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

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Outline

1. **High temperature QCD on the lattice**
    - Problems and Solutions
2. **Screening masses spectrum**
    - Pseudoscalar-Vector splitting
    - Spectrum degeneracy
    - Ward Identities and chiral multiplets

The problem of simulating very high temperatures

The problem

- Renormalize the theory with a hadronic scheme
- Hadronic scale M_{had} and temperature T may differ by orders of magnitude

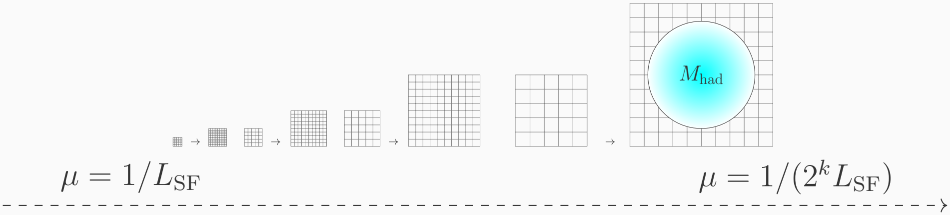
$$a \ll \frac{1}{T} \ll \frac{1}{M_{\mathrm{had}}} \ll L$$

Computationally demanding

A possible solution: finite-volume couplings

Massless scheme: $\bar{g}^2_{\rm SF}(L_{\rm SF})$ at $\mu = 1/L_{\rm SF}$ [ALPHA Collaboration, 2016-18]

- Set the scale on each lattice with $\bar{g}^2_{\rm SF}(L_{\rm SF})$
- Explore different scales with step-scaling technique
- Fix the overall scale at low energy with a dimensionful hadronic quantity $M_{\rm had}\left(r_0, f_\pi, f_{\pi K}\right)$ [M. Bruno et al.,Phys. Rev. D 95 (2017) 074504]



The strategy

Finite volume scheme with SF b.c.

Step-scaling function

↓

Matching with hadronic scheme (M_{had})

↓

Known relation between

$$M_{\mathrm{had}} \Longleftrightarrow L_{\mathrm{SF}} \Longleftrightarrow \bar{g}_{\mathrm{SF}}(L_{\mathrm{SF}})$$

Finite Temperature with periodic b.c.

Temperature fixed by imposing the relation

$$1/T = L_0 = L_{\mathrm{SF}} = 1/\mu$$

↓

Known relation between

$$T \Longleftrightarrow \bar{g}_{\mathrm{SF}}(L_0)$$

- No large volumes needed
- FV effects exponentially small for large LT

Mesonic screening masses

- Large-distance behaviour of fermionic bilinears

$$C_{\mathcal{O}}(x_3) = \int dx_0\, dx_1\, dx_2\, \langle \mathcal{O}(x)\mathcal{O}(0)\rangle \overset{x_3 \to \infty}{=} Ae^{-mx_3} + \ldots$$

- Here $\mathcal{O} = \{P^a, S^a, V_2^a, A_2^a\}$ from 1 GeV to 160 GeV
- EFT + 1-loop perturbative result $\to$ degeneracy [Laine et al., JHEP 02 (2004) 004]

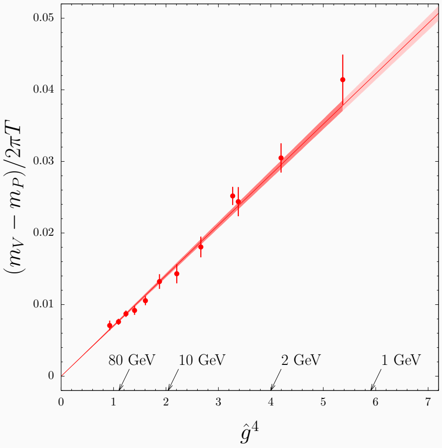
➥ For asymptotically high temperatures $m \to 2\pi T$ in every channel

➥ Probes of chiral symmetry restoration $\to$ degeneracy of various channels

Vector-Pseudoscalar mass splitting

- Spin-dependent term of $O(\hat{g}^4)$ in the entire range of temperature
- Mass-splitting visible at the highest temperature

$$\frac{1}{\hat{g}^2(T)} \equiv \frac{9}{8\pi^2}\ln\frac{2\pi T}{\Lambda_{\overline{\mathrm{MS}}}} + \frac{4}{9\pi^2}\ln\left(2\ln\frac{2\pi T}{\Lambda_{\overline{\mathrm{MS}}}}\right)$$

