Exploring the thermodynamic properties of QCD matter through temperature fluctuations

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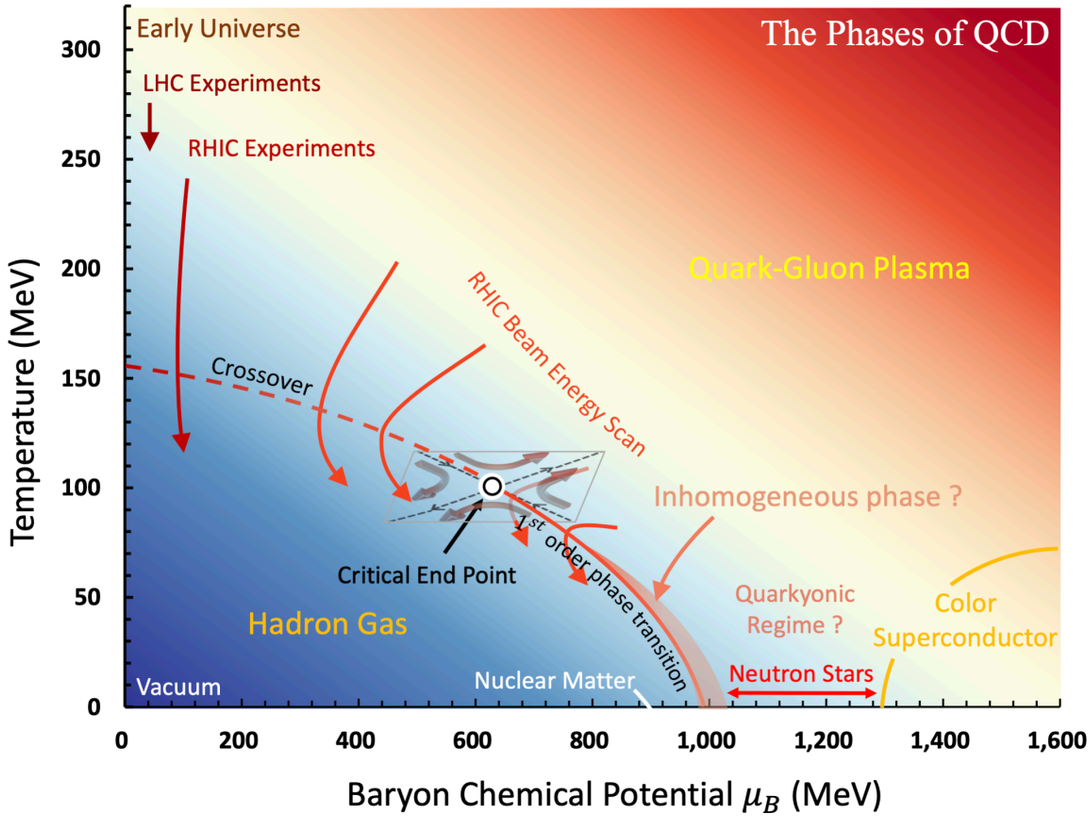
Based on:

Jinhui Chen, WF, Shi Yin, Chunjian Zhang, *PRD* 114 (2026) 014064, arXiv:2504.06886.

QCD thermodynamics

$\chi_n^T = T^{n-4}\dfrac{\partial^n p}{\partial T^n}$: Response of thermodynamic potential to the temperature, which corresponds to the entropy, heat capacity, fluctuations of entropy, etc.

QCD phase diagram

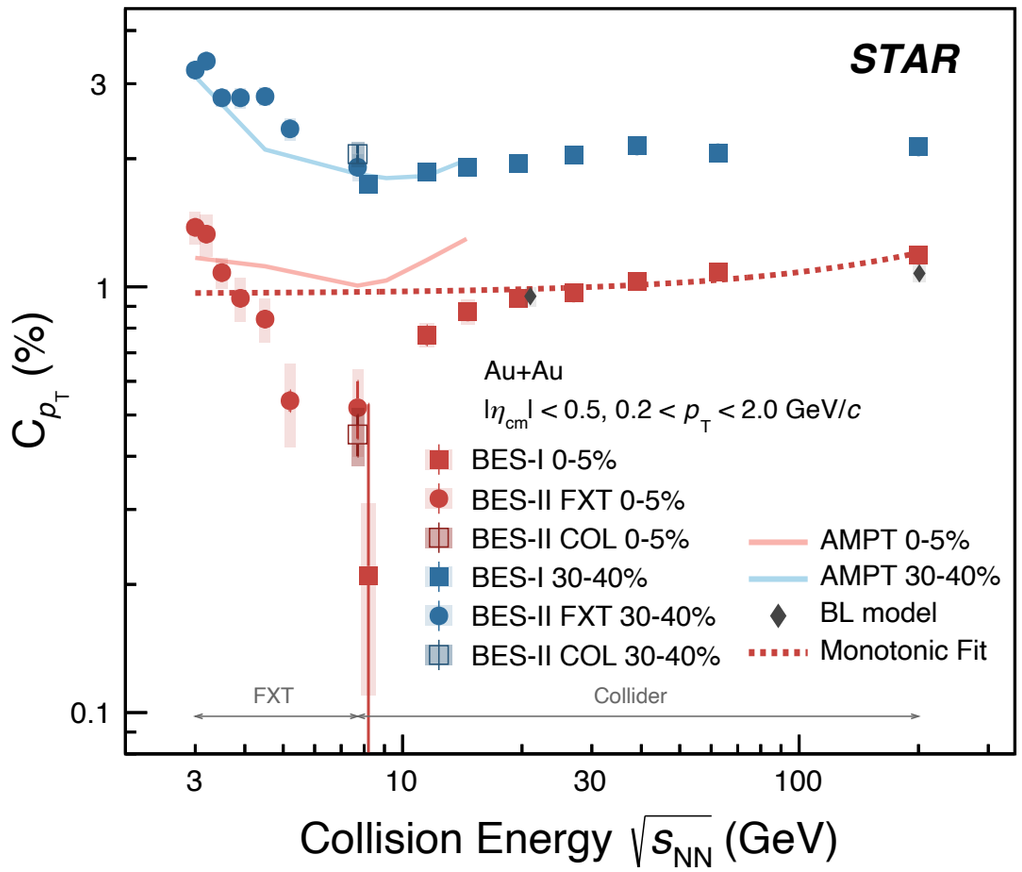


- **Naturally, it is expected that one can investigate the QCD thermodynamics along the two directions: μ_B and T.**

