Non-perturbative behavior of thermal QCD up to the Electroweak scale: Computational strategy and screening masses

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Introduction

Screening masses: inverse correlation lengths of different channels ⇒ length scale over which strong interaction is screened when a given particle is placed in the QCD thermal medium

Extracted from **spatial correlators:** $\mathcal{C}_O^{(n)}(x_3) = \int_0^{L_0} dx_0 \int dx_1 dx_2 \exp\{i\omega_n x_0\}\langle O(x)O^\dagger(0)\rangle \underset{x_3\to\infty}{\propto} \exp\{-m_O^{(n)} x_3\}(1+\mathcal{O}(\exp\{-\Delta_m x_3\})),\ \omega_n = 2\pi nT$ (boson), $\pi T(2n+1)$ (fermion)

We consider flavor non-singlet **mesonic** operators $P = \bar\psi\frac{\lambda^a}{2}\gamma_5\psi,\ V_\mu = \bar\psi\frac{\lambda^a}{2}\gamma_\mu\psi$ with both $\omega = 0$ and $\omega = 2\pi T$, and **baryon** $N = \varepsilon^{abc}((u^a)^T C\gamma_5 d^b)d^c$ with $\omega = \pi T$

High Temperature Effective Field Theory

Integrate out non-static gauge fields → **3D EFT tower**

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- πT (**Hard**): $\psi,\ A_0,\ A_i$: Non-Relativistic QCD; Perturbation theory: series in $g(T)$
- ↓
- gT (**Soft**): $A_0,\ A_i$: Electrostatic QCD; Perturbation theory: series in $g(T)$
- ↓
- g^2T (**Ultra-soft**): A_i : Magnetostatic QCD; Series in $g^2(T)$, coefficients from lattice

- **Meson** screening masses $2\pi T\left(1 + c_n\cdot g^2 + \mathcal{O}\left(g^3\right)\right)$ [1,2]
- **Nucleon** screening mass $3\pi T\left(1 + b\cdot g^2 + \mathcal{O}\left(g^3\right)\right)$ [3]
- **Hyperfine splitting** in static mesons: $sg^4 + \mathcal{O}\left(g^5\right)$ [4,5]

Non-perturbative lattice strategy

LQCD at High T→ **Window problem:** $a \ll T^{-1} \ll M_{\rm Had}^{-1} \ll L$

Unfeasible for $T > 1$ GeV

Solution: non-perturbative renormalization of the coupling [6]

$$g^2_{\rm SF}(a\mu, g_0^2) = \bar g^2_{\rm SF}(\mu),\ a\mu \ll 1,\ \mu = L_0^{-1} = \sqrt{2}T$$

Contact with hadronic scale at low μ, reach high μ with non-perturbative RG running

Finite volume effects exponentially suppressed with g^2TL

12 temperatures, 3-4 lattice spacings each: **43** ensembles

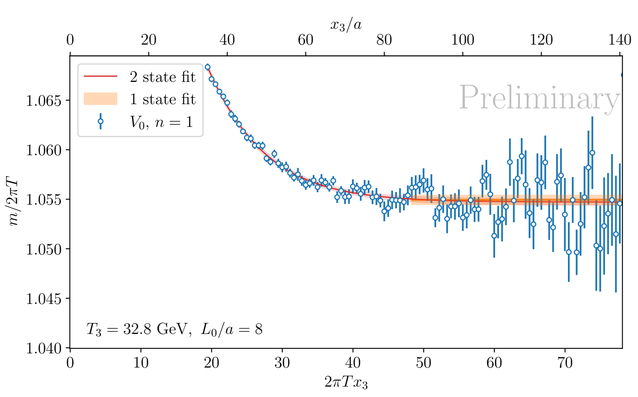
$$L_0\times L^3,\ L_0/a = \{4,6,8,10\},\ L/a = 288$$

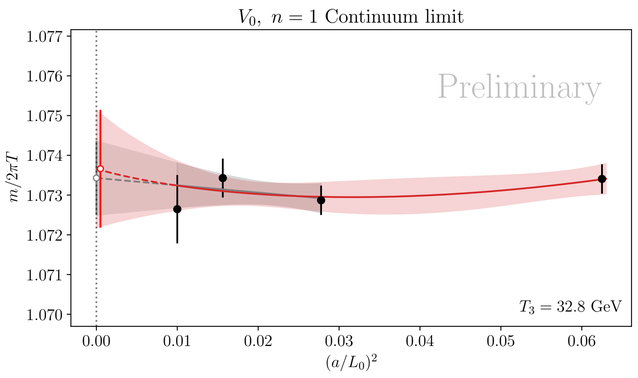
$N_f = 3$ $\mathcal{O}(a)$-improved Wilson Fermions at the chiral limit

