Holography QCD versus QCD data

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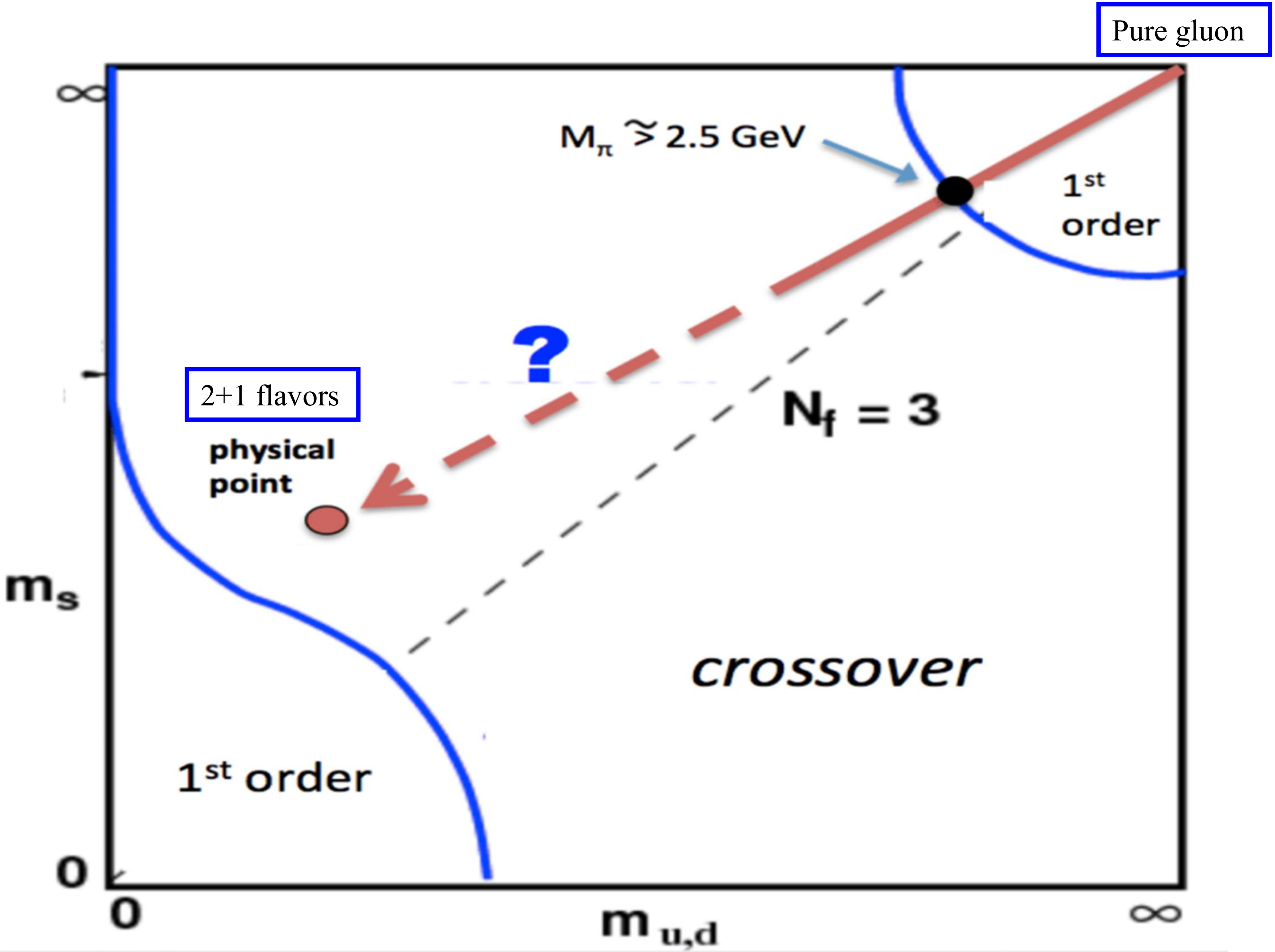
@The 7th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

w/. Rong-Gen Cai, Li Li, Yuan-Xu Wang, Phys.Rev.D 106 (2022) 12, L121902,
w/. Li Li, Zhibin Li, Shao-Jiang Wang, 2210.14094,
w/. Li Li, Zhibin Li, Jingmin Li, 2305.13874,
& Working in progress.

Outline

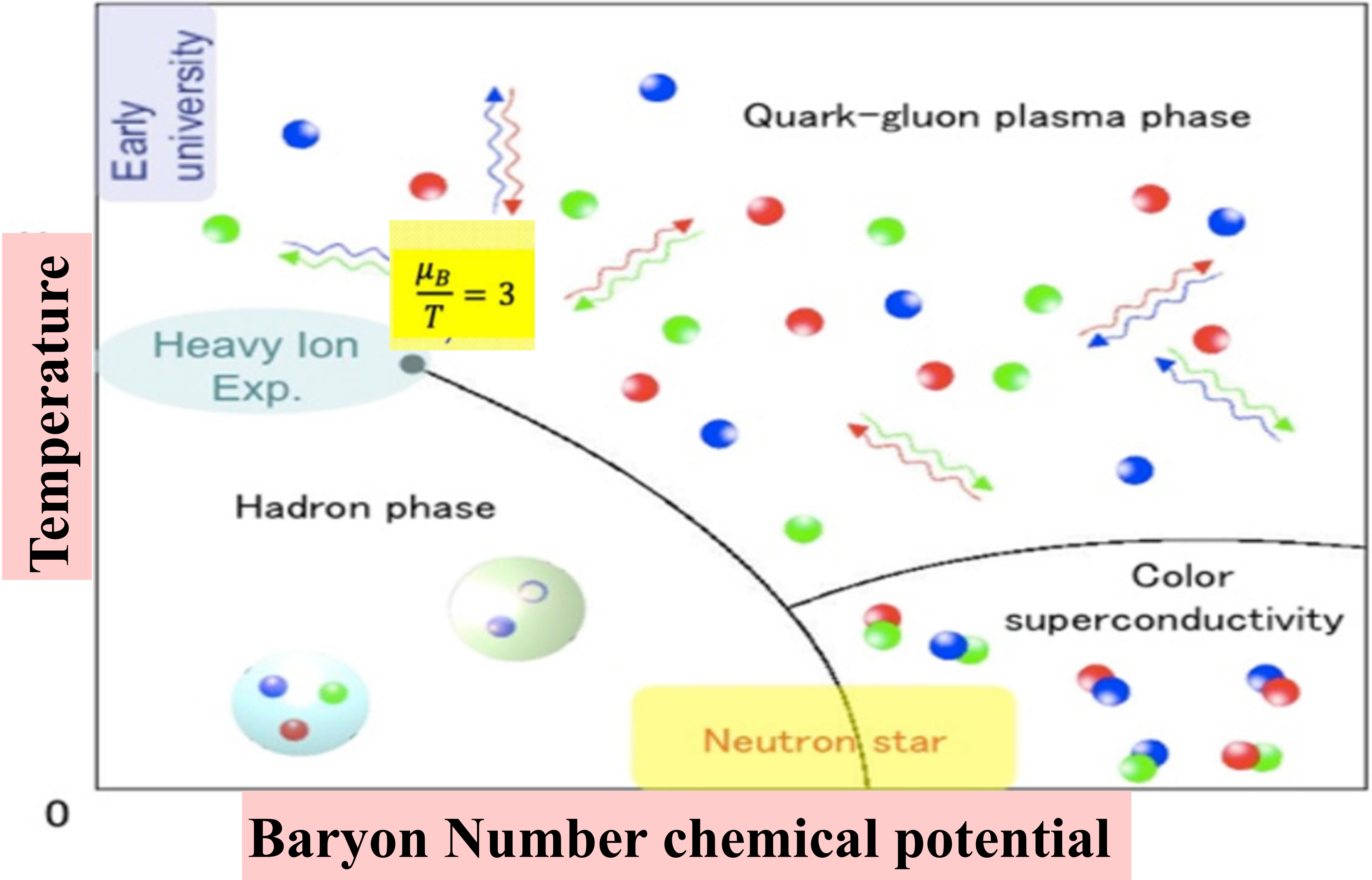
I. Motivations & hQCD
II. Holographic QCD model (hQCD)
III. Confront with QCD Phase diagram
IV. Holographic pure gluon model
V. Summary

Motivations

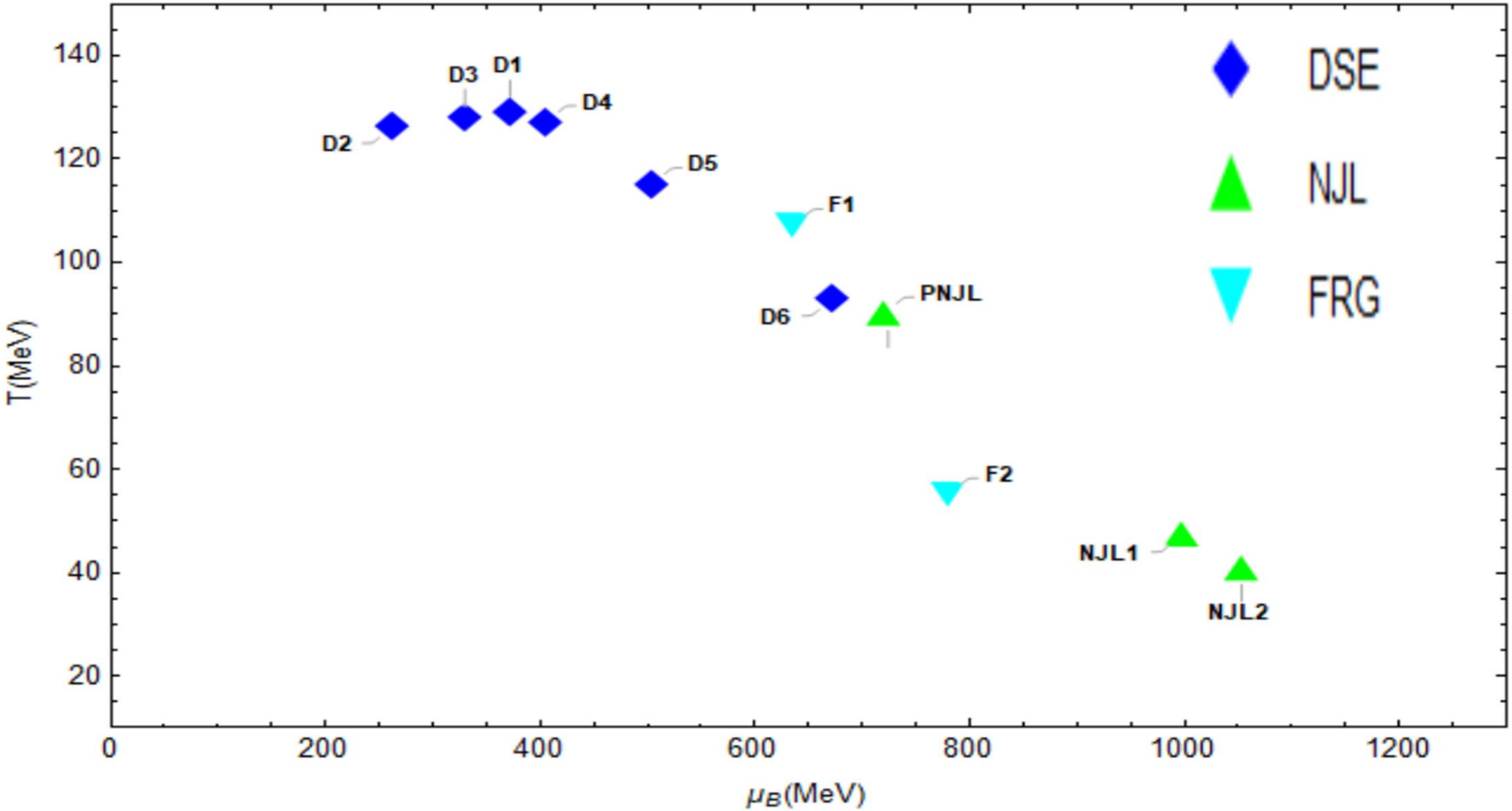


Pure gluon
$M_\pi \gtrsim 2.5$ GeV
1st order
?
$N_f = 3$
2+1 flavors
physical point
m_s
crossover
1st order
0
0
∞
$m_{u,d}$
∞

