

16th Symposium on QCD Phase Transition and Relativistic Heavy Ion Physics

Title: Heavy Quarkonium Dissociation Using Deep
Learning-Driven Medium Parameters

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Based on: arXiv:2509.14970 [hep-ph]

In Collaboration with: Fu-Peng Li, Long-Gang Pang, and Guang-You Qin



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Date: 24/10/2025 - 28/10/2025



Machines Learning (ML) is helping in high-energy / heavy-ion / QGP physics research mainly in four ways:

- ML is used to infer QGP medium properties (equation of state, quasi-parton masses, $\alpha_s(T)$, $m_D(T)$) directly from lattice data instead of guessing them.

F.P.Li et al., PLB 844, 138088(2023)

- ML reconstructs in-medium quarkonium spectral functions and effective complex potentials, giving data-driven binding energies and in-medium widths.

A. Kades et al., PRD 102 (2020) 096001.

arXiv:2509.14970 [hep-ph] (current work)

- ML acts as a fast surrogate for expensive simulations, letting us map final-state hadrons/jets back to QGP properties and scan high-dimensional parameter space.

L.-G. Pang et al., Nat. Commun. 9 (2018) 210.

- ML is used to calibrate theory to experiment: it learns which QGP transport parameters reproduce the measured heavy-ion observables and extracts those parameters with quantified uncertainty.

J. E. Bernhard et al., PRC 94 (2016) 024907.

Flow of the talk

- Motivation: Quarkonia as QGP Thermometers
- Framework Overview and Contributions
- Complex In-Medium Potential $V(r, T)$: Real and Imaginary Parts
- ML Extraction of $\alpha_s(T)$ and $m_D(T)$: ML Footprints
- Schrödinger Solver and Thermal Widths $\Gamma_n(T)$
- Dual Dissociation Criteria: $2E_B = \Gamma$ and $E_B = 3T$
- Results – Charmonium and Bottomonium
- Summary & Future Possibilities

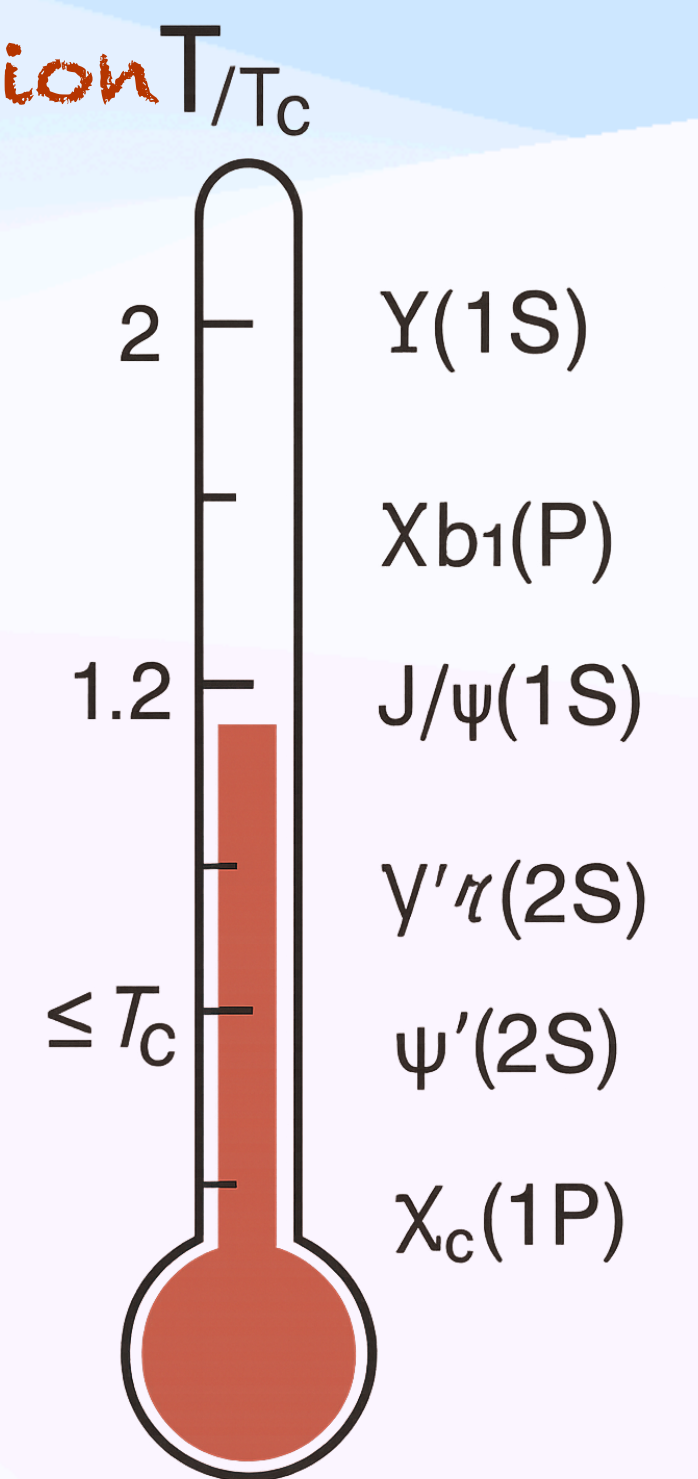


Motivation: Quarkonia as QGP Thermometers

- Heavy $Q\bar{Q}$ states probe $\mathcal{R}V$ (screening) and $\mathcal{I}V$ (damping) $\rightarrow$ melting at high T .
- Sequential suppression: excited states melt earlier; reflects the screening-length hierarchy.
- Need temperature - resolved medium inputs to predict $E_B(T)$, $\Gamma(T)$ and T_d .
- This work: ML-informed quasi particle masses, $\alpha_s(T)$, $m_D(T)$ to constrain dissociation T/T_c windows.

Matsui and Satz, Phys. Lett. B 178, 416 (1986).

CMS Collaboration, Phys. Rev. Lett. 118, 162301 (2017).



Framework Overview and Contributions

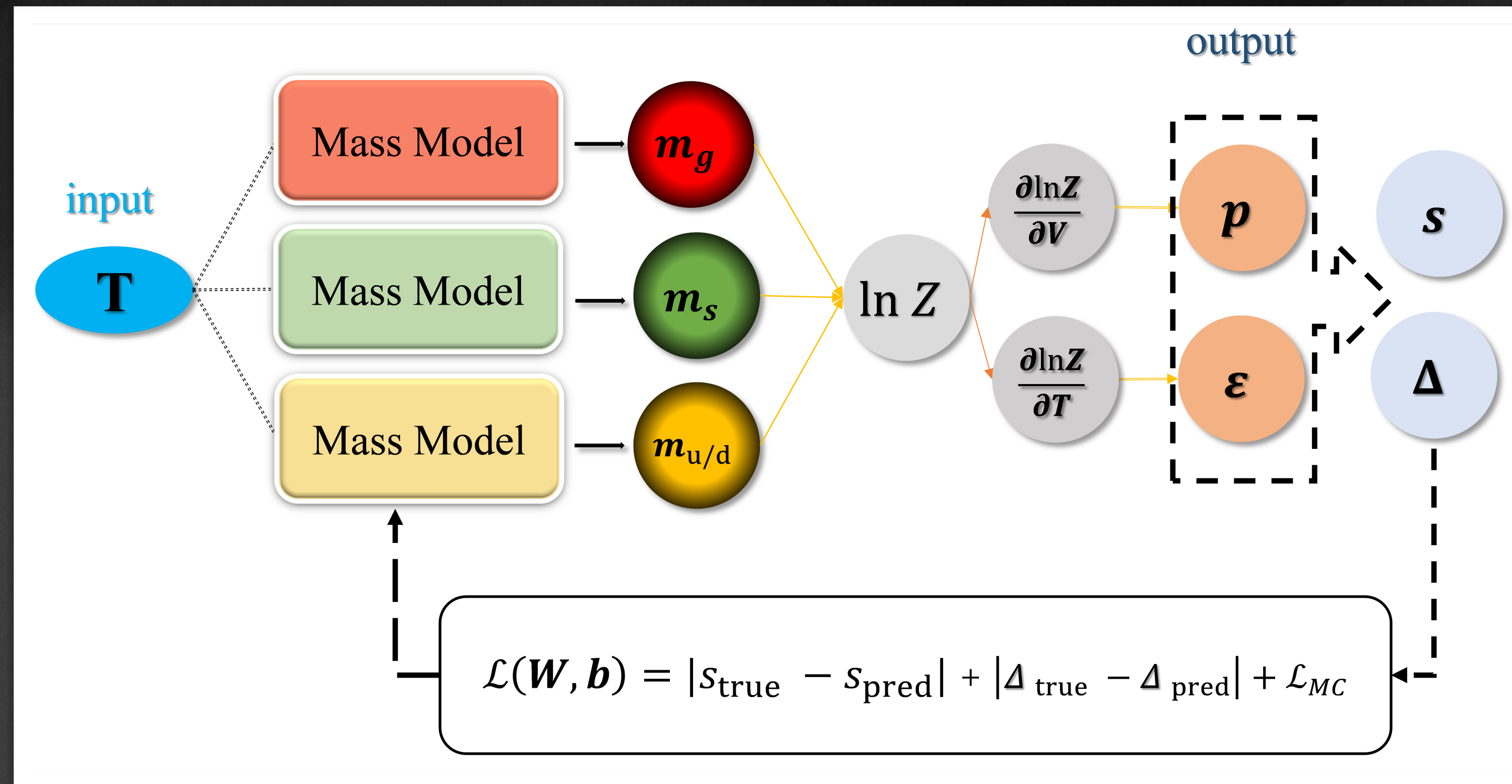
- Pipeline: data $\rightarrow$ ML (DLQPM) $\rightarrow m_i(T), \alpha_s(T), m_D(T) \rightarrow$ complex $V(r, T) \rightarrow$ Schrödinger Eq $\rightarrow E_B(T), \Gamma(T) \rightarrow T_d$
- Inputs: Lattice-informed quasi-parton masses; HTL-consistent $m_D(T)$; monotonic $\alpha_s(T)$ across T/T_c
- Potential: Cornell in vacuum; medium modification via dielectric permittivity $\rightarrow$ split into $\Re V$ (binding) and $\Im V$ (Landau damping).
- Solver: radial Schrödinger on a dense r -grid; track ground and excited states vs T/T_c .
- Width: $\Gamma_n(T) = 4\pi \int_0^\infty r^2 |\psi_n(r; T)|^2 [-\Im V(r, T)] dr$
- Contributions (this work): ML-anchored α_s, m_D tighten temperature dependence; dual criteria $\Gamma = 2E_B$ and $E_B = 3T$ bracket T_d ; uncertainty from retrain ensembles.

• M. Laine, O. Philipsen, P. Romatschke, M. Tassler, JHEP 03 (2007) 054.

• N. Brambilla, J. Ghiglieri, A. Vairo, P. Petreczky, PRD 78 (2008) 014017; JHEP 09 (2011) 107.

ML Description: Inferring Quasi-Parton Masses (DLQPM)

- Inputs $\rightarrow$ Model: use lattice $s(T)$ and $\epsilon - 3p$; fit a quasiparticle EOS with $m_g(T), m_{u/d}(T), m_s(T)$.
- Network: DLQPM maps $T/T_c \rightarrow \{m_g, m_{u/d}, m_s\}$ with smoothness and HTL-consistent high- T behavior.



