Baryon number fluctuations at large baryon chemical potentials

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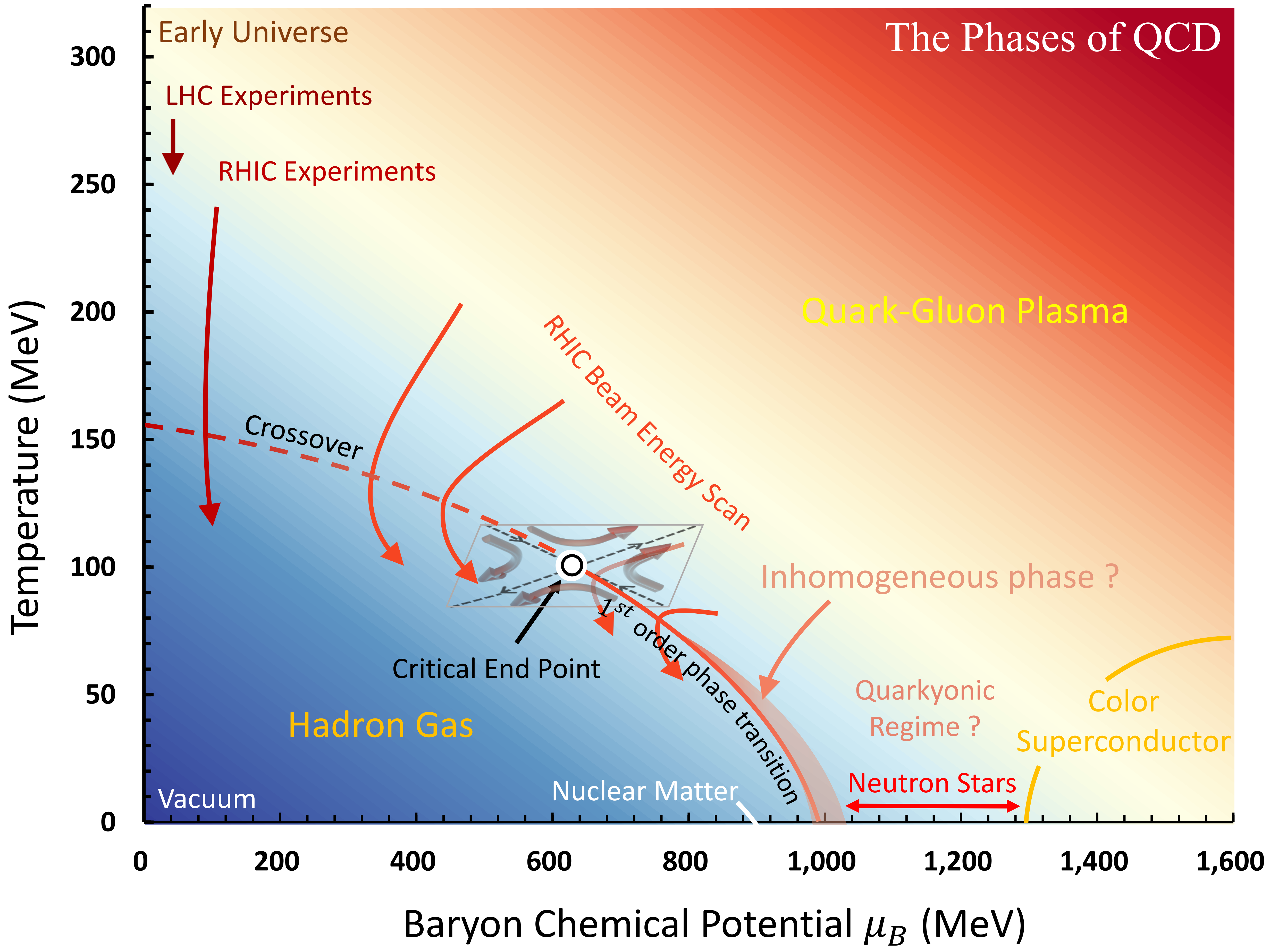
Based on:
[1] Wei-jie Fu, Xiaofeng Luo, Jan M. Pawlowski, Fabian Rennecke, Rui Wen, SY ; Phys. Rev. D 104 (2021), 094047.
[2] Wei-jie Fu, Xiaofeng Luo, Jan M. Pawlowski, Fabian Rennecke, Rui Wen, SY ; in preparation.

fQCD collaboration:
J. Braun, Y.-r. Chen, W.-j. Fu, F. Gao, Geissel, J. Horak, C. Huang, F. Ihssen, J. M. Pawlowski, F. Rennecke, F. Sattler, B. Schallmo, Y.-y. Tan, S. Töpfel, R. Wen, J. Wessely, N. Wink, S. Yin

Outline

- Introduction
- QCD-assisted LEFT within fRG
- Baryon number fluctuations on freeze-out curves
- Error estimates of theoretical predictions
- Summary and outlook

QCD phase diagram and CEP



Calls for:

- Nonperturbative approach of QCD.
- Error-controllable calculations at finite densities.
- Real-time description of strongly interacting systems.

Scaling of baryon number fluctuations

Baryon number fluctuations of the n-th order:

$$\chi_n^B = \frac{\partial^n}{\partial(\mu_B/T)^n}\frac{p}{T^4}$$

relation to the cumulant:

$$M = VT^3\chi_1^B, \qquad \sigma^2 = VT^3\chi_2^B,$$

$$S = \chi_3^B/(\chi_2^B\sigma), \qquad \kappa = \chi_4^B/(\chi_2^B\sigma^2)$$

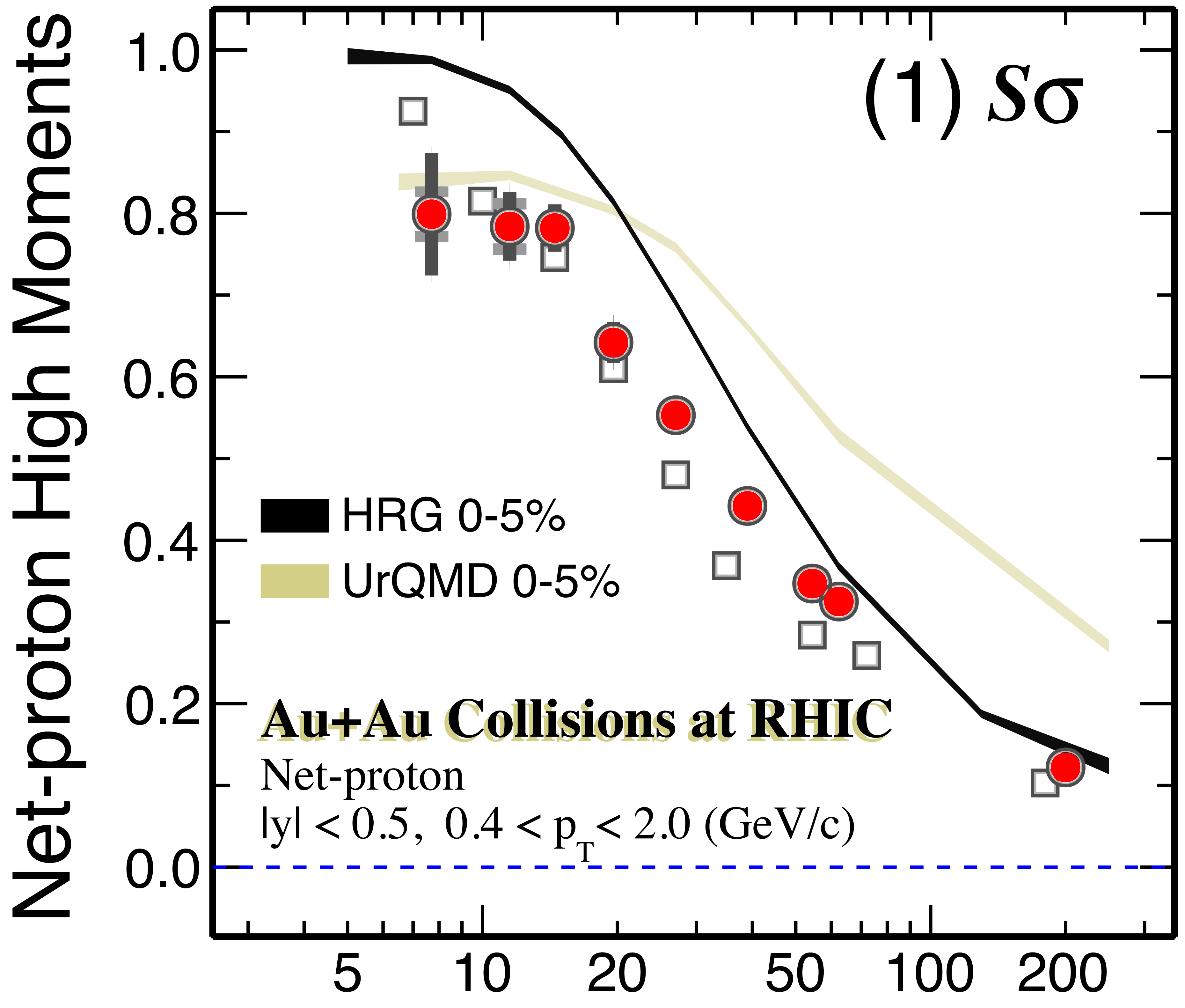
Scaling of fluctuations:

