color meets flavor

COLOR MEETS FLAVOR

Search for new phenomena in strong and weak interactions

Report from Research Area 3

M. Cristinziani and C. Duhr

09 March 2026

BONN

Summary of activities in RA3

- First RA kick-off meeting on 07 October 2025. 16 people attending.

- We identified broad classes of topics within which to form X-functional research teams:

  1. MC/Whizard/Tauola/Future Colliders
  2. Benchmarks, BSM, CPV, Vcb
  3. SMEFT: NLO, dim8, …
  4. ML / Jet tagging
  5. Algebraic tools (with connections to IAL)
  6. “Other”

Summary of activities in RA3

- We had an open call for funding proposals in RA3.
- In total, we received 20 project applications from 22 PIs.
- Available funding: 10.09 + 3.00 = 13.09 FTE
- In order to maximize the number of funded projects, we decided to
  - Merge projects if there are overlaps.
  - Fund (at most) 1.5 FTE per project.

color meets flavor

List of funded projects:

Bell, Shtabovenko	Multiloop FeynCalc
Krieg, Witzel	Grad. flow Λ and α with 4 fermions
Cristinziani	Quark-Gluon tagging using a unified jet flavour tagging algorithm
Diez Pardos	ttbar precision measurements and interpretation
Kilian	Whizard for LHC: $t\bar{t}$ and $t\bar{t}X$
Knue	Pseudo-bound state in ttbar

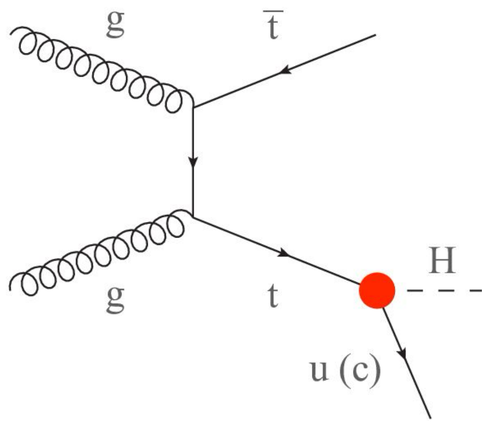
merged

color meets flavor

List of funded projects:

Duhr	Constraining anomalous Higgs Self-Couplings in gluon-fusion
Grefe, Bechtle, Desch, Hiller,	Higgs potential, high-Scale models & SMEFT for future collider measurements
Schopf	Search for FCNC in top-quark decays to a Higgs boson and a charm or up quark
T. Lenz	Search for new signatures in CP-violating 2HDM

Project: *Search for Flavour-Changing Neutral Currents in top-quark decays to a Higgs boson and a charm or up quark*