- Output $\rightarrow$ calibrated $m_g, m_{u/d}, m_s$ (with uncertainty)

Outputs: $\alpha_s(T)$ and $m_D(T)$ (from light-quark masses)

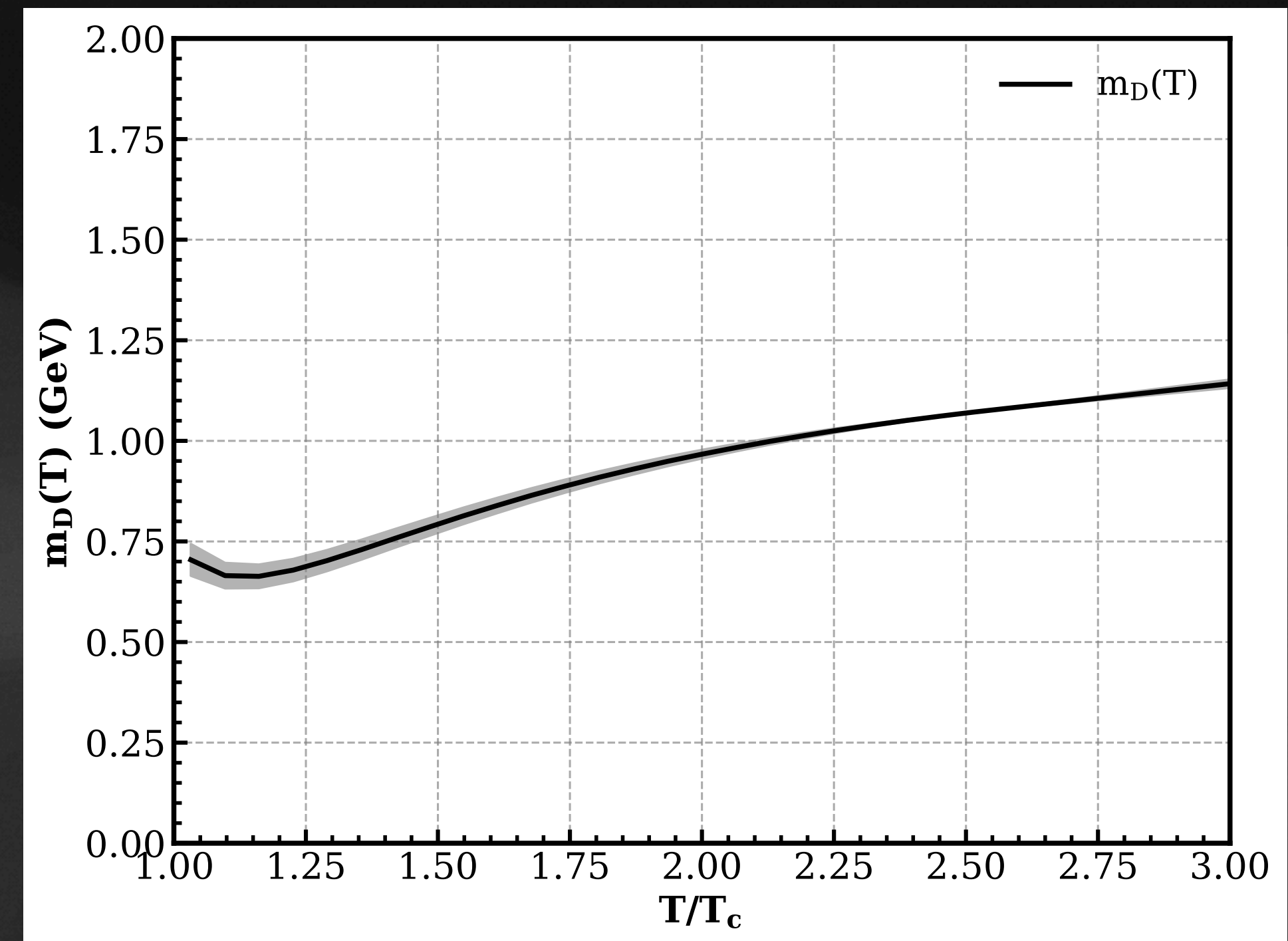
- From DLQPM masses $\{m_g(T), m_{u/d}(T)\}$ extract $\alpha_s(T)$:

$$m_g^2(T) = \frac{1}{6} g_s^2(T) \left(N_c + \frac{1}{2} N_f \right) T^2, \quad m_{u/d}^2(T) = \frac{N_c^2 - 1}{8N_c} g_s^2(T) T^2,$$

$$\Rightarrow g_s^2(T) = \frac{m_g^2(T) + m_{u/d}^2(T)}{\frac{1}{6} \left(N_c + \frac{1}{2} N_f \right) T^2 + \frac{N_c^2 - 1}{8N_c} T^2}$$

- Debye mass from HTL (Eq. (11)):

$$m_D(T) = T \sqrt{4\pi \alpha_s(T) \left(\frac{N_c}{3} + \frac{N_f}{6} \right)}, \quad \alpha_s(T) = g_s^2/4\pi.$$

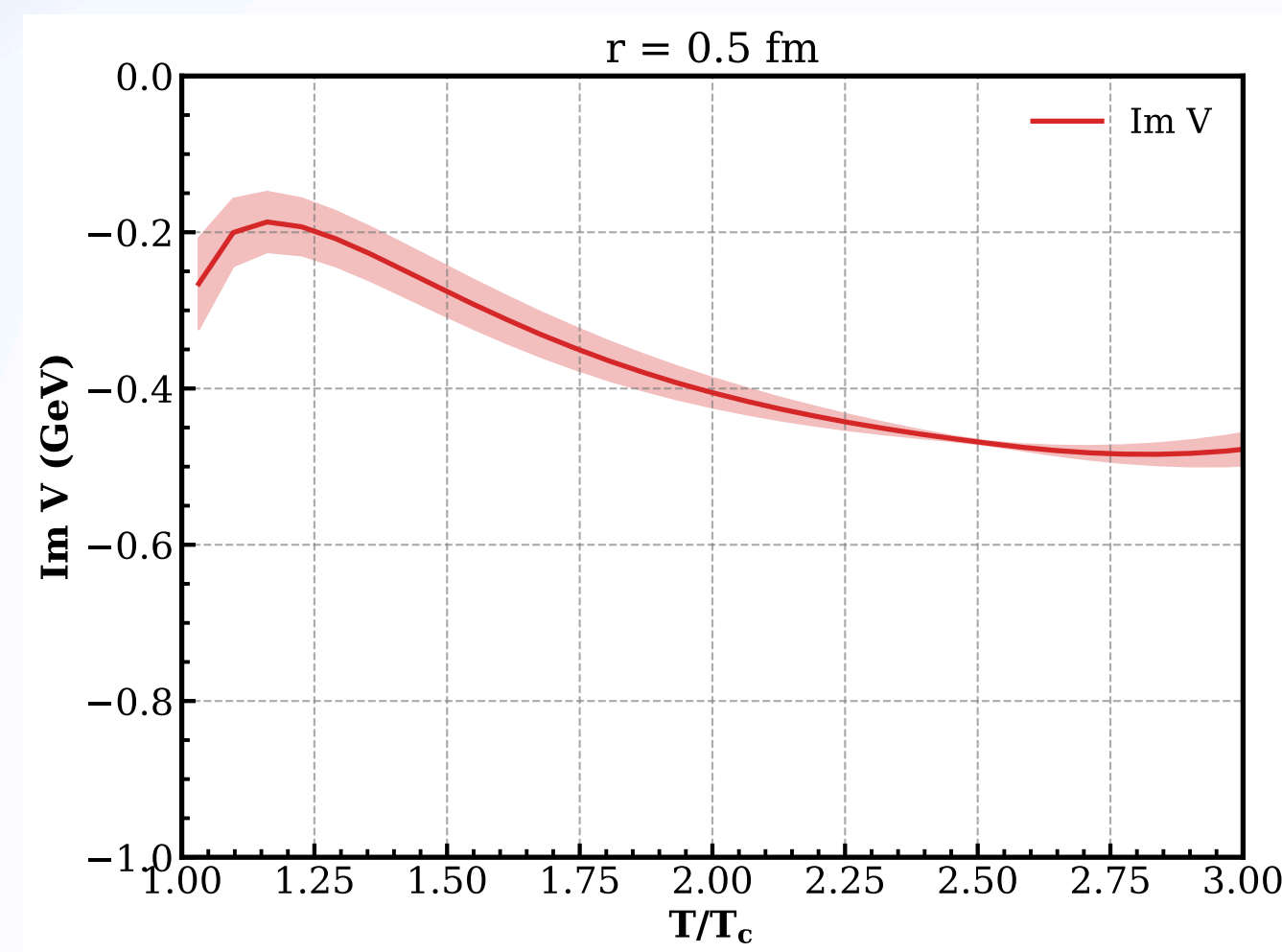
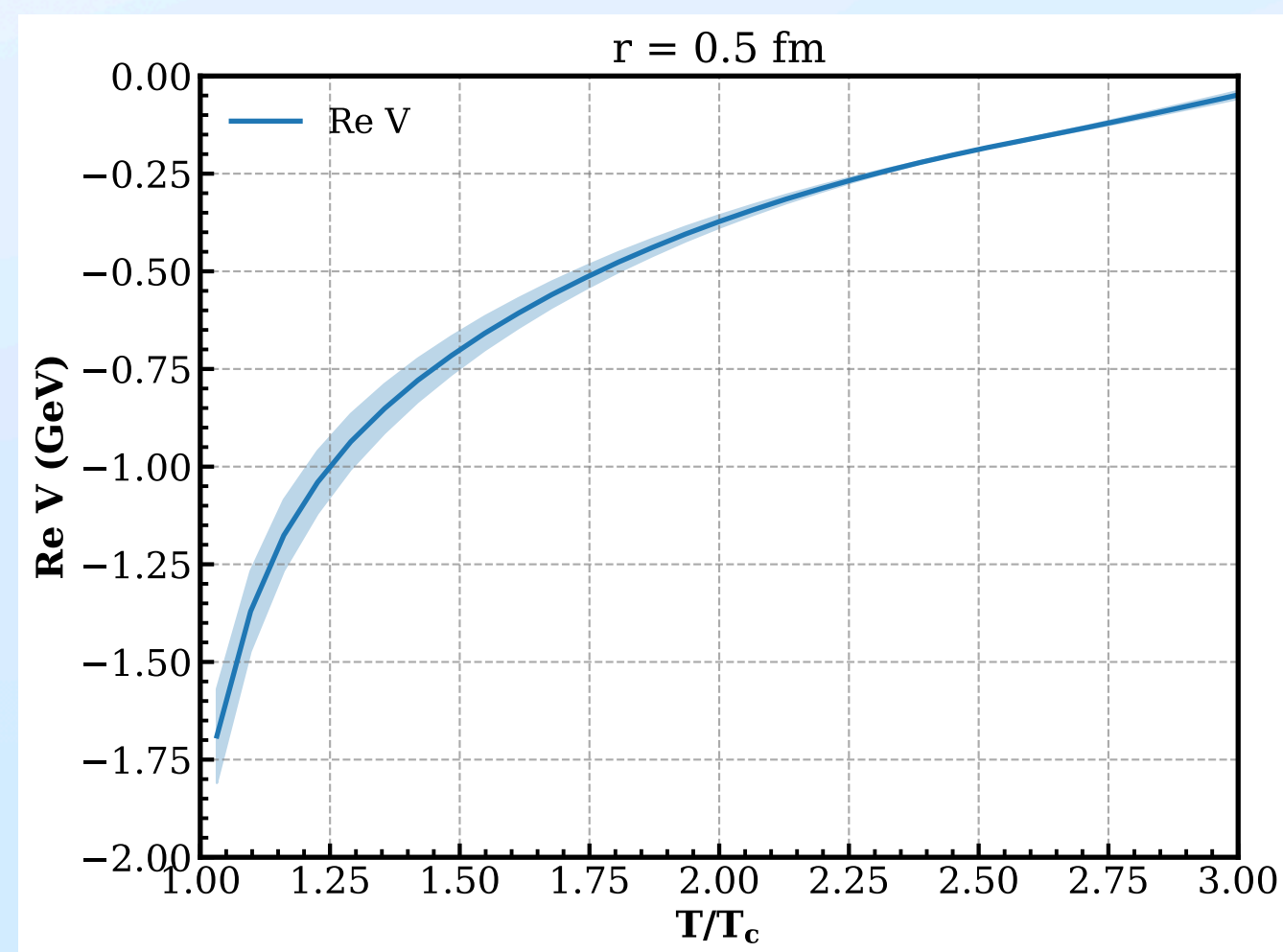


- HotQCD Collaboration (A. Bazavov et al.), Phys. Rev. D 90, 094503 (2014) – EOS training data.