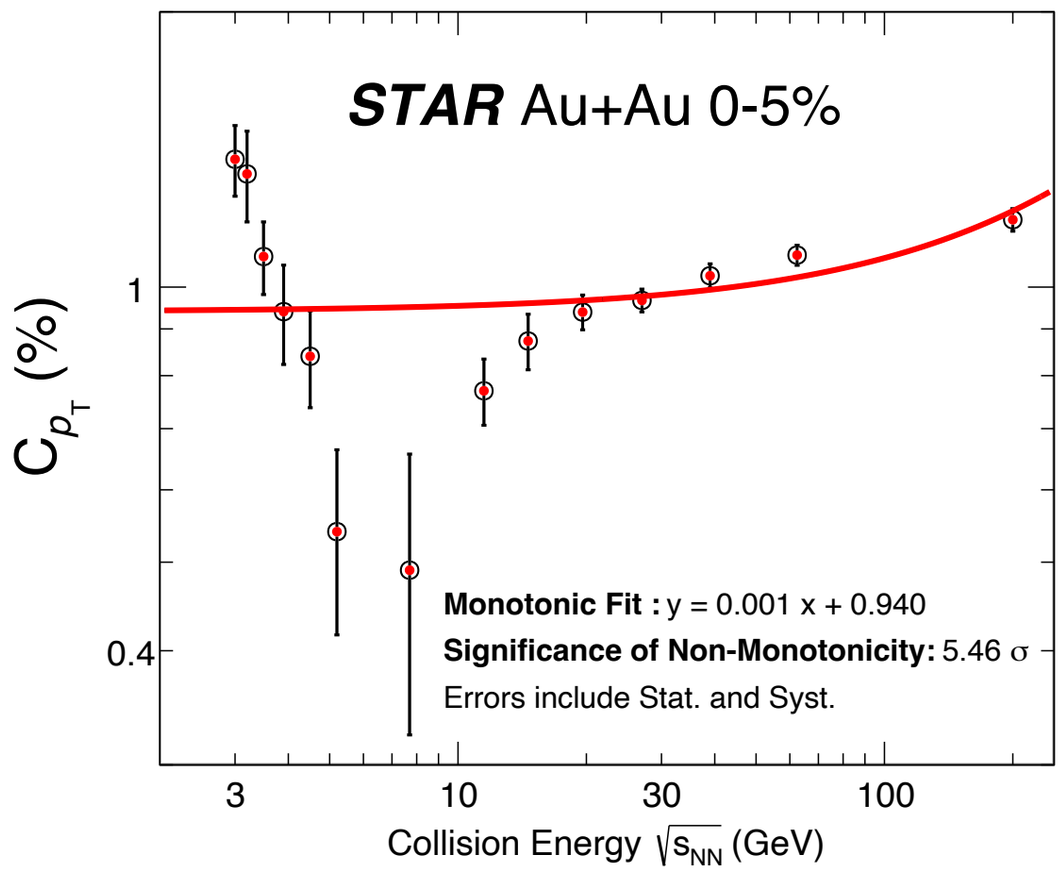
$\chi_n^B = T^{n-4}\dfrac{\partial^n p}{\partial \mu_B^n}$: Response of thermodynamic potential to the baryon chemical potential, which corresponds to the baryon number fluctuations.

Mean pt fluctuations recently measured By STAR

Variance of mean pt fluctuations vs collision energy:



STAR, *PRL* 137 (2026) 132301, arXiv:2604.06434.



See also the talk by Chunjian

- **Observation of non-monotonic behavior in the variance of mean pt fluctuations in most central collisions with significance $\sim 5\sigma$ by the STAR collaboration.**

Outline

- Introduction
- A new thermodynamic state function relevant to the mean pt experimental measurements
- Derivation of temperature fluctuations
- Results in fRG
- Results in Lattice QCD and other theoretical calculations
- Summary and outlook

A new thermodynamic state function

We begin with the very familiar thermodynamic potential

$$\mathrm{d}\Omega = -S\mathrm{d}T - p\mathrm{d}V - N_B\mathrm{d}\mu_B$$

In heavy-ion experiments, V and μ_B can be regarded to be approximately fixed within some acceptance window, but the temperature T is not. So, Ω is not the appropriate state function to describe the experiments.

Performing a Legendre transformation

$$W = \Omega + TS = U - \mu_B N_B$$

One arrives at

$$\mathrm{d}W = T\mathrm{d}S - p\mathrm{d}V - N_B\mathrm{d}\mu_B$$

In the experiments, events with fixed N_{ch} are selected, while one has $N_{\mathrm{ch}} \sim S$ approximately. Thus, S is fixed as well. Consequently, W is the appropriate state function we are looking for.

Jinhui Chen, WF, Shi Yin, Chunjian Zhang, *PRD* 114 (2026) 014064, arXiv:2504.06886.

Derivations of temperature fluctuations

For a fixed volume V, we define the intensive quantities: $w = W/V$, $s = S/V$. Using $\Omega = -pV$, one arrives at

$$w = -p + Ts$$

From the state function W, the temperature and its fluctuations can be obtained

$$\frac{\partial w}{\partial s} = T$$

and

$$\langle (\Delta T)^n \rangle_c = T^{4n-4} \frac{\partial^n w}{\partial s^n}, \qquad n \geq 2 \, (n \in Z)$$

Here $\Delta T = T - \langle T \rangle$, and the subscript c denotes the connected part. It is convenient to adopt a dimensionless temperature fluctuation

$$c_n = \frac{\langle (\Delta T)^n \rangle_c}{T^n}$$

Jinhui Chen, WF, Shi Yin, Chunjian Zhang, *PRD* 114 (2026) 014064, arXiv:2504.06886.

Relation to the thermal susceptibilities

The temperature fluctuations c_n can be easily related to the conventional thermal susceptibilities:

$$\chi_n^T = T^{n-4}\frac{\partial^n p}{\partial T^n}$$

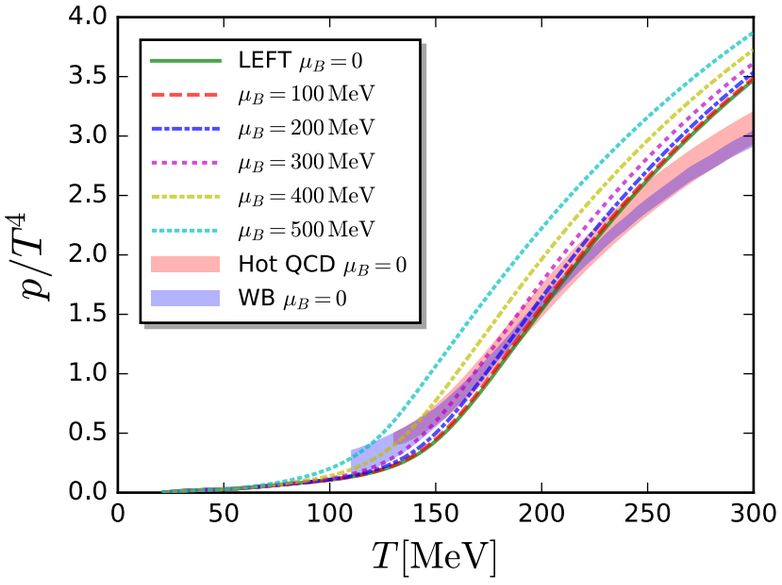
That is

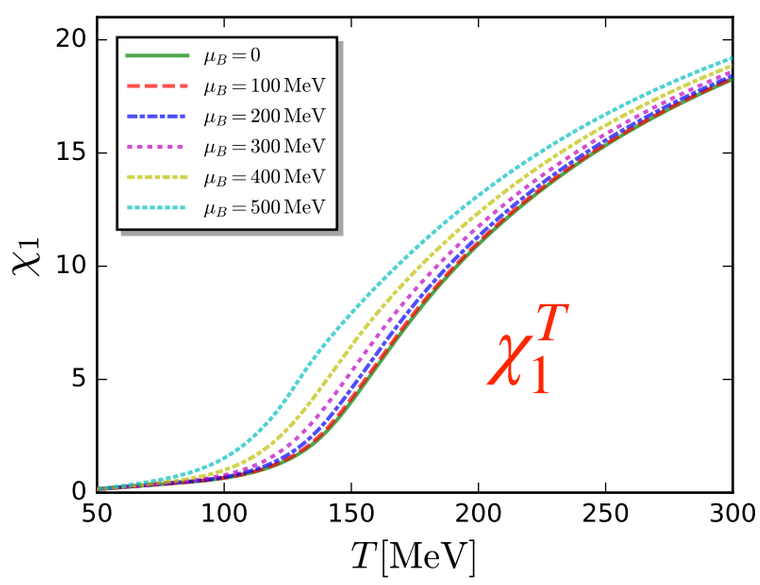
$$c_2 = \frac{1}{\chi_2^T}, \qquad c_3 = -\frac{\chi_3^T}{{\chi_2^T}^3}, \qquad c_4 = 3\frac{{\chi_3^T}^2}{{\chi_2^T}^5} - \frac{\chi_4^T}{{\chi_2^T}^4}$$

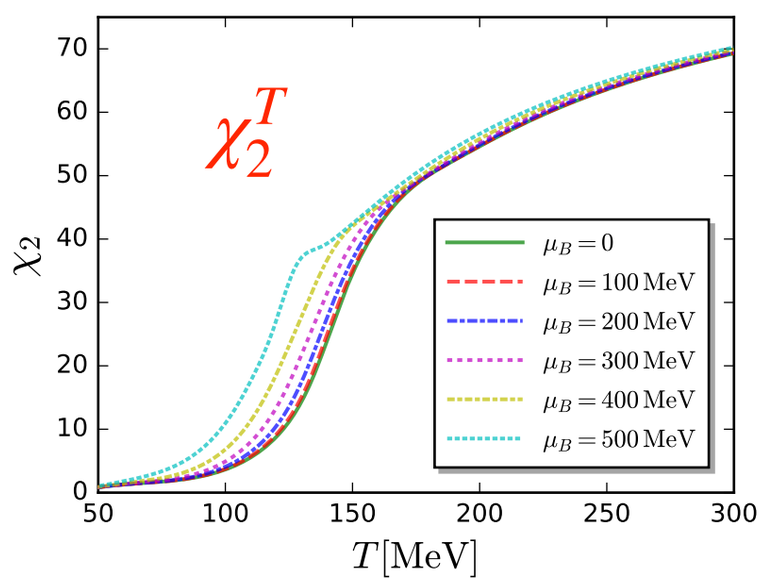
Here χ_2^T is the heat capacity, i.e., the variance of entropy fluctuations. χ_3^T and χ_4^T are the skewness and kurtosis of the entropy fluctuations, respectively.

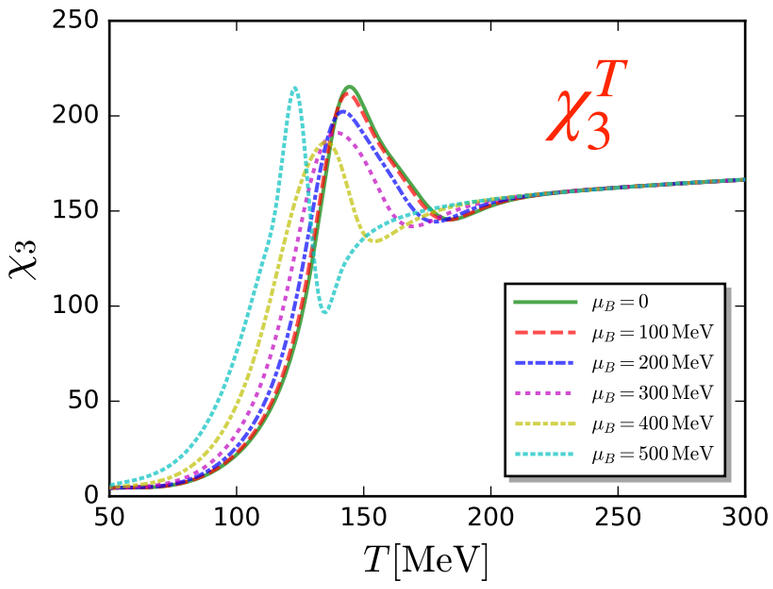
Jinhui Chen, WF, Shi Yin, Chunjian Zhang, *PRD* 114 (2026) 014064, arXiv:2504.06886.

