mu - 2$ matches its experimental precision. To this end we describe the status of our work calculating, on the lattice, the QED IB correction to the light connected HVP. We report results using physical $N_f = 2 + 1 + 1$ HISQ ensembles at 3 lattice spacings and 3 heavier-than-light valence quark masses.

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Muon g-2 with overlap valence fermions

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We present a lattice calculation of the window contribution ($t_0 = 0.4$ fm, $t_1 = 1.0$ fm, $\Delta = 0.15$ fm) of the leading order hadronic vacuum polarization contribution to the muon g-2 using overlap valence fermions on 4 physical-point ensembles. Two 2+1 flavor ensembles use the domain wall fermion (DWF) and Iwasaki gauge actions at $a = 0.084$ and 0.114 fm, and two 2+1+1 flavor ensembles use the highly improved staggered quark (HISQ) actions and Symanzik gauge actions at $a = 0.088$ and 0.121 fm. For $a^{\mathrm{W}}_{\mathrm{con},l}$, we find that our results on the two smaller lattice spacings are consistent with those using the unitary setup, but those at the two coarser lattice spacings have small differences.

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The muon anomalous magnetic moment with staggered fermions: is the lattice spacing small enough?

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We present new results for the light-quark connected part of the leading order hadronic-vacuum-polarization (HVP) contribution to the muon anomalous magnetic moment, using staggered fermions. We have collected more statistics on previous ensembles, and we added two new ensembles. This allows us to reduce statistical errors on the HVP contribution and related window quantities significantly. We also calculated the current-current correlator to next-to-next-to-leading order (NNLO) in staggered chiral perturbation theory, so that we can correct to NNLO for finite-volume, pion-mass mistuning and taste-breaking effects. We discuss the applicability of NNLO chiral perturbation theory, emphasizing that it provides a systematic EFT approach to the HVP contribution, but not to short- or intermediate-distance window quantities. This makes it difficult to assess systematic errors on the standard intermediate-distance window quantity that is now widely considered in the literature. In view of this, we investigate a longer-distance window, for which EFT methods should be more reliable. Our most important conclusion is that new high-statistics computations at lattice spacings significantly smaller than 0.06 fm are indispensable. The ensembles we use have been generously provided by MILC and CalLat.

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RBC/UKQCD update of the HVP contribution to the muon g-2

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This talk gives an update of the HVP contribution to the muon g-2 from the RBC/UKQCD collaborations.

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Hadronic vacuum polarization from twisted mass lattice QCD

Authors: Bartosz Kostrzewa[1]; Constantia Alexandrou[2]; Marcus Petschlies[3]; Carsten Urbach[3]; Francesco Sanfilippo[4]; Giuseppe Gagliardi[4]; Jacob Finkenrath[5]; Karl Jansen[6]; Kyriakos Hadjiyiannakou[7]; Marco Garofalo[3]; Petros Dimopoulos[8]; Roberto Frezzotti[9]; Silvano Simula[4]; Simone Bacchio[5]; Urs Wenger[10]; Vittorio Lubicz[11]

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The hadronic vacuum polarization (hvp) function Π is the basis quantity for high-precision lattice calculations of the hvp contribution to the muon anomalous magnetic moment, $a_\mu^{\mathrm{lo-hvp}}$.
Recently, tensions have emerged between lattice QCD based determinations of intermediate time-distance hvp ("window") contributions to $a_\mu^{\mathrm{lo-hvp}}$ and their counterparts based on $e^+e^- \to \mathrm{hadrons}$ R-ratio experimental data.
The investigation of the 4-momentum-dependent polarization function itself provides an alternative

approach to zero in on potential momentum regions where such discrepancies originate. We present results for our determination of $\Pi(Q^2)$ from twisted mass lattice QCD at physical quark masses, towards a Q^2-specific comparison with dispersive results.

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Contribution of QCD theta-term to nEDM with Stabilized Wilson Fermions

Authors: Jangho Kim[1]; Anthony Francis[None]; Thomas Luu[2]; Giovanni Pederiva[None]; Andrea Shindler[3]; Savvas Zafeiropoulos[4]

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The QCD theta term is a source of CP-violation that could potentially induce a non-vanishing neutron electric dipole moment (nEDM). Previous lattice calculations have had difficulties in extracting the nEDM, especially when close to the physical value of the pion mass. In this contribution we present first results obtained with Stabilized Wilson Fermions. We focus on SU(3) flavor-symmetric OpenLat ensembles at $\sim$ 400 MeV pion mass, and 3 different lattice spacings in the range of 0.065 fm $< a < 0.12$. We use O(100) stochastic source locations to improve the signal-to-noise ratio.

Software development and Machines / 162

Porting the COLA software library to AMD

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COLA is a software library for lattice QCD written in modern Fortran and NVIDIA CUDA. Intel and NVIDIA have dominated the HPC domain for a long time, but the status quo has been changed with the recent advent of AMD-based systems in the supercomputing Top‘500. Setonix is a next generation Cray AMD machine currently being installed at the Pawsey Supercomputing Centre in Perth, Australia. Setonix features both AMD CPUs and AMD Instinct GPUs. This talk will describe first experiences with porting COLA to the AMD platform.

Software development and Machines / 78

GPT

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In this talk I give an update on the status of the GPT software package. (https://github.com/lehner/gpt.)

Software development and Machines / 304

Lyncs-API: status update

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Lyncs-API is a Python API for Lattice QCD. It aims to create a complete framework for easily running applications via Python. It implements low- and high-level tools, including interface to common LQCD libraries. Last year, at this conference, we presented the API to the community for the first time. In this talk we will give a status update on its development and show the potential of the API via some applications we have implemented this year.

Software development and Machines / 260

Twisted mass ensemble generation on GPU machines

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We present progress in interfacing the Hybrid Monte Carlo implementation in the tmLQCD software suite with the QUDA library and compare its performance to our top of the line algorithms on CPU machines. We discuss the main challenges and overheads of our approach and scrutinize its fundamental architectural limitations before exploring ongoing improvements as well as current and future simulations.

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Solvers for Wilson fermions in Grid

Author: Felix Ziegler[1]

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In this talk we present work on extending the set of solvers for the inversion of the Dirac matrix for Wilson-Clover type fermions in Grid. Particular emphasis is put on the inexact deflation method put forward by Lüscher. Besides providing fast solves for configurations at the physical point one of the method's central advantages is that it can be included into the HMC algorithm at relatively low computational cost. We assess the performance of our implementation of the algorithm on both CPU and GPU architectures and carry out comparisons with other solvers.

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Avoiding the Jam

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Bandwidth and latencies are central performance limiters for Lattice QCD. To overcome bandwidth limiters one way is to reduce the number of bits need by e.g., mixed precision solvers. These provide great speedups but increase the relative importance of latency limiters. We discuss techniques that QUDA uses to reduce latencies from GPU-CPU and GPU-network transfers and their impact for strong-scaling HMC simulations, where these matter most.

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MPI Job Manager

Authors: Andre Walker-Loud[1]; Ken McElvain[2]

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MPI Job Manager (MPI_JM) is "scheduler" designed enable users to make maximum use of heterogenous architectures, particularly which require a "swarm" of independent MPI tasks is required for a complete calculation - such as lattice QCD calculations of correlation functions on pre-existing configurations. MPI_JM managers all these tasks through lightweight C++ code supported by Python3. MPI_JM allows users to describe the resource requirements of their tasks (GPU-intense, CPU-only, number of nodes, wall clock time, etc) as well as their dependencies. MPI_JM then schedules these tasks on an allocation on an HPC platform based upon user defined priority and dependencies. Jobs with GPU-intense and CPU-only requirements are placed upon the same nodes, maximizing the use of all node resources. This is all managed with a single mpirun call, minimizing the requirements of the service nodes that manage an HPC system. Planned features include (among others):

- Multiple job-configurations: as the wall clock of the allocation nears the end, the optimal run configuration may not have enough time to complete, but doubling the nodes at a performance loss would allow a job to complete in time. MPI_JM can try alternate configurations specified by the user, to use up the otherwise idle cycles towards the end of a job allocation
- Try again: sometimes, the GPUs on a node will just fail to start up in time, causing a job to time out. MPI_JM can be instructed to try N-times before giving up and trying a new job, or removing those nodes from the allowed ones to be used in the allocation.

- Use real wall-clock time rather than user specified estimate: Optinoally, MPI_JM will track performance of similar jobs in a database, and then use this information to provide more reliable estimates of wall-clock time requirements than what is specified by the user.
- etc.

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Performance Optimization of Baryon-block Construction in the Stochastic LapH Method

Authors: Phuong Nguyen[1]; Ben Hoerz[2]

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Implementations of measurement kernels in high-level Lattice QCD frameworks enable rapid prototyping, but can leave hardware capabilities significantly underutilized. This is an acceptable tradeoff if the time spent in unoptimized routines is generally small. The computational cost of modern spectroscopy projects however can be comparable to or even exceed the cost of generating gauge configurations and computing solutions of the Dirac equation. One such key kernel in the stochastic LapH method is the computation of baryon blocks; we discuss several implementation strategies and achieve a 3x speedup over the current implementation on Intel Ice Lake.