- M. Laine, O. Philipsen, P. Romatschke, M. Tassler, JHEP 03 (2007) 054 – HTL framework for screening.

Complex In-Medium Potential: Real and Imaginary Parts

- Vacuum baseline: Cornell $V_{\text{vac}}(r) = -\alpha/r + \sigma r$.
- Medium Modification $\rightarrow$ Real and Imaginary Parts of Potential
- $\Re V(r = 0.5 \text{ fm}, T)$: becomes less attractive with $T/T_c \rightarrow$ screening weakens binding.
- $\Im V(r = 0.5 \text{ fm}, T)$: magnitude grows around $1.2 T_c$ and stays sizable $\rightarrow$ in-medium damping / decoherence.
- Together: higher T means shallower well + stronger damping $\rightarrow$ quarkonium is easier to melt.



• M.Y.Jamal, F.P.Li, L.G.Pang and G.Y.Qin,
[arXiv:2509.14970 [hep-ph]]

Schrödinger Solver and Thermal Widths

- Radial bound states from

$$\left[-\frac{1}{2\mu} \frac{d^2}{dr^2} + \Re V(r, T) \right] u_n(r; T) = E_n(T) u_n(r; T), \quad \psi_n = u_n/r, \quad \mu = \frac{m_Q}{2}.$$

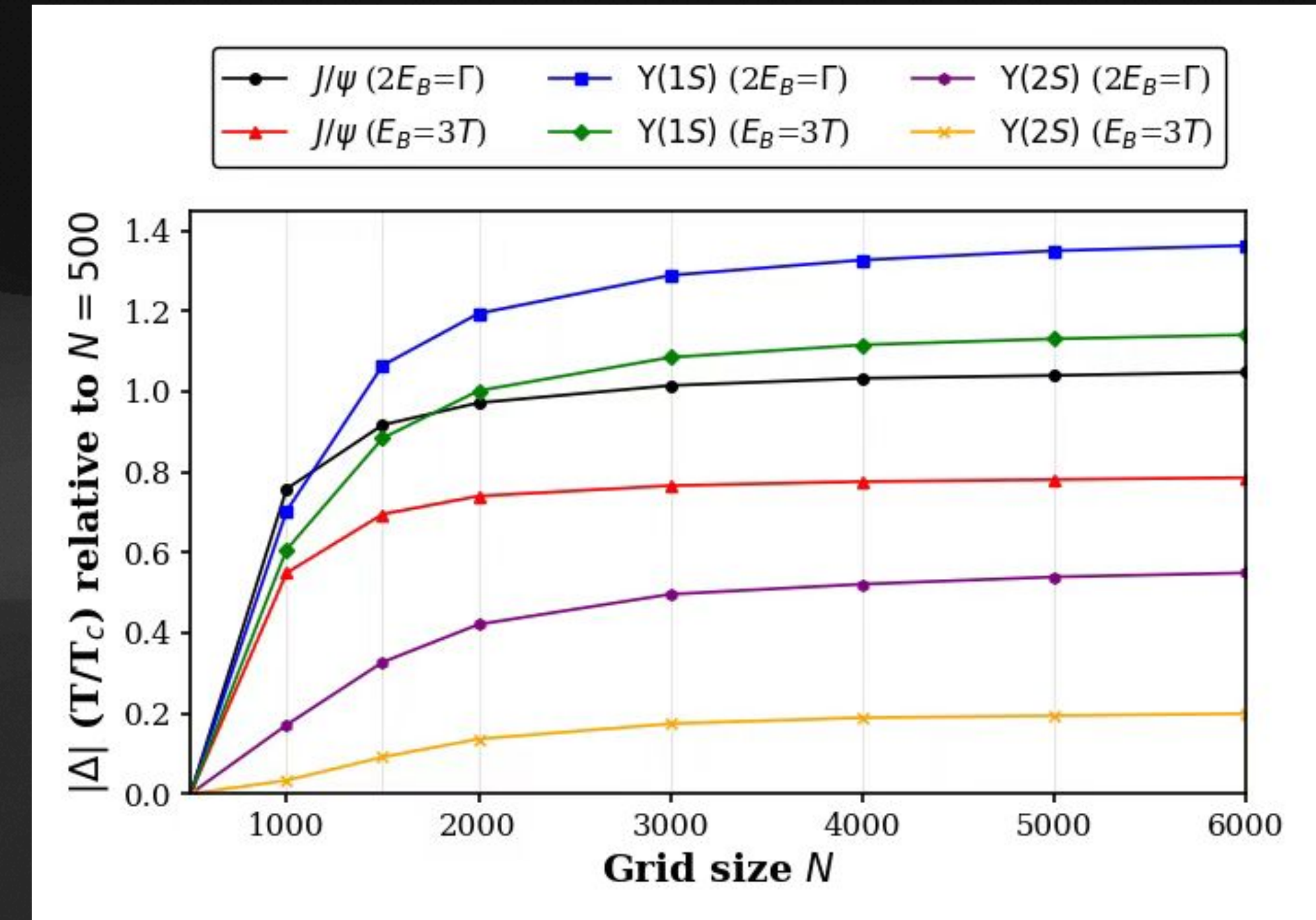
- Binding energy with thermal continuum:

$$E_B(T) = V_\infty(T) - E_n(T).$$

- Thermal width from Landau damping:

$$\Gamma_n(T) = 4\pi \int_0^\infty dr r^2 |\psi_n(r; T)|^2 \left[-\Im V(r, T) \right].$$

- Numerics: dense r -grid (finite-difference); Dirichlet at $r = 0$, $u_n(r_{\max}) \rightarrow 0$; check grid and $r_{\max}$ convergence.

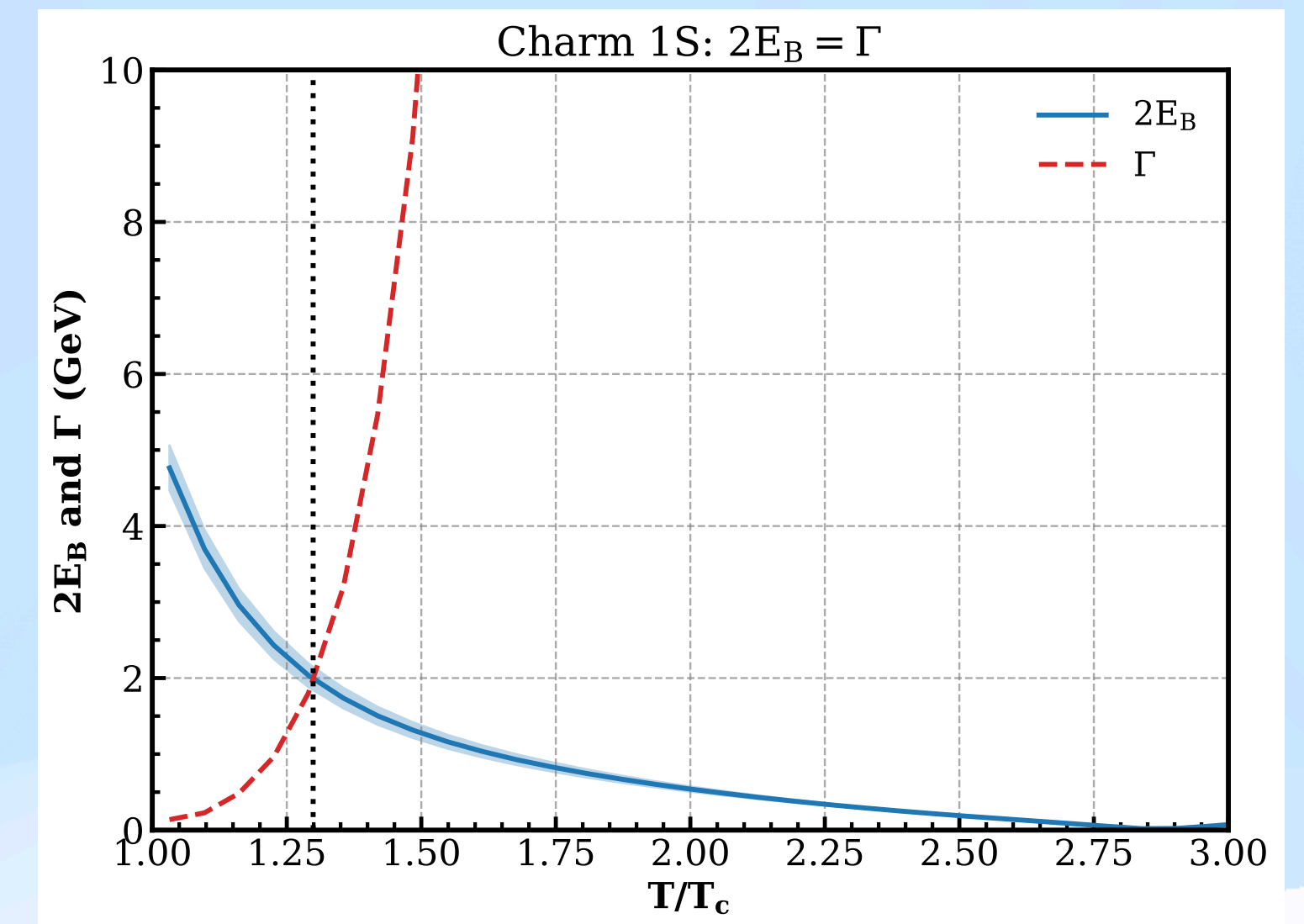


• M.Y. Jamal, F.P. Li, L.G. Pang and G.Y. Qin, [arXiv:2509.14970 [hep-ph]]