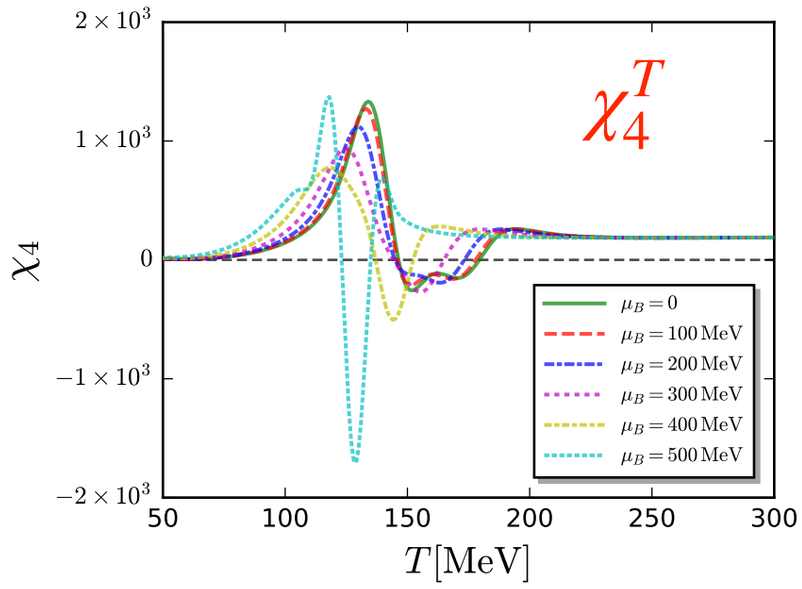
EoS and thermal susceptibilities





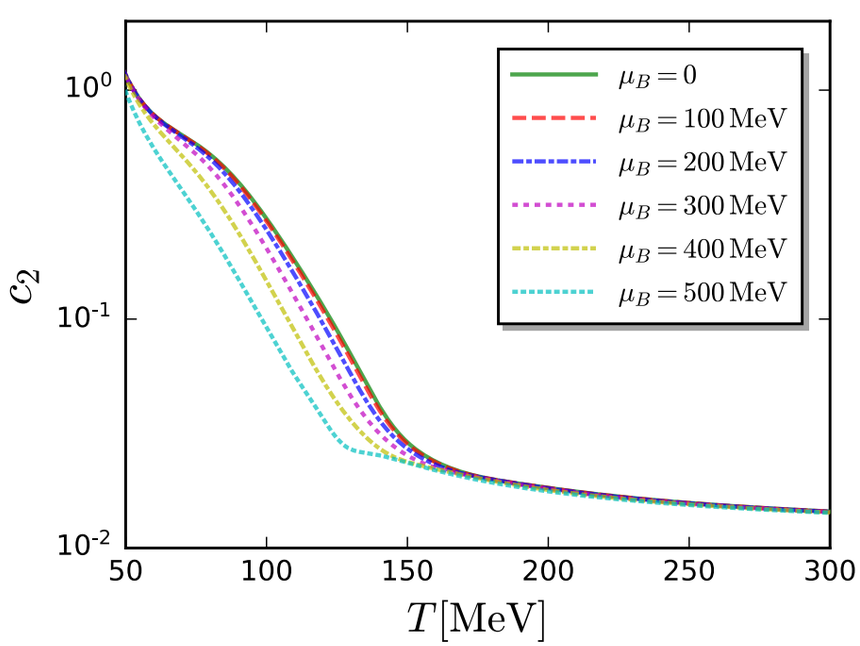


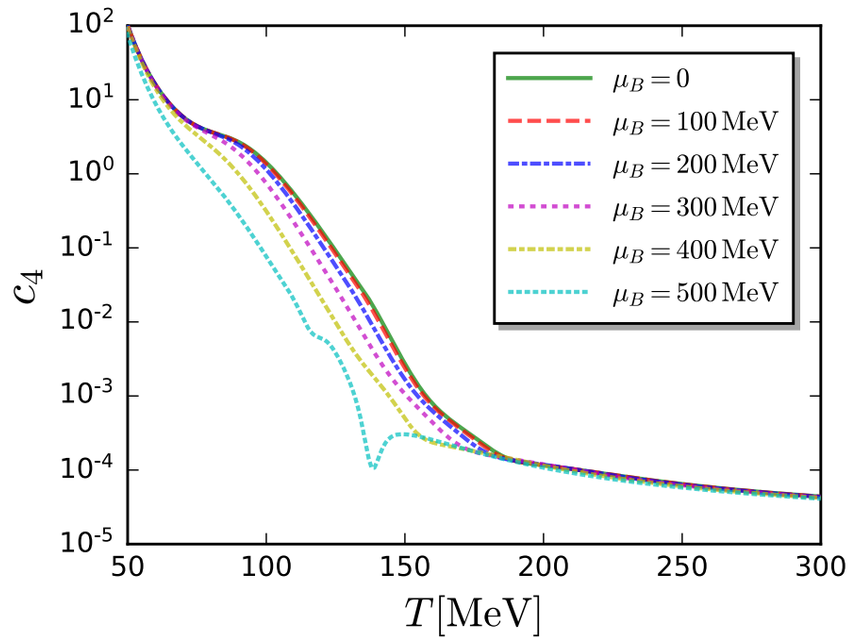


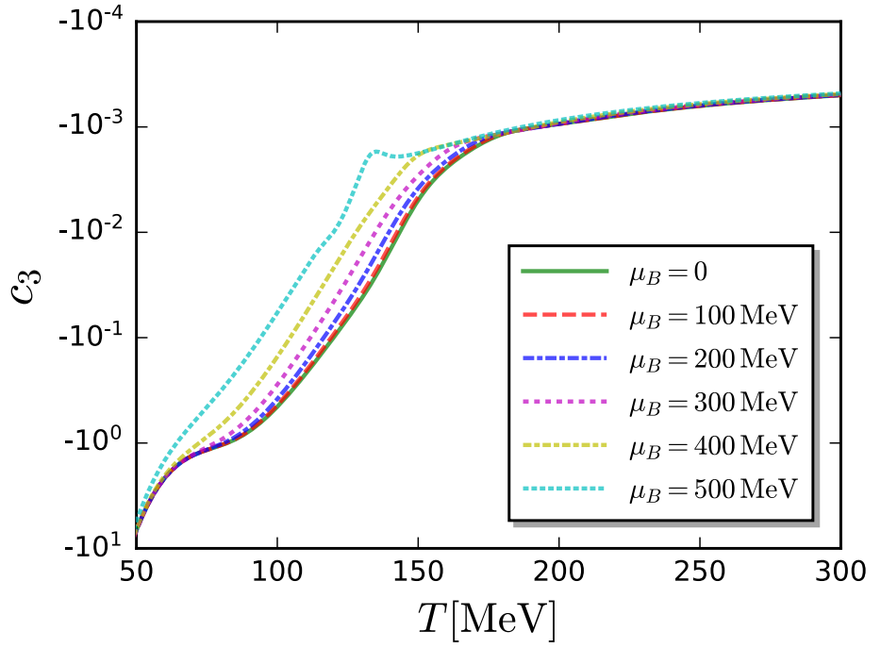


Jinhui Chen, WF, Shi Yin, Chunjian Zhang, *PRD* 114 (2026) 014064, arXiv:2504.06886.