A schematic view of QCD Phase diagram



Status of searching CEP



Schwinger–Dyson equation (DSE), 2109.09935 [hep-ph], 1607.01675 [hep-ph], 1011.2876 [nucl-th], 1403.3797 [hep-ph], 1405.4762 [hep-ph]], 2002.07500 [hep-ph]].
Nambu–Jona-Lasinio models (NJL, PNJL), arXiv:1801.09215 [hep-ph]], Nucl. Phys. A 504 (1989), 668-684
Functional renormalization group (FRG). 1909.02991 [hep-ph]], 1709.05654 [hep-ph]].

Motivations

I. Low energy QCD is strong coupled system

P. Braun-Munzinger and J. Wambach, Rev. Mod. Phys. 81 (2009), 1031-1050 [arXiv:0801.4256 [hep-ph]].
S. Gupta, X. Luo, B. Mohanty, H. G. Ritter and N. Xu, Science 332 (2011), 1525-1528 [arXiv:1105.3934[hep-ph]].

II. Finite density QCD v.s. sign Problem

O. Philipsen, Prog. Part. Nucl. Phys. 70 (2013), 55-107 [arXiv:1207.5999 [hep-lat]].

III. AdS/QCD offers a practical approach

O. DeWolfe, S. S. Gubser and C. Rosen, Phys. Rev. D 84 (2011), 126014 [arXiv:1108.2029 [hep-th]].
R. G. Cai, S. He and D. Li, JHEP 03 (2012), 033 [arXiv:1201.0820 [hep-th]].
U. Gursoy, M. Jarvinen and G. Nijs, Phys. Rev. Lett. 120 (2018) no.24,242002 [arXiv:1707.00872 [hep-th]].
J. Grefa, J. Noronha, J. Noronha-Hostler, I. Portillo,C. Ratti and R. Rougemont,Phys. Rev. D 104 (2021) no.3, 034002 [arXiv:2102.12042[nucl-th]]. ….

AdS/QCD

AdS/CFT conjecture

$$AdS_5 \times S^5 \longleftrightarrow N = 4 \text{ SYM theory}$$

If it is true for any gauge theory (???)

String theory, quantum gravity $\longleftrightarrow$ **Non-Abelian gauge theory**

Then what is the dual string theory of QCD?
(It is nature to ask the question here)

? $\longleftrightarrow$ **QCD**

Whether there is a holographic QCD model to caputre the numerical simulation and phenomenon data in quantitative level?

hQCD model for 2+1-flavor QCD

HQCD model for 2+1 flavor system

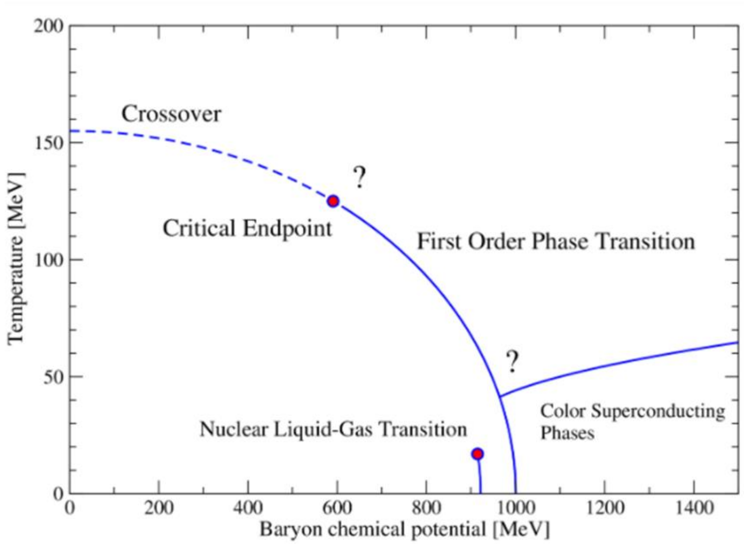
Einstein-Maxwell-Dilaton system

Motivation

To cover the degree of freedom in QCD phase Diagram.
Quarks (chemical potential) & gluons(dilaton potential)

Gravity Action

$$S = \frac{1}{2\kappa_N^2}\int d^5x\sqrt{-g}\Big[\mathcal{R} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{Z(\phi)}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi)\Big],$$



ϕ Break conformal symmetry

$F^{\mu\nu}$ Introduce baryon chemical potential

HQCD model for 2+1 flavor system

Einstein-Maxwell-Dilaton system

$$S = \frac{1}{2\kappa_N^2}\int d^5x\sqrt{-g}\Big[\mathcal{R} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{Z(\phi)}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi)\Big],$$

Model Parameters

Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

$$V(\phi) = -12\cosh[c_1\phi] + (6c_1^2 - \frac{3}{2})\phi^2 + c_2\phi^6,$$

$$Z(\phi) = \frac{1}{1+c_3}\mathrm{sech}[c_4\phi^3] + \frac{c_3}{1+c_3}e^{-c_5\phi},$$

Effective Newton constant κ_N^2 Scalar source+Renormalization **b**

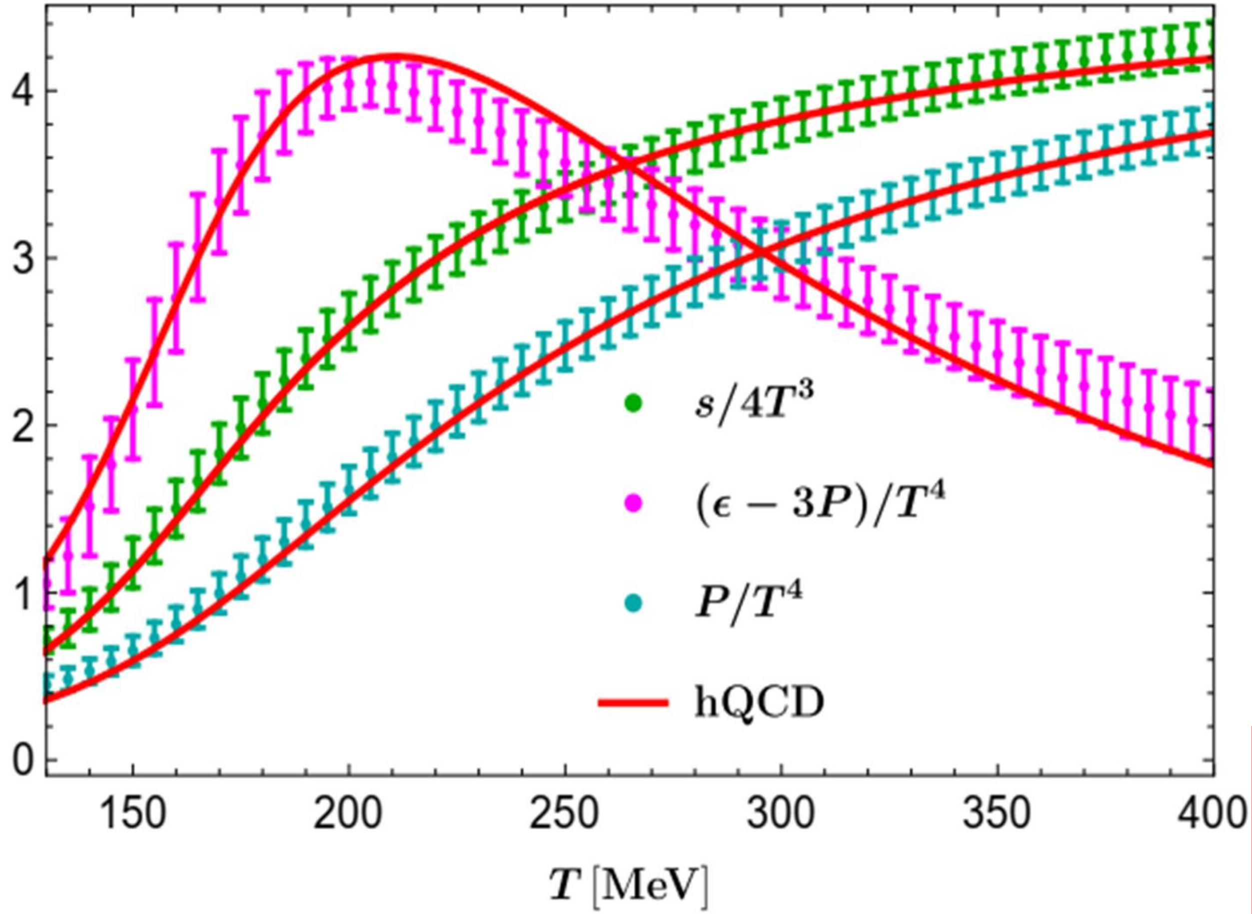
model	c_1	c_2	c_3	c_4	c_5	κ_N^2	ϕ_s(GeV)	b
pure $SU(3)$	0.735	0				$2\pi(4.88)$	1.523	-0.36458
2+1 flavor	0.710	0.0037	1.935	0.085	30	$2\pi(1.68)$	1.085	-0.27341

To fix model parameters by thermal dynamics

Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

$c_1, c_2, \cancel{c_3, c_4, c_5}$ Effective Newton constant κ_N^2 Scalar source ϕ_s+**Renormalization b**