Dual Dissociation Criteria: $2E_B = \Gamma$ and $E_B = 3T$

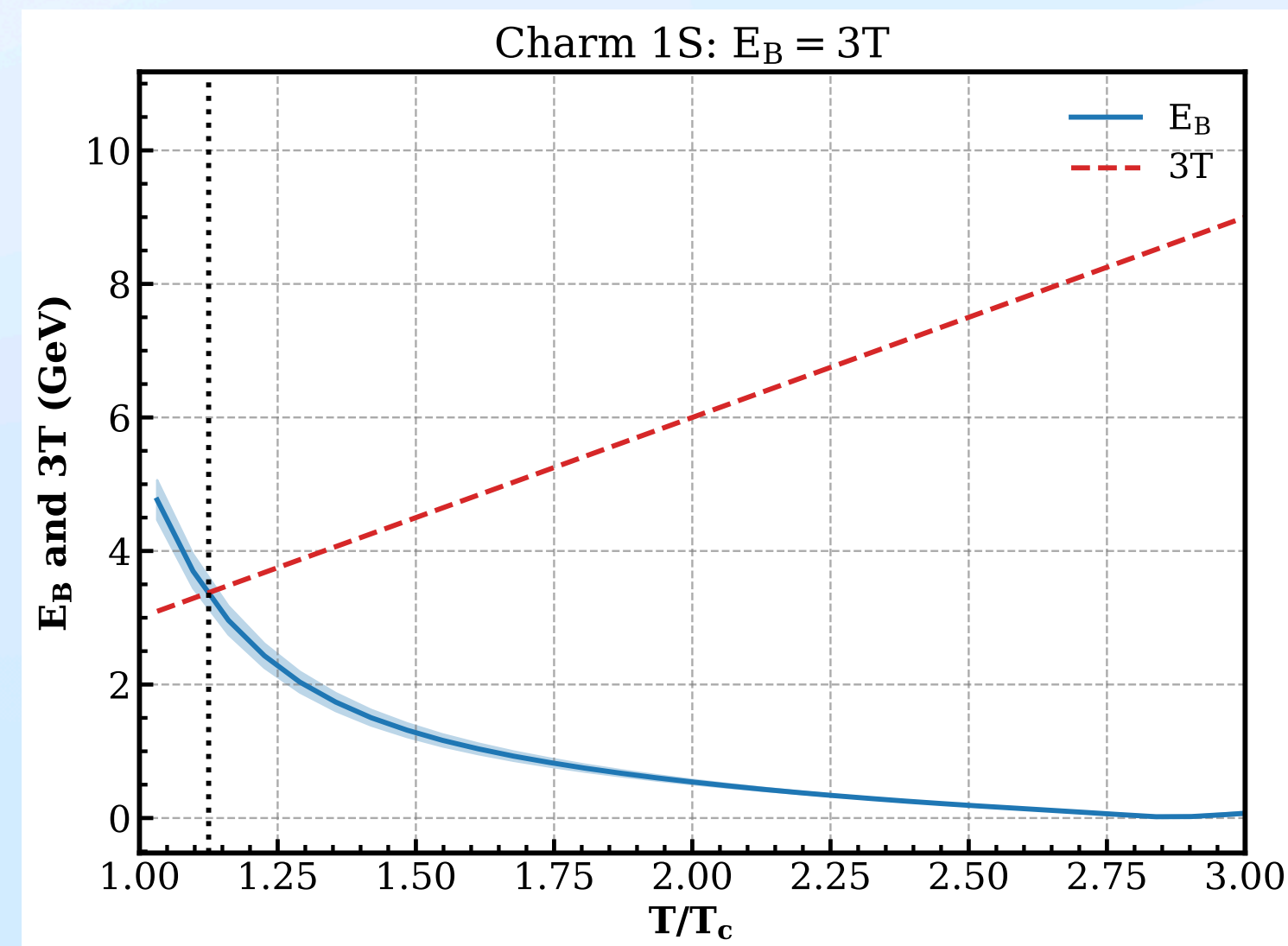
- Width-binding crossover (upper bound): $2E_B(T) = \Gamma(T)$.

Interpretation: decoherence overtakes binding $\rightarrow$ rapid melting.



- Kinetic lower-bound (thermal smearing): $E_B(T) = 3T$.

Interpretation: binding comparable to typical thermal energy $\rightarrow$ weak survival.



- N. Brambilla, J. Ghiglieri, A. Vairo, P. Petreczky, PRD 78, 014017 (2008).
- Y. Burnier and A. Rothkopf, PRL 111, 182003 (2013).

Results—Charmonium and Bottomonium (Dissociation Temperatures)

$$T_d(\Upsilon(1S)) > T_d(J/\psi) \sim T_d(\Upsilon(2S)) > T_d(\psi(2S)),$$

- Hierarchy: $\Upsilon(1S)$ survives to the highest T ; excited states melt earlier (sequential suppression).

Method / Reference	Dissociation Temperatures T_d (in units of T_c)			
	$\Upsilon(1S)$	$\Upsilon(2S)$	J/ψ	$\psi(2S)$
This work: ($2E_B = \Gamma$)	1.99	1.29	1.30	≤ 1.00
This work: ($E_B = 3T$)	1.38	1.10	1.13	≤ 1.00
Mocsy and Petreczky ¹	2.00	1.20	1.20	≤ 1.00
Digal et al. ²	2.31	1.10	1.10	< 1.00

1: A. Mocsy and P. Petreczky, PRL 99, 211602 (2007)

2: S. Digal, P. Petreczky, and H. Satz, PRD 64, 094015 (2001)

$$R_{AA}(\Upsilon(1S)) > R_{AA}(J/\psi) \sim R_{AA}(\Upsilon(2S)) > R_{AA}(\psi(2S)),$$

A.M.Sirunyan et al. [CMS],PLB 790, 270–293 (2019)

Summary & Future Possibilities

Summary:

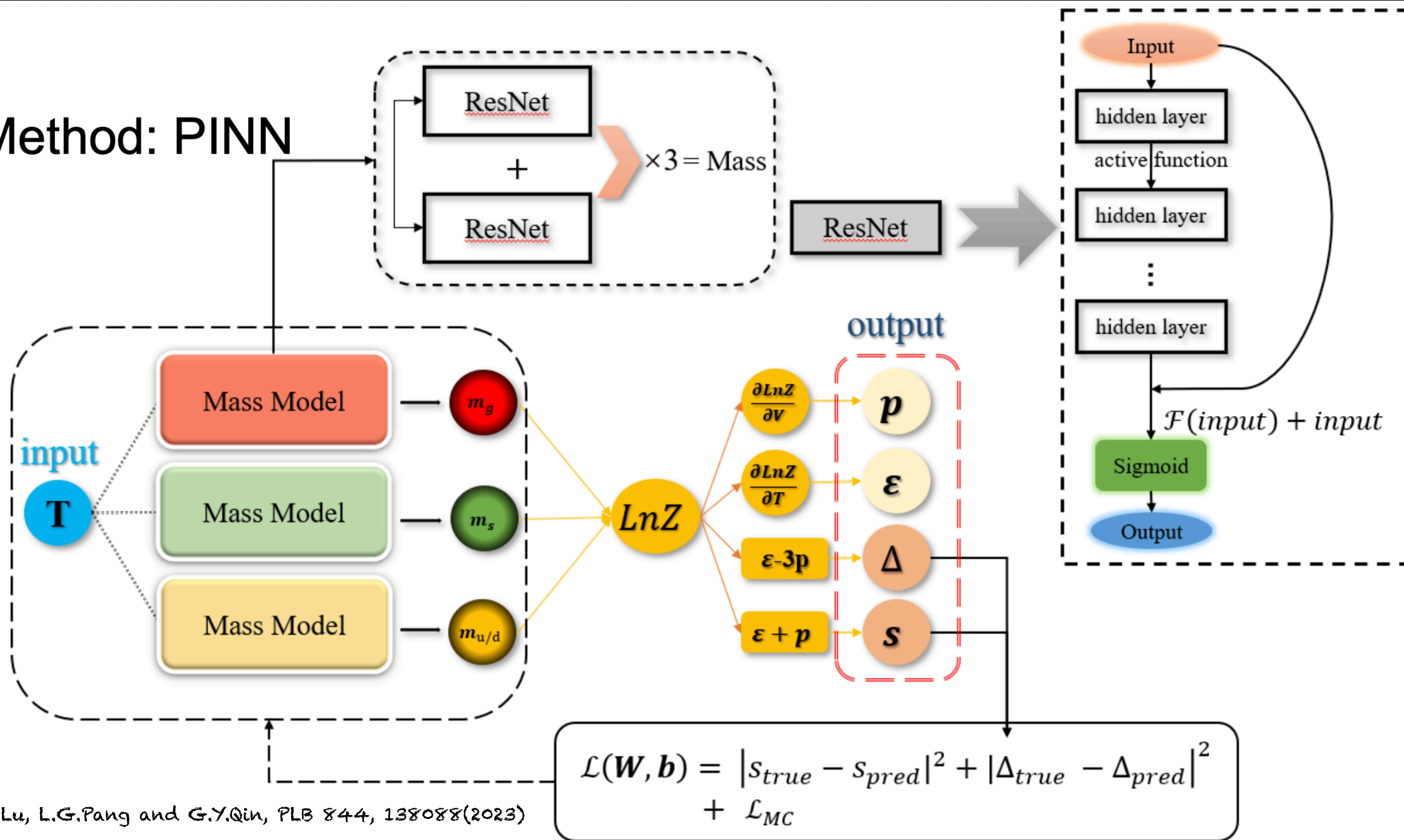
- DLQPM learns $m_g(T), m_{u/d}(T), m_s(T) \rightarrow$ infers $g(T), \alpha_s(T) \rightarrow m_D(T)$; builds a complex $V(r, T)$ with softening $\Re V$ and growing $\Im V$.
- Schrödinger + $\Re V \rightarrow E_B(T)$; overlap with $\Im V \rightarrow \Gamma(T)$; dual criteria ($2E_B = \Gamma, E_B = 3T$) bracket T_d .
- Sequential hierarchy holds $\Upsilon(1S)$ most robust; $\psi(2S)$ near T_c ; results stable under grid/ $r_{\max}$ checks; uncertainty shown via retrain bands.