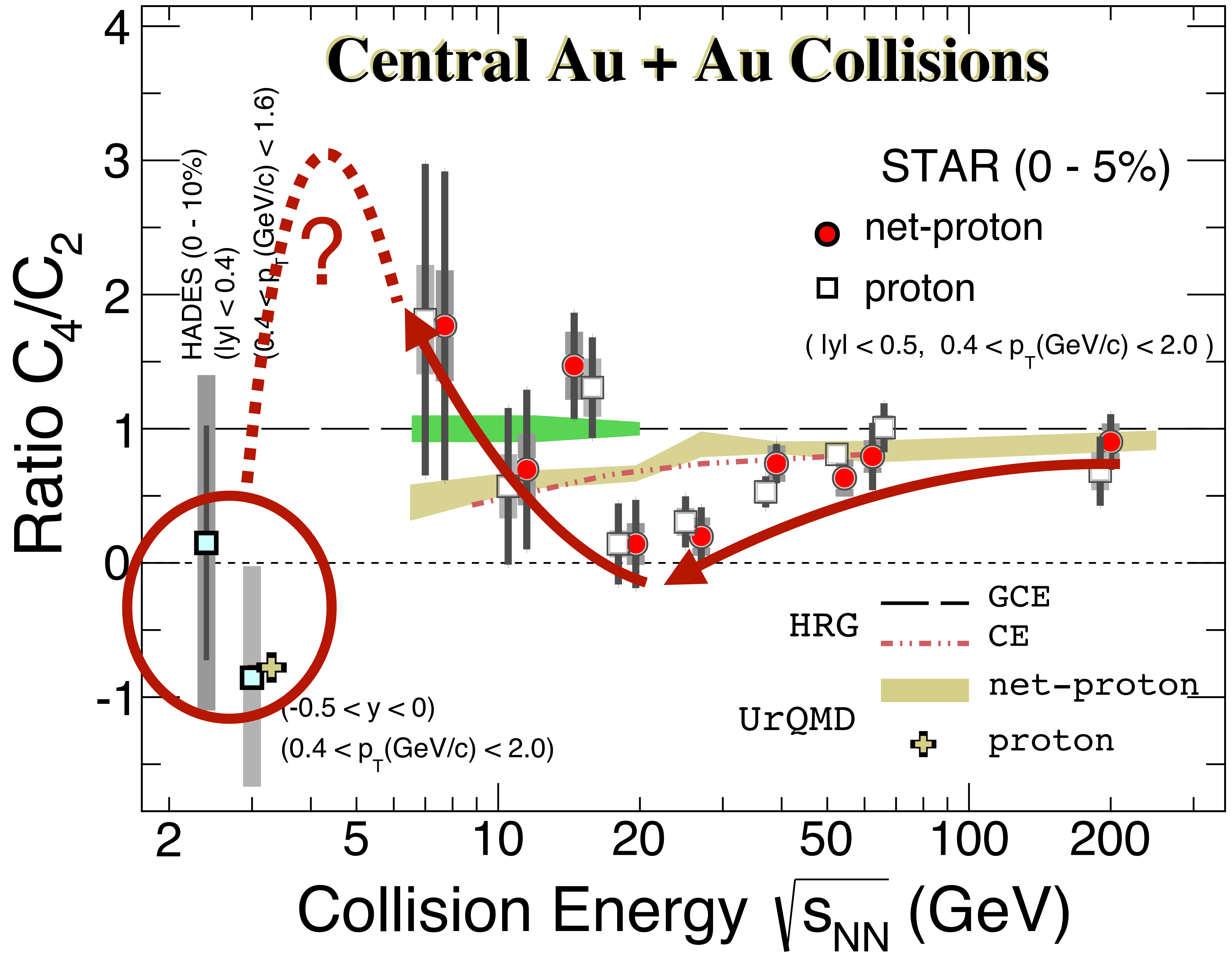
$$\chi_2^B \sim \xi^2, \qquad \chi_3^B \sim \xi^{4.5}, \qquad \chi_4^B \sim \xi^7$$

ξ: correlation length

Stephanov, *PRL* 102 (2009), 032301

Recent experimental results at RHIC



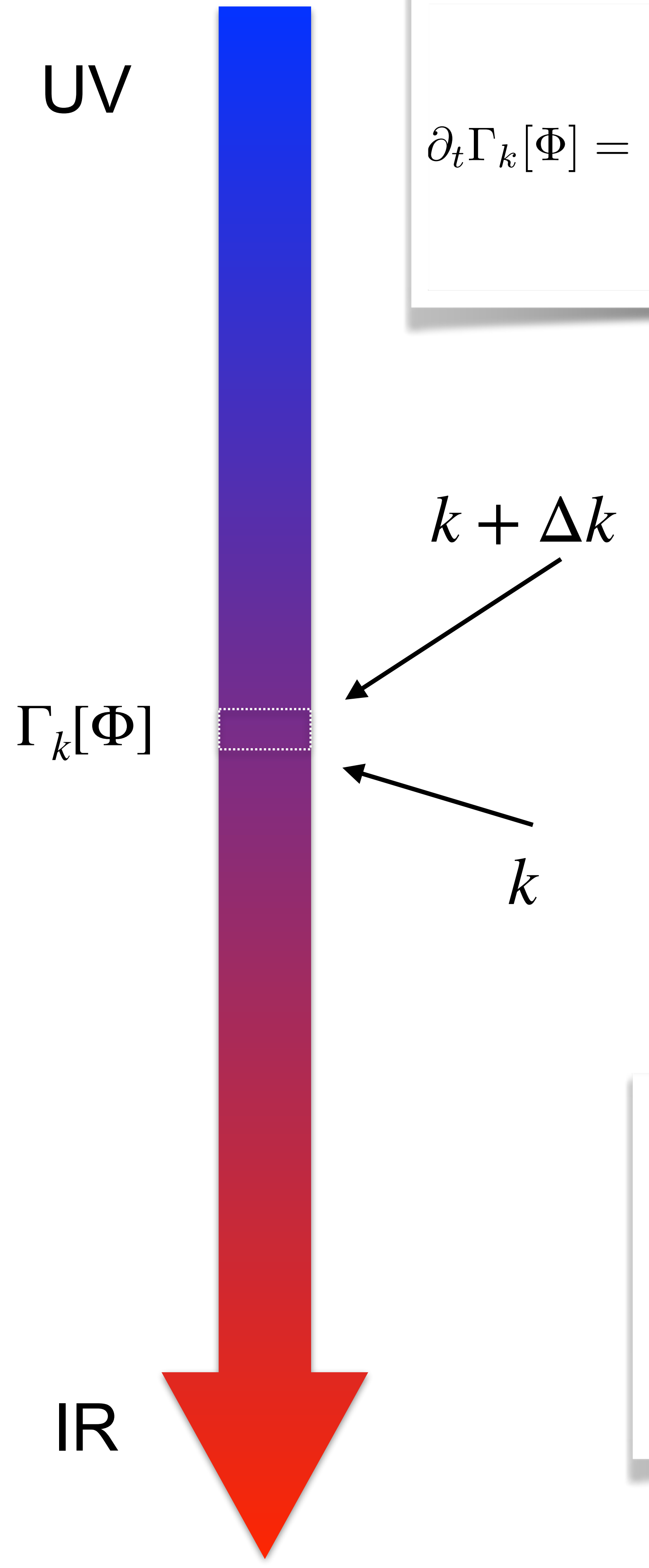


J. Adam *et al.* (STAR), *PRL* 126 (2021), 092301

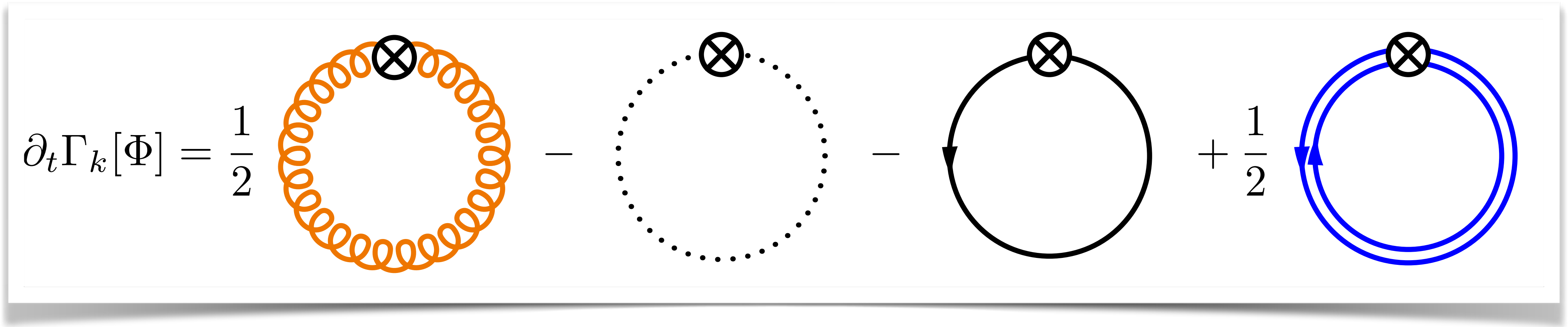
M. Abdallah *et al.* (STAR), *PRL* 128 (2022) 20, 202303

- The non-monotonicity of the kurtosis is observed with 3.1σ significance.
- Is there a "peak" structure in the regime of low colliding energy?