Equations of state at vanishing chemical potential, s, trace anomaly, pressure



$$T = \frac{1}{4\pi} f'(r_h) e^{-\eta(r_h)/2},$$

$$s = \frac{2\pi}{\kappa_N^2} r_h^3$$

$$\epsilon := T_{tt}$$

$$P := T_{xx}$$

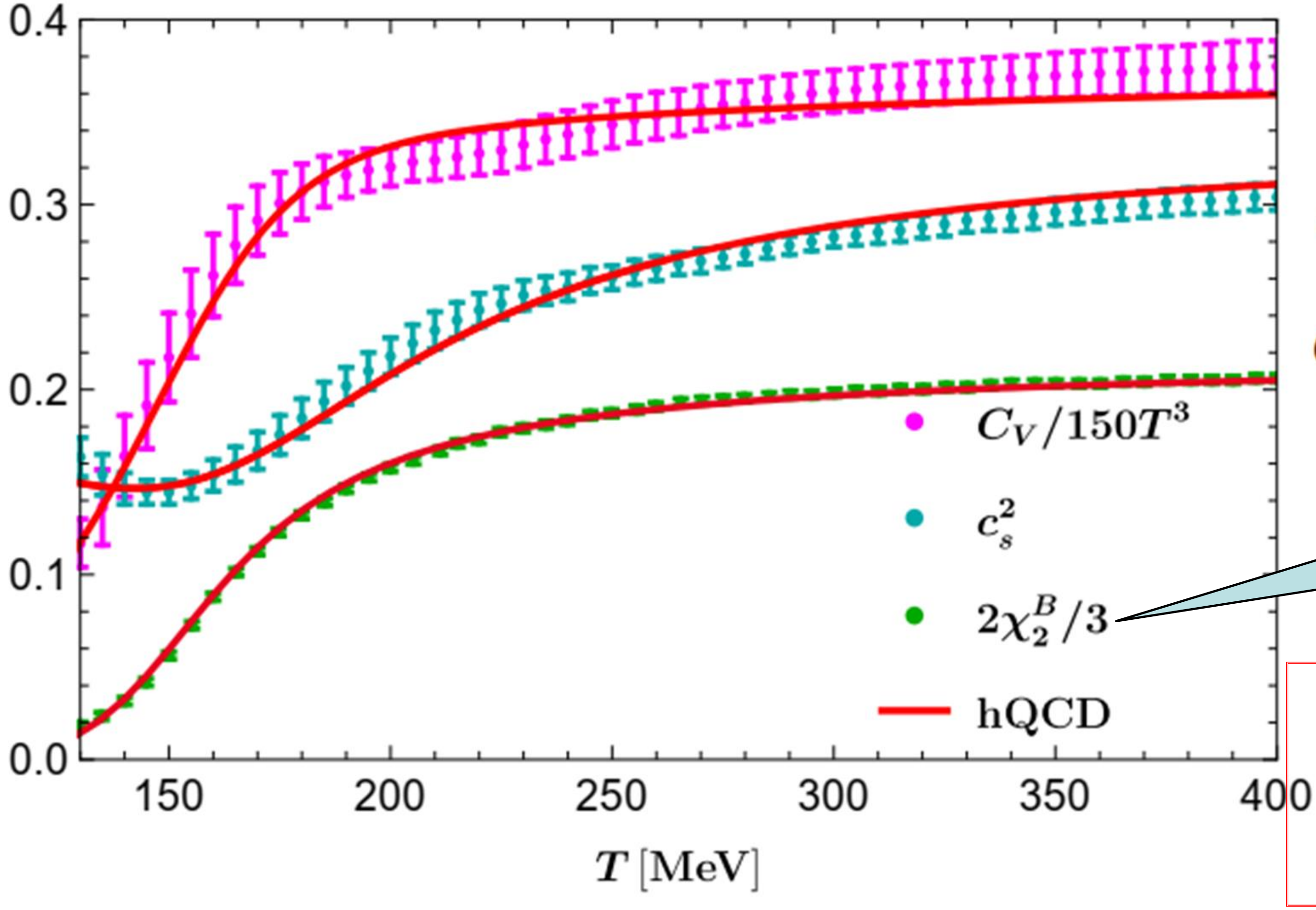
A. Bazavov *et al.* [HotQCD], Phys. Rev. D 90 (2014), 094503[arXiv:1407.6387 [hep-lat]].

To fix model parameters by thermal dynamics

Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

$c_1, c_2, \boxed{c_3, c_4, c_5}$ Effective Newton constant κ_N^2 Scalar source ϕ_s+Renormalization **b**

Sound speed,specific heat, second-order baryon susceptibility **at vanishing chemical potential**



$$c_s = \sqrt{(dP/d\epsilon)_{\mu_B}}$$

$$C_V = (d\epsilon/dT)_{\mu_B}$$

$$\boxed{\chi_2^B = (d\rho_B/d\mu_B)_T}$$

Bazavov *et al.* [HotQCD], Phys.Rev. D 90 (2014), 094503[arXiv:1407.6387 [hep-lat]].

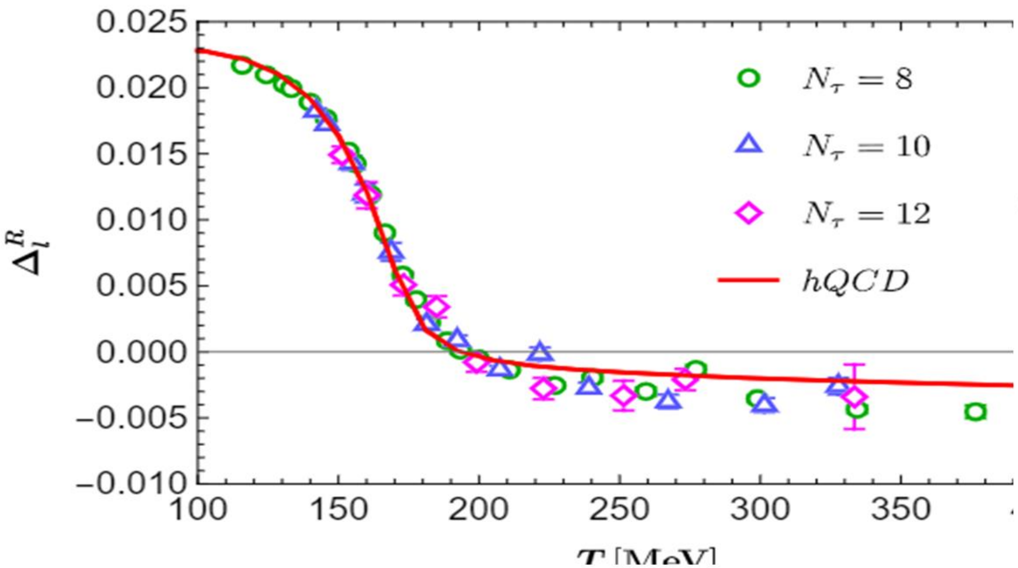
Predictions of hQCD model

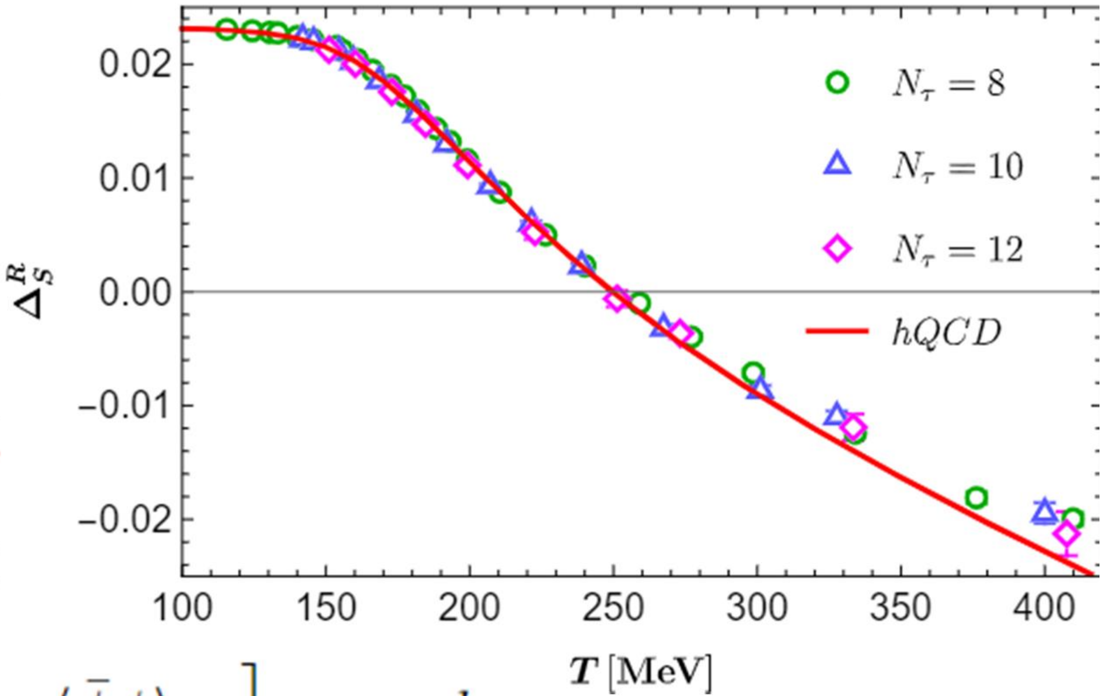
Condensations, Finite Chemical Potential, CEP

Condensation

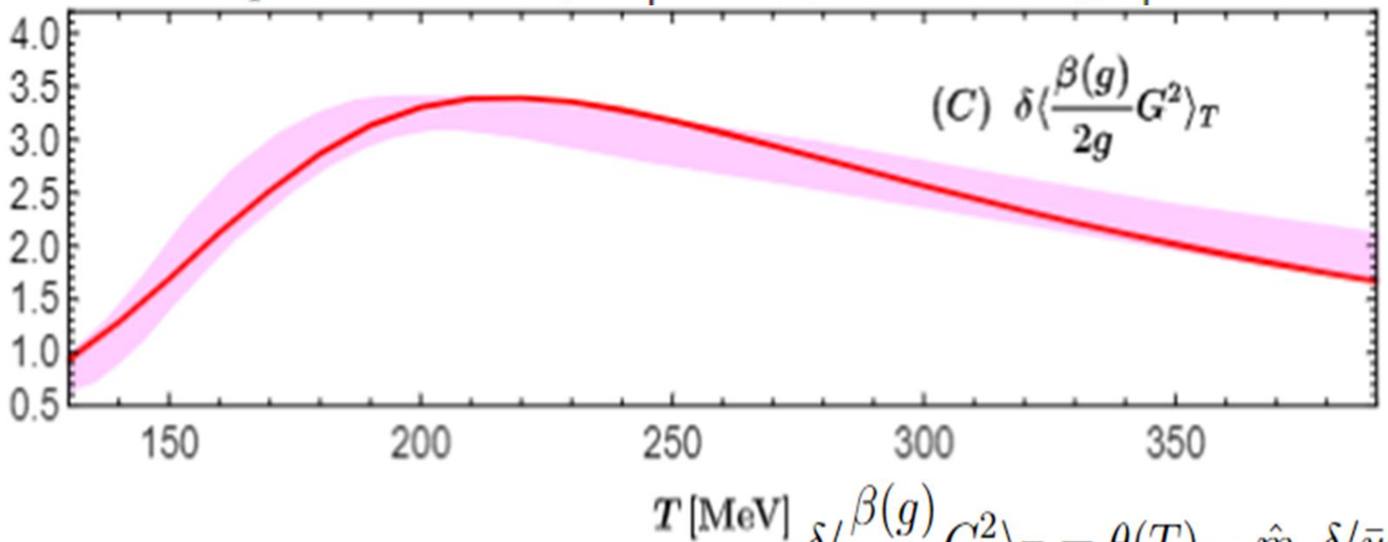
(2+1)-flavors

$m_u = m_d < m_s$





$$\Delta_q^R = \hat{d} + 2\, m_q r_1^4 \left[\langle \bar{\psi}\psi \rangle_{q,T} - \langle \bar{\psi}\psi \rangle_{q,0} \right], \quad q = l, s,$$