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Optimizing Staggered Multigrid for Exascale performance

Author: Venkitesh Ayyar[1]

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Adaptive multigrid methods have proven very successful in dealing with critical slow down for the Wilson-Dirac solver in lattice gauge theory. New formulations for Multigrid methods with staggered fermions are currently being tested on pre-exascale GPU supercomputers such as Summit and Crusher. In this talk, I will discuss our implementation of staggered multigrid codes on the Summit Supercomputer and subsequent optimization efforts.

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Running HMC Simulations with Python via QUDA

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Lyncs-API is a Python API for lattice QCD. One of the goals of lyncs-API is to provide a common framework for lattice QCD calculation for different HPC architectures with and without accelerators by utilizing different software packages. As such, it contains interfaces to c-lime, DDalphaAMG, tmLQCD, and QUDA. In this talk, we focus on the interface to QUDA, named lyncs-QUDA, and present a small tutorial on how to use the Python interface to perform a Hybrid Monte Carlo simulations using computational kernels provided by QUDA.

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Maximizing the Bang Per Bit

Author: Kate Clark[1]

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We give an overview of the mixed-precision Krylov strategies of QUDA. These have evolved over the past decade and utilize a variety of numerical techniques to stabilize the convergence of solvers such as Conjugate Gradient. We describe a recently developed bit packing technique to increase precision at fixed word size. This improvement in precision stabilizes the mixed-precision solvers as the chiral limit is reached.

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Status of reproducibility and open science in hep-lat in 2021

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As a fully computational discipline, Lattice Field Theory has the potential to give results that anyone with sufficient computational resources can reproduce, going from input parameters to published numbers and plots correct to the last byte. After briefly motivating and outlining some of the key steps in making lattice computations reproducible, I will present the results of a survey of all 1,229 submissions to the hep-lat arXiv in 2021 of how explicitly reproducible each is. I will highlight areas where LFT has historically been well ahead of the curve, and areas where there are opportunities to do more. I will conclude by outlining some potential next steps to embracing reproducible open science as a community.

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Open Science in Lattice Gauge Theory community

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Open science aims to make scientific research processes, tools and results accessible to all scientific communities, creating trust in science and enabling digital competences to be realized in research, leading to increased innovation. It provides standard and transparent pathways to conducting research and fosters best practices for collecting, analysing, preserving, sharing and reusing data, software, workflows and other outputs through collaborative networks. Open Science appears to becoming the norm with its applications spanning throughout the whole research cycle of a project. The importance of making Open Science a reality is reflected in the policy and implementation actions of the European Commission incorporated in research and innovation funding programmes (FP7, Horizon 2020, Horizon Europe) and the development of the European Open Science Cloud (EOSC) as it improves the quality, efficiency and responsiveness of research. EOSC will enable researchers across disciplines and countries to store, curate and share data under a common policy framework with rules of participation and pre-defined set of technical specifications that are expected to help shape the "Internet of FAIR data and services" in Europe. In this talk we will present the basic Open Science principles explaining briefly best practices for materialising open science. Subsequently, we will present the results of the landscaping survey of Open Science in the Lattice Gauge Theories community (https://latticesurvey.hpcf.cyi.ac.cy/index.php/157898). Finally, we will provide directions in which the LGT community could move in order to enhance Openness and FAIRness (Finability, Accessibility, Interoperability, Reusability) in Science.

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The light quark masses from $N_f = 2 + 1$ CLS ensembles

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We determine the strange quark mass and the isospin averaged up/down quark mass from QCD in the isospin limit. We utilize 46 CLS ensembles generated with $N_f = 2 + 1$ non-perturbatively $O(a)$ improved Wilson fermions comprising six lattice spacings in the range $a = 0.1$ fm down to $a = 0.04$ fm, spatial volumes with $LM_\pi > 4$ and pion masses ranging from around 420 MeV down to the physical point. The quark masses, obtained from axial Ward identities, are fitted simultaneously as functions of the squared pion and kaon masses with all correlations taken into account. The main source of uncertainty at present is from the renormalization of the quark masses and we check the universality of the continuum limit, employing different sets of renormalization constants, obtained from the step scaling function with Schrödinger boundary conditions as well as employing the RI'-SMOM scheme with a subsequent conversion to the $\overline{\mathrm{MS}}$ scheme at the three-loop level.

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Scale setting from a mixed action with Wilson twisted mass valence quarks

Author: Alejandro Saez[1]

Co-authors: Gregorio Herdoiza [2]; Alessandro Conigli [1]; Julien Frison [3]; Carlos Pena [1]; Javier Ugarrio [1]

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We present preliminary results for a scale setting procedure based on a mixed action strategy, consisting of Wilson twisted mass valence fermions at maximal twist on CLS ensembles with $N_f = 2+1$ flavours of O(a)-improved Wilson sea quarks. Once the matching of valence and sea quark masses is performed, universality tests are carried out by comparing the continuum-limit results of the mixed action setup to those of the regularisation based solely on O(a)-improved Wilson fermions. The scale setting uses the pion and kaon decay constants, in units of flow scale t_0, obtained from combining computations with the unitary Wilson action and the mixed action. The proper isolation of ground states as well as the continuum-chiral extrapolations are evaluated through model variation techniques. An update on the determination of t_0 will be presented.

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Light quark masses from a mixed action with Wilson twisted mass valence quarks

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We report on the determination of light quark masses with three sea-quark flavours based on a mixed action with maximally twisted valence fermions on CLS ensembles with O(a)-improved Wilson sea quarks. The renormalisation and the renormalisation group running over a wide range of scales are based on existing non-perturbative computations in the Schrodinger functional scheme. The determinations of the light (u,d) and strange quark masses are based on a combination of the results from the unitary Wilson action with those from the mixed action.

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f_K and f_π from staggered QCD

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The decay constants of the kaon and pion provide important input into the determination of light CKM matrix elements. Here we present current progress in computing these quantities using the ensembles and analysis techniques employed by the Budapest-Marseille-Wuppertal collaboration in our recent determination of $a_\mu^{LO,HVP}$. This work will provide input on the current 2.6-sigma tension between lattice-based determinations and CKM unitarity. It also serves as a cross-check of the many aspects of the analysis shared with our $a_\mu^{LO,HVP}$ determination. While this analysis includes considerably more statistics than previous lattice calculations, the total errors on the ratio f_K/f_π are similar to the best existing determinations. This is a result of our comprehensive and conservative approach to systematic error estimation, which was developed for $a_\mu^{LO,HVP}$.

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Electroweak box diagrams on the lattice for pion and neutron decay

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We present our calculation of radiative correction to the pion and nucleon decay given by the γW box contribution and needed for the determination of V_{ud}.
The pion box contribution is computed on five 2+1+1-flavor HISQ ensembles using with Clover action.
The preliminary nucleon box contribution is being analyzed on one ensemble.
In both contributions, the loop momentum is integrated with discrete sums.

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Towards precision charm physics with a mixed action

Author: Alessandro Conigli[1]

Co-authors: Carlos Pena [1]; Gregorio Herdoiza [1]; Javier Ugarrio [1]; Alejandro Saez [1]; Frison Julien [2]

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We report on our first set of results for charm physics, using a mixed-action setup with maximally twisted valence fermions on CLS $N_f = 2+1$ ensembles. This setup avoids the need of improvement coefficients to subtract $\mathrm{O}(am_c)$ effects. The charm quark mass, D and D_s decay constants, and some charmonium observables are computed on a subset of CLS ensembles, which allows to take the continuum limit and extrapolate to the physical pion mass, and assess the scaling properties. Special attention is paid to the implementation of techniques to deal with systematic uncertainties. Our results show excellent prospects for high-precision computations on the full set of ensembles.

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Observations and results with the gradient flow

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The gradient flow has become a common tool for state-of-the-art lattice
calculations. I will present observations and selected results obtained with the gradient flow.

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Nonperturbative renormalisation and the QCD Lambda parameter via the gradient flow

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The gradient flow, which exponentially suppresses ultraviolet field fluctuations and thus removes ultraviolet divergences (up to a multiplicative fermionic wavefunction renormalization), can be used to describe real-space Wilsonian renormalization group transformations and determine the corresponding beta function. We recently proposed a new nonperturbative renormalization scheme for local composite fermionic operators that uses the gradient flow and is amenable to lattice QCD calculations. Here we present nonperturbative results for the beta function and the Lambda parameter in two flavour QCD, along with the nonperturbative running of quark bilinear operators, obtained using our gradient flow scheme.