Future possibilities:

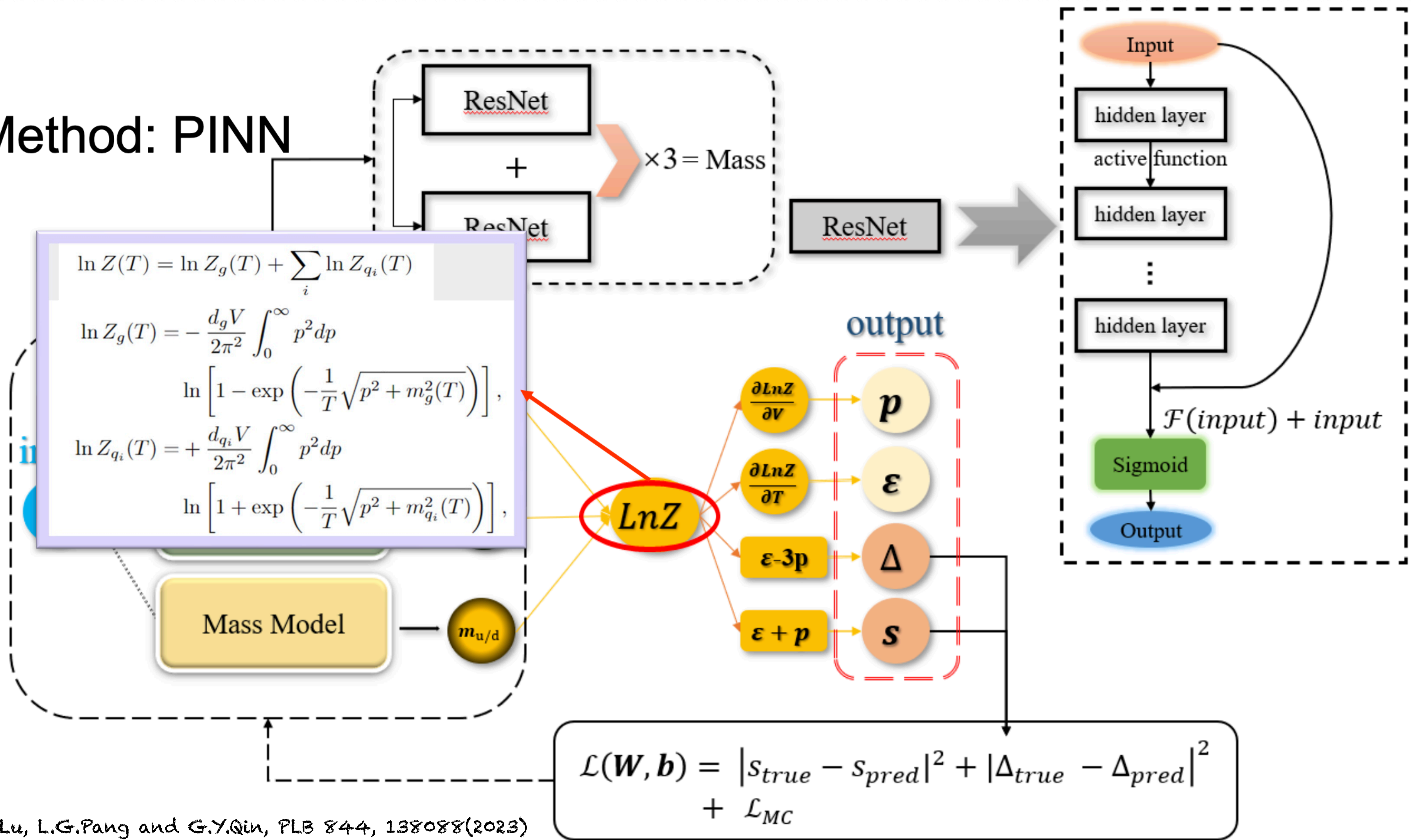
- Add P-waves and feed-down; confront state-resolved R_{AA} systematics (Pb-Pb, Run-3).
- Finite-momentum quarkonia and medium anisotropy; temperature-dependent charm/bottom transport inputs for coupled evolution.
- Beyond static potential—open-quantum-system (Lindblad) dynamics to capture stochastic decoherence; tighter lattice-ML cross-validation of near- T_c inputs.

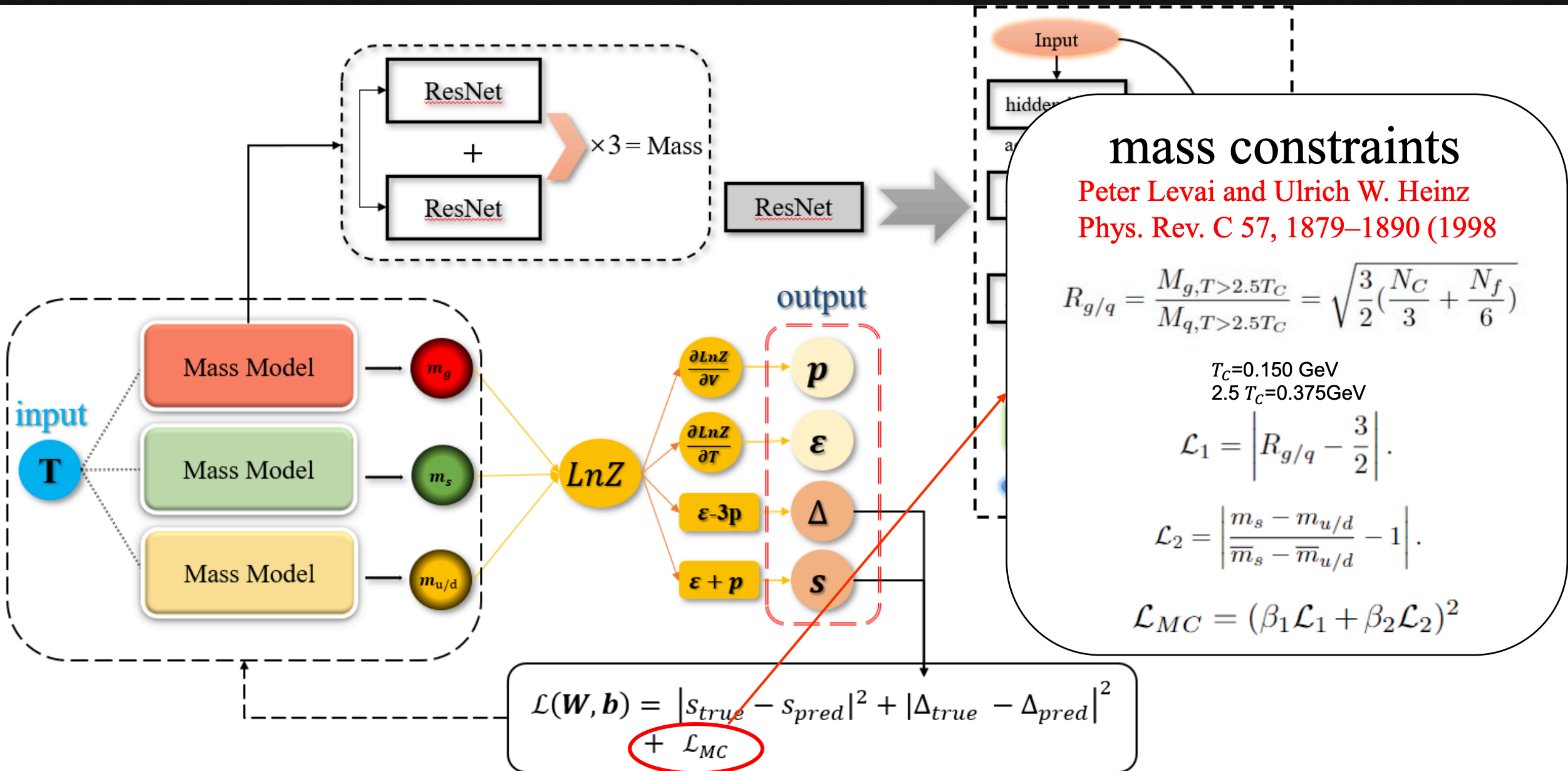
Thank you for your attention

Method: PINN



Method: PINN



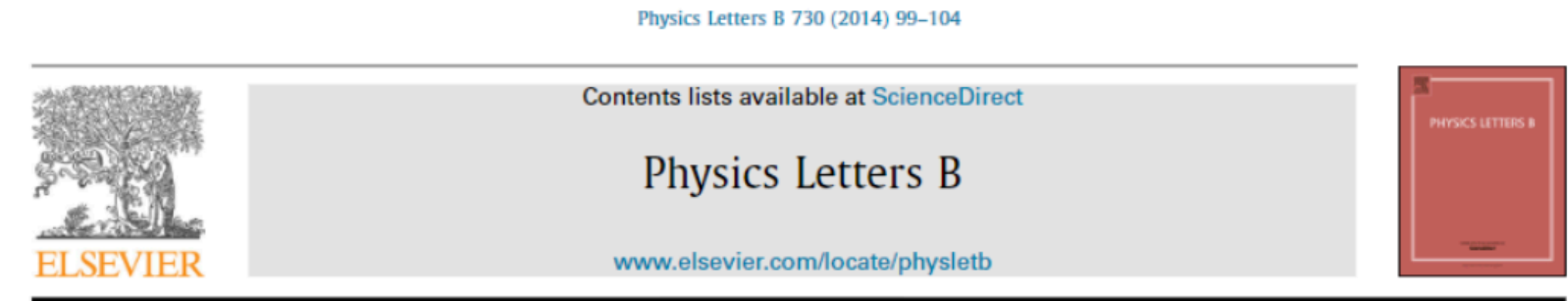
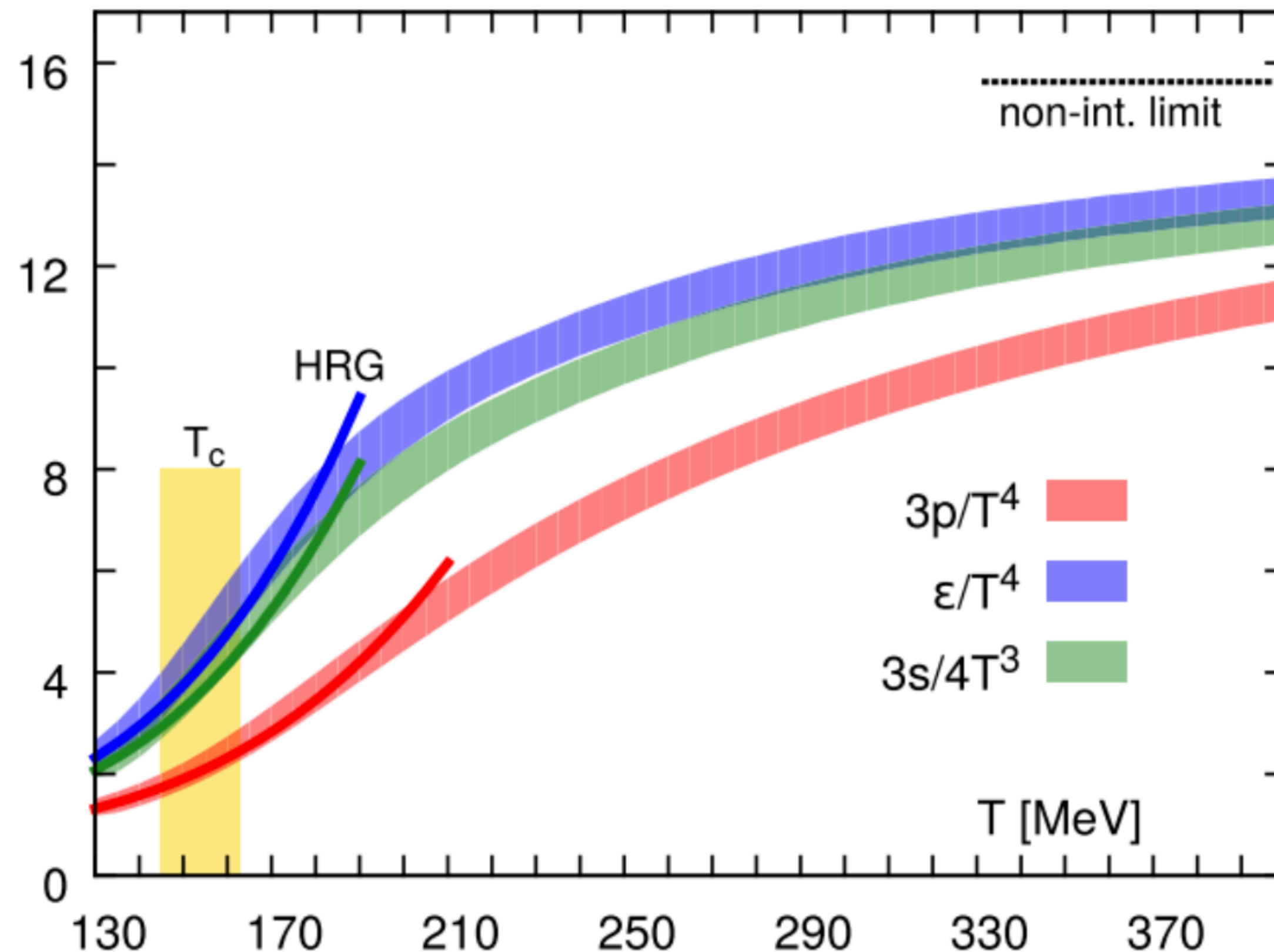


