Neural network extraction of chromo-electric and chromo-magnetic gluon masses

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Outline

Introduction

- Understanding the thermodynamics of QCD at finite temperature is a key goal in high-energy nuclear physics.
- Around the crossover transition ($T_c \sim 150$–170 MeV), different degrees of freedom are liberated:

  Quarks: dominate entropy and particle number.
  Gluons: dominate pressure and energy density.
- Disentangling chromo-electric and chromo-magnetic gluons is crucial for understanding the QCD medium.

Introduction

- At finite temperature, the Euclidean O(4) symmetry is reduced to spatial O(3):

  Longitudinal (electric) and transverse (magnetic) gluons become physically distinct.
- In the high-T limit, perturbative and effective field theory approaches suggest:

$$m_e \sim gT, \quad m_m \sim g^2 T$$

- Magnetic screening masses are absent at any finite order in perturbation theory; they arise from non-perturbative dynamics and are captured by dimensionally reduced effective theories or lattice QCD.

Introduction

Top-Down Approach

Effective Field Theory

↓

Gluonic Masses

Bottom-Up Approach

Lattice QCD Data

↓

Mass Functions
$m_e(T),\ m_m(T)$

Essence: Extracting gluon properties directly from thermodynamic data without specifying a Lagrangian — a data-driven inverse problem.

Quasiparticle Model: Thermodynamics with Gluon Masses

- In the Quasiparticle model (QPM), gluons are treated as massive bosons with effective thermal masses $m_e(T)$ and $m_m(T)$.
- The total thermodynamic potential is:

$$\ln Z(T) = \ln Z_e(T) + \ln Z_m(T)$$

- Each follows Bose-Einstein statistics:

$$\ln Z_i(T) = -\frac{d_i V}{2\pi^2} \int_0^\infty dp\, p^2 \ln\left(1 - e^{-\frac{\sqrt{p^2+m_i^2(T)}}{T}}\right)$$

- Key observables computed:

$$P(T), \quad \epsilon(T), \quad \Delta(T) = \frac{\epsilon - 3P}{T^4}$$

Degeneracy

$$d_e = 8, \quad d_m = 16 \quad \text{(chromo-electric and -magnetic gluons)}$$

Thermal Mass vs. Screening Mass

Thermal Mass

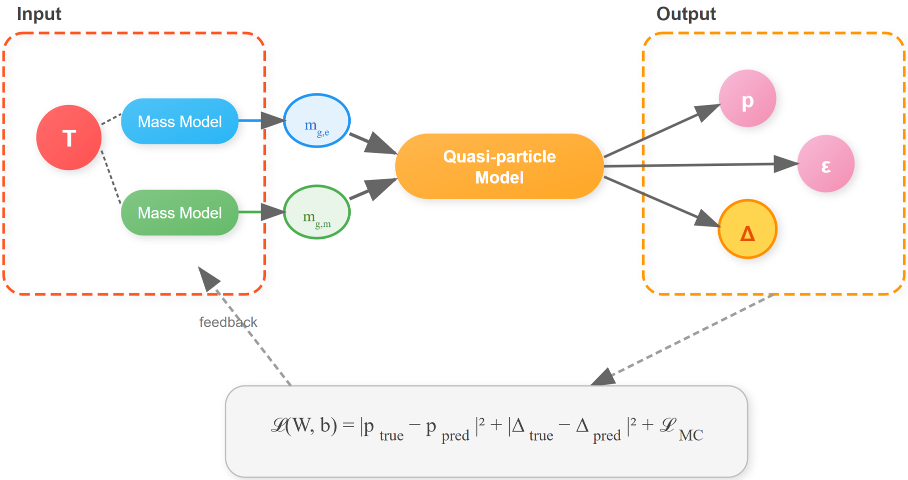
- Arises from medium interactions and enters the energy-momentum dispersion relation
- Related to the pole of the gluon propagator: $E^2 = p^2 + m_{\text{thermal}}^2$
- Governs real-time dynamics and transport properties

Screening Mass

- Characterizes exponential decay of spatial two-point correlations
- Defined from the asymptotic behavior: $\langle A(x)A(0)\rangle \sim e^{-m_{\text{screening}}|x|}$
- Probed in lattice QCD via Polyakov loop correlators
- Does not necessarily coincide with thermal mass, especially near T_c

These two mass definitions reflect different physical aspects of the medium

Framework



Input
T
Mass Model
Mass Model
$m_{g,e}$
$m_{g,m}$
Quasi-particle Model
Output
p
ε
Δ
feedback
$\mathscr{L}(W, b) = |p_{true} - p_{pred}|^2 + |\Delta_{true} - \Delta_{pred}|^2 + \mathscr{L}_{MC}$

Neural Network Structure and Physics-Informed Regularization

- Each gluonic mass $m_i(T)$ is modeled by a separate ResNet:

  ResNet structure helps alleviate the vanishing gradient problem in deep networks.
  Softplus output ensures $m(T) > 0$.