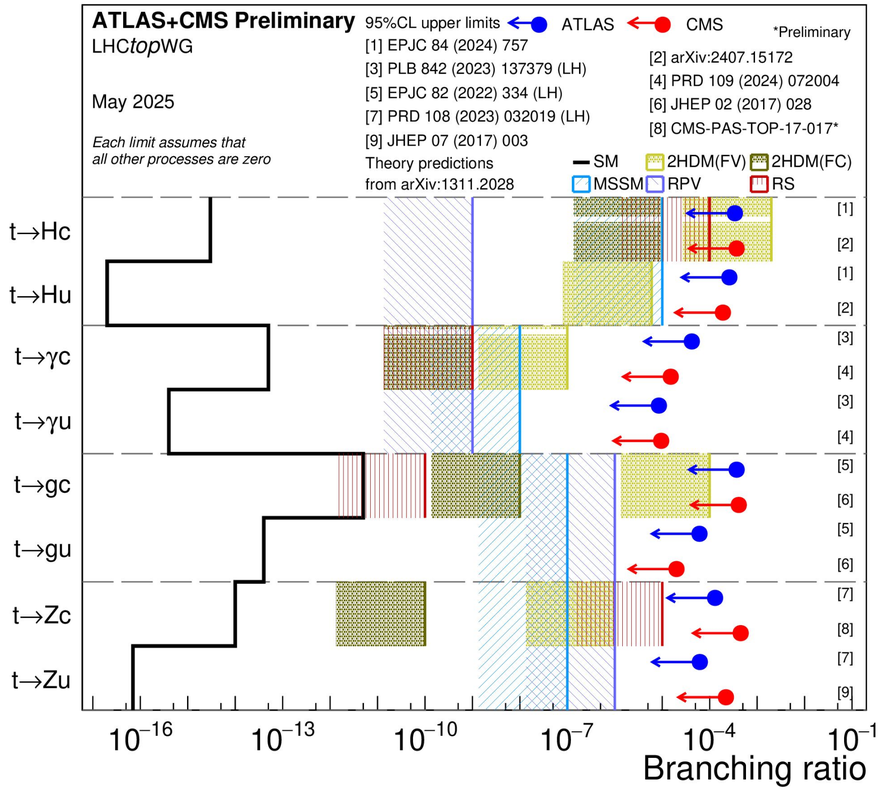
ATLAS Run-2+3 search for FCNCs

- Top quark pair production
- One SM top decay
- One FCNC t→Hc,Hu decay
- Target H→bb decays

Why this search and why now?

- Exp. sensitivity on verge of probing more BSM models
- Higgs channel brings extra Yukawa dimension
- Several new or updated BSM models (e.g. EFT)
- New exp. tools allow distinction of t→Hu and t→Hc channels (prev. searches always assumed one to vanish)

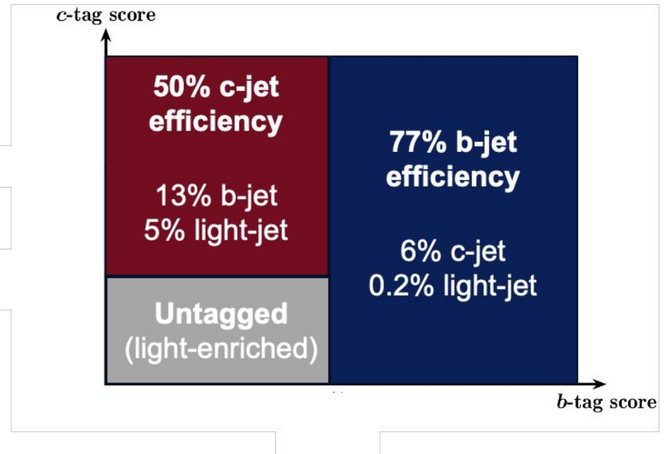
Overview of ATLAS+CMS top-quark FCNC searches



Improvements and Collaborations within CmF

Experimental improvements planned for this search

- Larger data set: 140 fb^{-1} → 360-500 fb^{-1}
- Improved heavy flavour jet ID:
  - reliable c-jet identification
  - improved distinction between b-jets and c-jets
  - promising developments in quark-gluon tagging for better light-jet ID
- Improved signal-vs-background using latest developments in ML



Opportunities within CmF

- Review of latest BSM models and their incorporation into ATLAS simulation
  - Complementarity or combination with FCNC searches in Belle and LHCb
- Efforts on ML tools: q/g-tagging, jet origin classification (e.g. “b from top”-ID)

CmF Project: Search for new signatures in CP-violating 2HDM

Tatjana Lenz, Jochen Dingfelder
Uni Bonn

9 - 11 March

CmF Retreat

UNIVERSITÄT BONN

CP Violation in the Extended Higgs Sector

- **Goal**: find new sources of CP violation in the extended Higgs sector
  - C2HDM = 2HDM with complex coupling parameters
- **Indirect measurements**: electron EDM, Higgs rates
  - CP violating couplings expected to be small
- **Direct measurements**:
  - Higgs distributions, e.g. in $h \to \tau\tau$
  - Neutral Higgs bosons h_1, h_2, h_3 with CPV signatures:

Simultaneous measurement of rates

CP-even decays and CP-odd decays

$\sigma(h_2) \times \mathcal{B}(h_2 \to h_1 h_1) = 191\,\text{fb}$ $\sigma(h_2) \times \mathcal{B}(h_2 \to h_1 Z) = 122\,\text{fb}$