• Data: HotQCD

PHYSICAL REVIEW D 90, 094503 (2014)

Equation of state in (2 + 1)-flavor QCD

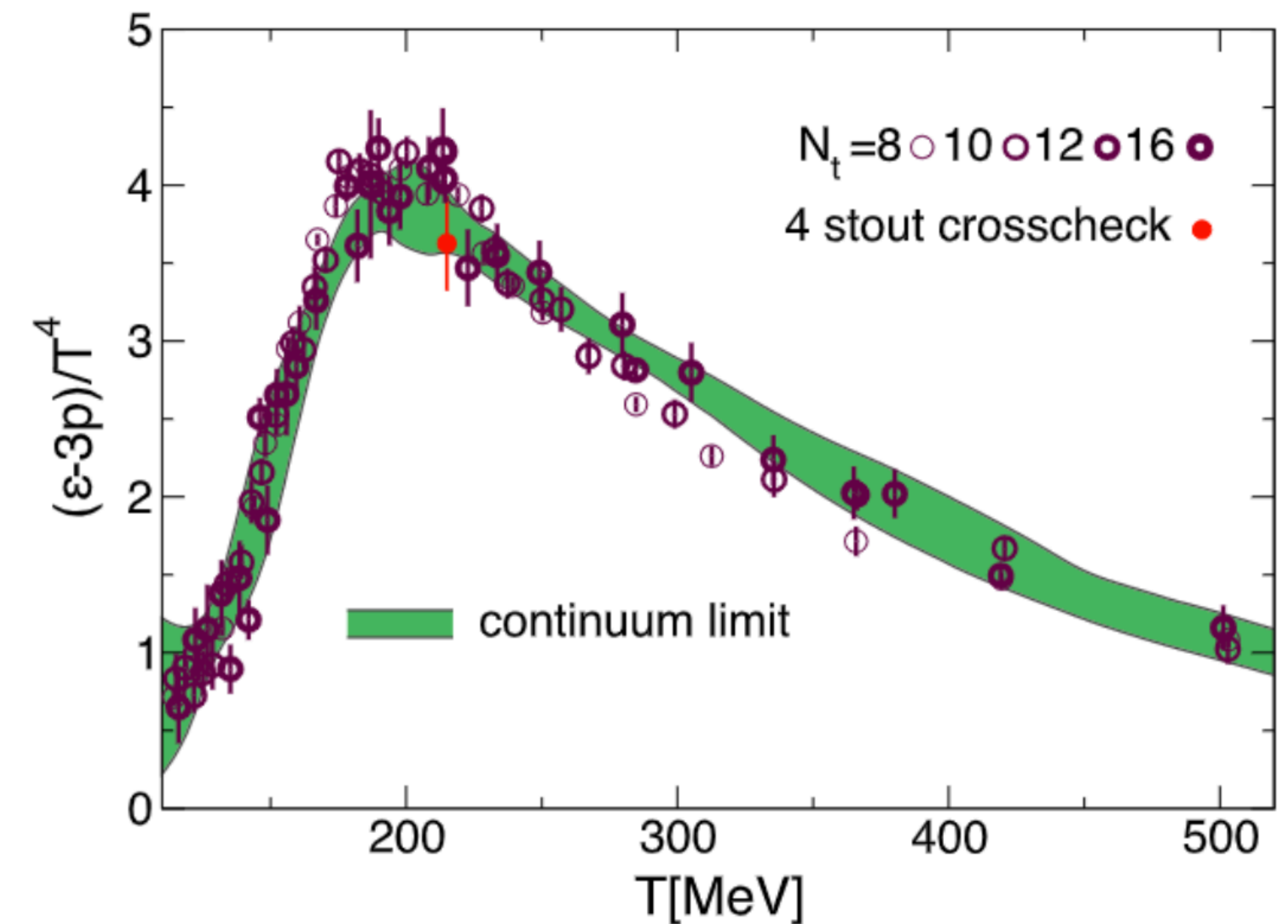
A. Bazavov,¹ Tanmoy Bhattacharya,² C. DeTar,³ H.-T. Ding,⁴ Steven Gottlieb,⁵ Rajan Gupta,² P. Hegde,⁴ U. M. Heller,⁶ F. Karsch,^{7,8} E. Laermann,⁸ L. Levkova,³ Swagato Mukherjee,⁷ P. Petreczky,⁷ C. Schmidt,⁸ C. Schroeder,⁹ R. A. Soltz,⁹ W. Soeldner,¹⁰ R. Sugar,¹¹ M. Wagner,⁵ and P. Vranas⁹
(HotQCD Collaboration)



Full result for the QCD equation of state with 2 + 1 flavors



Szabolcs Borsányi^a, Zoltán Fodor^{a,b,c}, Christian Hoelbling^a, Sándor D. Katz^{c,d,*}, Stefan Krieg^{a,b}, Kálmán K. Szabó^{a,e}



Method: Quasi particle method

$$\ln Z(T) = \ln Z_g(T) + \sum_i \ln Z_{q_i}(T)$$

$$\ln Z_g(T) = -\frac{d_g V}{2\pi^2} \int_0^\infty p^2 dp \ln \left[1 - \exp \left(-\frac{1}{T} \sqrt{p^2 + m_g^2(T)} \right) \right],$$

$$\ln Z_{q_i}(T) = +\frac{d_{q_i} V}{2\pi^2} \int_0^\infty p^2 dp \ln \left[1 + \exp \left(-\frac{1}{T} \sqrt{p^2 + m_{q_i}^2(T)} \right) \right],$$

d_g :the degree of freedom for gluons

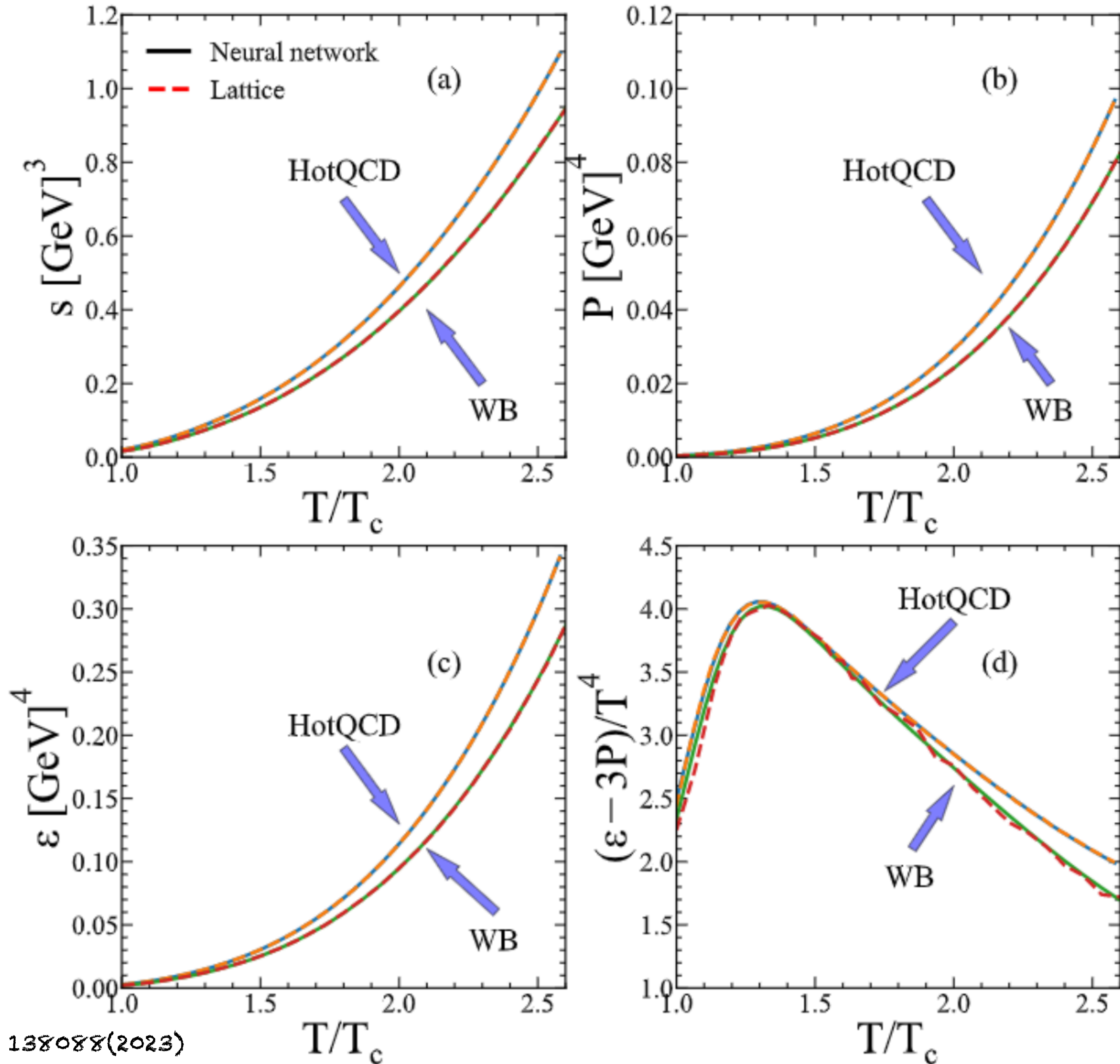
d_{q_i} :the degree of freedom for quarks

q_i :up/down, strange quarks

$$P(T) = T \left(\frac{\partial \ln Z(T)}{\partial V} \right)_T$$

$$\epsilon(T) = \frac{T^2}{V} \left(\frac{\partial \ln Z(T)}{\partial T} \right)_V$$