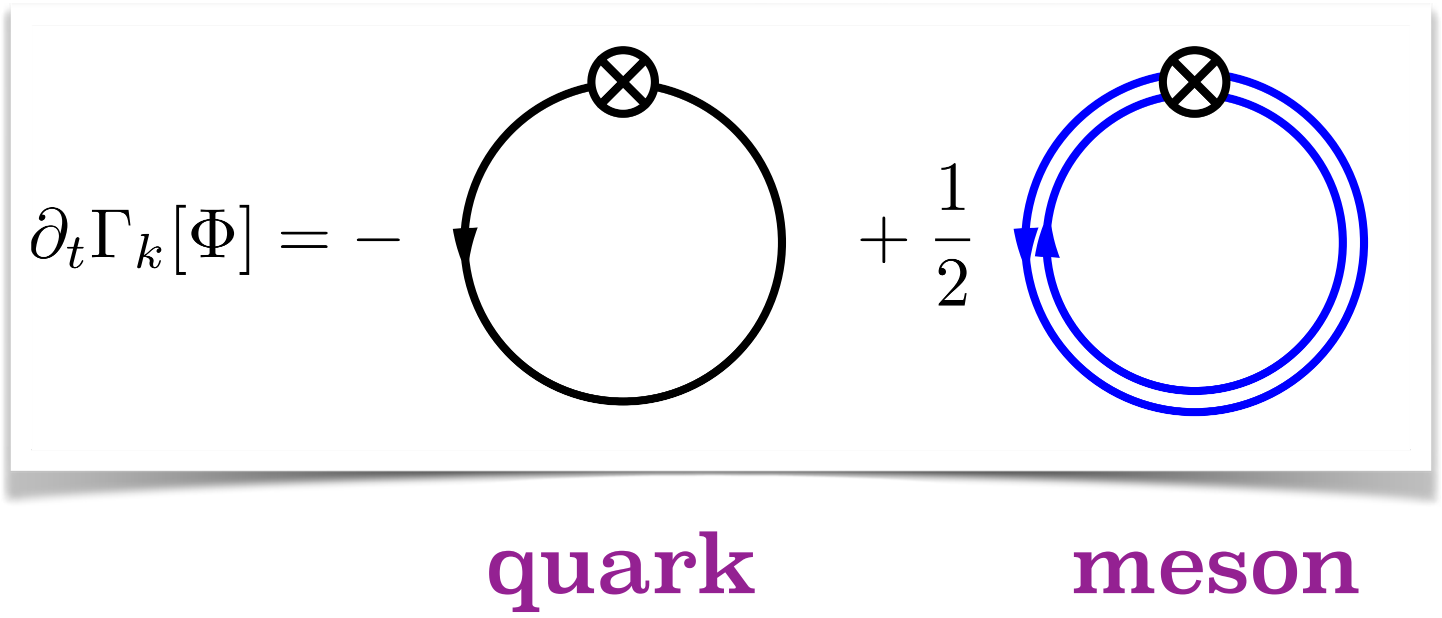
QCD-assisted LEFT within fRG

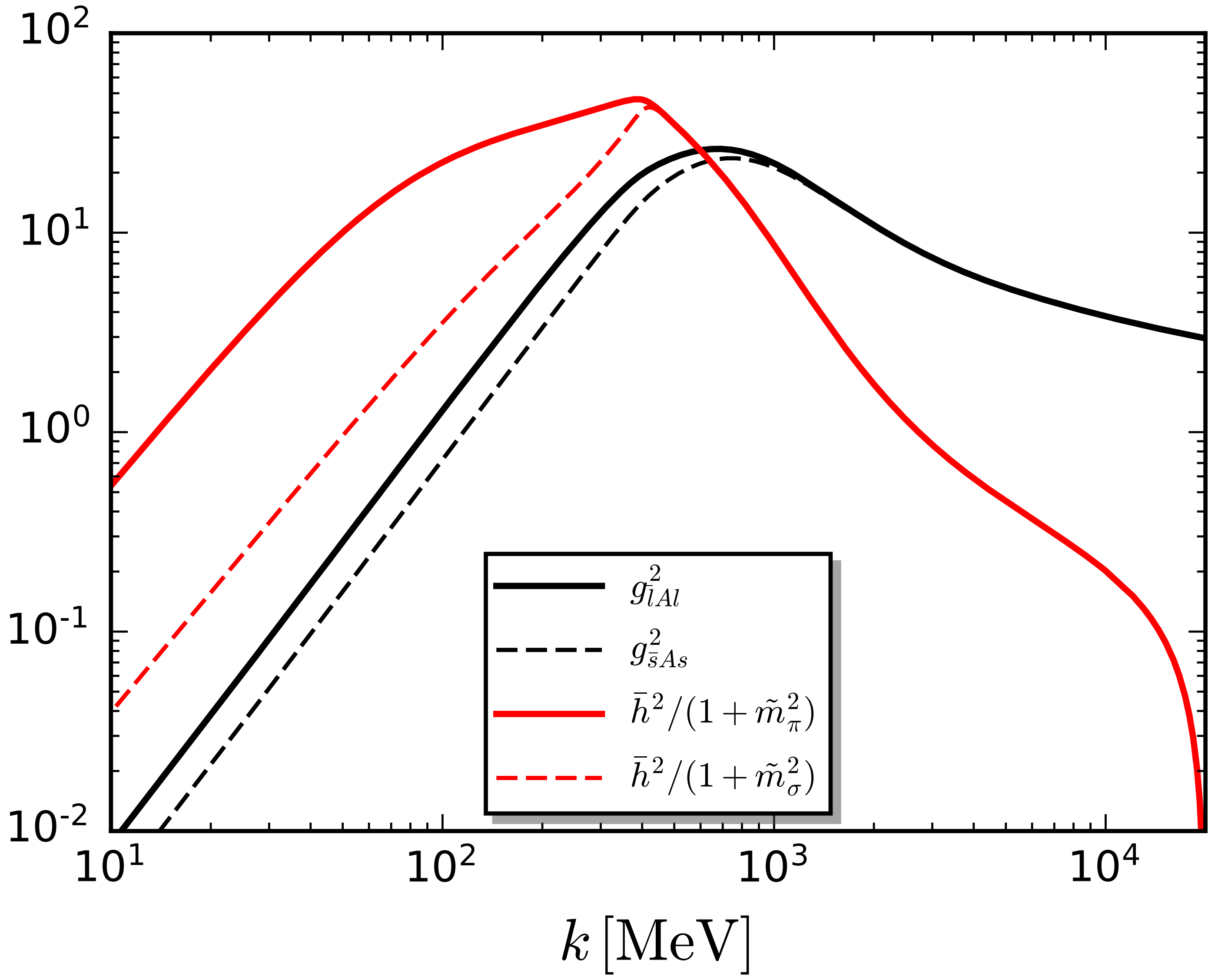


First Principle QCD flow equation:



LEFT flow equation:



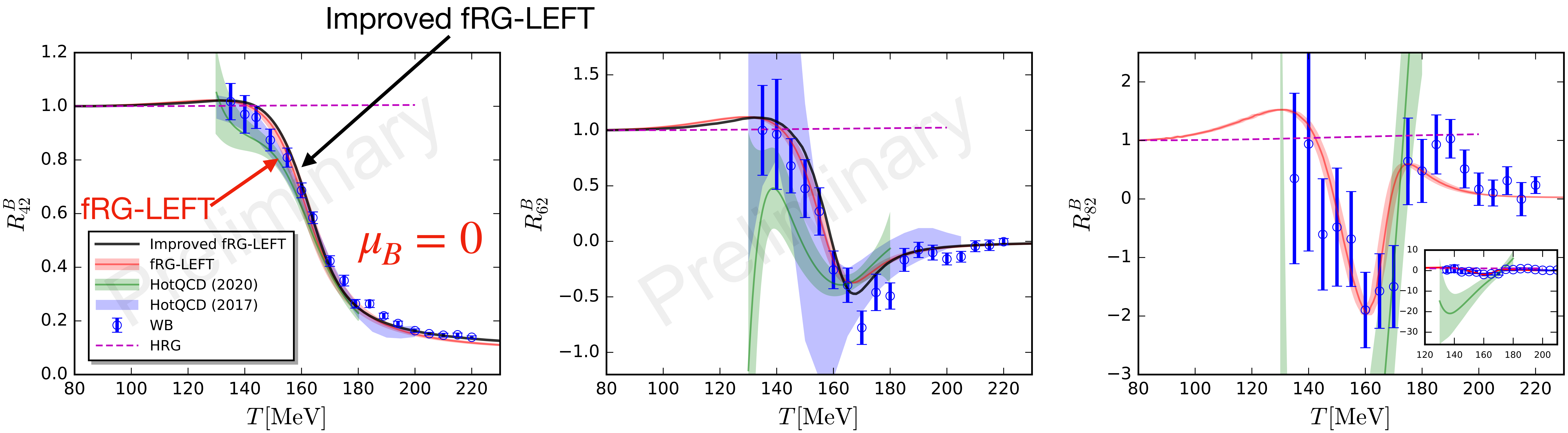


Exchange couplings

Fu, Pawlowski, Rennecke, *PRD* 101 (2020), 054032

- **fRG-LEFT have been improved.**
- **Dynamics of first-principle fRG-QCD has been encoded in the LEFT via the Yukawa coupling.**

Update: Baryon number fluctuations at $\mu_B = 0$



Improved fRG-LEFT: Fu, Luo, Pawlowski, Rennecke, Wen, SY; in preparation

fRG-LEFT: Fu, Luo, Pawlowski, Rennecke, Wen, SY, *PRD* 104 (2021) ,094047

HotQCD: A. Bazavov *et al.*, *PRD* 95 (2017), 054504; *PRD* 101 (2020), 074502

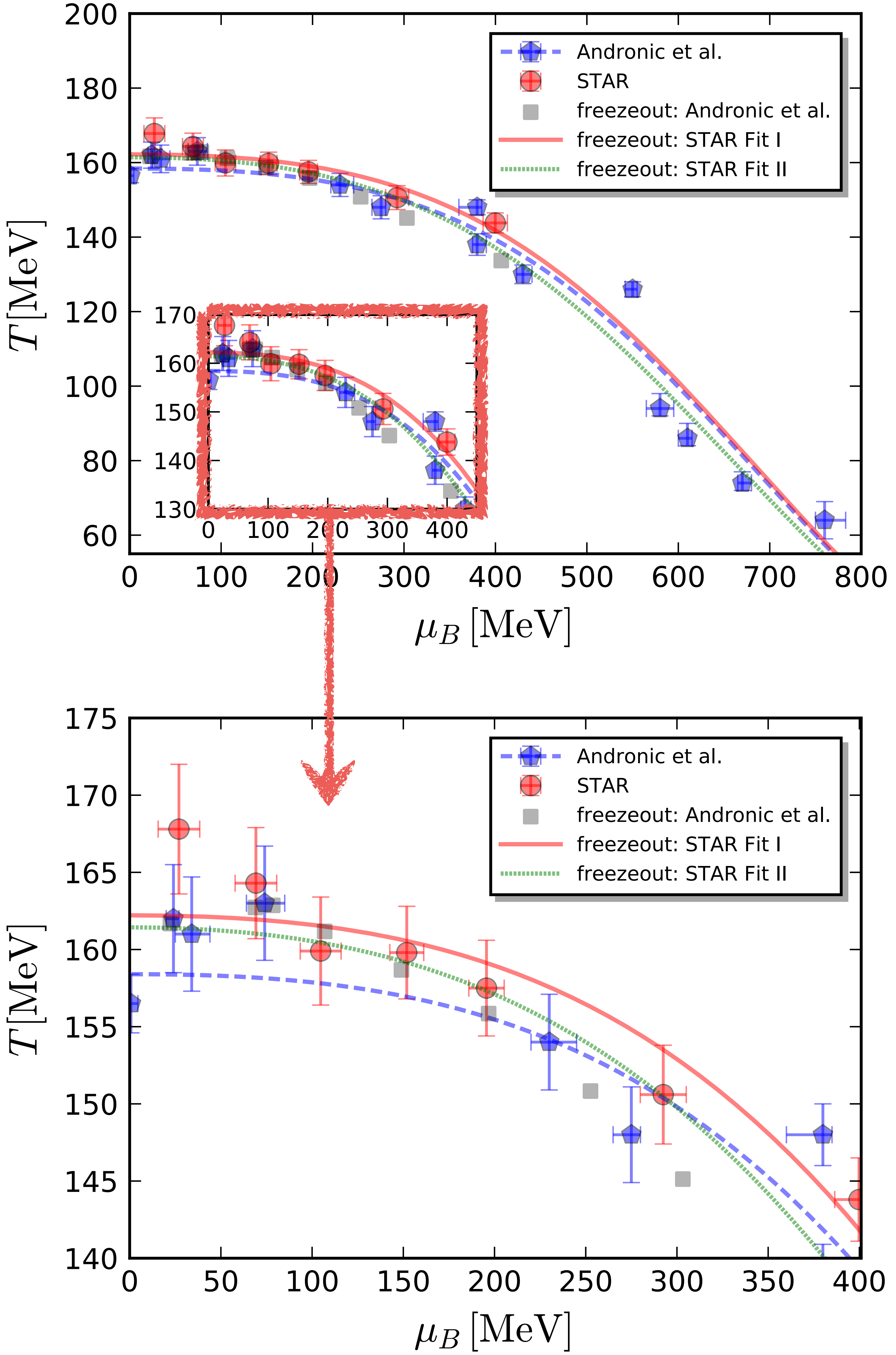
WB: S. Borsanyi *et al.*, *JHEP* 10 (2018) 205

baryon number fluctuations

$$\chi^B_n = \frac{\partial^n}{\partial(\mu_B/T)^n}\frac{p}{T^4} \qquad R^B_{nm} = \frac{\chi^B_n}{\chi^B_m}$$

⭐ In comparison to our former results and lattice results, the improved results of baryon number fluctuations at vanishing chemical potential are convergent and consistent.

Determination of the freeze-out curve



three freeze-out curves

1. freeze-out: Andronic *et al.*

Andronic, Braun-Munzinger, Redlich,
Nature 561 (2018) 7723, 321

$$\mu_{B\,\mathrm{CF}} = \frac{a}{1 + 0.288\sqrt{s_{\mathrm{NN}}}}\,,$$

$$T_{\mathrm{CF}} = \frac{T_{\mathrm{CF}}^{(0)}}{1 + \exp\left(2.60 - \ln(\sqrt{s_{\mathrm{NN}}})/0.45\right)}$$