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Implications of gradient flow on the static force

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We present new results for the pure gauge SU(3) static force computed in a novel way on the lattice. We use Wilson loops with a chromoelectric field insertion for measuring the force directly and compare it with the traditional way of performing a numerical derivative on the static potential. Extended Wilson loop calculations have a bad signal-to-noise ratio, and the use of discretized chromo field insertions causes finite extension effects. We extend our method to support the gradient flow algorithm to improve the signal-to-noise ratio and to challenge finite extension issues, which leads to a larger impact on the general usage of operators with chromo field insertions. Furthermore, we show that direct measurement of the static force can be used to extract the strong coupling constant α_s and to perform the scale setting.

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Log-enhanced discretization errors in integrated correlation functions

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Integrated time-slice correlation functions $C(t)$ with weights $K(t)$ appear e.g. in the moments method to determine α_s from heavy quark correlators, in the muon g-2 determination or in the determination of smoothed spectral functions. We show that the short distance part of the integral may lead to $\log(a)$-enhanced discretization errors when $C(t)K(t) \sim t$ for small t. Starting from the Symanzik expansion of the integrand we derive the asymptotic convergence of the integral at small lattice spacing.

For the (tree-level-) normalized moment R_4 of the heavy-heavy pseudo-scalar correlator R_4 we have non-perturbative results down to $a = 10^{-2}$ fm and for masses, m, of the order of the charm mass. A bending of the curve as a function of a^2m^2 is observed at small lattice spacings. We try to understand the behavior and extract an improved continuum limit.

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A Quenched Exploration of Heavy Quark Moments and their Perturbative Expansion

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The parametric error on the QCD-coupling can be a dominant source of uncertainty in several important observables. One way to extract the coupling is to compare high order perturbative computations with lattice evaluated moments of heavy quark two-point functions. The truncation of the perturbative series is a sizeable systematic uncertainty that needs to be under control.
In this talk we give an update on our study [hep-lat/2203.07936] on this issue. We measure pseudoscalar two-point functions in volumes of $L = 2$ fm with twisted-mass Wilson fermions in the quenched approximation. We use full twist, the non-perturbative clover term and lattice spacings down to $a = 0.010$ fm to tame the large discretization effects.
Our results show that both the continuum extrapolations and the extrapolation of the Λ-parameter to the asymptotic perturbative region are very challenging.

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RG-running of the tensor currents for N_f= 3 QCD in a χSF setup

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We perform the complete non-perturbative running of the flavour non-singlet tensor operator from hadronic to elecroweak scales in $N_f = 3$ massless QCD, comparing four different definitions of the renormalisation constant. We use the same configuration ensembles of arXiv:1802.05243, subject to Schrödinger Functional (SF) boundary conditions, whereas we use valence quarks with (χSF) boundary conditions, which results in $O(a)$ improvement for observables after tuning of boundary counterterms. Following the recent ALPHA strategy, we exploit two different running couplings: at high energies ($\mu >\sim$2GeV) we use a SF-type coupling, while at low energies ($\mu <\sim$2GeV) a Gradient Flow (GF)-type coupling.

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Exploring Non-Peturbative Renormalisation of Two- and Four-Fermion Operators on a Range of Valence Actions

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We present progress in using momentum-subtraction schemes (RI/MOM and RI/SMOM) to renormalise four-fermion operators, in particular with Wilson fermions. To assess the feasibility and limitations, we study the extraction of renormalisation factors across six different valence actions (including Wilson-Clover and Domain-Wall fermions with and without link smearing). The study uses quenched gauge fields and thus serves mainly to provide guidance in the feasibility of extracting renormalisation factors for different set- ups. We also summarise the status of the publicly available Grid and Hadron libraries for implementing these calculations and explain how different twist trajectories are used to remove higher-order cutoff effects.

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General kinematics three-gluon vertex in Landau-gauge from quenched-lattice QCD

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We report novel lattice QCD results for the three-gluon vertex from quenched lattice-QCD simulations. Using standard Wilson action, we have computed the three gluon vertex beyond the usual kinematic restriction to the symmetric ($q^2 = r^2 = p^2$) and soft-gluon ($p = 0$) cases where it depends on a single momentum scale. We will present a detailed analysis of the asymmetric case ($r^2 = q^2 \neq p^2$) where the transversely projected vertex can be cast in terms of three independent tensors.
The lattice data show a clear dominance of the form-factor corresponding to the tree-level tensor.

For the general kinematical configuration ($q^2 \neq r^2 \neq p^2$); we have computed the projection of the three-gluon vertex providing the relevant information on the ghost-gluon kernel-related function $W(q^2)$ that appears in the recently discussed smoking-gun signals of the Schwinger mechanism in QCD. This projection exhibits a striking scaling in terms of $(q^2 + r^2 + p^2)/2$.

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Extracting Non-Abelian Coulomb Potential from SU(3) N=4 Lattice SYM

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In this talk we present numerical simulations of N = 4 super Yang-Mills for 3 color gauge theory over a wide range of 't Hooft coupling $5 \leq \lambda \leq 30$ using a supersymmetric lattice action. By explicit computations of the fermion Pfaffian we present evidence that the theory possesses no sign problem and exists in a single phase out to arbitrarily strong coupling. Furthermore, preliminary work shows that Non-Abelian Coulomb potential extracted via Polyakov loop correlators shows the 1/R scaling and a dependence on square root of the 't Hooft coupling at large values of λ as expected from the holographic calculations.

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Translating topological benefits in very cold master-field simulations

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Master-field simulations offer an approach to lattice QCD in which calculations are performed on a small number of large-volume gauge-field configurations. This is advantageous for simulations in which the global topological charge is frozen due to a very fine lattice spacing, as the effect of this on observables is suppressed by the spacetime volume. Here we make use of the recently developed Stabilised Wilson Fermions to investigate a variation of the master-field approach in which only the temporal direction (T) is taken larger than in traditional calculations. As compared to a hypercubic master-field geometry, this has the advantage that finite-L effects can be useful, e.g. for multi-hadron observables, while compared to open boundary conditions time-translation invariance is not lost.

In this proof-of-concept contribution, we study the idea of using very cold, i.e. long-T, lattices to topologically 'defrost' observables at fine lattice spacing. We identify the scalar-scalar meson two-point correlation function as useful probe and present first results from Nf=3 ensembles with time extents up to T=2304 and a lattice spacing of a=0.055fm.

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Study of SU(2) gauge theories with multiple Higgs fields in different representations

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We study two different SU(2) gauge-scalar theories in 3 and 4 spacetime dimensions. Firstly, we focus on the 4 dimensional theory with 2 sets of fundamental scalar (Higgs) fields, which is relevant to the 2 Higgs Doublet Model (2HDM), a proposed extension to the Standard Model of particle physics. The goal is to understand the particle spectrum of the theory at zero temperature and the electroweak phase transition at finite temperature. We present exploratory results on scale setting and the multi-parameter phase diagram of this theory.

On the other hand, we are interested in the 3 dimensional SU(2) theory with multiple Higgs fields in the adjoint representation, that can be mapped to cuprate systems in condensed matter physics which host a rich phase diagram including high-Tc superconductivity. It has been proposed that the theory with 4 adjoint Higgs fields can be used to explain the physics of hole-doped cuprates for a wide range of parameters while the theory with 1 real adjoint Higgs field would describe the physics of electron-doped cuprates. We show exploratory results on the phase diagram of these theories.

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Probing center vortices and deconfinement in SU(2) lattice gauge theory with persistent homology

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Topological Data Analysis (TDA) is a field that leverages tools and ideas from algebraic topology to provide robust methods for analysing geometric and topological aspects of data. One of the principal tools of TDA, persistent homology, produces a quantitative description of how the connectivity and structure of data changes when viewed over a sequence of scales. We propose that this presents a means to directly probe topological objects in gauge theories. In this talk I will present recent work on using persistent homology to detect center vortices in SU(2) lattice gauge theory configurations in a gauge-invariant manner. I will introduce the basics of persistence, describe our construction, and demonstrate that the result is sensitive to vortices. Moreover, I will discuss how with simple

machine learning, one can use the resulting persistence to quantitatively analyse the deconfinement transition via finite-size scaling, providing evidence on the role of vortices in relation to confinement in Yang-Mills theories.

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Loop-string-hadron formulation of an SU(3) gauge theory with dynamical quarks

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The Hamiltonian formalism for lattice gauge theories has experienced a resurgence of interest in recent years due to its relevance for quantum simulation, a major goal of which is the solution of sign problems in QCD. The particular formulation of the Hamiltonian formalism is itself an important design decision, where factors to consider include (non)locality of the degrees of freedom, (non)Abelian constraints, and computational costs associated with simulating the Hamiltonian.
This work represents a key step toward understanding the costs and benefits associated with the loop-string-hadron (LSH) formulation of lattice gauge theories by generalizing the original SU(2) construction to SU(3) (in 1+1 dimensions). We show that the SU(3) LSH construction is indeed a straightforward generalization of its SU(2) counterpart with all salient theoretical features left intact—particularly the conversion of SU(3) Clebsch-Gordan coefficients into explicit functions of LSH number operators. The validity of the LSH approach is underscored by demonstrating numerical agreement with the better-known purely-fermionic formulation of the theory (with open boundary conditions).