Temperature fluctuations



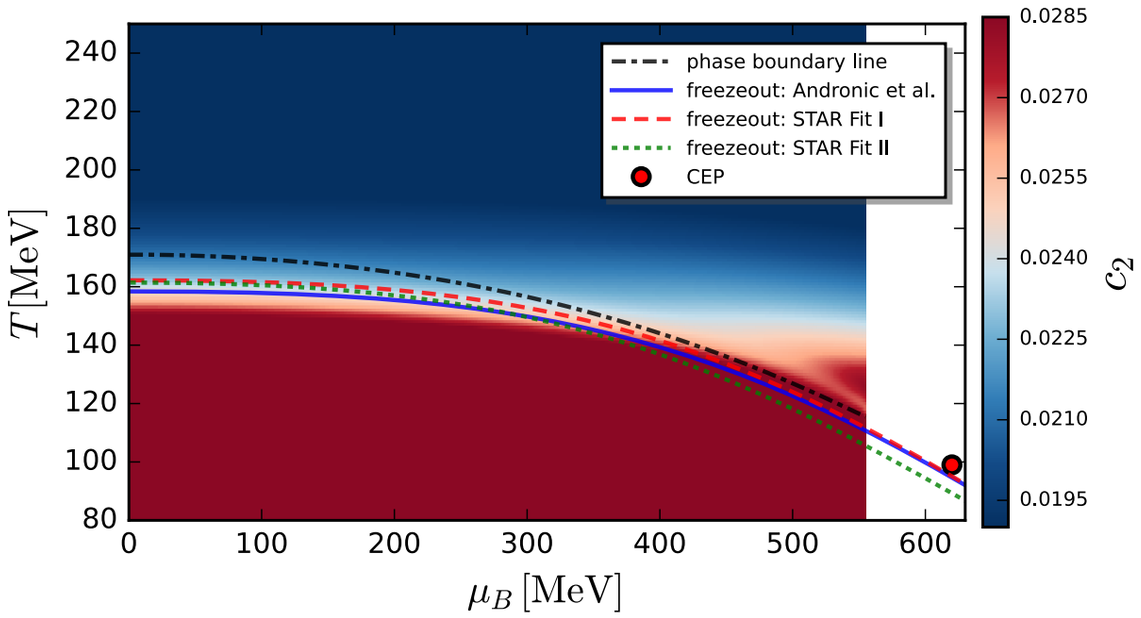


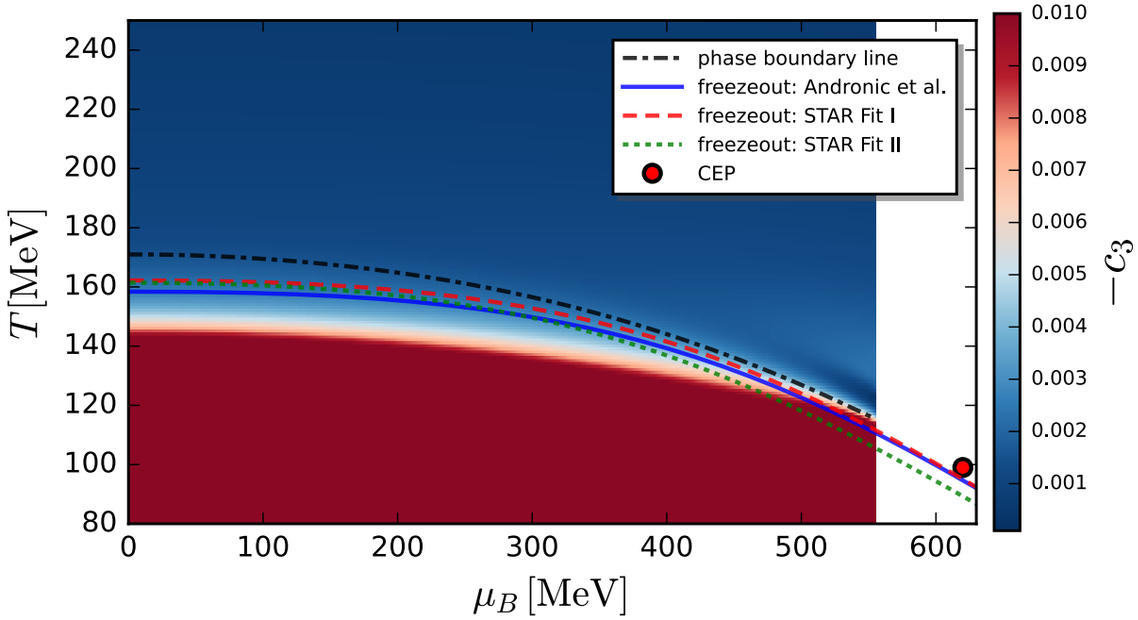


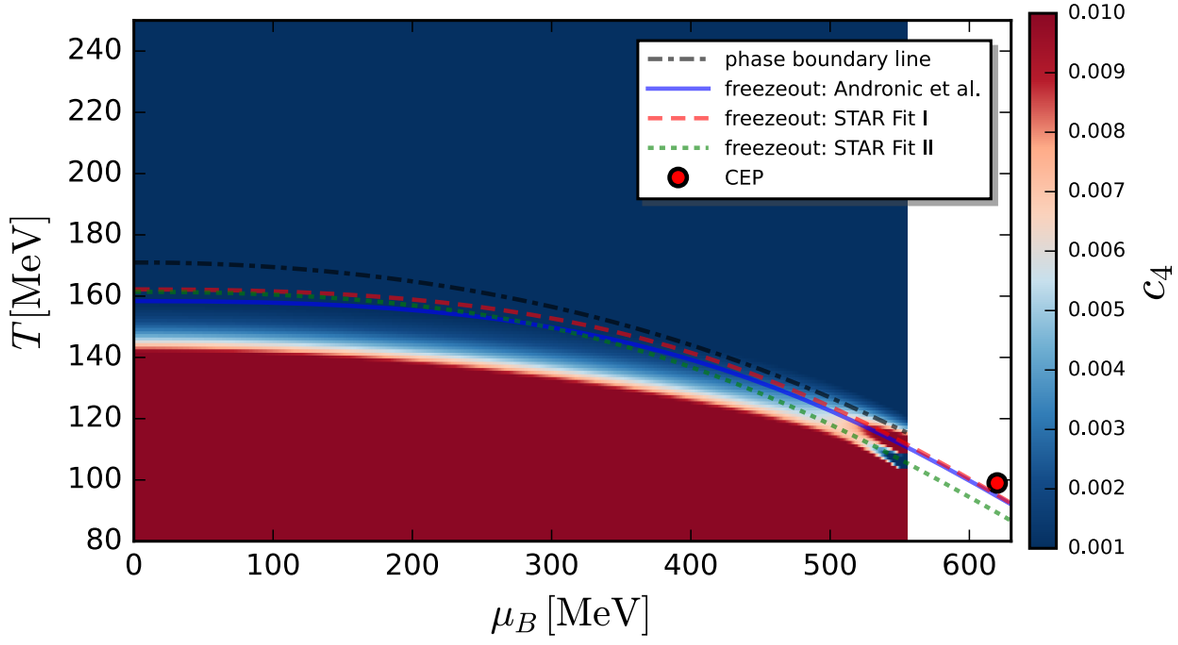
Jinhui Chen, WF, Shi Yin, Chunjian Zhang, *PRD* 114 (2026) 014064, arXiv:2504.06886.

- **T fluctuations are suppressed remarkably as the system transitions from HRG to the QGP.**
- **Skewness of T fluctuations is negative, a smoking-gun signature of the temperature fluctuations.**
- **Due to the fact that the heat capacity of QGP is significantly larger than that of HRG.**