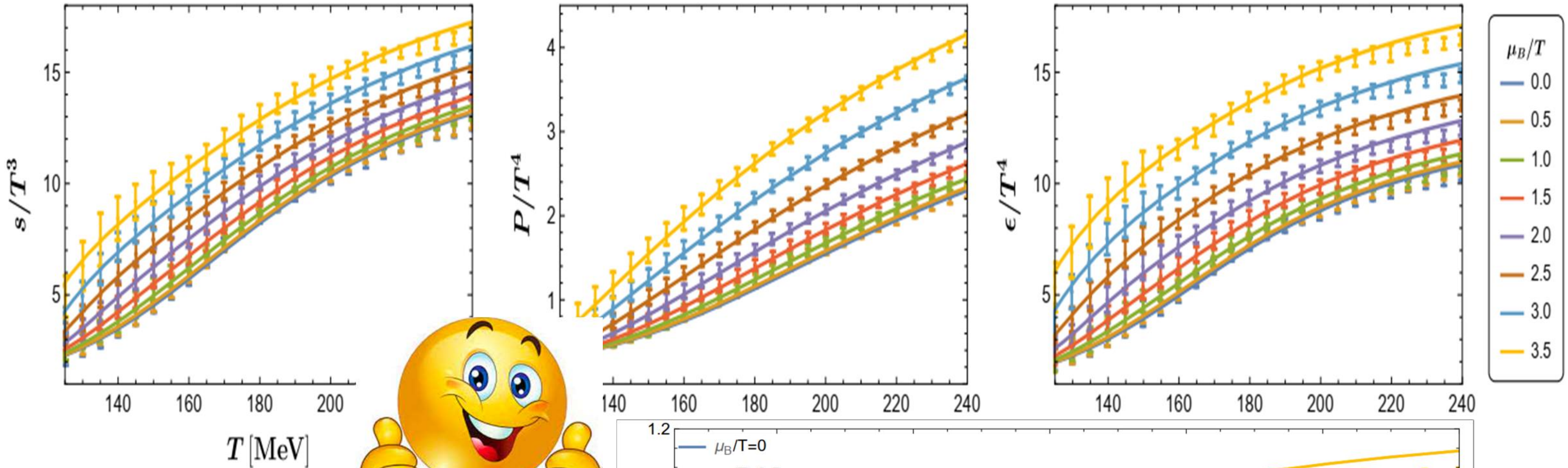


$$\delta\langle \frac{\beta(g)}{2g} G^2 \rangle_T = \theta(T) - \hat{m}_u \delta\langle \bar{u}u \rangle_T - \hat{m}_d \delta\langle \bar{d}d \rangle_T - \hat{m}_s \delta\langle \bar{s}s \rangle_T$$

Gubler P, Satow D., [1812.00385]

Predictions of thermal dynamical quantities at finite chemical potential

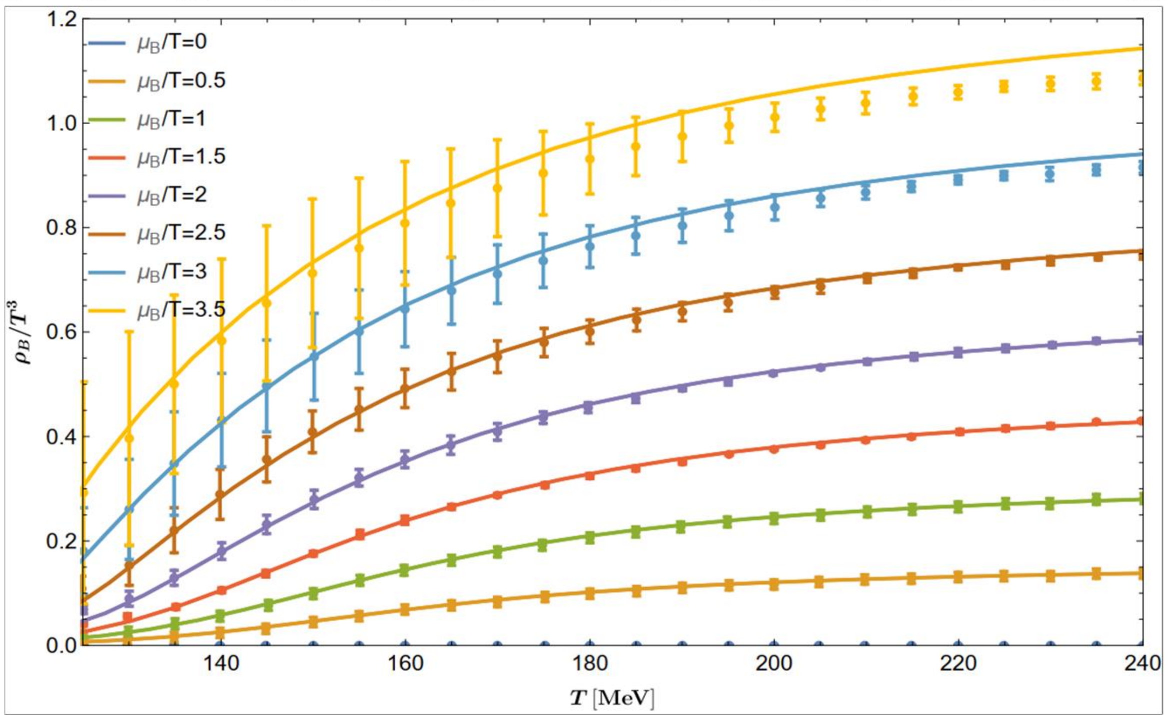
S. Bors´ anyi, etc., Phys. Rev. Lett. 126 (2021) no.23, 232001 [arXiv:2102.06660 [hep-lat]]



More challenging fitting

Rho_B

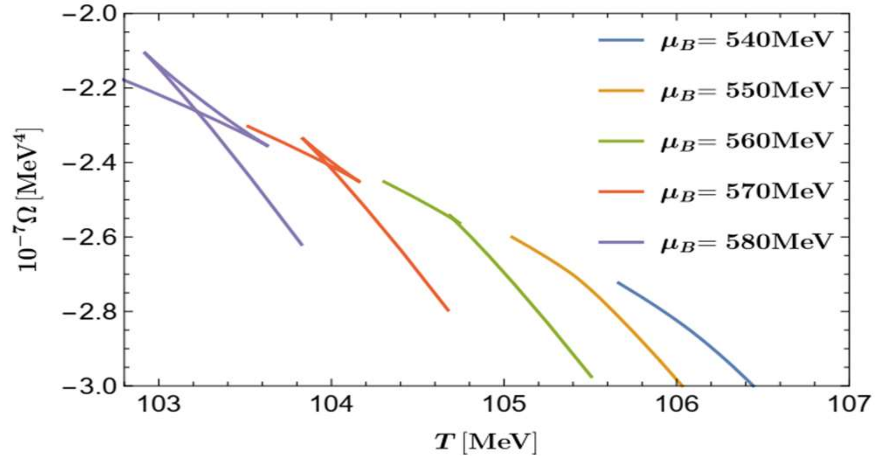
Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