2. freeze-out: STAR Fit I

L. Adamczyk *et al.* (STAR), *PRC* 96 (2017), 044904

all data points

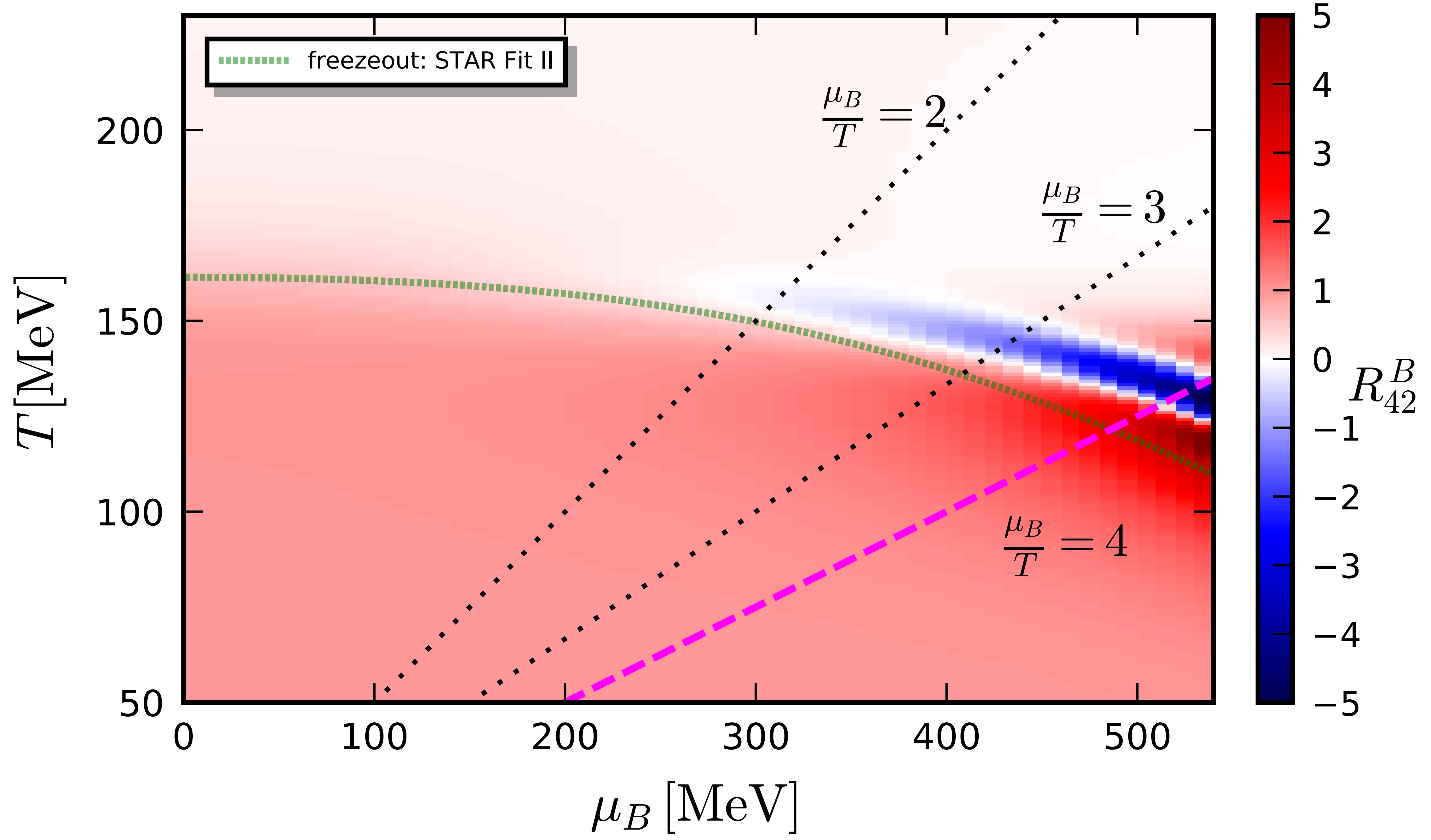
3. freeze-out: STAR Fit II

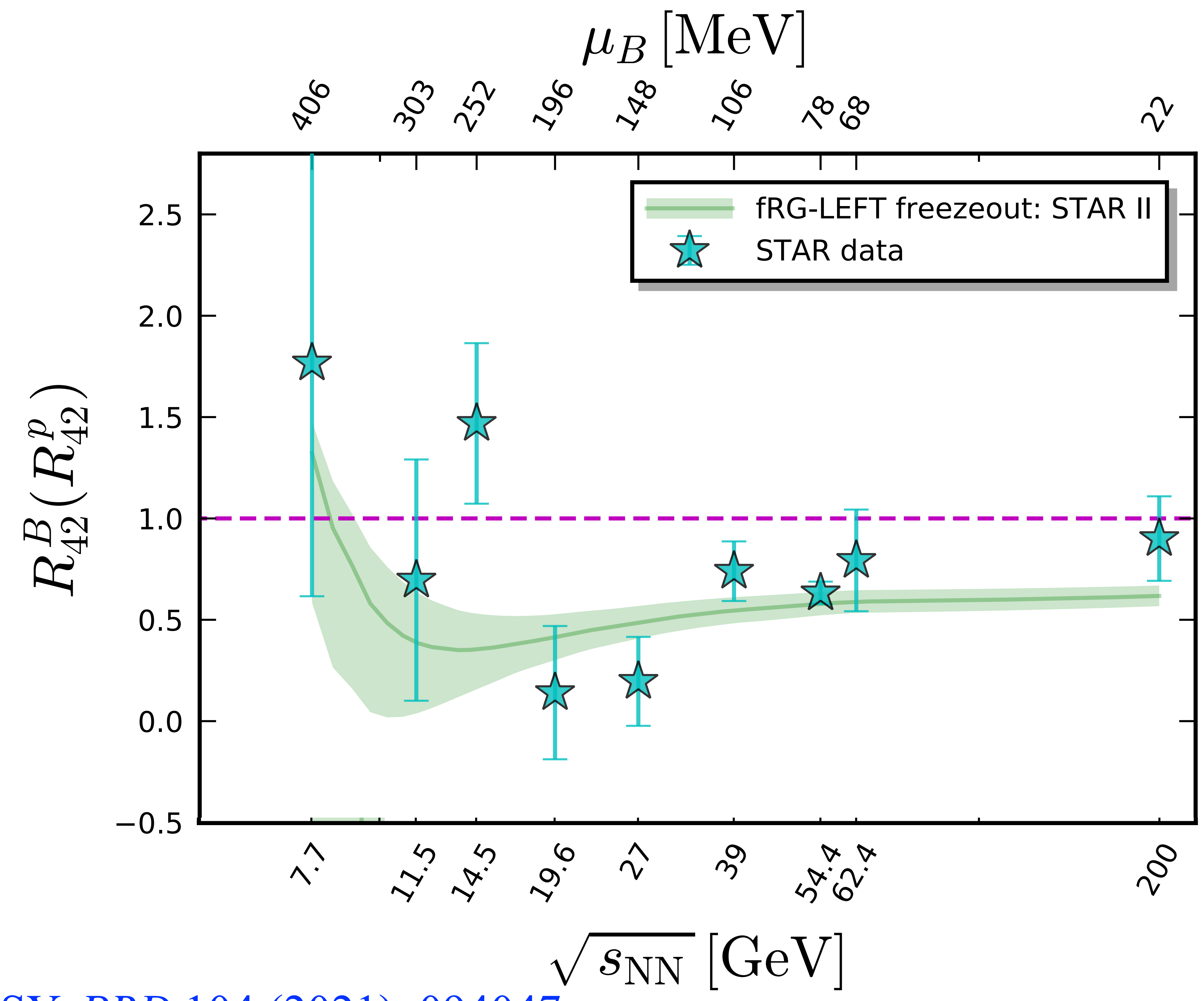
neglecting first two at low μ_B and the last one

- freeze-out curve should not rise with μ_B
- convexity of the freeze-out curve

Fluctuations on the freeze-out curve

fRG-LEFT





Fu, Luo, Pawlowski, Rennecke, Wen, SY, *PRD* 104 (2021) ,094047

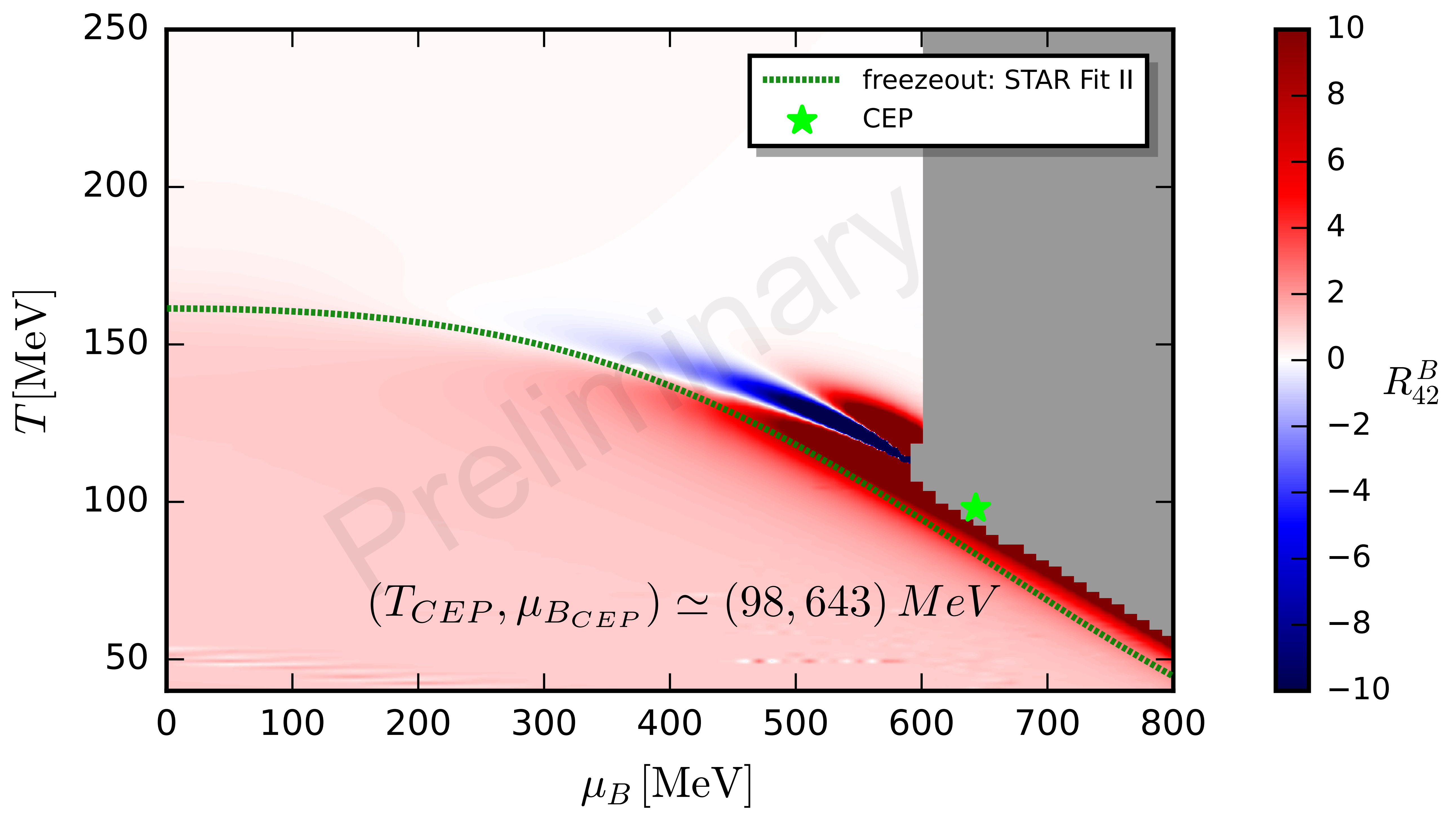
Caveat !