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Lattice Non-Linear Sigma Model on the Supersphere

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Co-authors: Agostino Patella [1]; Johannes Heinrich Weber [2]; Valentina Forini [3]; Ben Hoare [4]

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The 2D O(N) non-linear sigma models are exactly solvable theories and, on the lattice, they have many applications from statistical mechanics to QCD toy models. In this talk, I will consider a particular generalization of the O(N) model, i.e. the non-linear sigma model on the supersphere. The global symmetry group of this model − the OSp(N+2M|2M) supergroup − mixes bosonic and fermionic degrees of freedom, hence the sigma model can be thought of as a toy model for string worldsheet theories with target space supersymmetry. In this talk, I will describe the non-linear sigma model on the supersphere, its discretization on the lattice, its renormalization properties, and the relation between this model and its non-supersymmetric equivalent. I will also present our strategy for numerical simulations and some preliminary numerical results.

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A new type of lattice gauge theory through self-adjoint extensions

Authors: Alessandro Mariani[1]; Gurtej Kanwar[1]; Tobias Rindlisbacher[2]; Uwe-Jens Wiese[3]; Debasish Banerjee[4]; Aditya Banerjee[4]

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A generalization of Wilsonian lattice gauge theory may be obtained by considering the possible self-adjoint extensions of the electric field operator in the Hamiltonian formalism. In the special case of $3D$ $U(1)$ gauge theory these are parametrised by a phase θ, and the ordinary Wilson theory is recovered for $\theta = 0$. We consider the case $\theta = \pi$, which, upon dualization, turns into a theory of staggered integer and half-integer height variables. We investigate order parameters for the breaking of the relevant symmetries, and thus study the phase diagram of the theory, which could reveal a new universality class of $3D$ Abelian gauge theories with a broken $\mathbb{Z}_2$ symmetry absent in the ordinary theory.

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Numerical studies on the finite-temperature CP restoration in 4D SU(N) gauge theory at $\theta = \pi$

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Recent studies on the ‘t Hooft anomaly matching condition have suggested
a nontrivial phase structure in 4D SU(N) gauge theory at $\theta = \pi$.
In the large-N limit, it has been found that CP symmetry at $\theta = \pi$ is broken
in the confined phase, while it restores in the deconfined phase,
which is indeed one of the possible scenarios.
However, at small N, one may find other situations that are consistent
with the consequence of the anomaly matching condition.
Here we investigate this issue for $N = 2$ by direct lattice calculations.
The crucial point to note is that the CP restoration can be probed
by the sudden change of the tail of the topological charge distribution at $\theta = 0$,
which can be seen by simulating the theory at imaginary θ without the sign problem.
Our results suggest that the CP restoration at $\theta = \pi$ occurs at temperature
higher than the deconfining temperature unlike the situation in the large-N limit.

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Computing the Central Charge of the 3D Ising CFT Using Quantum Finite Elements

Author: Anna-Maria Elisabeth Glück[1]

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The 3D Ising conformal field theory (CFT) describes different physical systems, such as uniaxial magnets or fluids, at their critical points. In absence of an analytical solution for the 3D Ising model, the scaling dimensions and operator product expansion (OPE) coefficients characterizing this CFT must be determined numerically. The currently most-cited values for these quantities have been obtained from the conformal bootstrap, while lattice calculations have so far only produced reliable results for the scaling dimensions involved in calculating the critical exponents. Using Quantum Finite Elements to investigate critical ϕ^4-theory on $\mathbb{R}\times\mathbb{S}^2$, we have extracted scaling dimensions and OPE coefficients of the 3D Ising CFT by fitting the lattice four-point function with expectations from the operator product expansion for a radially quantized CFT and extrapolating to the continuum limit. This way, we have for the first time been able to use Monte Carlo simulations to compute the central charge of the theory, as well as scaling dimensions and OPE coefficients of high-spin operators.

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The critical Ising model on an affine plane

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For the 2d Ising model on a triangular lattice, we determine the exact values of the three critical coupling coefficients which restore conformal invariance in the continuum limit as a function of an affine transformation of the triangle geometry. On a torus with a non-trivial modular parameter, we present numerical results showing agreement with the exact CFT solution. Finally, we discuss how this method may be applied to simulate the critical Ising model on curved 2d simplicial manifolds.

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Massless Schwinger model with a 4-fermi-interaction at topological angle $\theta = \pi$

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We study the massless Schwinger model with an additional 4-fermi interaction and a topological term. For topological angle $\theta = \pi$ charge conjugation is implemented in a non-trivial way and we study its spontaneous breaking. We use staggered fermions and the Villain action for the gauge fields, where the topological term is an integer and charge conjugation at $\theta = \pi$ is an exact symmetry. The complex action problem is overcome by a suitable worldline/worldsheet representation. We find that as a function of the 4-fermi coupling the system has a critical point where charge conjugation is broken spontaneously and we present first results on the nature of the critical point.

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't Hooft anomalies for staggered fermions

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We show how staggered fermions can be coupled to gravity by generalizing them to Kaehler-Dirac fermions. The latter experience a perturbative gravitational anomaly which breaks
a U(1) symmetry down to Z_4. This anomaly is captured exactly by the lattice theory. Furthermore we show that this theory exhibits a second
non-perturbative 't Hooft anomaly which can be seen
by considering propagation on non-orientable spaces. This anomaly can be
cancelled for multiples of two Kaehler-Dirac fields. This observation explains recent work that shows that multiples of two staggered fermions can be gapped without breaking symmetries.

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Reformulation of anomaly inflow on the lattice and construction of lattice chiral gauge theories

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This research aims to analyze the integrability condition of the chiral determinant of 4D overlap fermions and construct lattice chiral gauge theories.
We formulate the integrability condition with 5D and 6D lattice domain wall fermions. Our formulation parallels the recent cobordism classification of the global 't Hooft anomaly using the η-invariant based on the Dai-Freed theorem and the Atiya-Patodi-Singer index theorem in the continuum theory.
The necessary and sufficient condition for constructing a lattice chiral gauge theory comes down to the statement that "$\exp(2\pi i\eta) = 1$ for any gauge configurations satisfying the admissibility condition in 5D lattice space.", where $\exp(2\pi i\eta)$ is defined as the phase of the partition function of the 5D domain wall fermion.

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Casimir effect for fermions on the lattice

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We investigate the Casimir effect for relativistic lattice fermions, such as the naive fermion, Wilson fermion, and overlap fermion with the periodic or antiperiodic boundary condition. We also discuss anomalous behaviors for nonrelativistic particles. We apply our approaches to condensed matter systems described by low-energy effective Hamiltonian of Dirac semimetals such as Cd3As2 and Na3Bi.

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Adjoint fermions at large-N_c on the lattice

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Lattice simulations of Yang-Mills theories coupled with N_f flavours of fermions in the adjoint representation provide a way to probe the non-perturbative regime of a plethora of different physical scenarios, such as Supersymmetric Yang-Mills theory to BSM models. Although the large-N_c limit of these theories can give important insight into the strongly coupled regime of these models, the computational cost of standard lattice simulations involving dynamical adjoint fermions forces one to small-N_c gauge groups. In this talk I am going to present how this large-N_c limit is tackled on the lattice by exploiting volume reduction through twisted boundary conditions, which allows one to simulate these theories at high values of N_c such as 289,361. I will emphasise our most recent results on Yang-Mills theory coupled with one Majorana adjoint fermions ($N_f = \frac{1}{2}$), which corresponds to $\mathcal{N} = 1$ SUSY Yang-Mills.

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Density profiles and correlations of harmonically trapped ultracold fermions

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Standard lattice formulations of non-relativistic Fermi gases with two spin components suffer from a sign problem in the cases of repulsive contact interactions and attractive contact interactions with spin imbalance. We discuss the nature of this sign problem and the applicability of the complex

Langevin method in both cases. For repulsive interactions, we find the results to converge well using adaptive step size scaling and a Gaussian regulator to modify the lattice action. Finally, we present results on density profiles and correlations of a harmonically trapped, one dimensional system in both position and momentum space, which are also directly accessible via cold atoms experiments.

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Four-dimensional domain decomposition for the factorization of the fermion determinant

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The non-local dependence of the fermion determinant on the gauge field limits our ability of simulating Quantum Chromodynamics on the lattice. Here we present a factorization of the gauge field dependence of the fermion determinant based on an overlapping four-dimensional domain decomposition of the lattice. The resulting action is block-local in the gauge and in the auxiliary bosonic fields. Possible applications are multi-level integration, master field simulations, and more efficient parallelizations of Monte Carlo algorithms and codes.