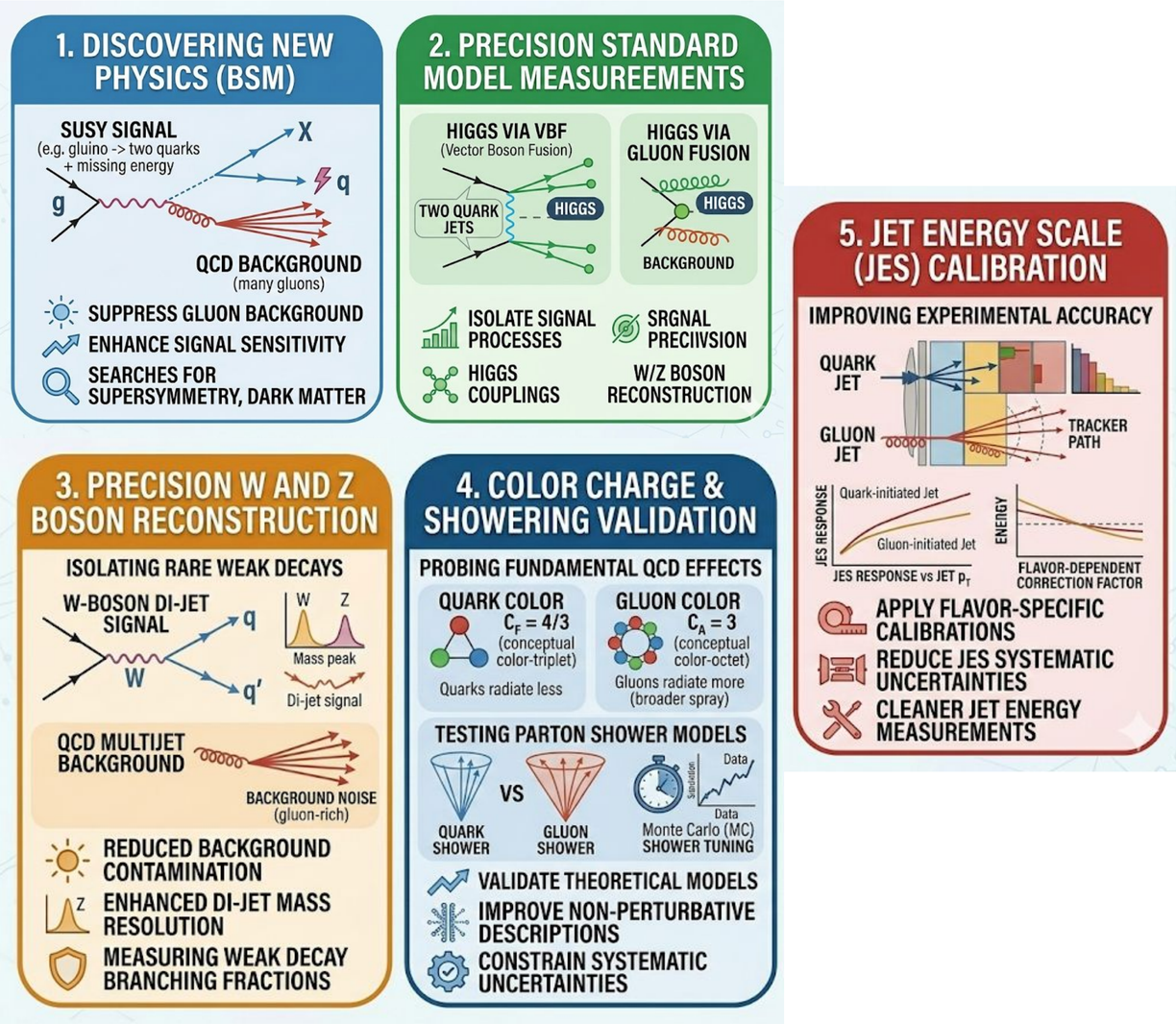
$\sigma(h_3) \times \mathcal{B}(h_3 \to h_1 h_1) = 235\,\text{fb}$ $\sigma(h_3) \times \mathcal{B}(h_3 \to h_1 Z) = 76\,\text{fb}$

JHEP 09 (2022) 011

Mass of additional Higgs bosons is close to the EW scale
New triple boson final states not studied at the LHC yet

- PhD project will start in May

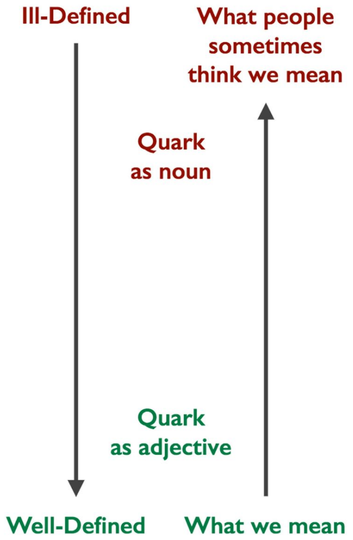
Quark-gluon tagging: Motivation



The inherent challenge of labelling a jet based on its origin

What is a Quark Jet?