Temperature fluctuations on the phase diagram



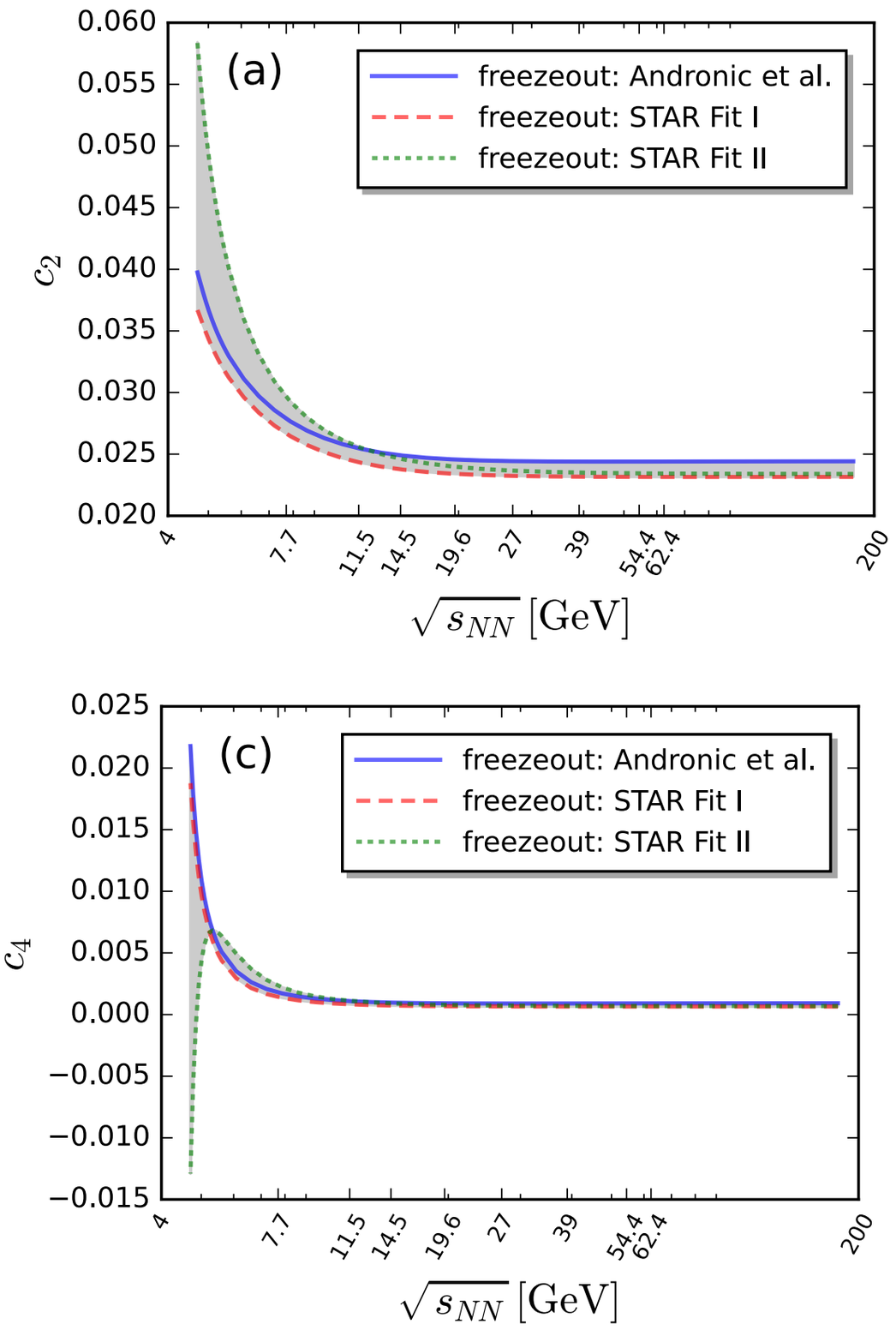


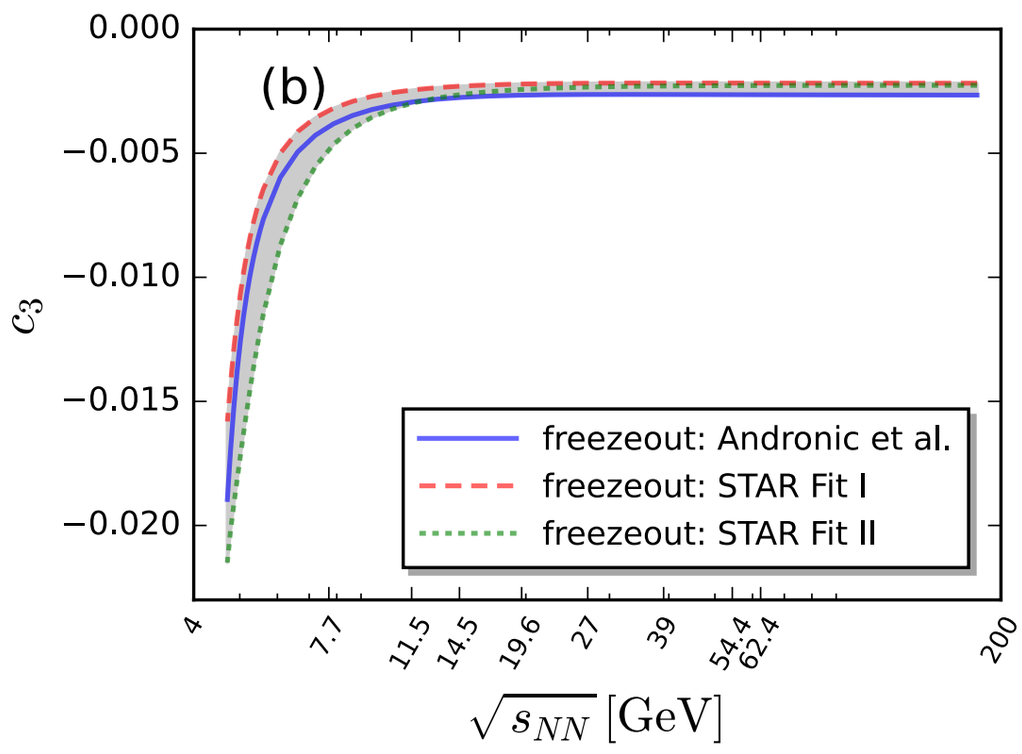


Jinhui Chen, WF, Shi Yin, Chunjian Zhang, *PRD* 114 (2026) 014064, arXiv:2504.06886.

- **There is a competition between the decreasing and increasing T fluctuations with the increase of μ_B, due to the heat capacity and critical fluctuations.**
- **T fluctuations can also reflect the critical fluctuations related to the CEP.**

Temperature fluctuations at the freeze-out curve

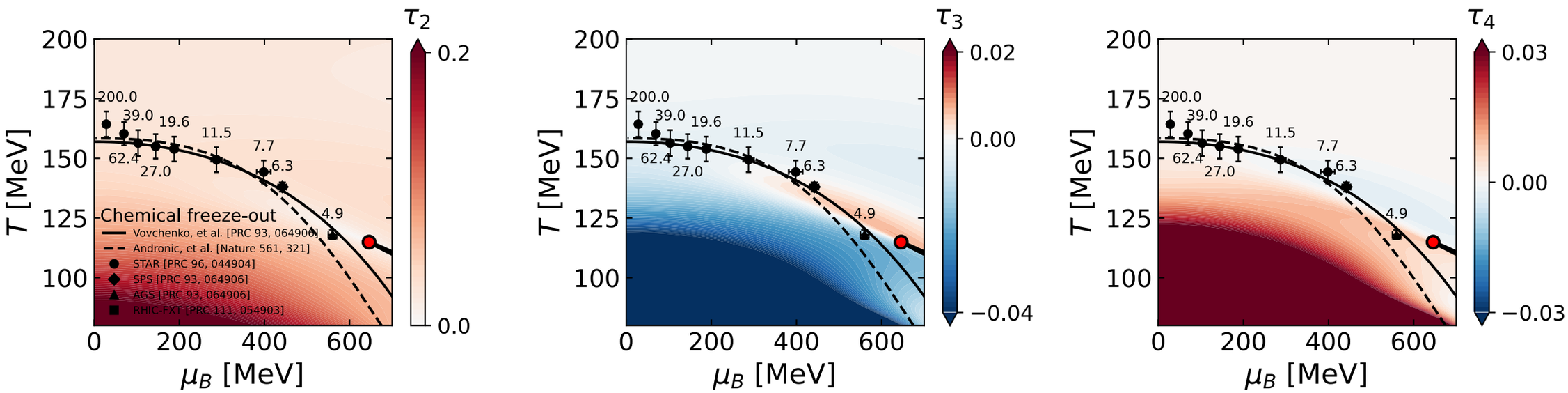




- **The magnitude of temperature fluctuations are increased with the decrease of collision energy.**
- **The skewness is negative.**

Jinhui Chen, WF, Shi Yin, Chunjian Zhang, *PRD* 114 (2026) 014064, arXiv:2504.06886.