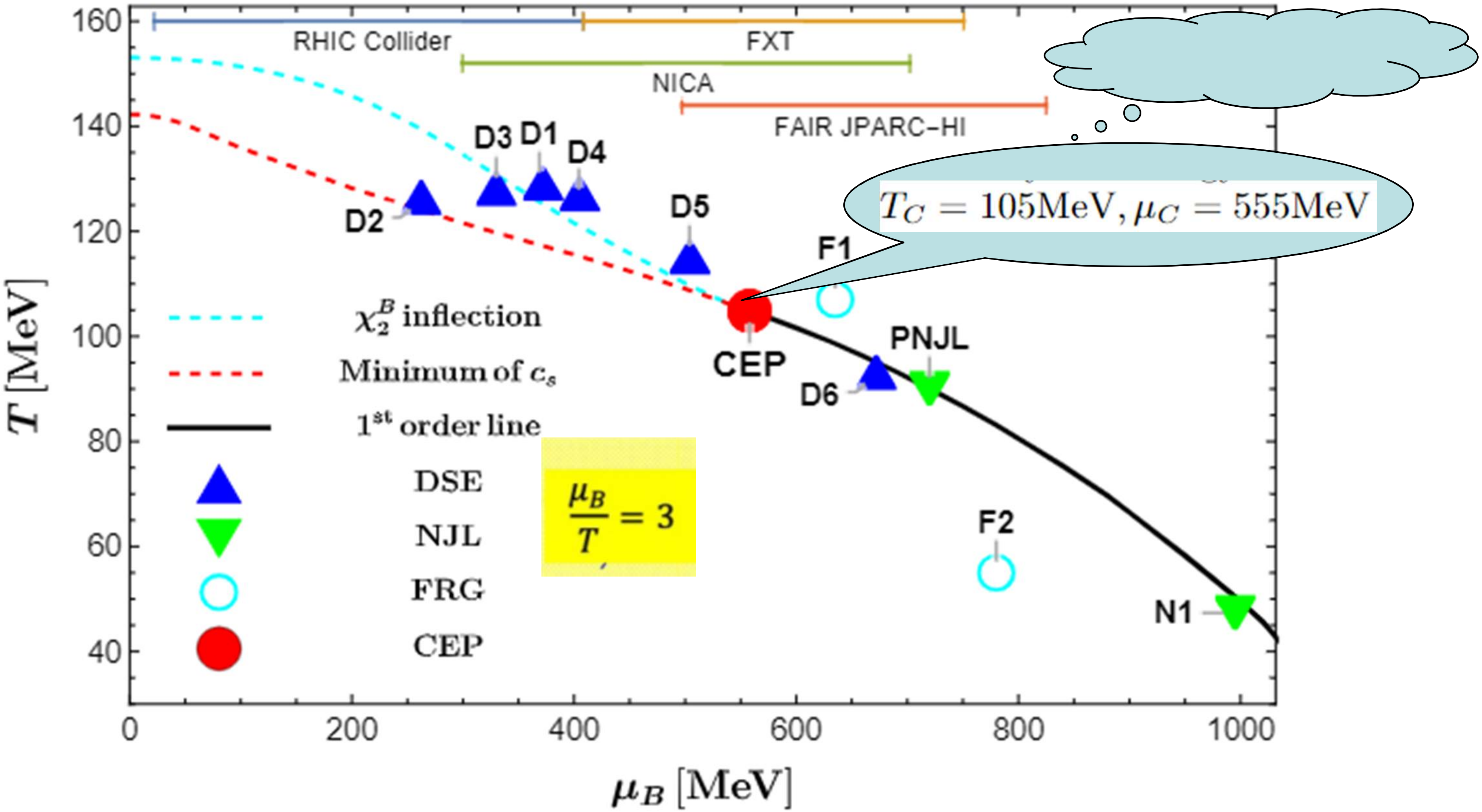


Predictions of QCD phase diagram

mu_B/T<=3 & mu_B< 300 MeV excluded by lattice simulation

A. Bazavov, etc.Phys. Rev. D 95 (2017) no.5, 054504 [arXiv:1701.04325 [hep-lat]].

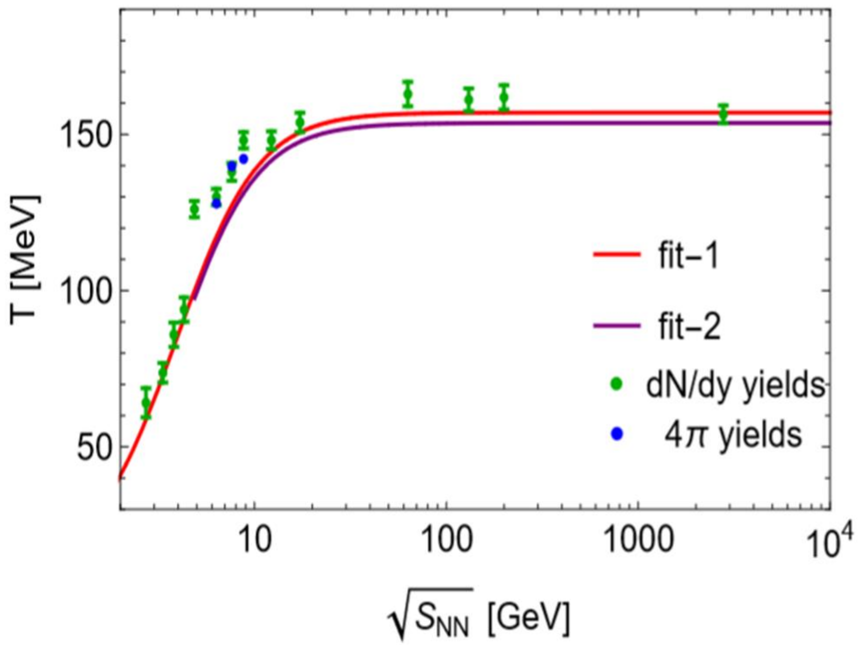


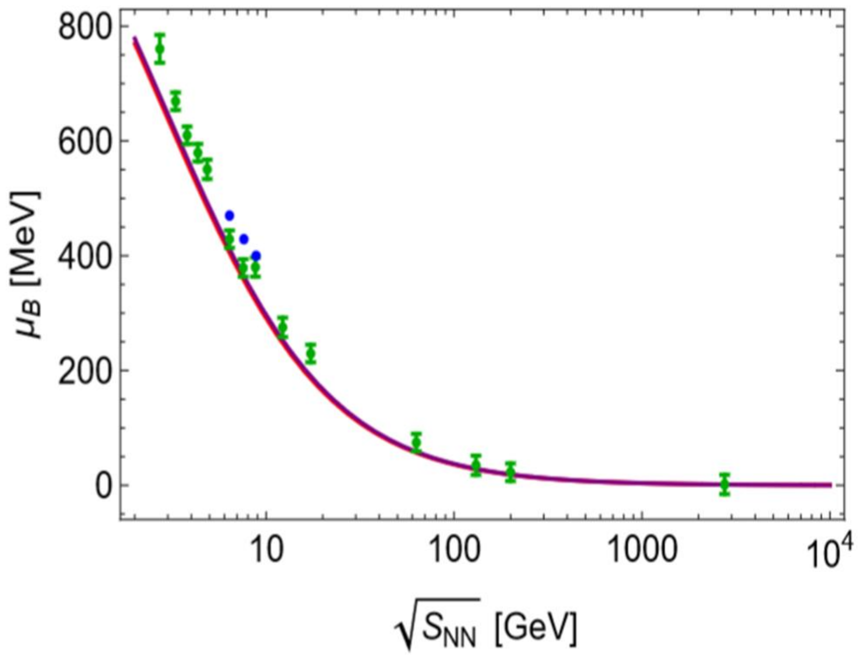


Emperical fitting formula from STAR Experimental group

w/. Li Li, Zhibin Li, Jing-Min Liang, 2305.13874

$$\mu_B = \frac{a}{1+b\sqrt{S_{NN}}}, \qquad T = \frac{T_{lim}}{1+exp\left[c-\ln\left(d\sqrt{S_{NN}}+e\right)/0.45\right]},$$



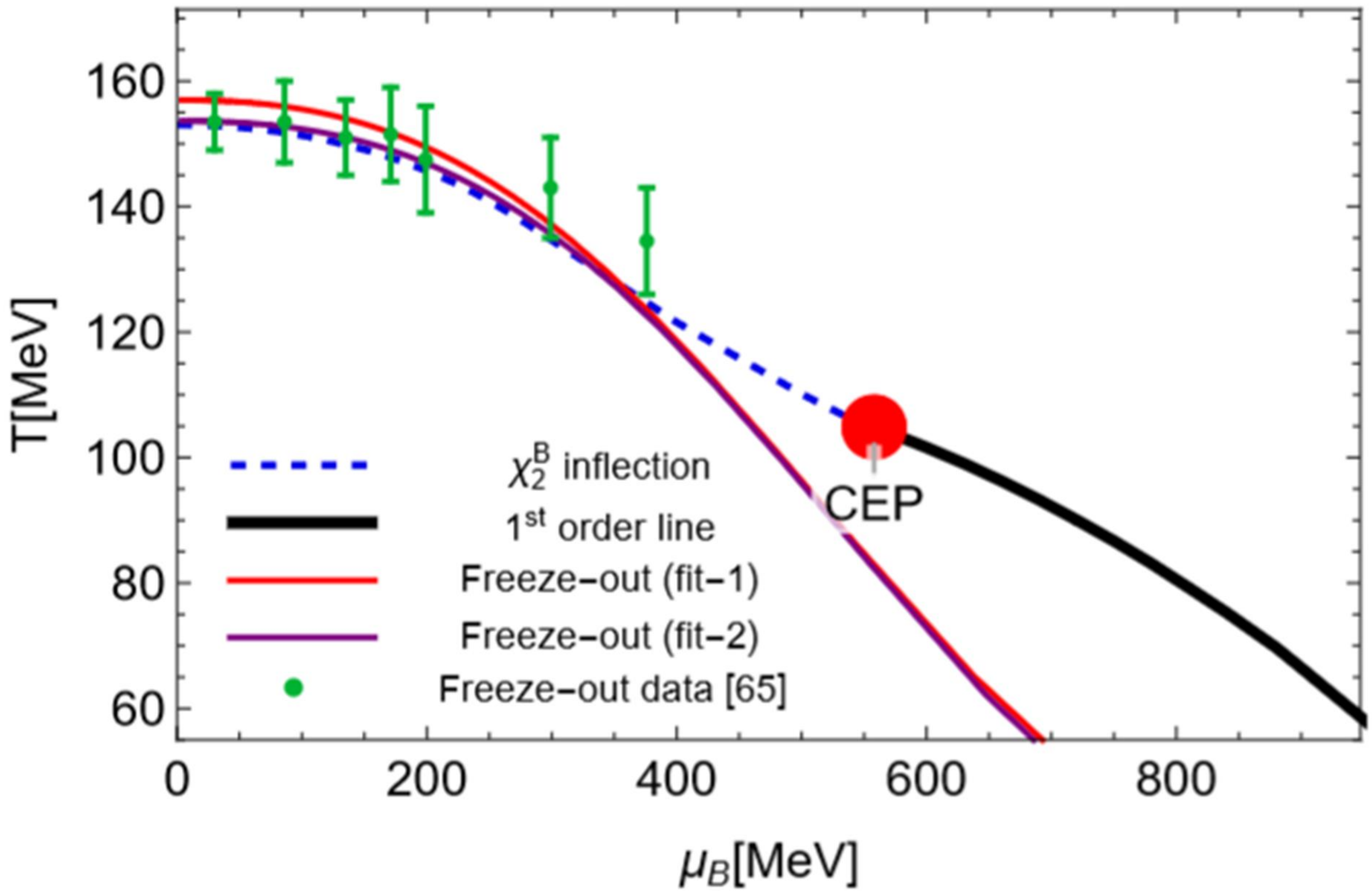


	a [MeV]	b	T_{lim} [MeV]	c	d	e
fit-1	1307.5	0.35	157.0	3.25	1	0.7
fit-2	1307.5	0.34	153.6	3.41	1.1	0.6

A. Andronic, P. Braun-Munzinger, and J. Stachel, Nucl. Phys. A 834 (2010) 237C–240C.
A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Nature 561 no. 7723, (2018) 321–330.

Frozen line versus Phase boundary

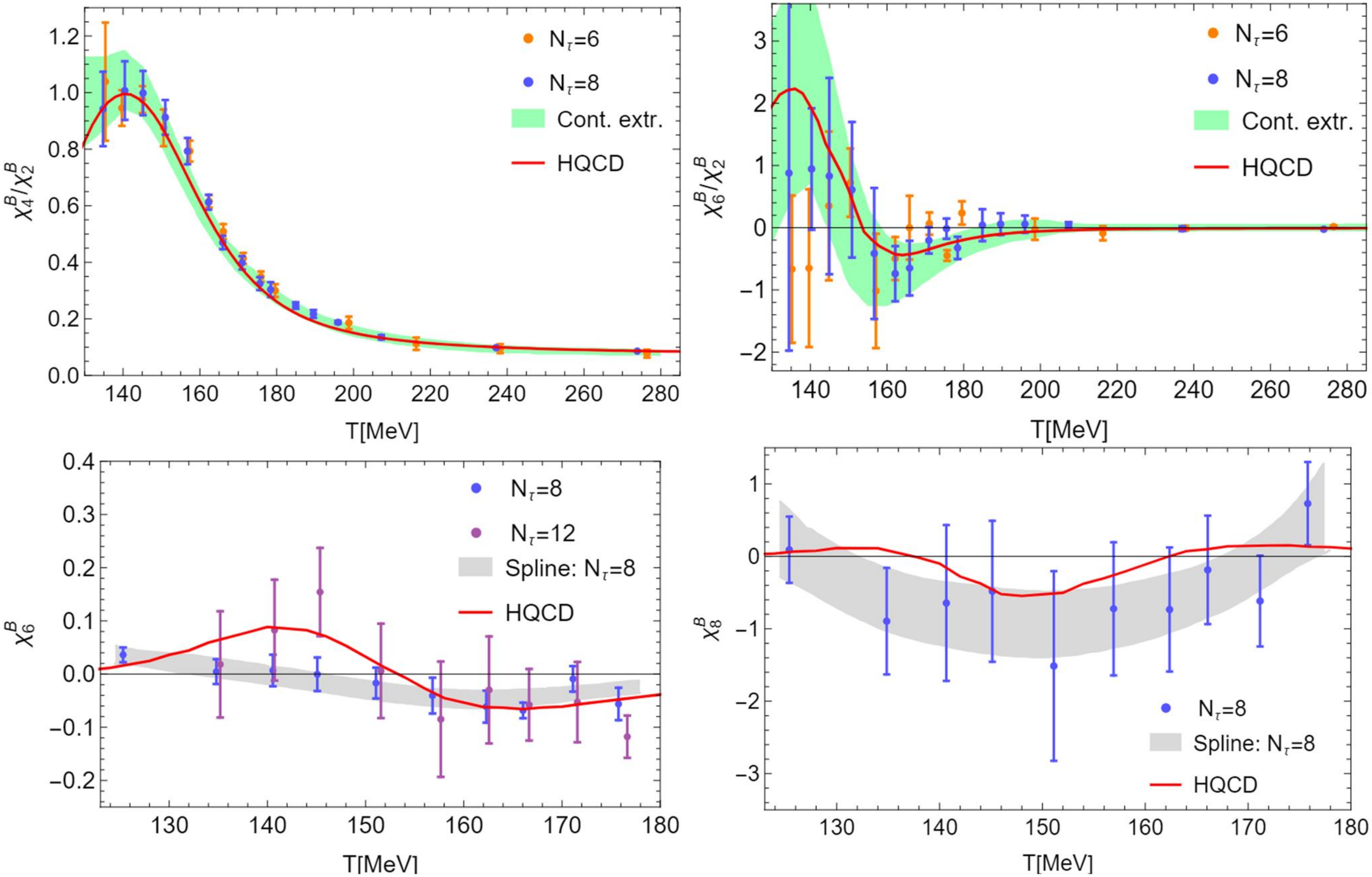
w/. Li Li, Zhibin Li, Jing-Min Liang, 2305.13874



S. Gupta, D. Mallick, D. K. Mishra, B. Mohanty, and N. Xu, "Freeze-out and
A. thermalization in relativistic heavy ion collisions," arXiv:2004.04681 [hep-ph].