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Probing the singularities of the Landau gauge gluon and ghost propagators with rational approximants

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Padé approximants are employed in order to study the analytic structure of the four-dimensional SU(2) Landau-gauge gluon and ghost propagators in the infrared regime. The approximants, which are model independent, are used as fitting functions to lattice data for the propagators, carefully propagating uncertainties due to the fit procedure taking into account all possible correlations. Applying this procedure systematically to the gluon propagator data, we observe the presence of a pair of complex poles at $p^2_{\rm pole} = (-0.37 \pm 0.05_{\rm stat} \pm 0.08_{\rm sys}) \pm (0.66 \pm 0.03_{\rm stat} \pm 0.02_{\rm sys})i\ {\rm GeV}^2$, where the first error is statistical and the second systematic, and also a zero at the negative real axis of p^2, at $p^2_{\rm zero} = (-2.9 \pm 0.4_{\rm stat} \pm 0.9_{\rm sys})\ {\rm GeV}^2$. For the ghost propagator, the Padés indicate the existence of the single pole at $p^2 = 0$, as expected. The presence of the pair of complex poles in the gluon propagator, already hinted upon in previous works, is now put into a more firm basis thanks to the model independence and careful error propagation of our procedure.

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The de Sitter Instanton from Euclidean Dynamical Triangulations

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In this talk, I will revisit the emergence of de Sitter space in Euclidean dynamical triangulations (EDT). Working within the semi-classical approximation, it is possible to relate the lattice parameters entering the simulations to the partition function of Euclidean quantum gravity. We verify that the EDT geometries behave semi-classically, and by making contact with the Hawking-Moss instanton solution for the Euclidean partition function, we show how to extract a value of the renormalized Newton coupling from the simulations. I will discuss new ways to extract the necessary quantities from the lattice configurations and present an updated value for the renormalized Newton coupling.

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Clifford Fourier Transforms in (2+1)D Lattice Simulations of Soliton Propagations

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In Non Destructive Testings (NDT), ultrasonic Time Revesal based Nonlinear Elastic Wave Spectroscopy (TR-NEWS) turned out to be an efficient method. In order to find out anomalies in the convolution of scattered phonetic waves one of which is time reversed (TR) phonon of the other, it is necessary to perform Fourier transforms of signals.

The energy flow of nonlinear waves detected in TR-NEWS has symmetry structure of quaternions, the path of phonetic waves are confined on a $2D$ plane spanned by e_1, e_2. The space can be regarded as projected one from the $(2+1)D$ space containing $e_1 \wedge e_2$.

In one loop approximation, we consider 7 A type loops which sit on $2D$ plane spanned by e_1, e_2, and 13 B type loops which include a pair of path proportional to $e_1 \wedge e_2$ and $e_2 \wedge e_1$ that connect two $2D$ planes.

We adopt a model of bosonic phonons propagating in Fermi-sea of neutral Weyl spinors which follow the Clifford algebra. Configurations in momentum space is transformed to real position space via Clifford Fourier Transform (CFT).

We propose application of Machine Learning (ML) or Neural Network (NN) technique for the analysis of
optimal weight of 20 kind of topological loops.

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Testing universality of gauge theories

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Using different observables we test the approach to the continuum limit of several lattice gauge actions. We use lattice spacings in the range that are usually found in typical lattice QCD simulations. As observables we use different flow observables. This allows to check the scaling properties of the different discretizations with high statistical precision.

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Simulation of self-dual U(1) lattice gauge theory with electric and magnetic matter

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We study U(1) lattice field theory in the Villain formulation and couple electrically as well as magnetically charged bosonic matter. The system has a manifest self-duality that allows to establish a relation between the weak and strong coupling regimes. The complex action problem can be overcome with a worldline representation such that numerical simulations are possible. We study the spontaneous breaking of self-duality and present results for the phase diagram.

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Thermal QCD for non-perturbative renormalization of composite operators

Authors: Matteo Bresciani[None]; Leonardo Giusti[None]; Mattia Dalla Brida[1]; Michele Pepe[2]

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We present our progresses in the use of the non-perturbative renormalization framework based on considering QCD at finite temperature with shifted and twisted (for quarks only) boundary conditions in the compact direction. We report our final results in the application of this method for the non-perturbative renormalization of the flavor-singlet local vector current. We then discuss the more challenging case of the renormalization of the energy-momentum tensor, and show preliminary results on the relevant one-point functions for the computation of the renormalization constants of its non-singlet components.

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Numerical Stochastic Perturbation Theory around instantons

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Numerical Stochastic Perturbation Theory (NSPT) has over the years proved to be a valuable tool, in particular being able to reach unprecedented orders for Lattice Gauge Theories, whose perturbative expansions are notoriously cumbersome. One of the key features of the method is the possibility to expand around non-trivial vacua.
While this idea has been around for a while, and it has been implemented in the case of the (non-trivial) background of the Schroedinger Functional, NSPT expansions around instantons have not yet been worked out. Here we present computations for the double well potential in Quantum Mechaniscs. We compute a few orders of the expansion of the ground state energy splitting in the one-instantons sector. We discuss how (already) known three-loop results are reproduced and present the current status of higher order computations.

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Towards symmetric discretization schemes via weak boundary conditions

Author: Alexander Rothkopf[1]

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The Szymanzik improvement program for gauge theories is most commonly implemented using forward finite difference corrections to the Wilson action. Central symmetric schemes (see e.g. [1]) naively applied, suffer from a doubling of degrees of freedom, identical to the well known fermion doubling phenomenon. And while adding a complex Wilson term remedies the problem for fermions, it does not easily transfer to real-valued gauge fields.

In this talk I report on recent progress in formulating symmetric discretization schemes for classical actions of simple one-dimensional problems [2]. They avoid doubling by exploiting the weak imposition of initial/boundary conditions. Inspired by recent work in the field of numerical analysis of partial differential equations, I construct a regularized summation-by-parts finite difference operator using affine coordinates, which is combined with Langrange multipliers to impose the boundary conditions weakly. Application to classical initial value problems with first and second order derivatives are presented.

[1] A. Rothkopf, arXiv:2102.08616
[2] A. Rothkopf, J. Nordström arXiv:2205.14028

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What is the best way to quantize non-linear electrodynamics?

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A class of non-linear, massive electrodynamics theories known as Generalized Proca (GP) was proposed in 2014 in the context of classical effective field theories and has held a prominent role in cosmology. As a quantum field theory GP has the potential to describe phenomena in condensed matter, optics, and lattice field theories. In this talk, we show how to quantize a family of GP theories using the symplectic approach, featuring two main advantages: it is algebraically simple and its outcome is amenable to numerical simulations. Additionally, by unveiling the existence of quantum consistency conditions, we conclude that not all classically well-defined (multi-)GP theories are amenable to quantization, and discuss the implications of our results.

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The gradient flow formulation of the electroweak Hamiltonian

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Flavor observables are usually computed with the help of the electroweak Hamiltonian which separates the perturbative from the non-perturbative regime. The Wilson coefficients are calculated perturbatively, while matrix elements of the operators require non-perturbative treatment, e.g. through lattice simulations. The resulting necessity to compute the transformation between the different renormalization schemes in the two calculations constitutes an important source of uncertainties. An elegant solution to this problem is provided by the gradient flow formalism because its composite operators do not require renormalization. In this talk we report on the construction of the electroweak Hamiltonian in the gradient flow formalism through NNLO in QCD.

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The emergence of expanding space-time in a novel large-N limit of the Lorentzian type IIB matrix model

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Co-authors: Asato Tsuchiya [2]; Jun Nishimura [3]; Kohta Hatakeyama [3]; Konstantinos Anagnostopoulos [4]; Stratos Papadoudis [4]; Takehiro Azuma [5]

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The Lorentzian type IIB matrix model is a promising candidate for a nonperturbative formulation of superstring theory. However, it was found recently that a Euclidean space-time appears in the conventional large-N limit. In this work, we add a Lorentz invariant mass term and consider a limit, in which the coefficient of the mass term vanishes at large N. By performing complex Langevin simulations to overcome the sign problem, we observe the emergence of expanding space-time with the Lorentzian signature.

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The influence of gauge field smearing on discretisation effects

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When designing lattice actions, gauge field smearing is frequently used to define the lattice Dirac operator. Since the smearing procedure removes effects of ultraviolet fluctuations, the fermions effectively see a larger lattice spacing than the gauge fields. Creutz ratios, formed from ratios of rectangular Wilson loops, based on smeared gauge fields are an adequate observable to investigate the effect of smearing since they do not need renormalisation and provide a measure of the physical forces felt by the fermions. We study their behaviour at various smearing radii (fixed in lattice units) and in particular how the smearing influences the scaling towards the continuum limit. Since we employ the Wilson gradient flow as smearing, the same Creutz ratios have another, well defined continuum limit, when the flow time is fixed in physical units. We make an attempt to approximately separate the close-to-continuum region for smearing from the one of the physically flowed Creutz ratios.