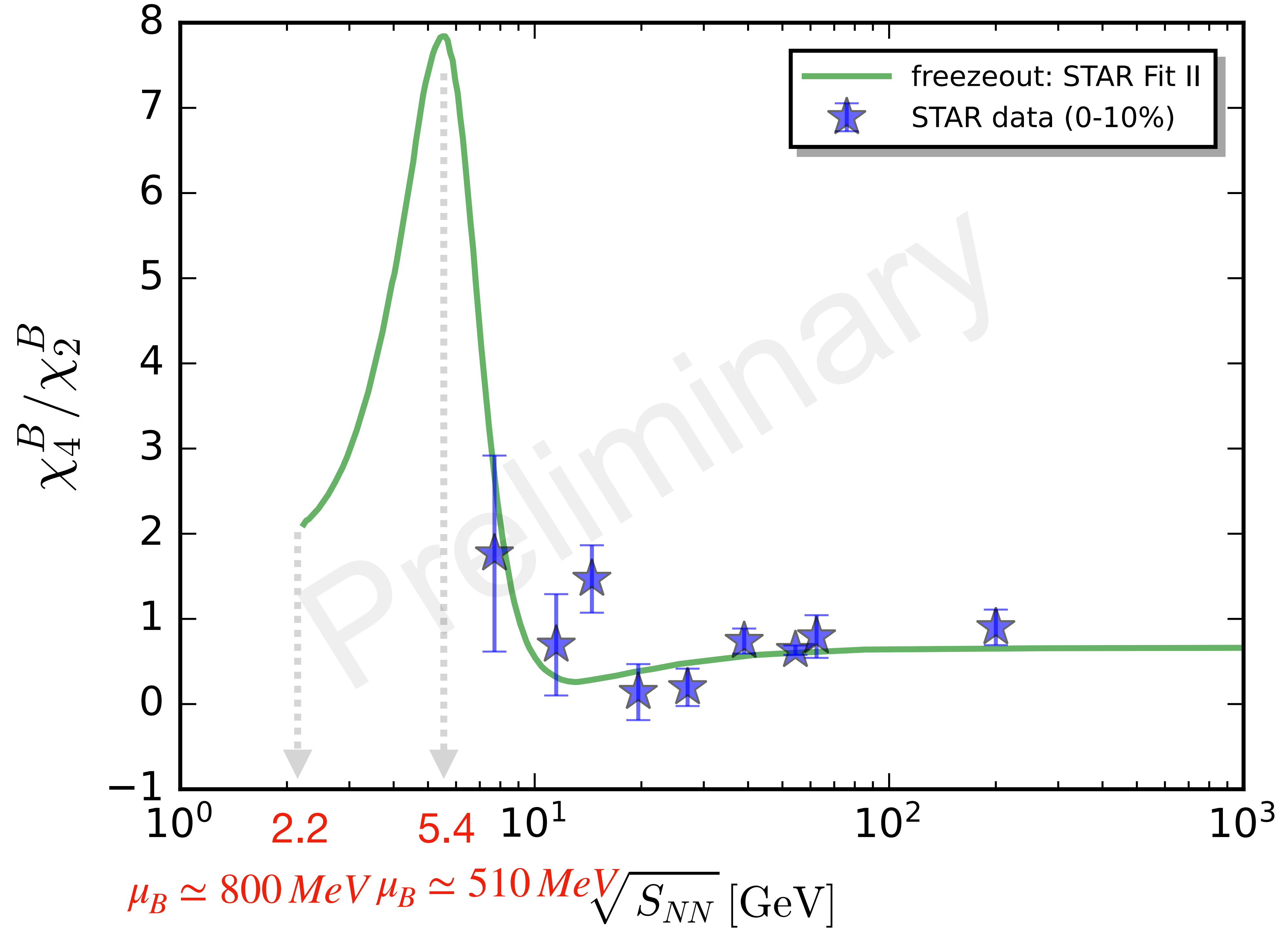
⭐ The calculation here is based on the grand canonical ensemble. The global charge conservation effect is not taken into account.

⭐ The current results are obtained in the equilibrium system.