From lunch/dinner discussions



A quark parton

A Born-level quark parton

The initiating quark parton in a final state shower

An eikonal line with baryon number 1/3 and carrying triplet color charge

A quark operator appearing in a hard matrix element in the context of a factorization theorem

A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)

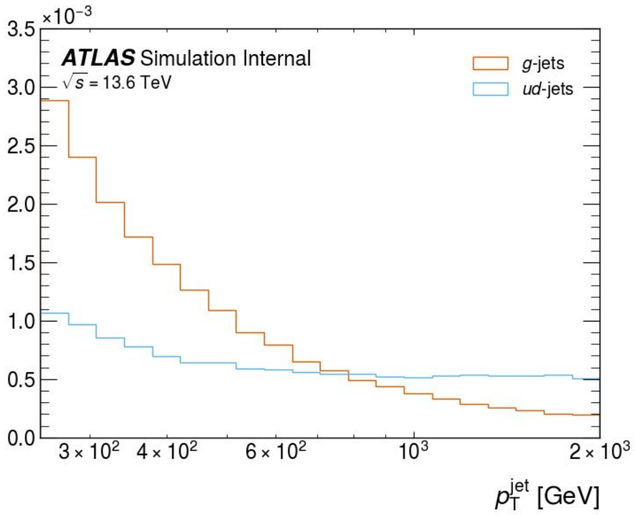
A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

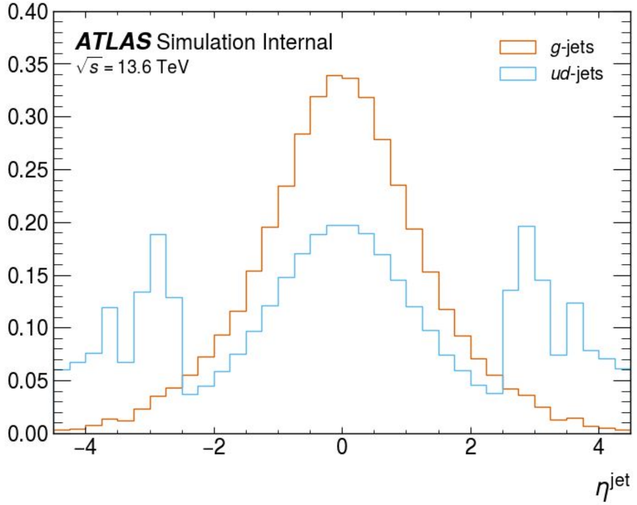
A schematic diagram showing different possible definitions when classifying a jet based on its quark or a gluon origin. This was the summary of an after dinner discussion in Les Houches workshop in 2015. © Philippe Gras, Stefan Höche, Deepak Kar, Andrew Larkoski, Leif Lönnblad, Simon Plätzer, Andrzej Siódmok, Peter Skands, Gregory Soyez and Jesse Thaler.

Source: *Experimental Particle Physics: Understanding the measurements and searches at the Large Hadron Collider* by Deepak Kar

Quark-gluon tagging at ATLAS: Status and updates

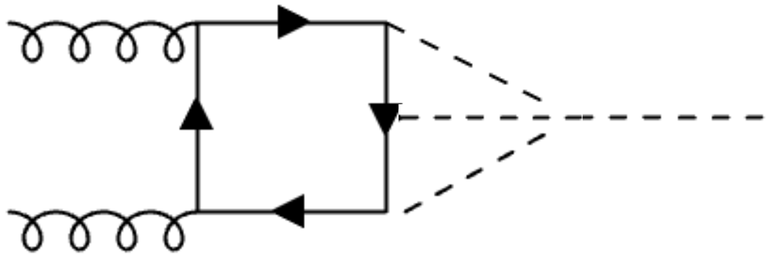
- The current *q*/*g*-tagger at ATLAS suffers from a few limitations:
  - ➢ Poor rejection of *b*/*c*-jets. Likely because of the lack of tracks IP information.
  - ➢ Quark-flavour agnostic binary classifier.
  - ➢ Trained using only leading order jets from di-jet events.
- Goal: Make a better q/g-tagger using the technologies used for FTAG.
- Challenges:
  - ➢ FTAG targets only central jets ($|\eta| < 2.5$), but *q*/*g*-tagging needs to work in forward region as well.
    - A new training dataset has been produced that includes the forward jets.
    - Information from forward calorimetry has been included as input.
  - ➢ FTAG uses *Z'* sample for high-p_T jets, but $Z' \rightarrow gg$ decay was not implemented.
    - This decay has been implemented, and the latest training dataset now contains high-p_T gluon jets.