	T[GeV]	$\bar g^2_{\rm SF}(\mu)$
T_0	165(6)	1.01636
T_1	82.3(2.8)	1.11000
T_2	51.4(1.7)	1.18446
T_3	32.8(1.0)	1.26569
T_4	20.6(6)	1.3627
T_5	12.8(4)	1.4808
T_6	8.03(22)	1.6173
T_7	4.91(13)	1.7943
T_8	3.04(8)	2.0120

	T[GeV]	$\bar g^2_{\rm GF}(\mu)$
T_9	2.83(7)	2.7359
T_{10}	1.82(4)	3.2029
T_{11}	1.167(23)	3.8643

From the lattice to the continuum





- Analyze the **effective mass**, identify the region where the ground state dominates correlator
- Obtain the **screening mass** from a single state fit in the plateau
- Repeat for all lattice spacings at fixed temperature

⇓

- **Continuum limit:** remove lattice artifacts by extrapolating to $a \to 0$
  Improved action: discretization effects start at $\mathcal{O}\left(a^2\right)$: employ different ansätze and data cuts
- Repeat for all temperatures, channels and sectors

Spectrum hierarchy

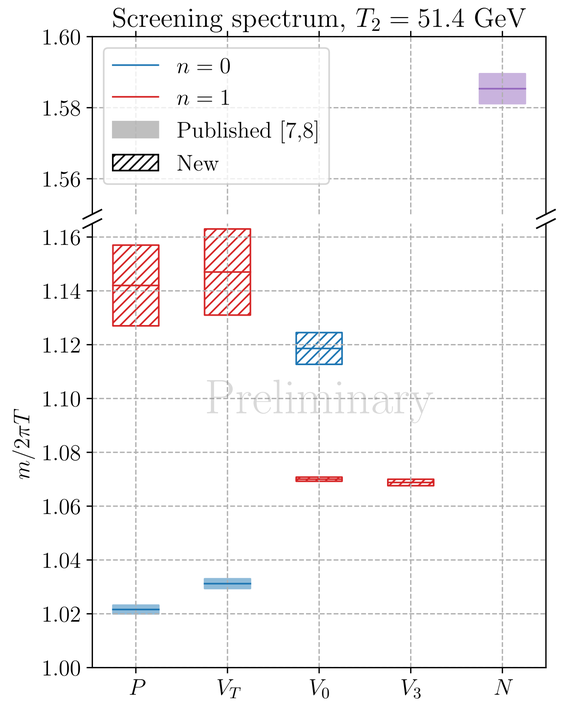
High precision:
0.1% precision in $P,\ V_T\ n=0;\ V_0\ n=1;\ N$
1% precision in $P,\ V_T\ n=1$ and $V_0\ n=0$