Higher precision checking EOS, Zero Mu_B
Higher-order baryon susceptibility.

$$\chi_n^B = \frac{\partial^n P/T^4}{\partial \hat{\mu}_B^n}.$$

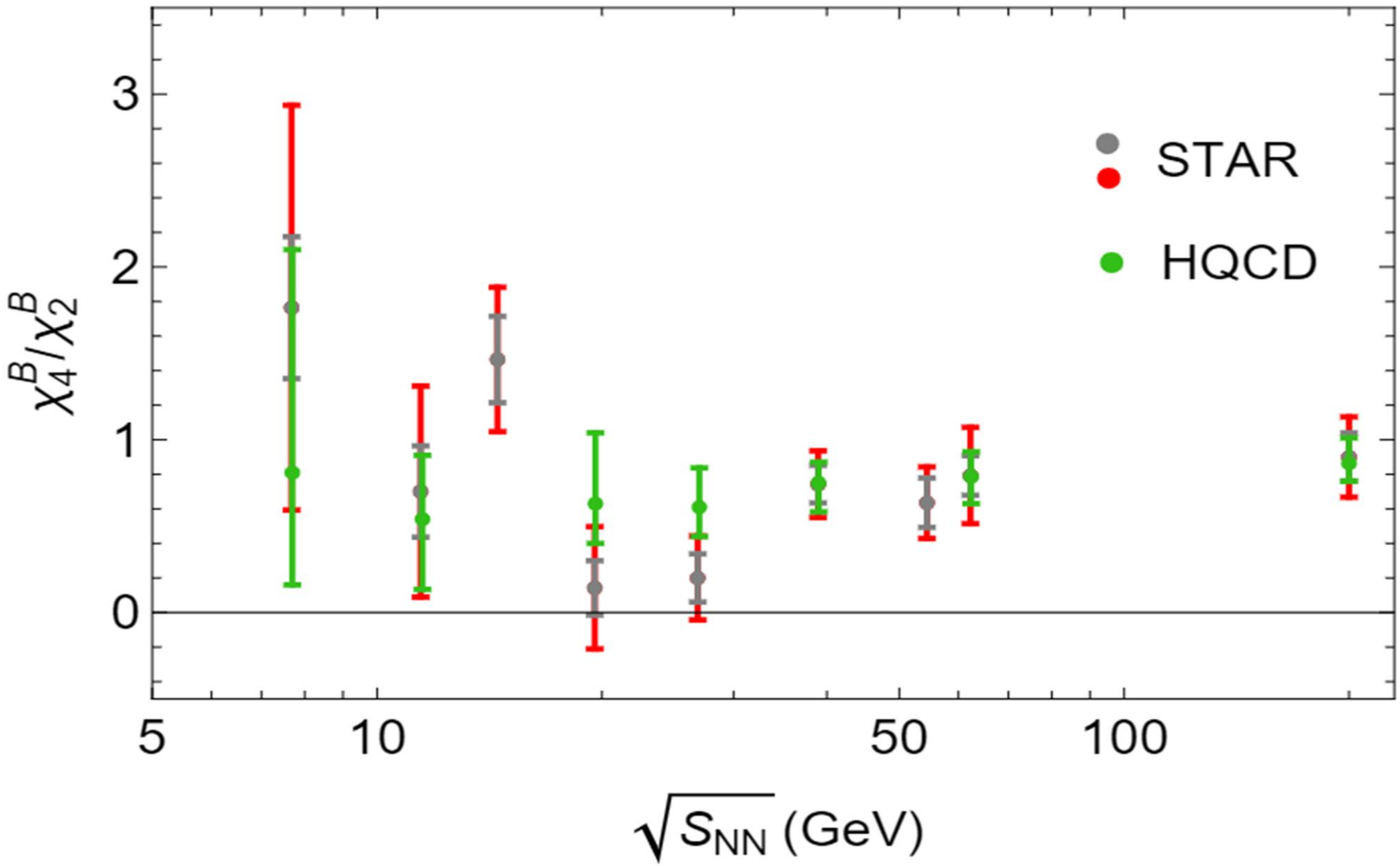


A. Bazavov *et al.* [HotQCD], Phys. Rev. D 95 (2017) 5, 05404 [arXiv:1701.04325[hep-lat]].

Higher precision checking EOS, finite Mu_B

Higher-order baryon susceptibility.

$$\chi_n^B = \frac{\partial^n P/T^4}{\partial \hat{\mu}_B^n}.$$

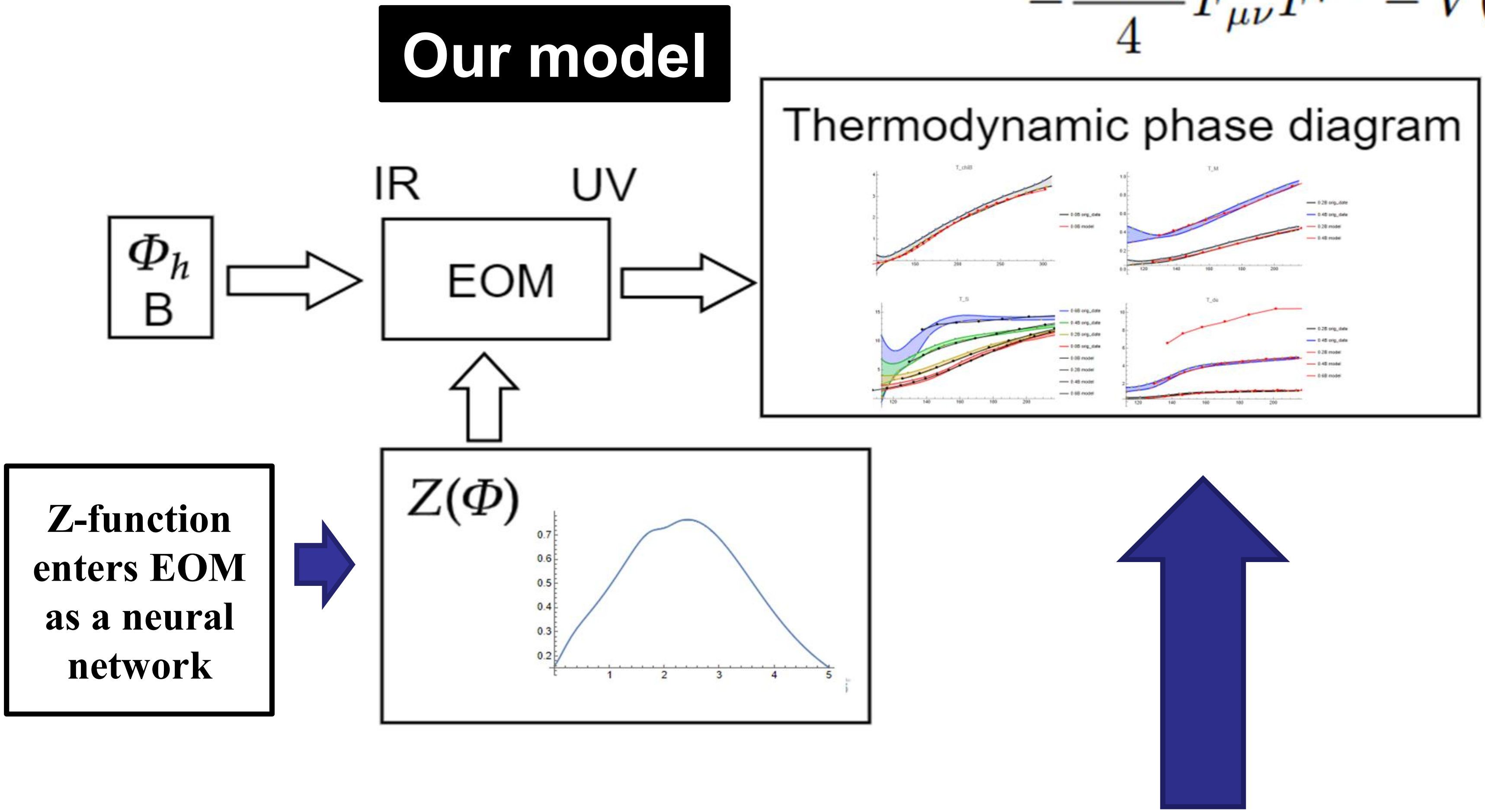


w/. Li Li, Zhibin Li, Jing-Min Liang, 2305.13874

hQCD model for 2+1 flavors with B field

Neural Network

$$S = \frac{1}{2\kappa_N^2}\int d^5x\sqrt{-g}\Big[\mathcal{R} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{Z(\phi)}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi)\Big],$$



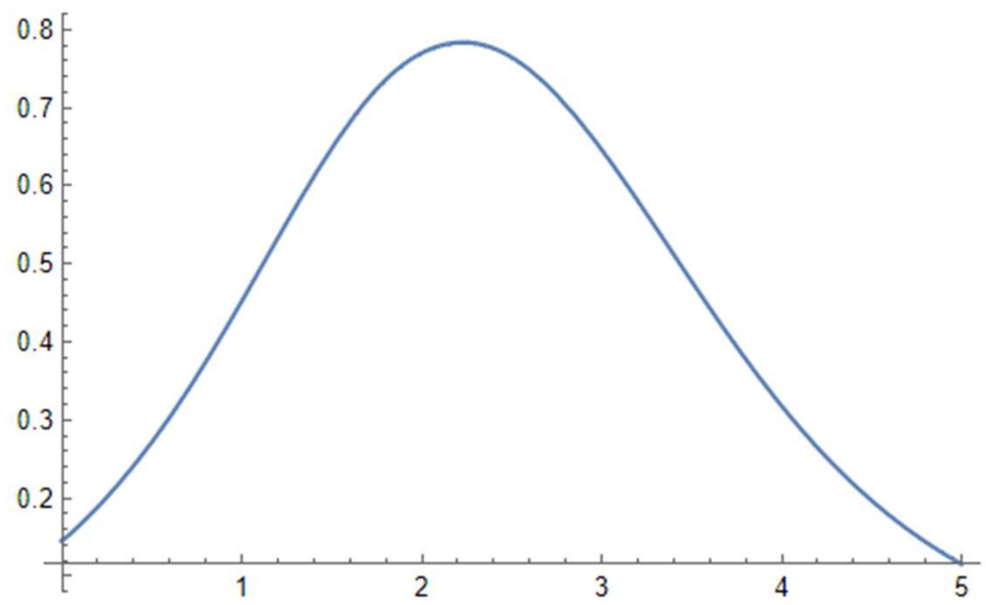
Target: To find a Z-function that matches the thermodynamic quantities of the boundary with the Lattice QCD data