- Result: QCD EoS



- Result: $M(T)$ and η/s

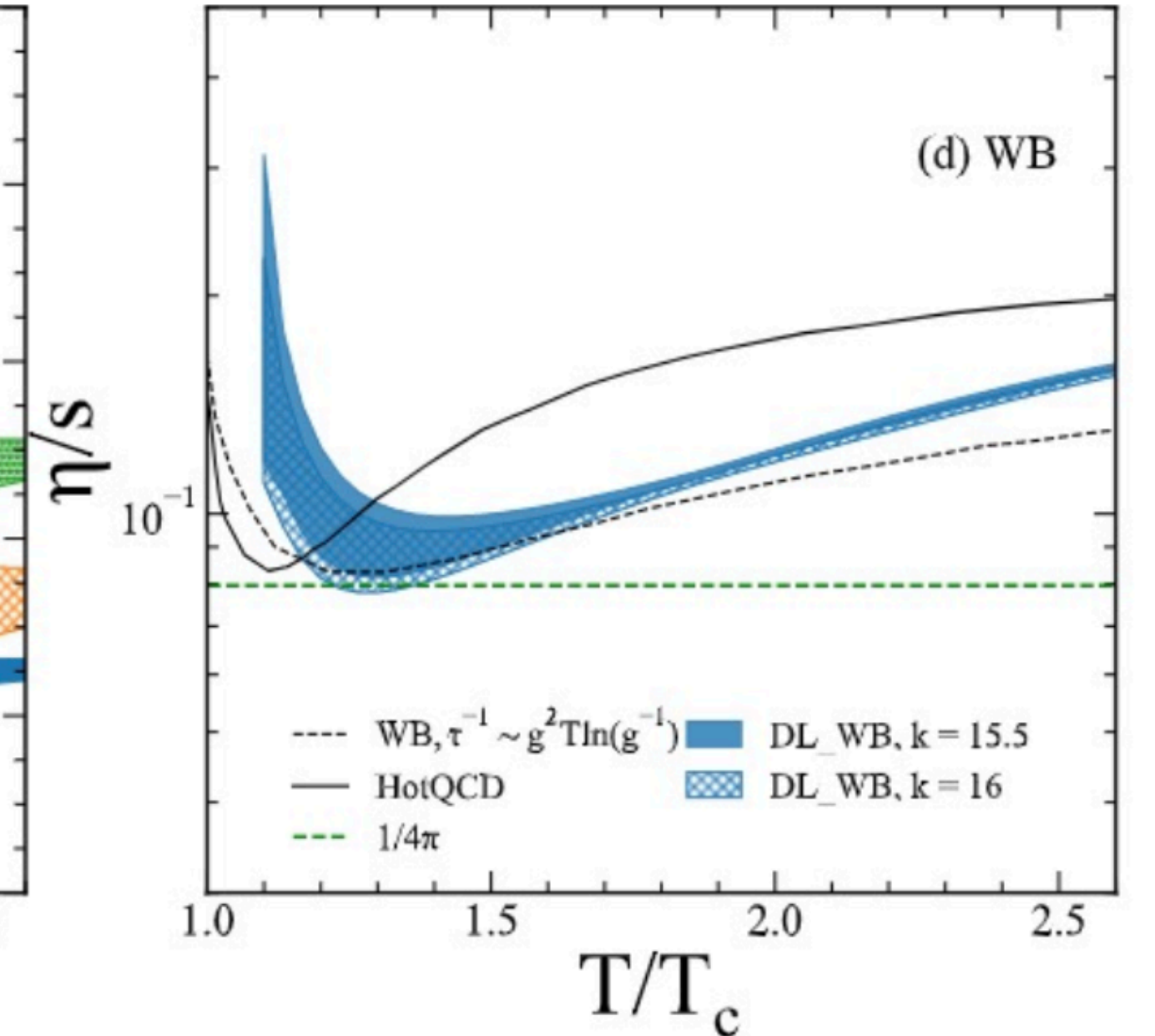
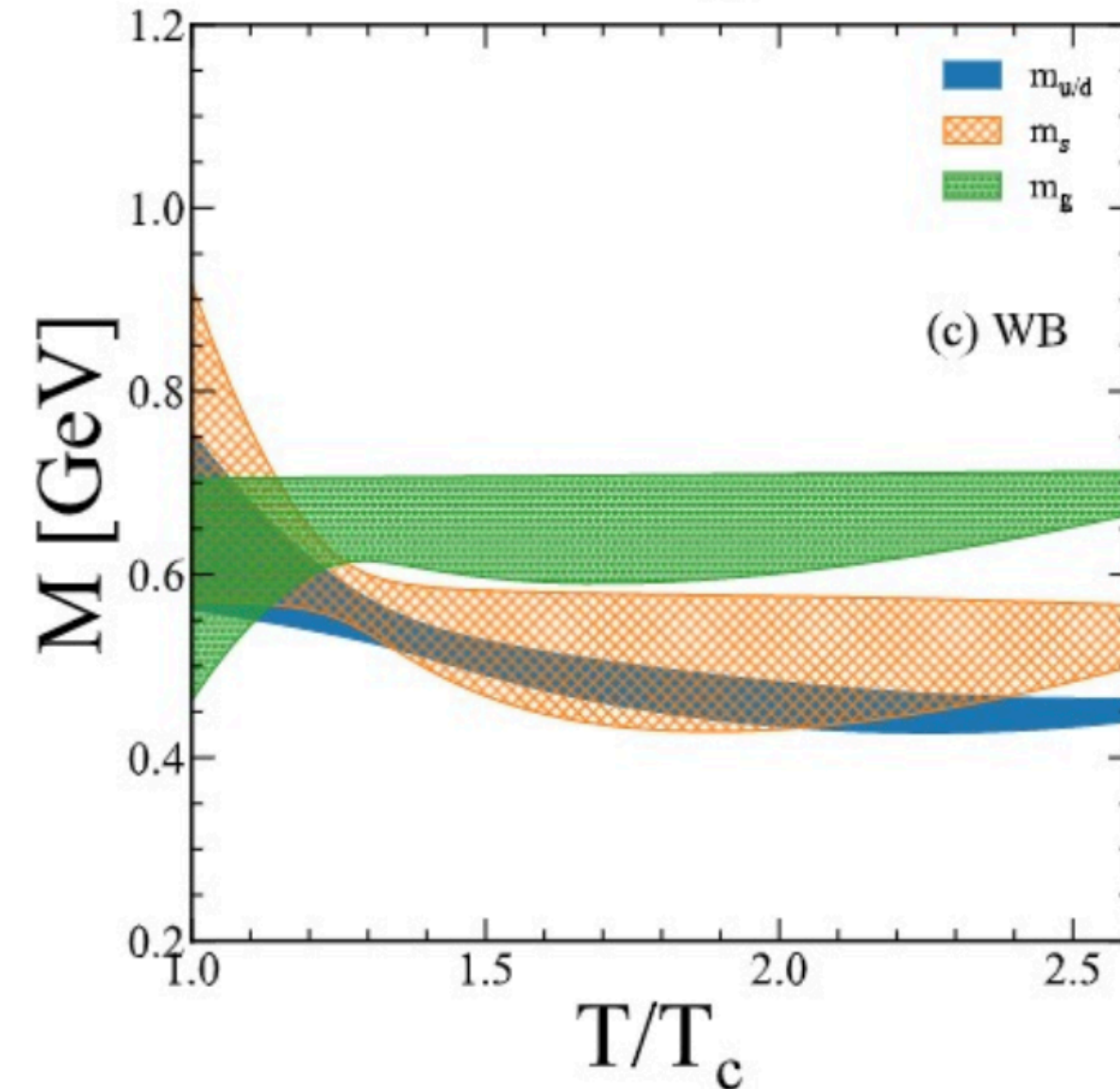
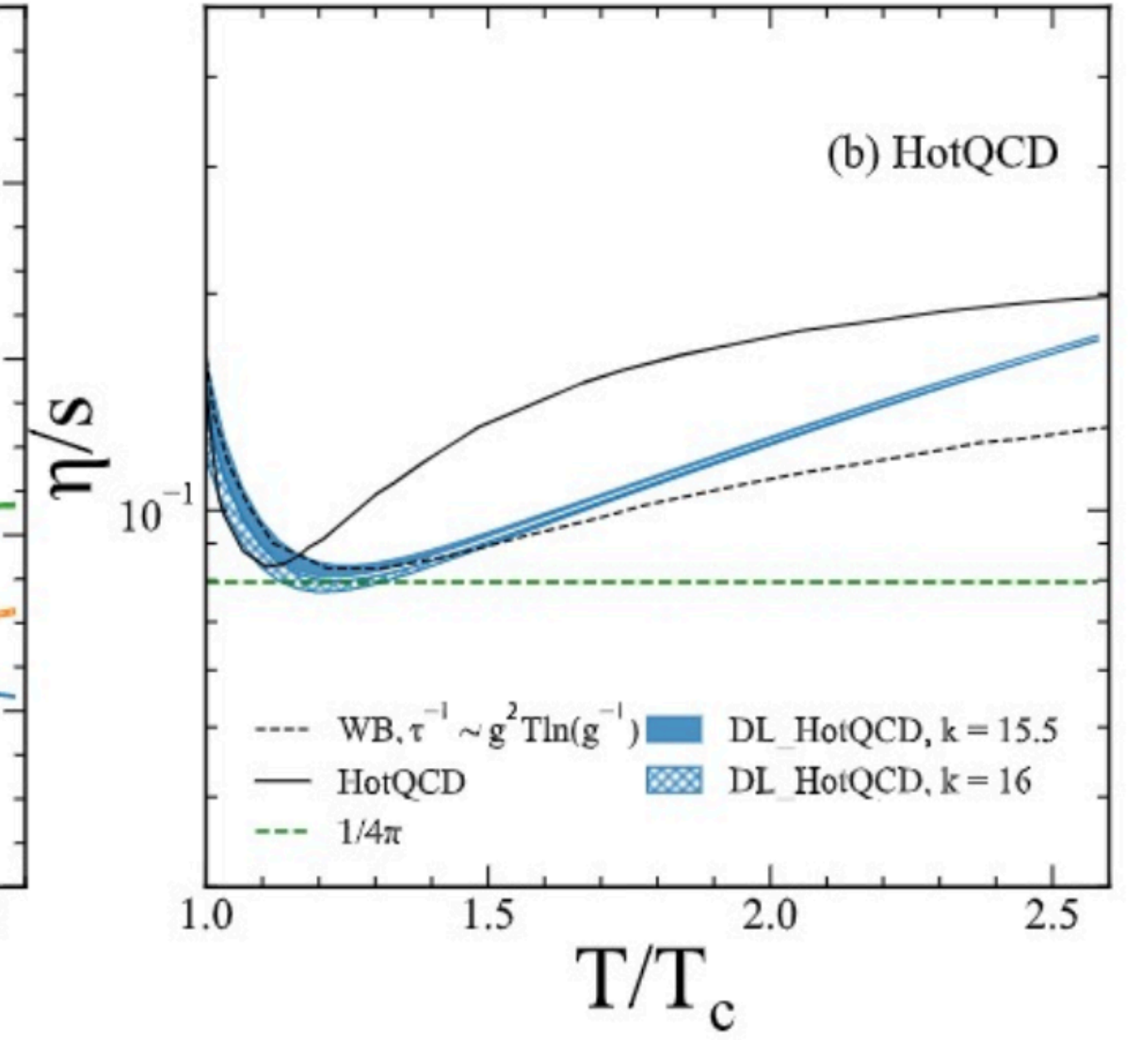
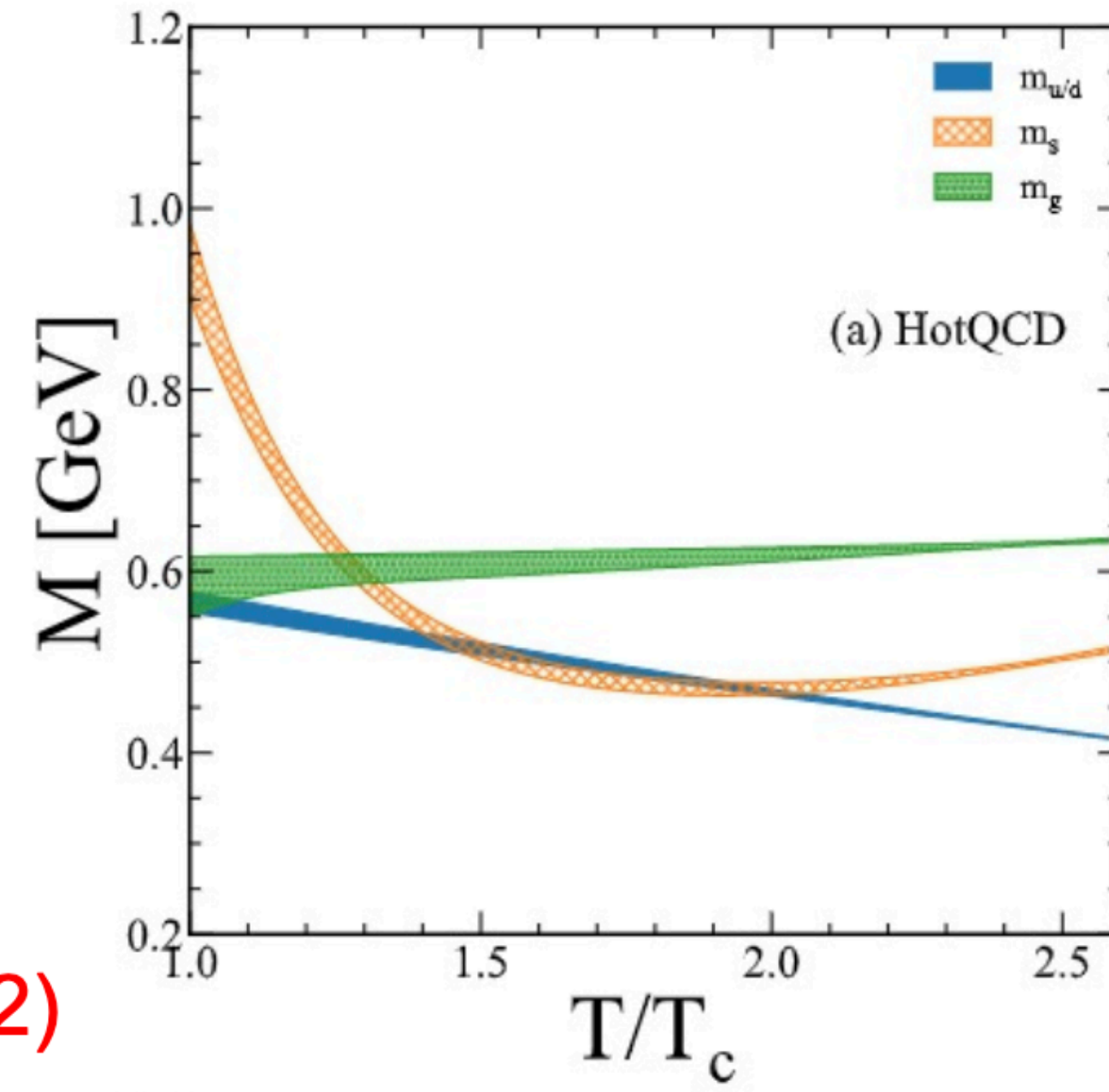
$$\eta = \frac{1}{15T} \sum_i d_i \int \frac{d^3p}{(2\pi)^3} \tau_i \frac{p^4}{E_a^2} f_i (1 \mp f_i) \quad (1)$$