Constraining anomalous Higgs Self-Couplings in gluon-fusion

- Project leaders: C. Duhr, F. Maltoni
- Idea: constrain the Higgs trilinear and quadrilinear couplings from higher-order self-interactions. [G. Degrassi, P. Giardino, F. Maltoni, D. Pagani]
  - ➡ Requires 2-loop computation to see LO effect.
  - ➡ Only trilinear coupling enters at 2-loops (+quarilinear in self-energy)
- Cmf Project: Constrain quadrilinear coupling from self-interactions in gluon fusion.
  - ➡ Requires 3-loop computation!



FeynCalc in Color Meets Flavour

- **FeynCalc** is a widely used code in particle physics [Mertig, Böhm, Denner 91]
  Initially restricted to tree-level and one-loop calculations
- **FeynCalc** 10 aims at making highly-specialized multi-loop calculations accessible to wider community [Shtabovenko, Mertig, Orellana 23, Shtabovenko 25]
  - Topology identification and minimization
  - Mappings between master integrals
  - Interfaces to tools for integration-by-parts reduction and numerical evaluation
  - Parallelization
- Common bottleneck: analytic calculation of master integrals
- What is needed to improve on this?
  - More easy-to-use tools that implement existing algorithms
    (differential equations, basis changes, expansions, direct integration)
  - Avoid recomputing known integrals $\rightarrow$ library of analytic results

FeynCalc in Color Meets Flavour

- CmF RA3: A unique chance to make **FeynCalc** a key tool for master integral studies
- Reimplement existing ideas/algorithms to have everything in one program
  - Solving differential equations in canonical form [Henn 2013]
  - Finding a better basis of master integrals e.g. quasi-finite [von Manteuffel, Panzer, Schabinger 14] or ε-factorized [Smirnov, Smirnov 20]
  - Direct integration of Feynman parameters similar to HyperInt [Panzer 14] and HyperFORM [Kardos, Moch, Schnetz 25]
  - Asymptotic expansion using method of regions [Beneke, Smirnov 97]
- Collect existing analytic results for multi-loop integrals
  - Unlike Loopedia [Bogner et al 17], provide explicit expressions, not references
  - Many complications to resolve: function bases, ε-order, non-standard propagators, exact or expanded, ...
  - Start with single-scale integrals up to 3-loops to keep things simple

Uncertainties in the indirect “measurement” of the trilinear Higgs Coupling from single Higgs Observables

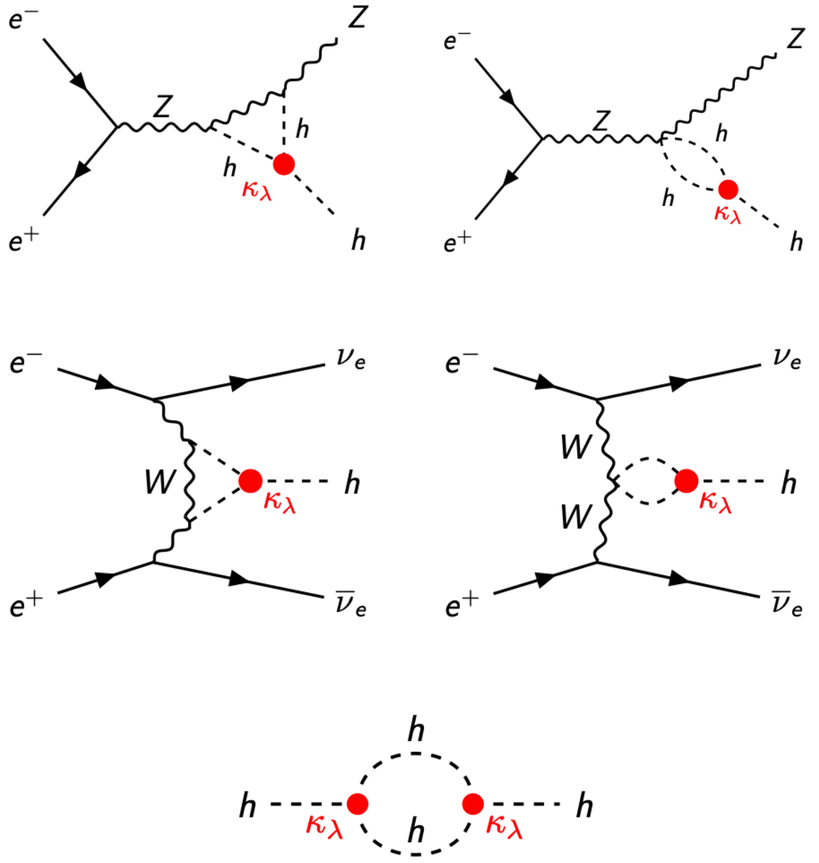
Christian Grefe, Philip Bechtle, Klaus Desch