Neural Network

$$S = \frac{1}{2\kappa_N^2}\int d^5x\sqrt{-g}\Big[\mathcal{R} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{Z(\phi)}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi)\Big],$$

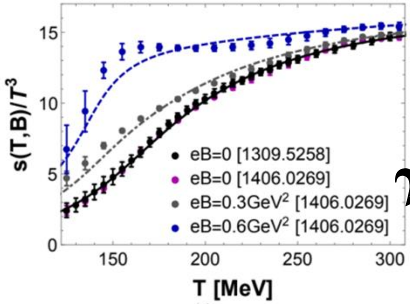
Z-function

result



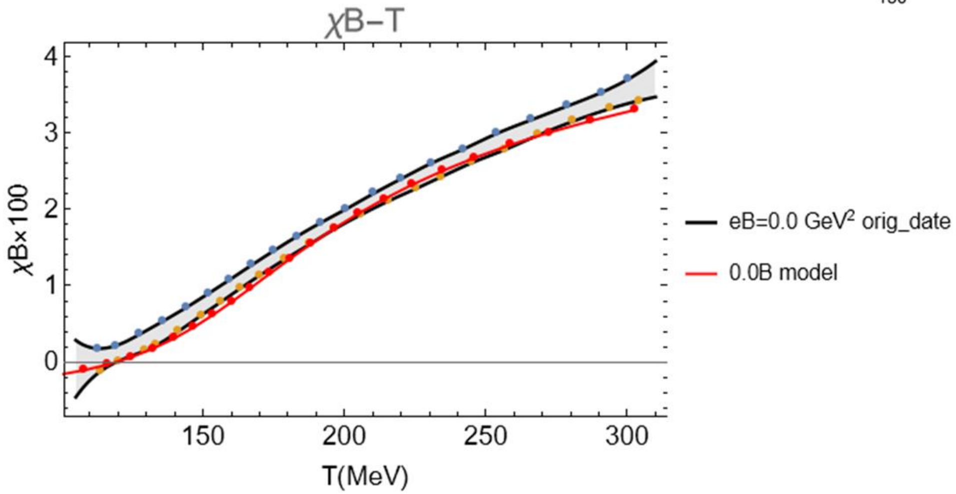
After some optimization of the neural network, the graph of the Z-function (neural network) is drawn as a graph above, and there is a small gap between the data obtained from this model and the lattice QCD data

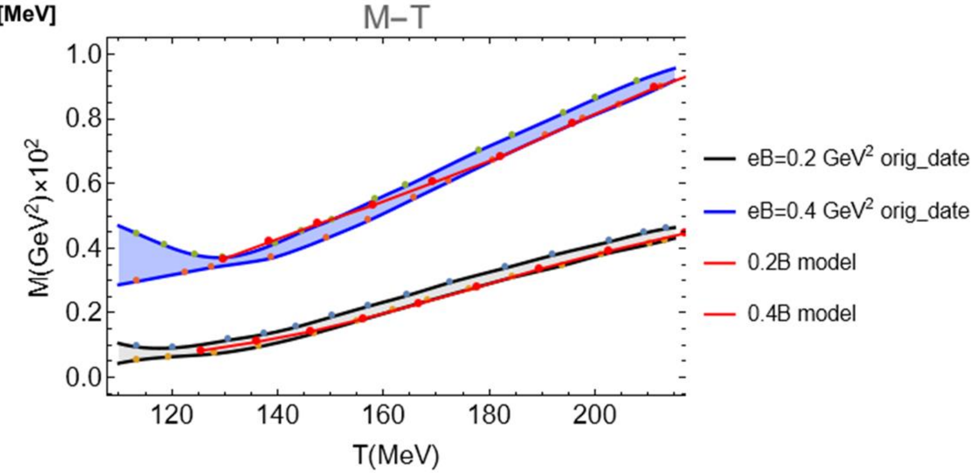
Neural Network

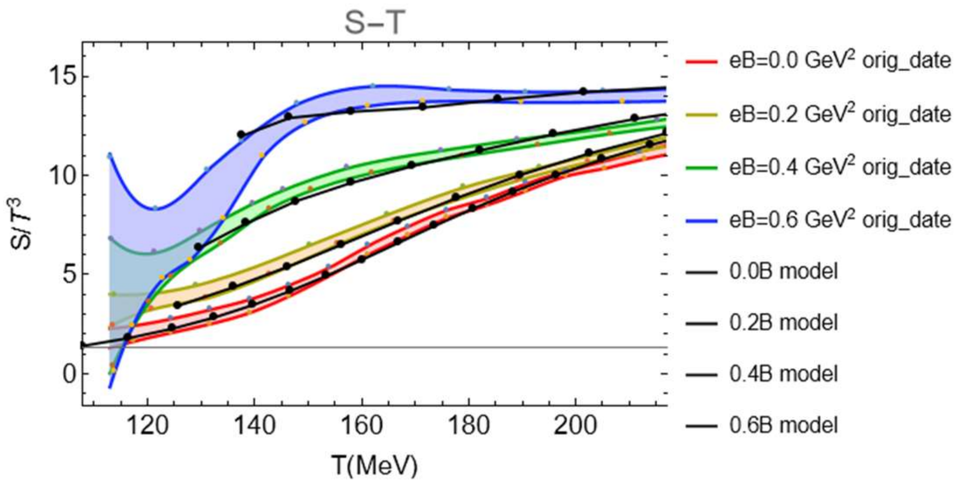


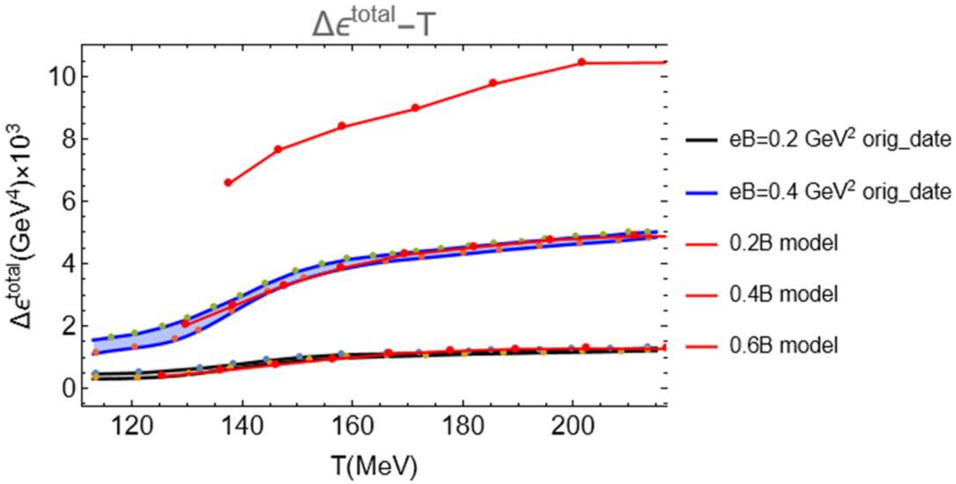
2307.03885

result









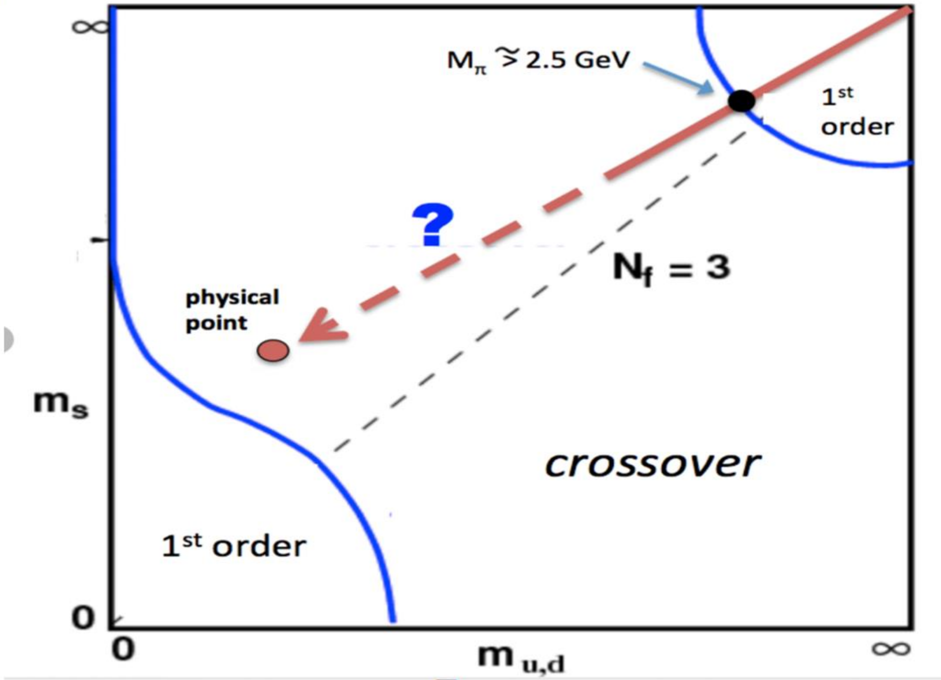
Bali G S, Bruckmann F, Endrődi G, et al. The QCD equation of state in background magnetic fields[J]. Journal of High Energy Physics, 2014, 2014(8): 1-35.