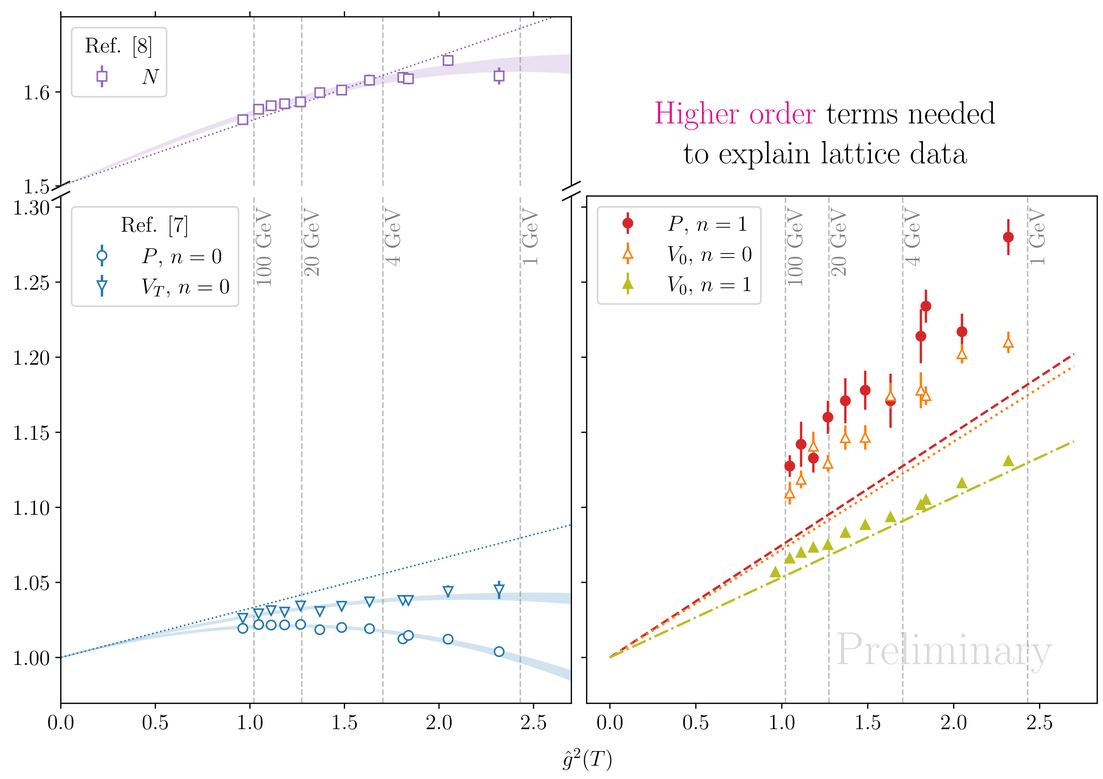
V_0 channel in the $n=1$ sector lighter than the static $n=0$ sector (see also [2])

V_0 and V_3 at $n=1$ degenerate due to WI (current conservation)

Temperature dependence:
Study lattice data as function of 2-loop $\overline{\rm MS}$ coupling renormalized at $\mu = 2\pi T$: $\hat g^2(T)$

Compare with $\mathcal{O}\left(g^2\right)$ perturbation theory: general hierarchy and magnitude respected, but significant deviations are present

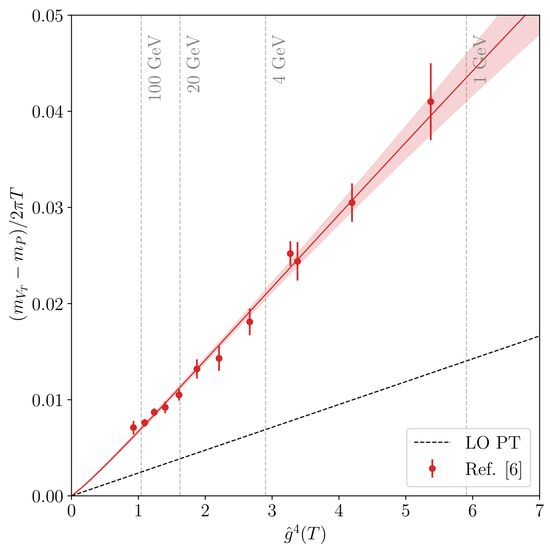




Higher order terms needed to explain lattice data

Hyperfine splitting

- At LO in EFT [5]:
  $\dfrac{m_{V_T} - m_P}{2\pi T} = 0.002376\cdot g^4$
- From the lattice [7]:
  $m_{V_T} - m_P \neq 0$ up to $T \sim 160$ GeV
  Single g^4 term fits data, but slope is $\sim 3\times$ perturbative value
  see M. Bresciani's talk, Fri 12:00
- Imposing PT at $\mathcal{O}\left(g^4\right)$, higer orders ($g^5$ and g^6) are needed, which receive non-perturbative contributions (e.g. string term)



Conclusions

Static and **non-static** properties of hot QCD can be computed non-perturbatively up to $T \sim 160$ GeV with sub-percent or percent precision, respectively

Comparison with PT shows discrepancies in the whole temperature range

Some sensible quantities (hyperfine splitting) point to the presence of relevant **non-perturbative** contributions

Want to read more?

References

[1] Laine and Vepsalainen 2004
[2] Brandt et al. 2014
[3] Giusti et al. 2024
[4] Bala et al. 2025
[5] Cè et al. 2025
[6] Bruno et al. 2017
[7] Dalla Brida et al. 2022
[8] Giusti et al. 2024