09. March 2026

Project Idea: Look at yet underappreciated challenges in indirect "measurement" of κ_λ

Alternative: precision measurements of **single** *h* observables

- κ_λ only present at **loop-level**
  - ➢ Need **high precision!**
- **"Indirect"** or **loop-level** sensitivity
  - ➢ **Circular** e^+e^- colliders
  - ➢ Studied by several groups [deBlas.2025, ter Hoeve.2025, Maura.2025]
- **Caveat:** sensitivity depends on the BSM theoretical framework, i.e.:
  - ➢ **BSM particles** in the **loop**
  - ➢ Theoretical **assumptions**



Objective: Study Uncertainties, especially related to truncation

In order to study the sensitivity of future colliders to $\kappa_\lambda \neq 1$, a framework for BSM physics is necessary:

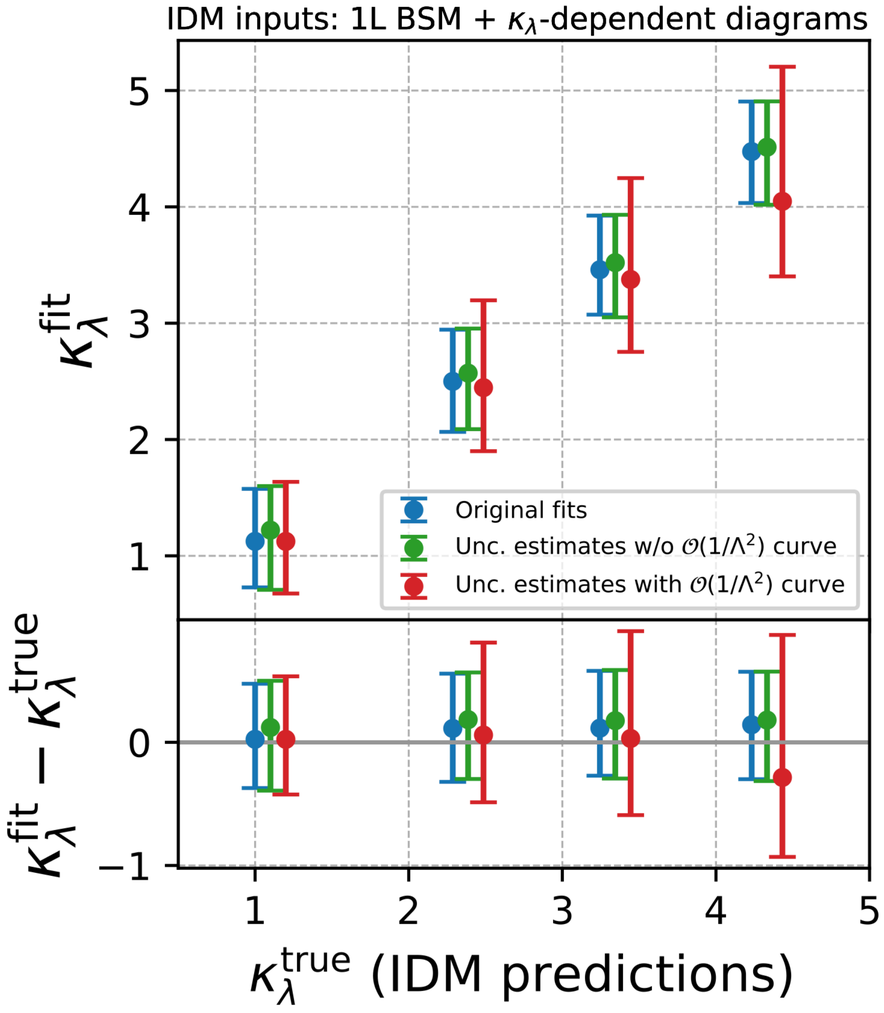
1. **kappa-framework**: Higgs couplings are modified by numerical factors
   - ➢ e.g. $\Gamma_{h\to bb} \to \kappa_b^2 \cdot \Gamma^{SM}_{h\to bb}$
   - ➢ **Not fully consistent** (cannot apply to different energies)

2. **Effective Field Theories (EFTs)** (e.g. SMEFT)
   - ➢ (Some) **model-independence**
   - ➢ **Which operators** to include and where to **truncate** the **EFT expansion**?