w/. Rong-Gen Cai, Li Li, Hongan Zeng

hQCD model for SU(3)
Pure gluon

HQCD model for Pure gluon syste in Einstein-Dilaton system

Motivation



SH, Li Li, Zhibin Li, Shao-Jiang Wang, 2210.14094

Gravity Action

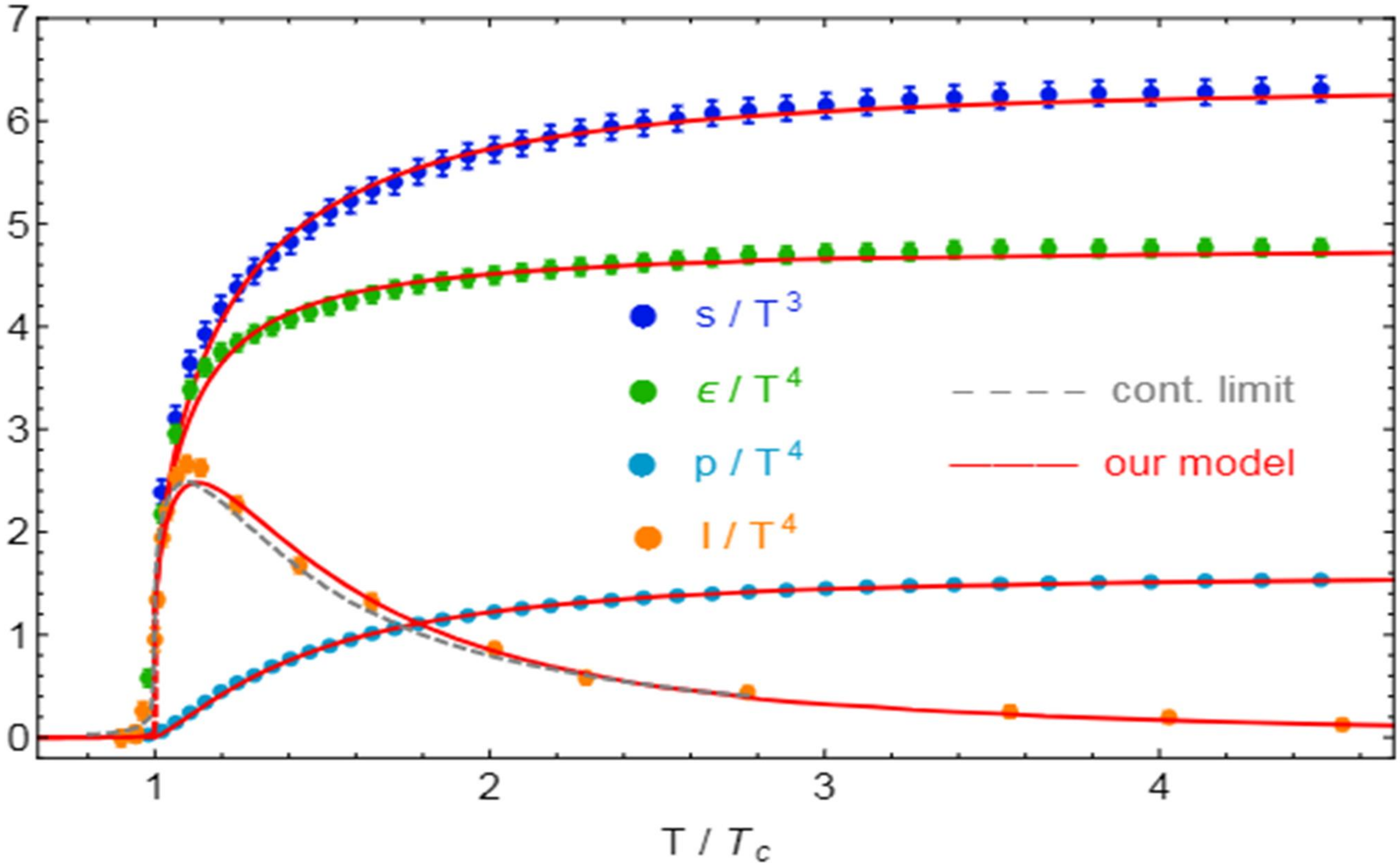
$$S = \frac{1}{2\kappa_N^2}\int \mathrm{d}^5x\sqrt{-g}\left[\mathcal{R} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)\right]$$

$$\mathrm{d}s^2 = -f(r)e^{-\eta(r)}\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{f(r)} + r^2\mathrm{d}\mathbf{x}_3^2, \quad \phi = \phi(r),$$

$$V(\phi) = \left(6\gamma^2 - \frac{3}{2}\right)\phi^2 - 12\cosh(\gamma\phi),$$

Break conformal symmetry

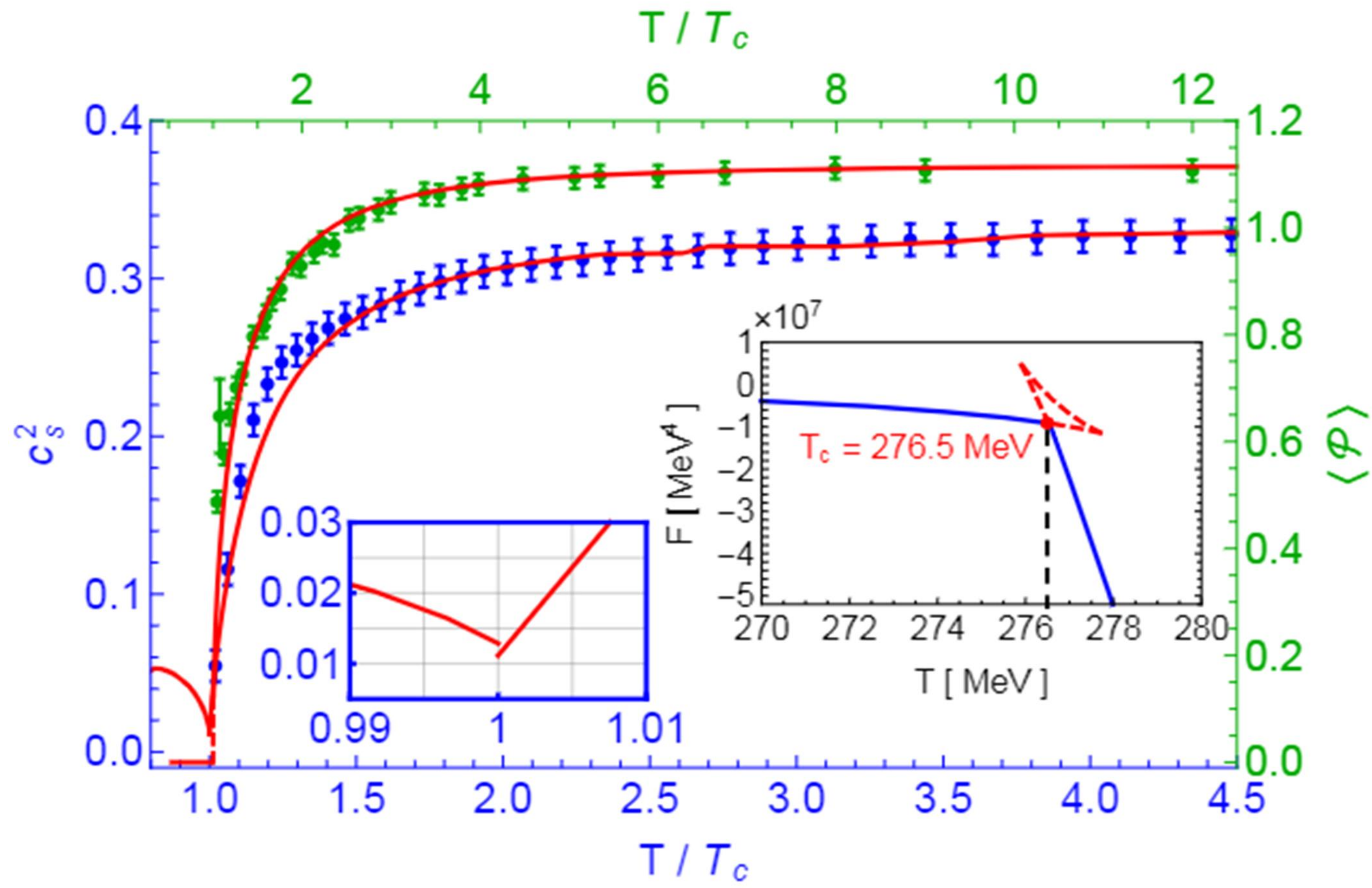
One parameter to fix all thermal dynamics lattice data



http://arxiv.org/abs/hep-lat/9602007

http://arxiv.org/abs/0711.2251

First order Phase transition vs Polyakov Loop



http://arxiv.org/abs/hep-lat/9602007

http://arxiv.org/abs/0711.2251

Gluon condensation- Probe

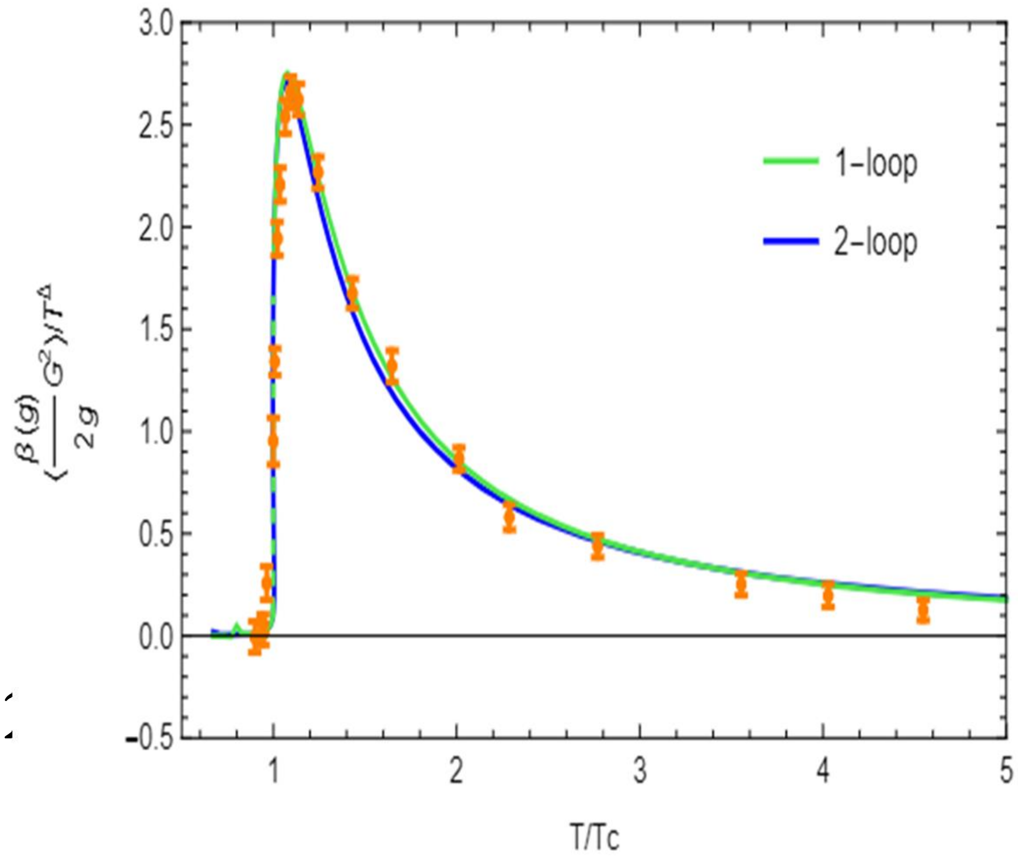
$$S = -\frac{1}{2\kappa_N^2}\int \mathrm{d}^5x\sqrt{-g^s}e^{-\sqrt{\frac{3}{8}}\phi}\left[\frac{1}{2}\nabla_\mu\chi\nabla^\mu\chi + \frac{1}{2}m_\chi^2\chi^2\right]. \quad (25)$$

$$\chi(r) = \chi_0 r^{\Delta-4} + \cdots + \chi_4 r^{-\Delta}$$

$$m_\chi^2 = \Delta(\Delta-4)$$

$$\chi_4 = \langle G^2\rangle$$

$$\left\langle\frac{\beta(g)}{2g}G^2\right\rangle_T = \langle T^\mu_\mu\rangle = \epsilon - 3P$$



http://arxiv.org/abs/hep-lat/960

http://arxiv.org/abs/0711.2251

Summary

I. **Propose a hQCD model on quantitative level to describe QCD phase diagram.**

II. **EOS confront with lattice simulations at zero/non-zero chemical potential.**

III. **Realize QCD CEP and quantitatively agrees with effective field results.**

IV. **Stochastic GW spectrum induced by QCD phase transition predicted.**

V. **Construct holographic pure gluon model.**

VI. **……**

Thanks for your attention！