Update: Fluctuations on the freeze-out curve

Improved fRG-LEFT

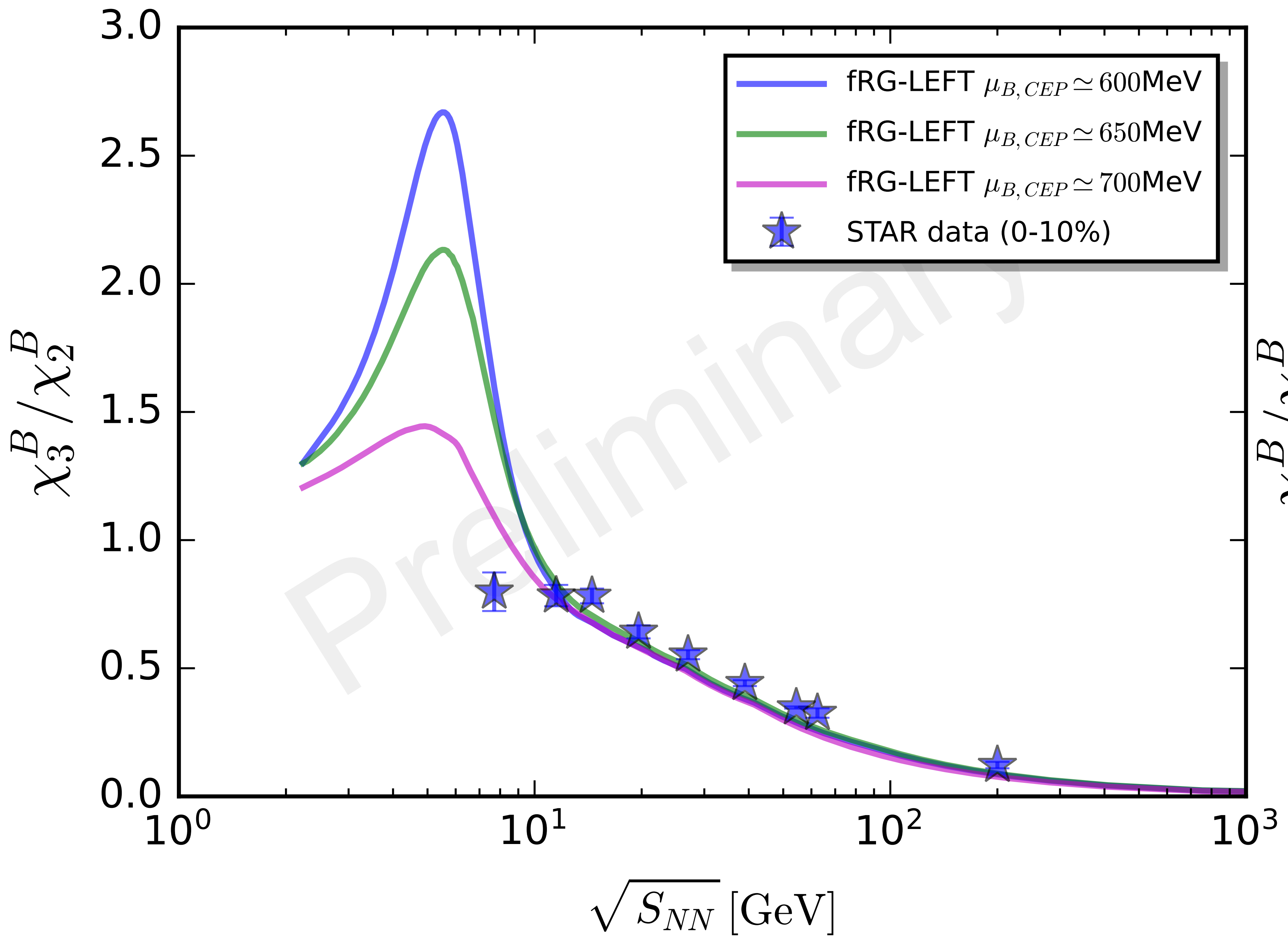


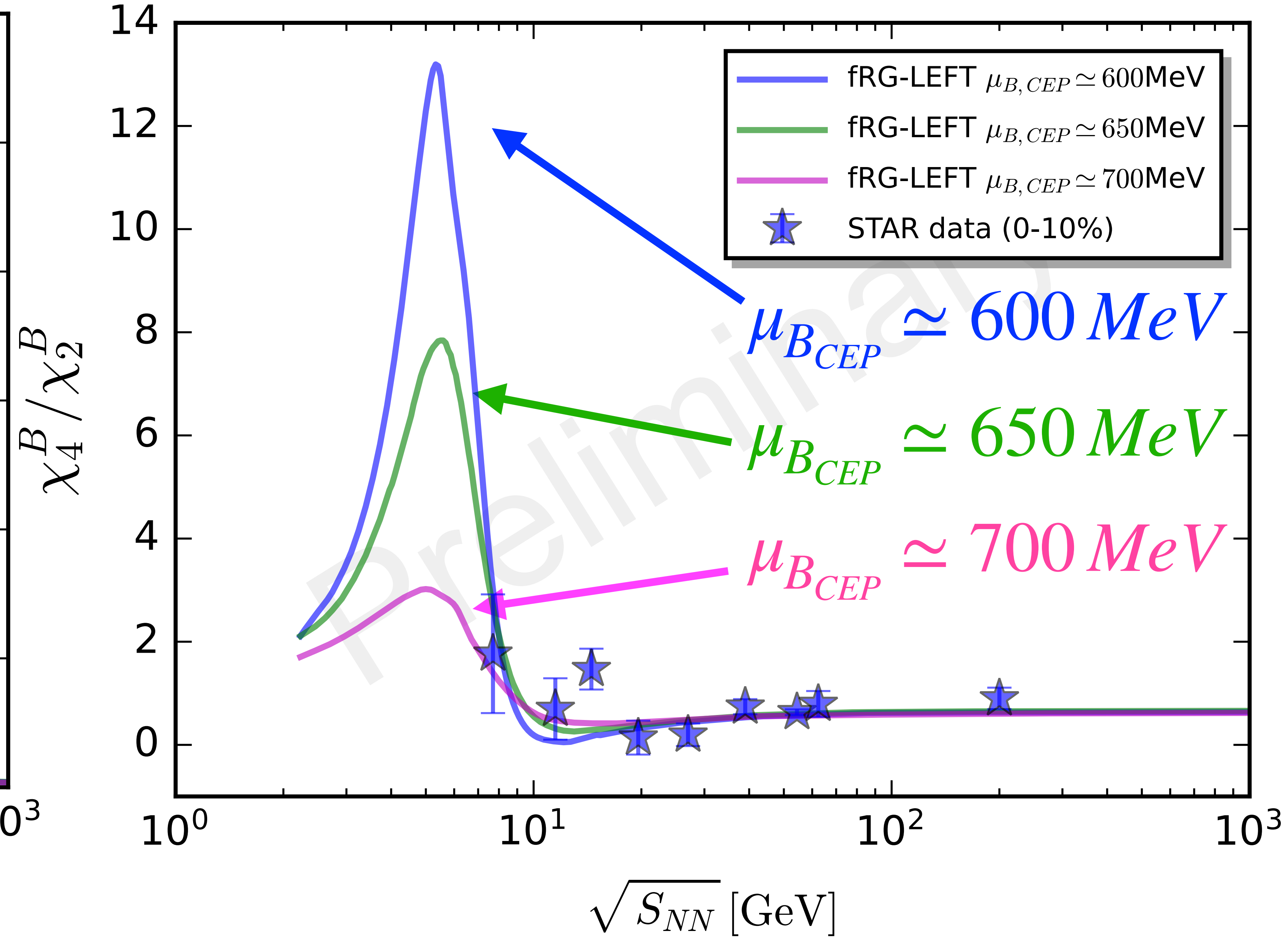


Fu, Luo, Pawlowski, Rennecke, Wen, SY; in preparation

- Calculations have been extended from $\mu_B \sim$ 500 to 800 MeV in the improved fRG-LEFT.
- A "peak" structure is found in the regime of low collision energy.