Temperature fluctuations from Lattice QCD

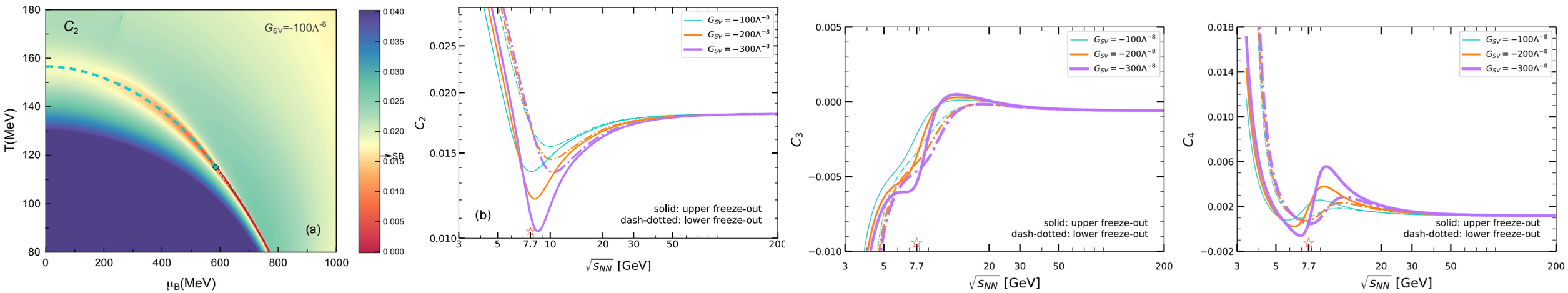


T. Gyure, H. Shah, L. Formaggio, F. Di Clemente, M. Hippert, C. Ratti, V. Vovchenko, arXiv:2610.20806.

- **The developed formalism has been used in the calculations.**
- **The EoS is based on lattice results at $\mu_B = 0$ and the extrapolation of contours of constant entropy density.**

Temperature fluctuations from other theoretical calculations

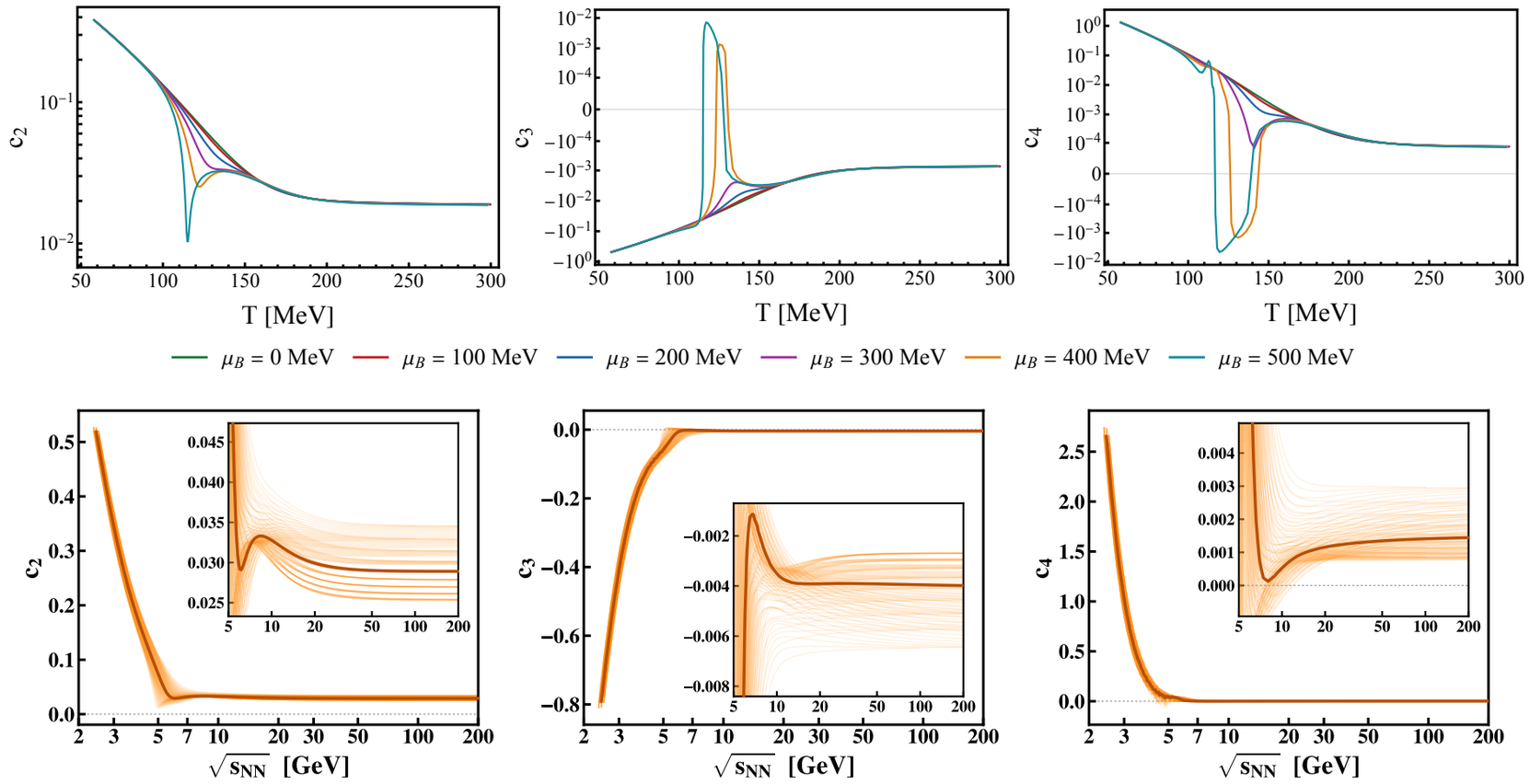
PNJL



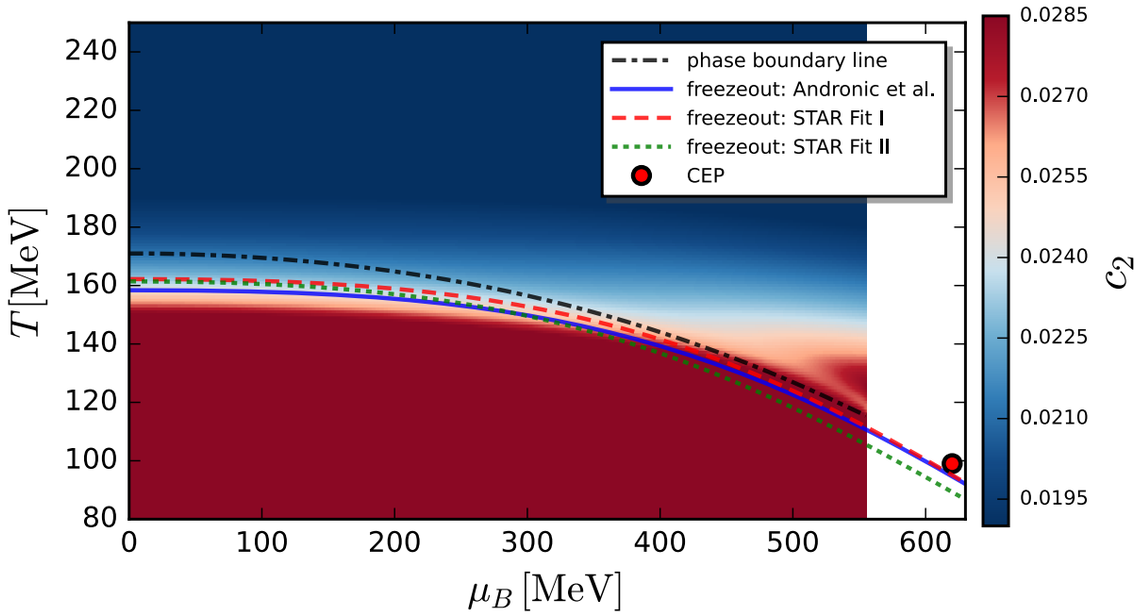
H. Liu, P. Wu, H.-M. Liu, P.-C. Chu, arXiv:2607.19275.