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Real time evolution of scalar fields in semiclassical gravity

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We report on the development of a lattice formalism for studying the realtime behaviour of radially symmetric configurations of massless scalar fields in radially symmetric, curved spacetimes in 3+1 dimensions.
It is intended to numerically study back reaction effects due to semiclassical gravity in the time evolution of scalar field configurations, especially for those that will eventually evolve into black holes.

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Chiral Symmetry Breaking in QED induced by an External Magnetic Field

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$3 + 1$ dimensional QED with massless electrons is chirally symmetric, at least in the perturbative regime. This is true, even though this symmetry is anomalous, because QED lacks instantons. However, in the presence of external magnetic fields, approximate calculations based on Schwinger-Dyson equations indicate that chiral symmetry is spontaneously broken. In a constant external magnetic field B, this produces a dynamical electron mass $\propto \sqrt{eB}$ and a chiral condensate $\propto (eB)^{3/2}$. The magnetic field catalyses chiral symmetry breaking with an effective dimensional reduction from $3+1$ dimensions to $1+1$ dimensions. We simulate lattice QED in a constant homogeneous magnetic field using the RHMC algorithm. We increase α from $1/137$ to $1/5$ to make the chiral symmetry breaking measurable. To access the chiral limit, we need to increase the lattice size. By using a large eB, the localization of the motion in the plane perpendicular to the magnetic field due to the dominance of low lying Landau levels means that we only need a large lattice size in the directions of B and time. Our preliminary 'data' show clear evidence for a non-zero condensate in the zero electron mass limit and hence chiral symmetry breaking.

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Towards glueball masses of large-N SU(N) Yang-Mills theories without topological freezing via parallel tempering on boundary conditions

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Standard local updating algorithms experience a critical slowing down close to the continuum limit, which is particularly severe for topological observables. In practice, the Markov chain tends to remain trapped in a fixed topological sector. This problem further worsens at large N, and is known as *topological freezing*.

To mitigate it, we adopt the parallel tempering on boundary conditions proposed by M. Hasenbusch. This algorithm allows to obtain a reduction of the auto-correlation time of the topological charge up to several orders of magnitude.

With this strategy we are able to provide the first computation of low-lying glueball masses at large N free of any systematics related to topological freezing.

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Quarks and Triality in a Finite Volume

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In order to understand the puzzle of the free energy of an individual quark in QCD, we explicitly construct ensembles with quark numbers $N_V \neq 0 \mod 3$, corresponding to non-zero triality in a finite subvolume V on the lattice. We first illustrate the basic idea in an effective Polyakov-loop theory for the heavy-dense limit of QCD, and then extend the construction to full Lattice QCD, where the electric center flux through the surface of V has to be fixed at all times to account for Gauss's law. This requires introducing discrete Fourier transforms over closed center-vortex sheets around the spatial volume V between all subsequent time slices, and generalizes the construction of 't Hooft's electric fluxes in the purge gauge theory. We derive this same result from a dualization of the Wilson fermion action, and from the transfer matrix formulation with a local $\mathbb{Z}_3$-Gauss law to restrict the dynamics to sectors with the required center charge in V.

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Emergent phenomena from centre vortices in dynamical QCD

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Quark confinement is perhaps the most important emergent property of the theory of quantum chromodynamics. I review recent results studying centre vortices in SU(3) lattice gauge theory with dynamical quarks. Starting from the original Monte Carlo gauge fields, a vortex identification procedure yields vortex-removed and vortex-only backgrounds. The comparison between the original 'untouched' Monte Carlo gauge fields and these so called vortex-modified ensembles supports the notion that centre vortices are fundamental to confinement in full QCD.

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Topological susceptibility in high temperature full QCD via staggered spectral projectors

Authors: Andreas Athenodorou[1]; Antonino Todaro[2]; Claudio Bonanno[3]; Claudio Bonati[4]; Francesco D'Angelo[4]; Francesco Sanfilippo[5]; Giuseppe Clemente[6]; Guido Martinelli[7]; Lorenzo Maio[4]; Massimo D'Elia[4]

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We compute the topological susceptibility of $N_f = 2 + 1$ QCD at physical point in a temperature range going from 200 to 600 MeV. We adopt a multicanonical approach to enhance topological fluctuations and a definition of the susceptibility based on the spectral projectors over the eigenmodes of the staggered Dirac operator. This method allows to reduce lattice artifacts affecting the standard gluonic definition, making the continuum limit extrapolation more reliable.

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Numerical investigation of automatic fine-tuning in the Schwinger model

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We investigate the isospin symmetry breaking effects in the two-flavour Schwinger model. Specifically, we check a prediction by Howard Georgi about automatic fine-tuning effects, i.e. that the isospin breaking is suppressed exponentially in the fermion mass m_f.

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Non-invertible self-duality defects of Cardy-Rabinovici model and mixed gravitational anomaly

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We study non-invertible defects constructed from dualities in the Cardy-Rabinovici model. The Cardy-Rabinovici model is a four-dimensional $U(1)$ lattice gauge theory with both electrically and magnetically charged particles, which is used as a playground for investigating the dynamics of the Yang-Mills theory with θ angle. A notable feature of this model is that the conjectured phase diagram has the electromagnetic $SL(2,\mathbb{Z})$ invariance generated by S and T transformations. Although this model does not enjoy the $SL(2,\mathbb{Z})$ duality in a naive way, we notice that the $SL(2,\mathbb{Z})$ transformations can be understood as dualities between the Cardy-Rabinovici model and $\mathbb{Z}_N$ 1-form gauged one. Based on this observation, we construct non-invertible symmetries and determine their non-group-like fusion rules in a formal continuum description of the Cardy-Rabinovici model. Moreover, for some self-dual points, we find that this symmetry turns out to have a mixed gravitational anomaly, which rules out the trivially gapped phase. We also address how the conjectured phase diagram matches this anomaly. This talk is based on arXiv:2204.07440 [hep-th].

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Topological susceptibility, scale setting and universality from $Sp(N_c = 2N)$ gauge theories

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In this contribution, we report on our study of the properties of the Wilson flow and on the calculation of the topological susceptibility of $Sp(N_c = 2N)$ gauge theories for $N = 1, \cdots, 4$.
The Wilson flow is shown to scale according to the quadratic Casimir operator of the gauge group, as was already observed for $SU(N_c)$, and the commonly used scales t_0 and w_0 are obtained for a large interval of the inverse coupling for each probed value of N_c.
The continuum limit of the topological susceptibility is computed and it is conjectured that it scales with the dimension of the group. Our estimates of the topological susceptibility and the measurements performed in the $SU(N_c)$ Yang-Mills theories by several independent collaborations allow us to test this conjecture and to obtain the universal large-N limit of the rescaled topological susceptibility.

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Charged Particles in C-periodic Volumes

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Charged particles in an Abelian Coulomb phase are non-local infra-particles that are surrounded by a cloud of soft photons which extends to infinity. Gauss' law prevents the existence of charged particles in a periodic volume. In a C-periodic volume, which is periodic up to charge conjugation, on the other hand, charged particles can exist. This includes vortices in the 3-d XY-model, magnetic monopoles in 4-d U(1) gauge theory, as well as protons and other charged particles in QCD coupled to QED. In four dimensions non-Abelian charges are confined. Hence, in an infinite volume non-Abelian infra-particles cost an infinite amount of energy. However, in a C-periodic volume non-Abelian infra-particles (whose energy increases linearly with the box size) can indeed exist. Investigating these states holds the promise of deepening our understanding of confinement.

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SU(N) fractional instantons

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We present our ongoing study of a set of solutions to the $SU(N)$ Yang-Mills equations of motion with fractional topological charge. The configurations are obtained numerically by minimising the action with gradient flow techniques on a torus of size $l^2 \times \tilde{l}^2$ (with $\tilde{l} \equiv Nl$) and twisted boundary conditions. We pay special attention to the large N limit, which is taken along a very peculiar sequence, with the number of colours N and the magnetic flux m selected respectively as the n and (n-2) terms of the Fibonacci sequence. We discuss the large N scaling of the solutions and analyze several gauge invariant quantities as the Polyakov and Wilson loops. We also discuss the

Hamiltonian limit, with one of the large directions sent to infinity, where these instantons represent tunnelling events between inequivalent pure gauge configurations.

Weak Decays and Matrix Elements / **127**

Quasi-degenerate baryon energy states, the Feynman–Hellmann theorem and transition matrix elements

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The standard method for determining matrix elements in lattice QCD requires the computation of three-point correlation functions. This has the disadvantage of requiring two large time separations: one between the hadron source and operator and the other from the operator to the hadron sink. Here we consider an alternative formalism, based on the Dyson expansion leading to the Feynman-Hellmann theorem, which only requires the computation of two-point correlation functions. Both the cases of degenerate energy levels and quasi-degenerate energy levels which correspond to diagonal and transition matrix elements respectively are considered in this formalism. Numerical results for the Sigma to nucleon transition are presented in a further contribution by M. Batelaan.