3. **UV-complete models** (e.g. 2HDM)
   - ➢ **Limited applicability** (model might not be realized in nature)

Goal of the project: compare the EFT approach with a simple BSM model: Inert Doublet Model (IDM)

Intermediate Results



Assessing uncertainties in the determination of the trilinear Higgs self-coupling from single-Higgs observables #1

Henning Bahl (Heidelberg U.), Philip Bechtle (Bonn U.), Johannes Braathen (DESY), Sven Heinemeyer (Madrid, IFT), Jenny List (DESY) et al. (Dec 1, 2025)

Published in: *PoS* EPS-HEP2025 (2026) 384 • Contribution to: EPS-HEP2025, 384, EPS-HEP2025 • e-Print: 2512.02111 [hep-ph]

pdf DOI cite claim reference search 0 citations

ECFA Higgs, electroweak, and top Factory Study #2

J. Altmann (Monash U.), P. Skands (Monash U.), A. Desai (Melbourne U. and Adelaide U.), W. Mitaroff (Vienna, OAW), S. Plätzer (Vienna U. and Graz U.) et al. (Jun 18, 2025)

Published in: CERN Yellow Reports: Monographs, 5/2025 • Published in: *CERN Yellow Rep.Monogr.* 5 (2025) • e-Print: 2506.15390 [hep-ex]

pdf links DOI cite claim reference search 40 citations

The Linear Collider Facility (LCF) at CERN #3

Linear Collider Collaboration • H. Abramowicz (Tel Aviv U.) et al. (Mar 31, 2025)

e-Print: 2503.24049 [hep-ex]

pdf links cite claim reference search 36 citations

A Linear Collider Vision for the Future of Particle Physics #4

Linear Collider Vision Collaboration • H. Abramowicz (Tel Aviv U.) et al. (Mar 25, 2025)

e-Print: 2503.19983 [hep-ex]

pdf links cite claim reference search 80 citations

UNIVERSITÄT BONN

Outlook

- Finalize the current project within 1/2 year
- Then focus on project from within RA3 to be discussed with Gudrun, Kevin, Manu, etc.
- Would like to understand more deeply how a genuine loop level SMEFT would be more consistent and more precise than the current naive truncations

UNIVERSITÄT BONN

color meets flavor

Top in Dortmund

Status

Kevin Kröniger and Andrea Knue, TU Dortmund University

ATLAS projects

color meets flavor

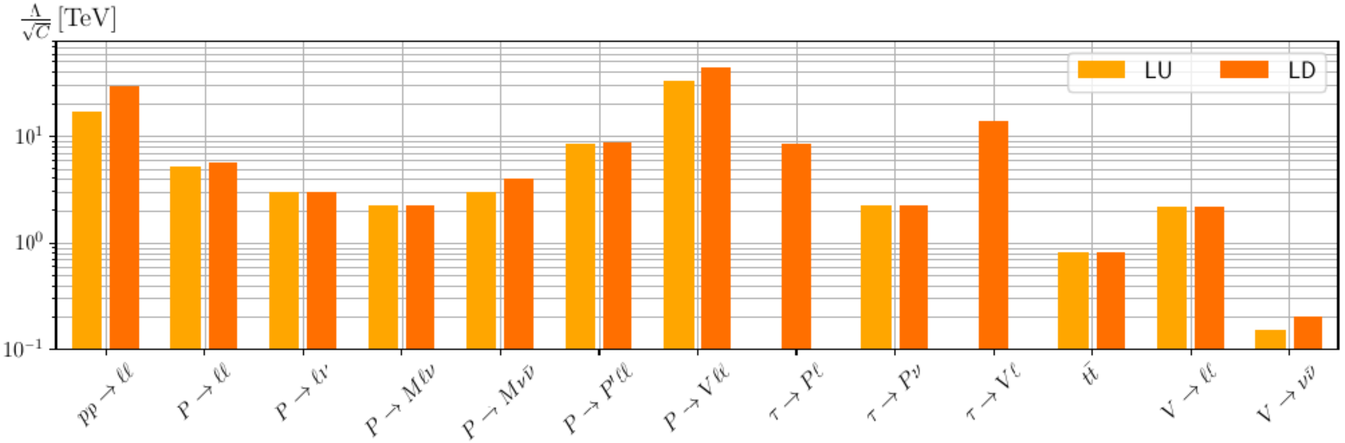
- **Toponium**
  - Paper on dileptons: arXiv:2601.11780 (01/2026)
  - Paper on l+jets with Run 2 data this year
  - Paper on l+jets with Run 3 data next year
  - Cluster connection: Signal modelling together with Wolfgang Kilian (Siegen / theory)