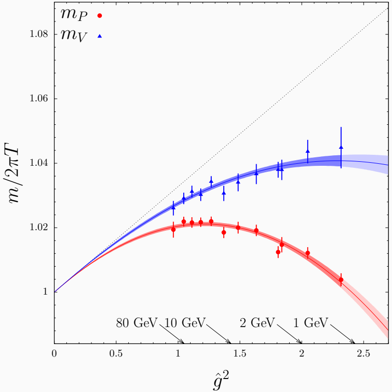


Vector-Pseudoscalar spectrum

$$\begin{cases} \frac{m_P}{2\pi T}(\hat{g}) = p_0 + p_2\hat{g}^2 + p_3\hat{g}^3 + p_4\hat{g}^4 \\ \frac{m_V}{2\pi T}(\hat{g}) = \frac{m_P}{2\pi T} + s_4\hat{g}^4 \end{cases}$$

p_3	0.0038(22)
p_4	-0.0161(17)
s_4	0.00704(14)

- Results compatible with EFT
- 1-loop matching not reliable:
  - ➥ Pseudoscalar: $\hat{g}^4$ term cancels $\hat{g}^2$ term at $T \sim 1$ GeV
  - ➥ Vector: $\hat{g}^4$ term dominant at 1 GeV
  - ➥ Mass-splitting at **high temperature**



Continuum Chiral Ward Identities

- Non-singlet axial Ward Identities

$$\mathcal{O} = A^b_\mu(z)V^c_\nu(y) \quad \longrightarrow \quad \langle V^a_k(z)V^a_k(y)\rangle \;=\; \langle A^a_k(z)A^a_k(y)\rangle$$

$$\mathcal{O} = P^b(z)S^0(y) \quad \longrightarrow \quad 2\,\langle P^a(z)P^a(y)\rangle \;= -\frac{1}{2}\,\langle S^0(z)S^0(y)\rangle$$

$$\mathcal{O} = S^b(z)P^0(y) \quad \longrightarrow \quad 2\,\langle S^a(z)S^a(y)\rangle \;= -\frac{1}{2}\,\langle P^0(z)P^0(y)\rangle$$

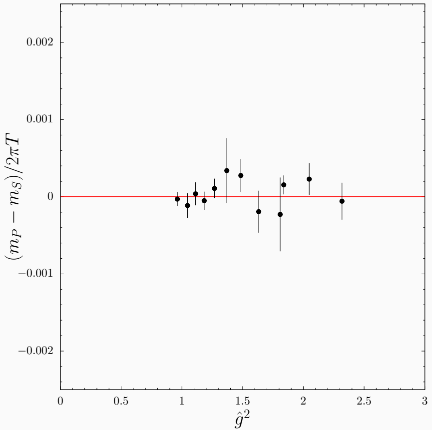
- Singlet axial Ward Identities

$$\mathcal{O} = P^0(z)S^0(y) \quad \longrightarrow \quad \langle S^0(z)S^0(y)\rangle + \langle P^0(z)P^0(y)\rangle = N_f\,\langle QP^0(z)S^0(y)\rangle$$

$$\mathcal{O} = P^a(z)S^a(y) \quad \longrightarrow \quad \langle S^a(z)S^a(y)\rangle + \langle P^a(z)P^a(y)\rangle = N_f\,\langle QP^a(z)S^a(y)\rangle$$

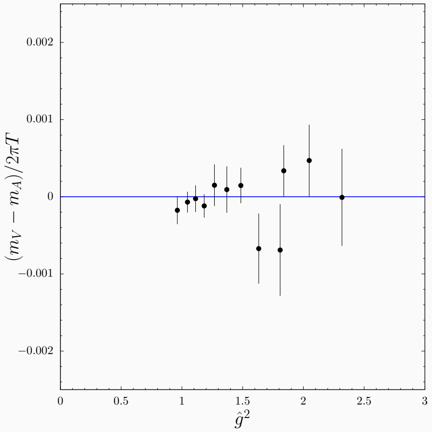
Pseudoscalar-Scalar spectrum

- Complete degeneracy between the Pseudoscalar and the Scalar channels
  - ➥ Only $Q = 0$ sector contributes to the path integral

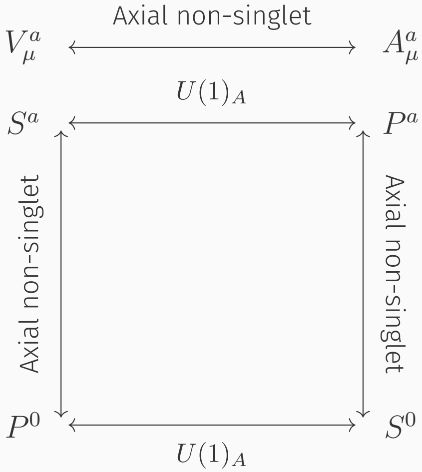


Vector-Axial spectrum

- Complete degeneracy between the Vector and the Axial channels
  - ➥ Non-singlet chiral symmetry restoration



Chiral Multiplets



Conclusion

- Step-scaling technique provides a solid strategy to study QCD at very high temperature

- $O(\hat{g}^4)$ terms needed to explain the Vector-Pseudoscalar spectrum in the entire range of temperature

- No signal of chiral symmetry breaking
- Degeneracy pattern consistent with Ward Identities