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Calculation of hyperon transition form factors from two-point functions using the Feynman-hellmann method

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Theoretical calculations of the transition form factors of the hyperons are an important component of the determination of the CKM matrix elements. These calculations historically have been performed using ratios of lattice three point functions and two-point functions to extract the form factors, this requires the careful balancing of control over excited states and the preservation of a strong signal. We present a novel method which uses the Feynman-Hellmann method to relate a shift in energy due to a perturbation to the required form factors, this method requires only the calculation of two-point functions. The formalism of this Method is expanded on in the presentation by R. Horsley, the details of the numerical computation and the results of the Sigma to nucleon transition will be presented here.

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A lattice QCD study of the B \to \pi\pi \ell \nu transition

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V_{ub} is the smallest and least known of all CKM matrix elements; the community determines its current value primarily through the exclusive process $B \to \pi\ell\nu$. This talk will present our progress toward a lattice QCD determination of the V_{ub} matrix element from a novel transition - $B \to \pi\pi\ell\nu$ process, where the $\pi\pi$ rescattering features the $\rho(770)$ resonance as an enhancement. We perform our calculation on $N_f = 2 + 1$ clover fermions on a lattice of $L = 3.6$ fm and a pion mass of 320 MeV. After a brief overview of the theoretical framework, we will discuss some preliminary results.

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$B\pi$ excited-state contamination in B-meson observables

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Multi-particle states with additional pions are expected to result in a non-negligible excited-state contamination in lattice simulations at the physical point. We show that heavy meson chiral perturbation theory (HMChPT) can be employed to calculate the contamination due to two-particle $B\pi$ states in various B-meson observables like the decay constant f_B and the $B^*B\pi$ coupling g_π. We work in the static limit and to next-to-leading order (NLO) in the chiral expansion. The $B\pi$ states are found to typically overestimate the observables at the few percent level depending on the size of two currently unknown NLO low-energy coefficients. A strategy to independently measure one of them with the 3-point function of the light axial vector current will be discussed.

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Estimating Excited-States Contamination of $B \to \pi$ Form Factors Using Heavy Meson Chiral Perturbation Theory

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Combining experimental input, perturbative calculations, and form factors computed in lattice QCD simulations, it is possible to deduce $|V_{ub}|$ from semileptonic decays of B mesons. But the results of the form factors are contaminated by excited-states, which may lead to noticeable systematic errors in the desired CKM matrix element.
This talk presents our recent computations of the dominant $B\pi$ excited-states contamination in $B \to \pi$ form factors in Heavy Meson Chiral Perturbation Theory. The results were obtained in the static limit and to NLO in the chiral expansion and include new, to date unknown, low energy constants. Depending on their value, the effects for lattice simulations can be considerable.

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Towards precision lattice determination of semileptonic $D \to \pi\ell\nu$, $D \to K\ell\nu$ and $D_s \to K\ell\nu$ decay form factors

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CKM matrix elements can be obtained from lattice determinations of semileptonic decay form factors by combining them with experimental results for decay rates. We give a status update on our study using the Domain Wall Fermion action for up/down, strange and charm quarks to determine semileptonic form factors for $D \to \pi\ell\nu$, $D \to K\ell\nu$ and $D_s \to K\ell\nu$ decays. Data have been produced on three lattice spacings and pion masses in the range 250 Mev to 400 Mev, and preliminary form factor data are presented. These will subsequently be included in a global fit.

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The search for new physics in $B \to K\ell^+\ell^-$ and $B \to K\nu\bar{\nu}$ using precise lattice QCD form factors

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We present HPQCD's improved scalar, vector and tensor form factors for $B \to K$ semileptonic decays, using the heavy-HISQ formalism for more accurate normalisation of the weak currents. Working with masses close to the physical b on the finest ensemble and including three ensembles with physical light quarks, we cover the full physical q^2 range with good precision. Our uncertainties at $q^2 = 0$ are a factor of three better than earlier work.

We compare Standard Model observables using our form factors to experimental measurements for the rare flavour changing neutral current processes $B \to K\ell^+\ell^-$ and $B \to K\nu\bar{\nu}$ and discuss the significance of the tensions that arise.

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Lattice Results for the $K^+ \to \ell^+ \, \nu_\ell \, \ell'^+ \, \ell'^-$ Form Factors and Branching Ratios

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We study, with lattice QCD, the radiative leptonic decays $P \to \ell \, \nu_\ell \, \ell'^+ \, \ell'^-$, where P is a charged pseudoscalar meson and ℓ and ℓ' are charged leptons. These processes are mediated by the emission of a virtual photon and, in addition to the "point-like" contribution in which the virtual photon is emitted either from the lepton or the meson treated as a point-like particle, four structure-dependent (SD) form factors contribute to the amplitude.
We present a strategy for the extraction of the SD form factors and implement it in an exploratory lattice computation of the decay rates for the four channels of kaon decays ($\ell, \ell' = e, \mu$). The lattice computation has been performed employing only one gauge ensemble, with simulated pion and kaon masses equal to 320 and 530 MeV, respectively.
It is the SD form factors which describe the interaction between the virtual photon and the internal hadronic structure of the decaying meson, and in our procedure we separate the SD and point-like contributions to the amplitudes. The form factors are extracted with good precision and used to reconstruct the branching ratio values, which are compared with the available experimental data.
These are very suppressed processes, which thus provide an excellent test of the Standard Model, and provide a useful avenue for the search for signatures of new physics.

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Structure-dependent form factors in radiative leptonic decays with Domain Wall fermions

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In the region of hard photon energies, radiative leptonic decays represent important probes of the internal structure of hadrons.
Moreover, radiative decays can provide independent determinations of Cabibbo-Kobayashi-Maskawa matrix elements with respect to purely leptonic or semileptonic channels.
Prospects for a precise determination of leptonic decay rates with emission of a hard photon are particularly interesting, especially for the decays of heavy mesons for which currently only model-dependent predictions, based on QCD factorization and sum rules, are available to compare with existing experimental data.
We present a non-perturbative lattice calculation of the structure-dependent form factors which contribute to the amplitudes for the radiative decays $H \to \ell \nu_\ell \gamma$, where H is a charged pseudoscalar

meson, using the Domain Wall formulation of lattice fermions.
With moderate statistics, thanks to the use of a sine-cardinal-reconstruction technique and improved estimators, we are able to provide rather precise, first-principles results for the form factors in the full kinematical (photon-energy) range for both light and heavy mesons.

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An update on RI/IMOM schemes

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We developed a strategy to implement RI/MOM schemes on quark bilinear and four-quark operators. In these schemes, the momentum transfer is not restricted to the exceptional point or to the symmetric point. In particular, we study the convergence of the perturbative series and the potential to reduce some systematic errors (discretisation and chiral symmetry breaking effects). In particular, we observe a notable reduction of the pseudo-Goldstone pole contributions which could lead to a significant improvement for the renormalisation of some four-quark operators.

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Lattice calculation of leading isospin breaking effects in $\Gamma(K_{\ell 2})/\Gamma(\pi_{\ell 2})$ with close-to-physical chiral fermions

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In this talk we present the first RBC-UKQCD lattice calculation of the leading isospin-breaking corrections to the ratio of leptonic decay rates of kaons and pions into muon and neutrino, $\Gamma(K_{\ell 2})/\Gamma(\pi_{\ell 2})$. This computation is performed using domain wall fermions with close-to-physical (light and strange) quark masses. The QED effects are implemented using a perturbative approach and infrared divergences are regulated according to the QED_L prescription. We describe the strategy to extract the relevant hadronic matrix elements from Euclidean correlation functions and we discuss the important role of finite volume effects in this calculation.

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Electromagnetic finite-volume effects to leptonic decays through order $1/L^3$ in QED_L

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Analytical techniques to derive the finite-volume dependence of observables calculated in lattice simulations can be used to improve numerical determinations. With the need for (sub-)percent precision in lattice predictions, also isospin-breaking effects have to be considered. When including electromagnetism in the so-called $\mathrm{QED_L}$ prescription, having good control of the associated finite-volume effects is particularly important, as the scaling with the spatial extent L typically is inverse polynomial. In this talk, we will discuss the finite-size effects in the RBC/UKQCD calculation of radiative corrections to leptonic decays. Particular emphasis will be put on the order $1/L^3$ contribution, where the non-locality of $\mathrm{QED_L}$ plays an important role.