- **Spin/entanglement**
  - Paper on top-pair threshold in l+jets channel this year
  - Paper on full spin density matrix with boosted events next year
  - Cluster connection: coordination with Carmen Diez Pardos in dilepton channel (Siegen / experiment)

ATLAS and EFT projects

color meets flavor

- **Single-top + photon**
  - First observation of process: Phys. Rev. Lett. **131**, 181901
  - Expanding to differential measurement using Run 2 + Run 3 data
  - Preparing INT note, Paper next year



- **EFT**
  - Test lepton-flavor-specific operators
  - Paper: arXiv:2511.07089 (11/2025)
  - Next steps: consolidate framework
    - Make code sustainable (so that it fits the duration of the cluster)
    - Easily modify / exchange models and statistical tools
  - Cluster connection: cooperation with Gudrun Hiller (Dortmund / theory) and Philip Bechtle (Bonn / experiment)

Gradient flow (GF) determination of the Λ parameter and α_s using simulations with $N_f = 4$ dynamical fermions

Stefan Krieg and Oliver Witzel

- Create dynamical, massdegenerate $N_f = 4$ lattice gauge field configurations
  - → Stout-smeared Möbius domain-wall fermions with Symanzik gauge action
  - → $16^3 \times 32$, $24^3 \times 48$, $32^3 \times 64$, $48^3 \times 96$ lattices
  - → Range of bare couplings $\beta_b \equiv 6/g_0^2$ from weak to strong coupling (confinement scale)
- Calculate gradient flow measurements on the lattice
  - → Renormalized coupling $g^2_{GF}(t; L, \beta_b) = \frac{128\pi^2}{3(N_c^2-1)}\langle tE(t)\rangle$
  - → Continuous renormalization group β function $\beta(g^2_{GF}) = \mu^2 \frac{dg^2_{GF}}{d\mu^2} = -t\frac{dg^2_{GF}}{dt}$
  - → At weakest coupling match to perturbative GF prediction/use short-flow-time expansion
  - → Integral over the β function determines Λ-parameter

$$\frac{\Lambda^2}{\mu^2} = \left(b_0 g^2(\mu)\right)^{-\frac{b_1}{b_0^2}} \exp\left(-\frac{1}{b_0 g(\mu)^2}\right) \times \exp\left[-\int_0^{g^2(\mu)} \mathrm{d}x \left(\frac{1}{\beta(x)} + \frac{1}{b_0 x^2} - \frac{b_1}{b_0^2 x}\right)\right]$$

Status

- Exploration at weak coupling by visiting PhD student Xue-Yin Han (09/2025 - 02/2026)
  - → Generation of deconfined, weak coupling ensembles using local resources (OMNI cluster SI)
  - → Small volumes: $16^3 \times 32$ and $24^3 \times 48$
  - → Thermalizing first $32^3 \times 64$ volume
  - → First GF measurement and initial data analysis

- Next steps
  - → Deduce from exploratory data set of values for the bare gauge coupling
  - → Drafting proposals for computing time
  - → Code (grid) ready to run on HPC CPU and GPU machines
  - → Seeking PhD candidate to continue project
  - → Xue-Yin returns to Siegen (at least) for a summer visit (June-September)
    (AvH fellowship application pending)

Next activities in RA3

- The goal is to meet on a regular basis in person (2-3x per year).
- **Next RA3 general meeting: 7 April 2026 in Siegen!**
- If you want to stay up to date, please register for the RA3 mailing list!

  cmf-ra3@listen.uni-bonn.de
- We will soon circulate more information about the meeting in Siegen.

  ➡ https://indico.hiskp.uni-bonn.de/event/1404/

Stay tuned!