$$\tau_q^{-1} = 2 \frac{N_C^2 - 1}{2N_C} \frac{g^2 T}{8\pi} \ln \frac{2k}{g^2}, \tau_g^{-1} = 2N_C \frac{g^2 T}{8\pi} \ln \frac{2k}{g^2} \quad (2)$$

$$g^2 = \frac{m_g^2 + m_{u/d}^2}{\left[\frac{1}{6} (N_C + \frac{1}{2} N_f) + \frac{N_C^2 - 1}{8N_C} \right] T^2} \quad (3)$$

F.P.Li, H.L.Lu, L.G.Pang and G.Y.Qin, PLB 844, 138088(2023)

PHYSICAL REVIEW D 84, 094004 (2011)

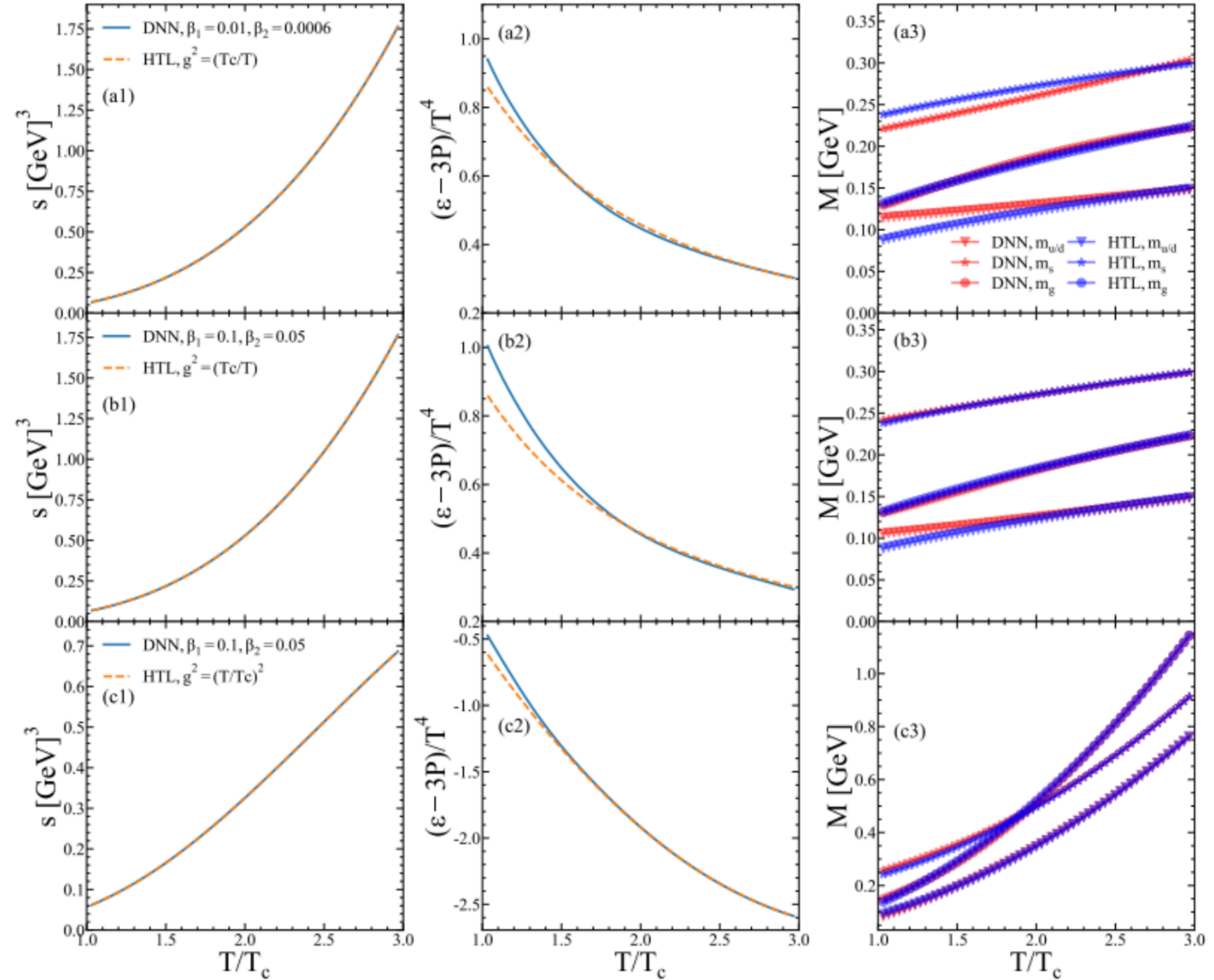


• Result: Closure test

F.P.Li, H.L.Lu, L.G.Pang and G.Y.Qin, PLB 844, 138088(2023)

$$m_g^2 = \frac{1}{6}g^2 \left[\left(N_C + \frac{1}{2}n_f \right) T^2 + \frac{N_C}{2\pi} \sum_q \mu_q^2 \right],$$

$$m_{u,d}^2 = \frac{N_C^2 - 1}{8N_C} g^2 \left[T^2 + \frac{\mu_{u,d}^2}{\pi^2} \right],$$



DLQPM Details (Inputs, Network, Training)

- Inputs: Lattice-QCD thermodynamics vs T : entropy $s(T)$ and interaction measure $\epsilon - 3p$ (HotQCD, continuum-extrapolated).
- Forward model: quasiparticle EOS with temperature-dependent masses $\{m_g(T), m_{u/d}(T), m_s(T)\}$; compute $p, s, \epsilon - 3p$ from these.
- Network: residual DNN mapping $T/T_c \rightarrow \{m_g, m_{u/d}, m_s\}$ with smoothness/monotonicity regularization and HTL-consistent high- T priors.
- Loss: $\text{MSE}[\text{EOS}_{\text{model}} - \text{EOS}_{\text{lattice}}] + \text{asymptotic penalties} + \text{regularizers}$; multiple random seeds $\rightarrow$ mean $\pm$ band.
- Output: calibrated $\{m_g, m_{u/d}, m_s\}$ with uncertainty; handed off to $\alpha_s(T)$ and $m_D(T)$ extraction.

Working Formulae (Potential, Widths):

• Vacuum Cornell:

$$V_{\text{vac}}(r) = -\frac{\alpha}{r} + \sigma r.$$

• Screened real part:

$$\Re V(r, T) \simeq -\alpha \frac{e^{-m_D r}}{r} + \frac{\sigma}{m_D} (1 - e^{-m_D r}), \quad V_{\infty}(T) = \frac{\sigma}{m_D} - \alpha m_D.$$

• Screened Imaginary Potential

$$\text{Im}[V(r, T)] = \text{Im}V_1(r, T) + \text{Im}V_2(r, T),$$

$$\text{Im}V_1(r, T) = -2\alpha T \int_0^{\infty} \frac{dz}{(z^2 + 1)^2} \left(1 - \frac{\sin(m_D r z)}{m_D r z} \right),$$

$$\text{Im}V_2(r, T) = \frac{4\sigma T}{m_D^2} \int_0^{\infty} \frac{dz}{z(z^2 + 1)^2} \left(1 - \frac{\sin(m_D r z)}{m_D r z} \right).$$

• Observables:

$$E_B(T) = V_{\infty}(T) - E_n(T), \quad \Gamma_n(T) = 4\pi \int_0^{\infty} dr r^2 |\psi_n(r; T)|^2 [-\Im V(r, T)].$$

Numerics, Validation, and Sensitivity

- Schrödinger solver: finite-difference radial grid; Dirichlet at $r = 0$, $u_n(r_{\max}) \rightarrow 0$; check orthonormality and node counting for excited states.
- Convergence checks: scan grid size N and $r_{\max}$; monitor $\Delta E_n/E_n$ and stability of T_d from both criteria.
- Potential consistency: $\Re V(r \rightarrow 0, T)$ tracks vacuum limit; $V_\infty(T)$ monotone with $m_D(T)$.
- Uncertainty: propagate DLQPM retrain band $(\alpha_s(T), m_D(T))$ through E_B, Γ to T_d ranges.
- Sensitivity (typical): small variations in σ or short-distance α shift T_d modestly; dominant effect comes from $m_D(T)$ slope near T_c .
- Cross-checks: sequential hierarchy $\Upsilon(1S) > J/\psi \sim \Upsilon(2S) > \psi(2S)$ consistent with lattice spectral reconstructions and LHC R_{AA} ordering.