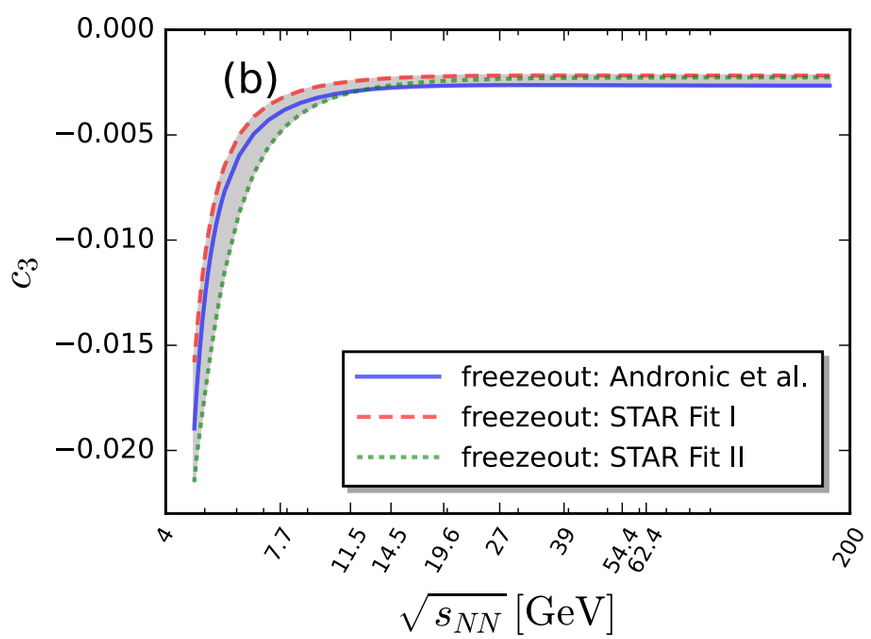
Holography

Y. Chen, P. Yan, Z. Li, arXiv:2610.34414.



Summary and outlook



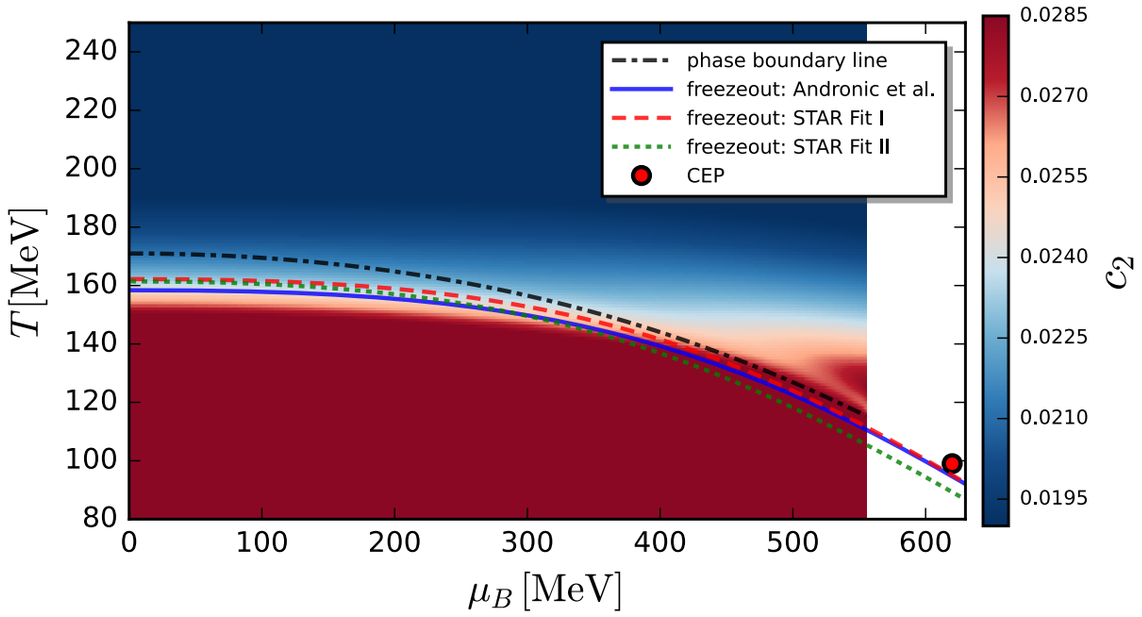


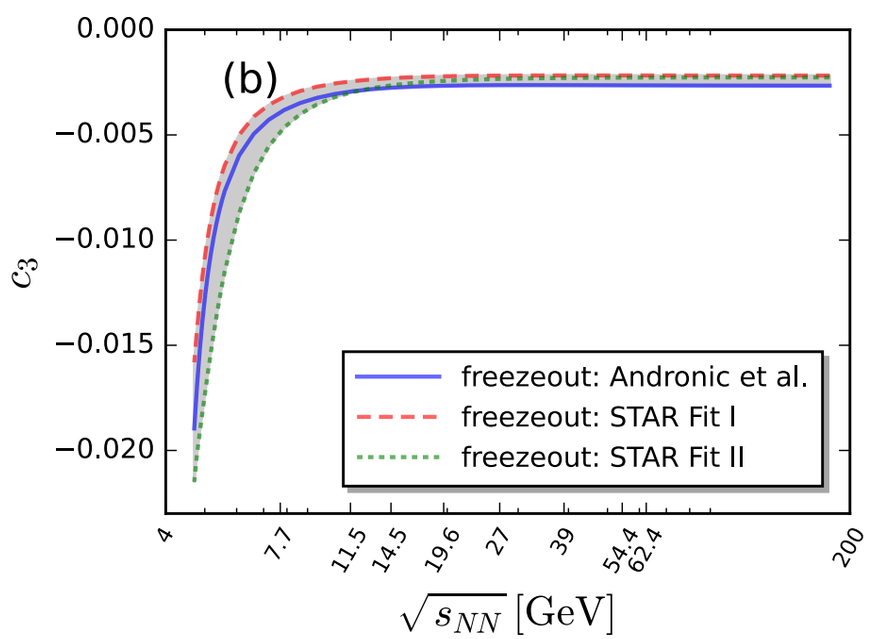
★ The temperature fluctuations carry information of thermodynamic properties of QCD matter at finite temperature and densities.

★ It is indispensable to separate the temperature fluctuations from other effects, such as the initial geometry fluctuations, flows, etc. in experiments, all of which are encoded in the mean pt fluctuations.

★ Skewness of temperature fluctuations may provide a clue, which is found to be negative, a general thermodynamic property of QCD matter. It may be a smoking-gun signature of the temperature fluctuations.

Summary and outlook





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Thank you very much for your attentions!

Backup