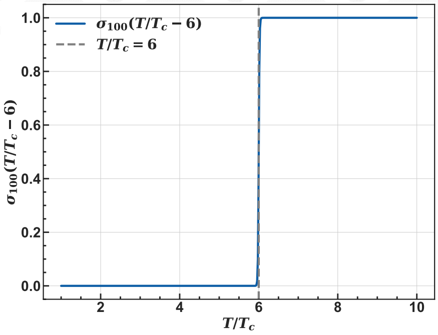
- Loss function:

$$\mathcal{L} = \mathrm{MSE}(p/T^4, \Delta) + \lambda \cdot \omega(T) \left(\frac{m_e(T)}{m_m(T)} - 2 \right)^2$$

- Regularization encodes the high-T theoretical prior:

$$\frac{m_e}{m_m} \to 2 \quad \text{as } T \gg T_c$$

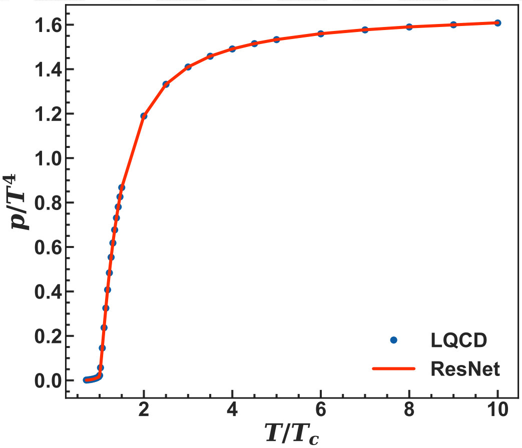
- $\omega(T)$ is a sigmoid weight centered around $T = 6T_c$.



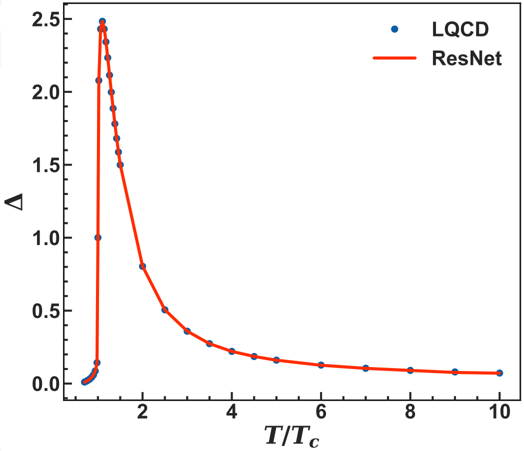
Regularization in High-T

ensures stable optimization and prevents the training instabilities often induced by hard, localized constraints.

Results and Discussion



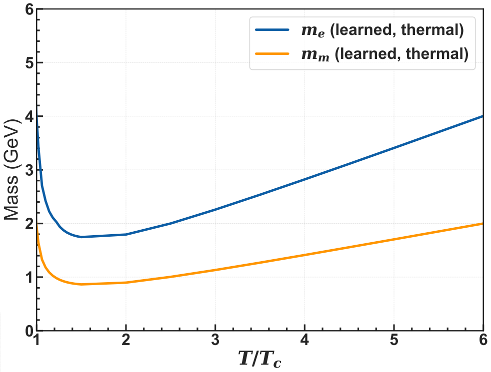
(a) Pressure p/T^4



(b) Trace anomaly Δ (Borsanyi *et al.*, 2012)

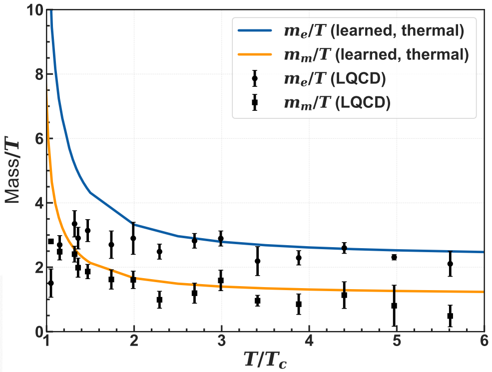
Extracted Gluon Mass Functions

- $m_e(T)$ and $m_m(T)$ both show rapid drop near T_c, reflecting liberation of degrees of freedom.
- At high T, both masses increase linearly, consistent with perturbative behavior.