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Estimation of scheme ambiguities in the separation of isospin-breaking effects in lattice QCD calculations

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In lattice calculations including isospin-breaking effects, low-energy Standard Model predictions can be unambiguously obtained providing external inputs to define the quark masses, the QCD scale and the value of the electromagnetic coupling. However, there is phenomenological interest to define an isospin-symmetric value of a given observable, or to define the corrections coming from the strong or electromagnetic isospin-breaking effects separately. This separation is known to be prescription-dependent, and a diversity of such prescriptions is used across the lattice community. Since these quantities are actively used, for example in the context of the muon g-2 or radiative corrections to weak decays, the question of quantifying scheme dependency is relevant. In this talk we discuss a general framework to describe these ambiguities, and how to estimate them using lattice data or effective field theories.

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A comparison of Wilson and twisted mass valence quarks for charmed semileptonic form factors

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We present the comparison of preliminary results of $D \to \pi$ semileptonic decays from two related projects: the first one is based on unitary Wilson fermions, and the second uses valence quarks rotated to maximal twist. While these projects differ by their goals and strategies, both studies are performed on CLS $N_f = 2+1$ configurations, with similar analysis techniques. The universality test can then be used as a non-trivial validation of our calculations, in particular regarding the notoriously difficult control of excited state contributions to form factors. Finally, we will discuss the scaling of these two fermionic actions, compared to their theoretical merits, with a focus on $O(am_c)$ and $O(ap)$ lattice artefacts.

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Momentum transfer dependence of kaon semileptonic form factor on (10 fm)^4 at the physical point

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We present our results for the kaon semileptonic form factors using the two sets of the PACS10 configuration, whose physical volumes are more than (10 fm)^4 at the physical point. The lattice spacings are 0.063 and 0.085 fm. The configurations were generated using the Iwasaki gauge action and $N_f = 2 + 1$ stout-smeared nonperturbatively $O(a)$ improved Wilson quark action. From the momentum transfer dependence of the form factors in the continuum limit, we evaluate the slope and curvature for the form factors at the zero momentum transfer. Furthermore, we calculate the phase space factor, which is used to obtain $|V_{us}|$ through the kaon semileptonic decay. These results are compared with previous lattice results and experimental values.

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B-meson semileptonic decays with highly improved staggered quarks

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In this talk we present results on B-meson semileptonic decays using the highly improved staggered quark (HISQ) action for both valence and 2+1+1 sea quarks. The use of the highly improved action, combined with the MILC collaboration's gauge ensembles with lattice spacings down to ~0.03 fm, allows the b quark to be treated with the same discretization as the lighter quarks. The talk will focus on updated results for $B_{(s)} \to D_{(s)}$, $B_{(s)} \to K$, and $B \to \pi$ scalar and vector form factors.

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D-meson semileptonic decays with highly improved staggered quarks

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We present new results on semileptonic decays of D-mesons using the highly improved staggered quark (HISQ) action for both valence and 2+1+1 sea quarks. Our calculation uses lattice spacings ranging from 0.12 fm down to 0.042 fm, including several ensembles with physical-mass pions. The focus on the talk will be on the vector and scalar form factors (f_+ and f_0) for the decays $D \to \pi$, $D \to K$ and $D_s \to K$. Phenomenological applications will be discussed.

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Progress towards an improved lattice calculation of Standard Model direct CP-violation in kaon decays

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We discuss progress towards the RBC & UKQCD collaborations' next generation of measurements of Standard Model direct CP-violation in kaon decays with G-parity boundary conditions, for which we aim to leverage the power of the upcoming exascale computers to perform the continuum limit and thus eliminate this dominant lattice systematic error.

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Direct CP violation in $K \to \pi\pi$ decay at the physical point with periodic boundary conditions

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Since our recent publication on direct CP violation and the Delta I = 1/2 rule in $K \to \pi\pi$ decay which was made with G-parity boundary conditions, we have revisited this problem with a conventional lattice setup employing periodic boundary conditions and two lattice spacings to check our previous result and to improve the precision. We show that the physical amplitude, which corresponds to an excited state in this case, can be obtained reliably with the Generalized Eigenvalue Problem (GEVP) method. Not only are periodic boundary conditions cheaper and allow the use of existing ensembles, but they provide a straightforward path to introduce electromagnetism and strong isospin symmetry breaking, which will be needed in the near future. In this talk, we show our preliminary results on 24^3 and 32^3 lattices with domain-wall fermions at physical masses and discuss the prospect of the high-precision calculation of $K \to \pi\pi$ decay with periodic boundary conditions.

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B Meson Decay Constants Using Relativistic Heavy Quarks

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We present the status of ongoing work to extract pseudoscalar and vector decay constants for $B^{(*)}$, $B_s^{(*)}$ and $B_c^{(*)}$ mesons and determine phenomenologically interesting ratios such as f_Bs/f_B or f_B*/f_B.
Our calculation is based on $N_f = 2 + 1$ dynamical flavour gauge field ensembles generated by the RBC/UKQCD collaborations using domain wall fermions and the Iwasaki gauge action.
Using domain wall light, strange and charm quarks, and relativistic b-quarks, we obtain results at multiple lattice spacings and valence quark masses.
We then extrapolate to physical quark masses and the continuum and compare to predictions by other lattice collaborations and QCD sum rules. Furthermore, we use our results to test heavy quark symmetry relations.

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Inclusive semi-leptonic decays of charmed mesons with Moebius domain wall fermions

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We report on our progress in the non-perturbative calculation of the decay rates for inclusive semi-leptonic decays of charmed mesons from lattice QCD. In view of the long-standing tension in the determination of the CKM matrix elements V_{ub} and V_{cb} from exclusive and inclusive processes, recently, the method of lattice QCD has been extended towards the description of inclusive decays through, e.g. the Chebyshev approximation, as used in this work. Since QCD based methods require independent tests, we chose to focus on the charm sector, since it not only provides a rich set

of experimental data, but also well defined CKM parameters.
We perform a pilot lattice simulation for the $D_s \to X_s \ell \nu$ and explore the possibilities of improving on existing techniques. Our simulation employs Moebius domain wall charm and strange quarks whose masses are tuned to be approximately physical and we cover the whole kinematical region. We report on our progress in analyzing different sources of statistical effects, such as the extrapolation of the kernel function chosen for the Chebsyhev approximation as well as the influence on the analysis from the region close to the kinematical limit. Furthermore, we give an outlook on our future plans where we strive to increase the data towards including different charmed mesons and towards a study with fully controlled statistical effects.

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Inclusive semi-leptonic $B_{(s)}$ mesons decay at the physical b quark mass

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We address the non-perturbative calculation of the decay rate of the inclusive semi-leptonic $B_{(s)}$ mesons decay from lattice QCD. Precise theoretical Standard Model predictions are key ingredients in searches for new physics. This type of computation may eventually provide new insight into the long-standing tension between the inclusive and exclusive determination of the V_{cb} and V_{ub} CKM matrix elements.
We perform a pilot lattice computation for $B_s \to X_c l \bar{\nu}$ and improve on existing techniques. The valence-quark masses in our simulations are approximately physical for the domain-wall strange and charm quarks as well as for the b quark, for which we use a relativistic heavy quark effective action. We report on our progress and discuss future plans toward a first study with fully controlled systematic effects.

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Inclusive semileptonic B-decays from lattice QCD

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Among the many anomalies and tensions in flavour physics, one of the most persistent ones is the V_{cb} puzzle, which is a difference of about 2.7σ between the inclusive and exclusive estimate of the CKM matrix element V_{cb}. In order to understand the origin of this tension from first principles, one needs calculations obtained using lattice QCD.

Over the years, lattice QCD has been extremely successful in calculating physical quantities needed for the exclusive determination of V_{cb} to a high level of precision.
It is only until recently that new methods have been proposed for computing inclusive decay rates of semileptonic B-decays using lattice QCD. These new methods rely on the extraction of the hadronic spectral density from Euclidean correlators computed on the lattice.
In this talk, one of these new methods will be discussed together with the presentation of the first results of the inclusive decay rate and related observables. We use one of the gauge ensembles provided by the ETM collaboration with an unphysical pion mass and unphysically light b-quark. The results obtained are also compared with the analytic predictions of the Operator Product Expansion (OPE) and provide a first systematic study of the quark-hadron duality.

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Lattice study of spectator effects in B-hadron decays with Domain-Wall Fermions

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In this talk, we present Lattice QCD measurements for the matrix elements of $\Delta B = 0$ four-quark operators that involve a light spectator quark in a b-hadron. These matrix elements contribute to the determination of V_{ub}, as well as the lifetime ratios of b-hadrons. Though the historical tension in the $\tau(\Lambda_b)/\tau(B_d)$-lifetime ratio has disappeared with newer measurements, much of the machinery we develop can be applied in the future to other puzzles such as the recent inversion of the measured charm-baryon lifetimes. We use $N_f = 2{+}1$ Domain Wall Fermion (DWF) sea-quarks at two different lattice spacings, as well as DWF light valence quark propagators. The heavy quark is treated as a static propagator, and we use Wilson Flow to improve the signal. We also propose a nonperturbative position-space renormalisation scheme for these dimension 6 operators.