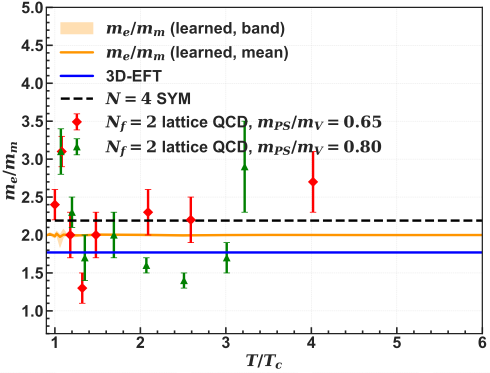
Comparison with Lattice Screening Masses

- Thermal masses from the quasiparticle model differ from screening masses (Nakamura; Saito; Sakai, 2004).
- Screening masses probe exponential fall-off of correlators; thermal masses affect real-time propagation.



High-T Behavior of m_e/m_m

- The regularization term effectively guides the network toward correct asymptotic behavior (Maezawa *et al.*, 2010).



Shear Viscosity from the Quasiparticle Model

- Using the extracted thermal masses, we compute the shear viscosity η via the relaxation time approximation (RTA):

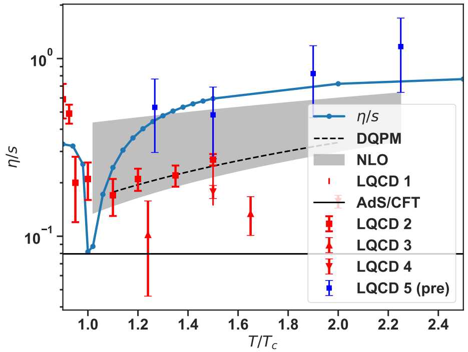
$$\eta = \frac{1}{15T}\sum_{i=e,m} d_i \int \frac{d^3p}{(2\pi)^3}\frac{p^4}{E_i^2}\tau_i f_i(1+f_i)$$

- The relaxation time is given by:

$$\tau_i^{-1} = \frac{N_c}{4\pi}g^2(T)\,T\ln\left(\frac{2k}{g^2(T)}\right)$$

with $g^2(T)$ extracted from $m_e^2 = \frac{N_c}{6}g^2T^2$

- Entropy density s is obtained from lattice data via $s = (\epsilon + p)/T$



DQPM: PRC 88, 045204 (2013). NLO: JHEP 03, 179 (2018). LQCD1: PRD 108, 014503 (2023). LQCD2: JHEP 04, 101 (2017). LQCD3: PRD 76, 101701 (2007). LQCD4: PRD 98, 014512 (2018). LQCD5: Zhang, et. al. Spicy Gluon 2025

Summary

- Developed a neural-network-based framework to extract temperature-dependent chromo-electric and chromo-magnetic gluon masses in pure SU(3) gauge theory.
- Used a quasiparticle model with two separate gluonic mass functions:

$$m_e(T), \quad m_m(T)$$

  trained to reproduce lattice pressure and trace anomaly data.
- Introduced a soft regularization term to guide the model towards the high-T theoretical limit:

$$\frac{m_e}{m_m} \to 2$$

- Successfully captured the non-perturbative features of gluon mass behavior near T_c, while reproducing perturbative scaling at high temperatures.
- Extracted thermal masses differ significantly from screening masses, highlighting the distinction between thermal and spatial correlation scales.
- Calculated shear viscosity η/s shows a minimum near T_c approaching the KSS bound, consistent with lattice QCD results.

Remarks on High-Temperature Regularization

Current Constraint from 3D-EFT and $\mathcal{N} = 4$ SYM

The regularization enforces $m_e/m_m \to 2$ based on:

- 3D effective field theory calculations
- $\mathcal{N} = 4$ Super Yang-Mills theory results

Subtle Issues Worth Noting

- Both 3D-EFT and SYM predictions refer to **screening mass ratios**, while our work extracts **thermal masses**—these need not share identical high-T behaviors
- The current temperature range $T/T_c \in [1, 10]$ remains pre-asymptotic

More discussions and comments are welcomed to refine the high-temperature constraints

References

BORSANYI, S.; ENDRODI, G.; FODOR, Z.; KATZ, S. D.; SZABO, K. K. Precision SU(3) lattice thermodynamics for a large temperature range. **JHEP**, v. 07, p. 056, 2012.

MAEZAWA, Y.; AOKI, S.; EJIRI, S.; HATSUDA, T.; ISHII, N.; KANAYA, K.; UKITA, N.; UMEDA, T. Electric and Magnetic Screening Masses at Finite Temperature from Generalized Polyakov-Line Correlations in Two-flavor Lattice QCD. **Phys. Rev. D**, v. 81, p. 091501, 2010.

NAKAMURA, A.; SAITO, T.; SAKAI, S. Lattice calculation of gluon screening masses. **Phys. Rev. D**, v. 69, p. 014506, 2004.