Error estimate: Location of CEP

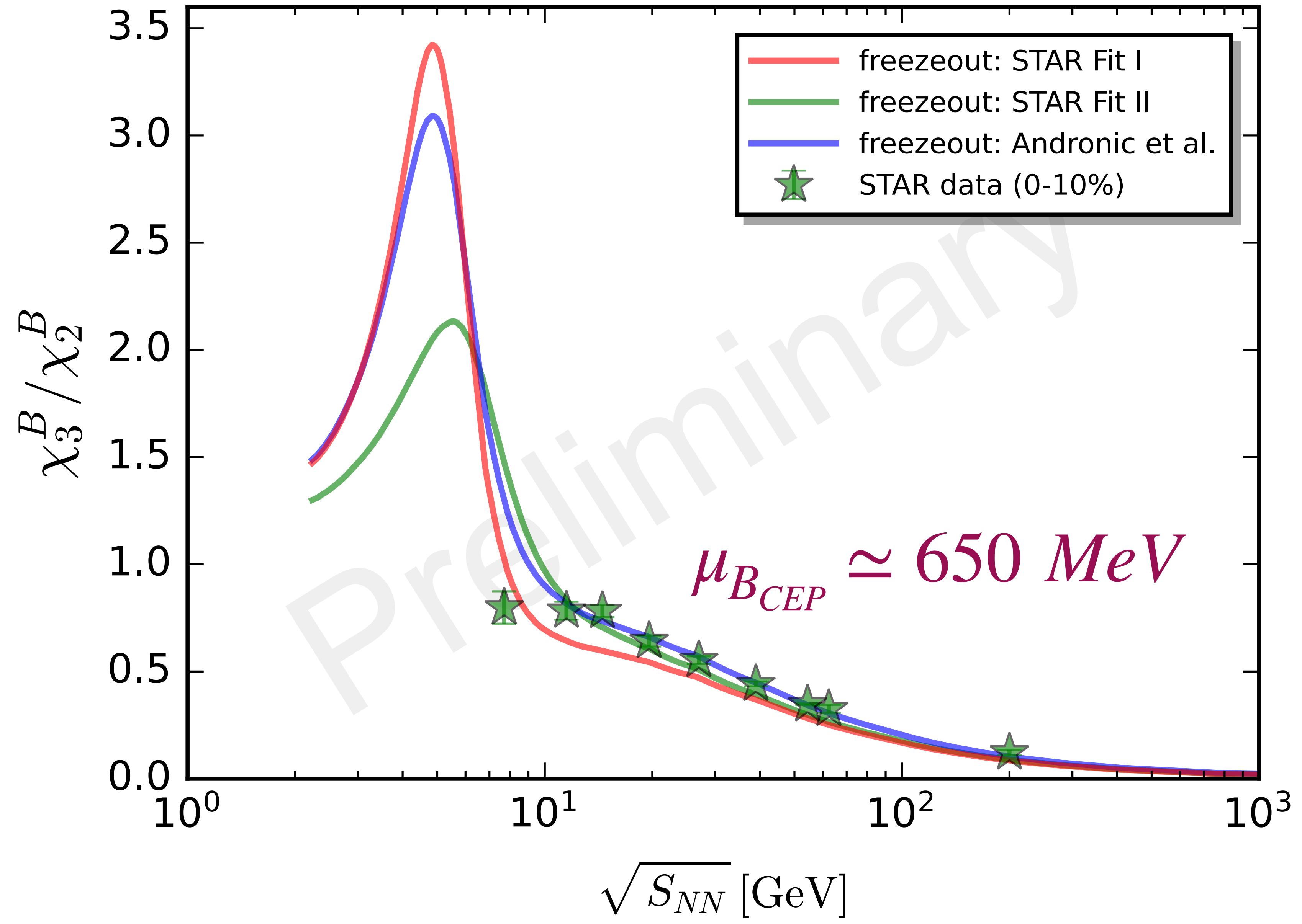


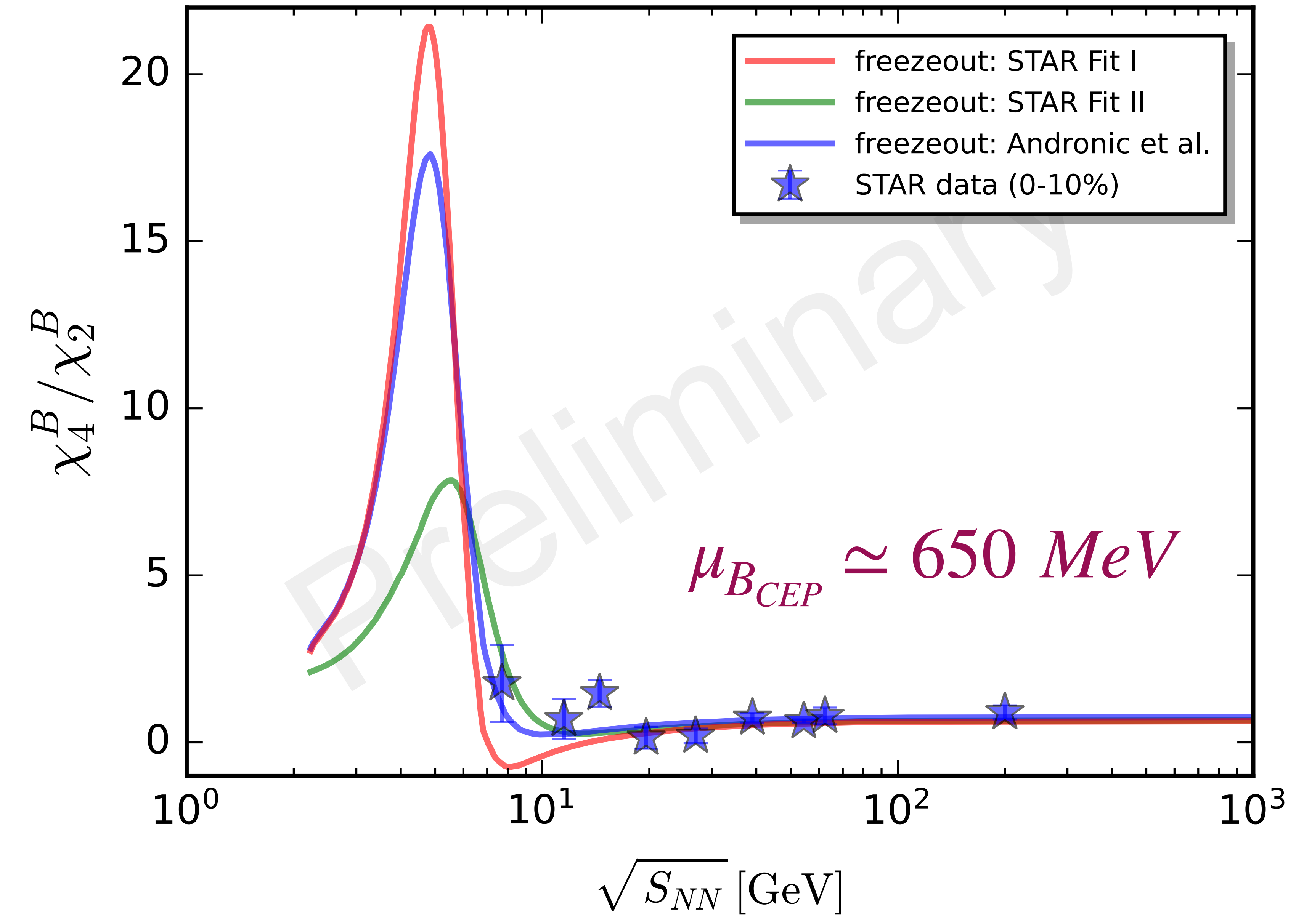


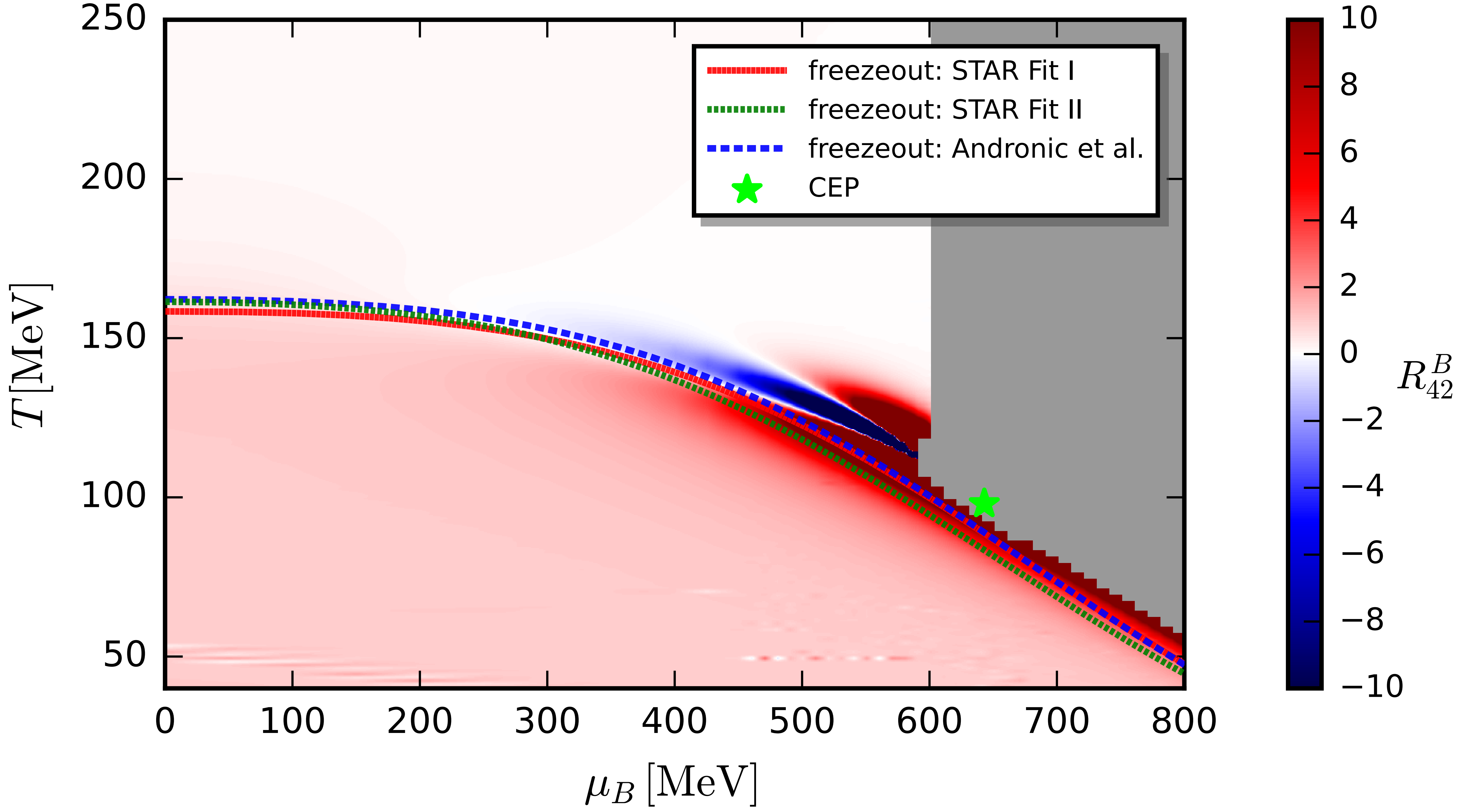
- Location of the peak, i.e., the corresponding collision energy shows very mild dependence on the location of CEP in the range $\mu_{B_{\rm CEP}} \simeq (600 \sim 700)$ MeV.
- While the height of the peak shows significant dependence.

Fu, Luo, Pawlowski, Rennecke, Wen, SY; in preparation

Error estimate: Different freeze-out curves







- Height and location of the peak are influenced by different freeze-out curves, especially for the height.
- Closer the freeze-out curve is to the phase boundary, higher the peak.

Fu, Luo, Pawlowski, Rennecke, Wen, SY; in preparation

Summary and outlook

- A peak structure of the kurtosis of the baryon number fluctuations as a function the collision energy is found in the regime of low collision energy, where the computation is done in a QCD assisted LEFT within the fRG approach.
- The height of peak is influenced by the location of CEP and freeze-out curves in the phase diagram.
- The location of the peak shows very mild dependence on the location of CEP, and weak dependence on freeze-out curves.

✦ First-principle QCD calculations at large baryon chemical potential to pin down the location of CEP and more experimental data to determine the freeze-out curves are highly required.

✦ Important effect in the region of large baryon chemical potentials, such as the global baryon number conservation, should be taken into account.

Thanks for your attention !

Back up

Considering Global charge conservation effect

$$\frac{\kappa_2[B_1]}{\kappa_1[B_1]} = (1-\alpha)\,\frac{\chi_2^B}{\chi_1^B},$$
$$\frac{\kappa_3[B_1]}{\kappa_2[B_1]} = (1-2\alpha)\,\frac{\chi_3^B}{\chi_2^B},$$
$$\frac{\kappa_4[B_1]}{\kappa_2[B_1]} = (1-3\alpha\beta)\,\frac{\chi_4^B}{\chi_2^B} - 3\alpha\beta\left(\frac{\chi_3^B}{\chi_2^B}\right)^2$$

V. Vovchenko et al., *Phys.Lett.B* 811 (2020) 135868

⭐Considering conserved charge measured in a subvolume of a thermal system.

$V_1 = \alpha V$ — α is the proportion of the subvolume to the total volume.

$\beta = 1 - \alpha$ — β is the proportion of the remaining volume.

QCD-assisted LEFT within fRG

Rescale coefficients

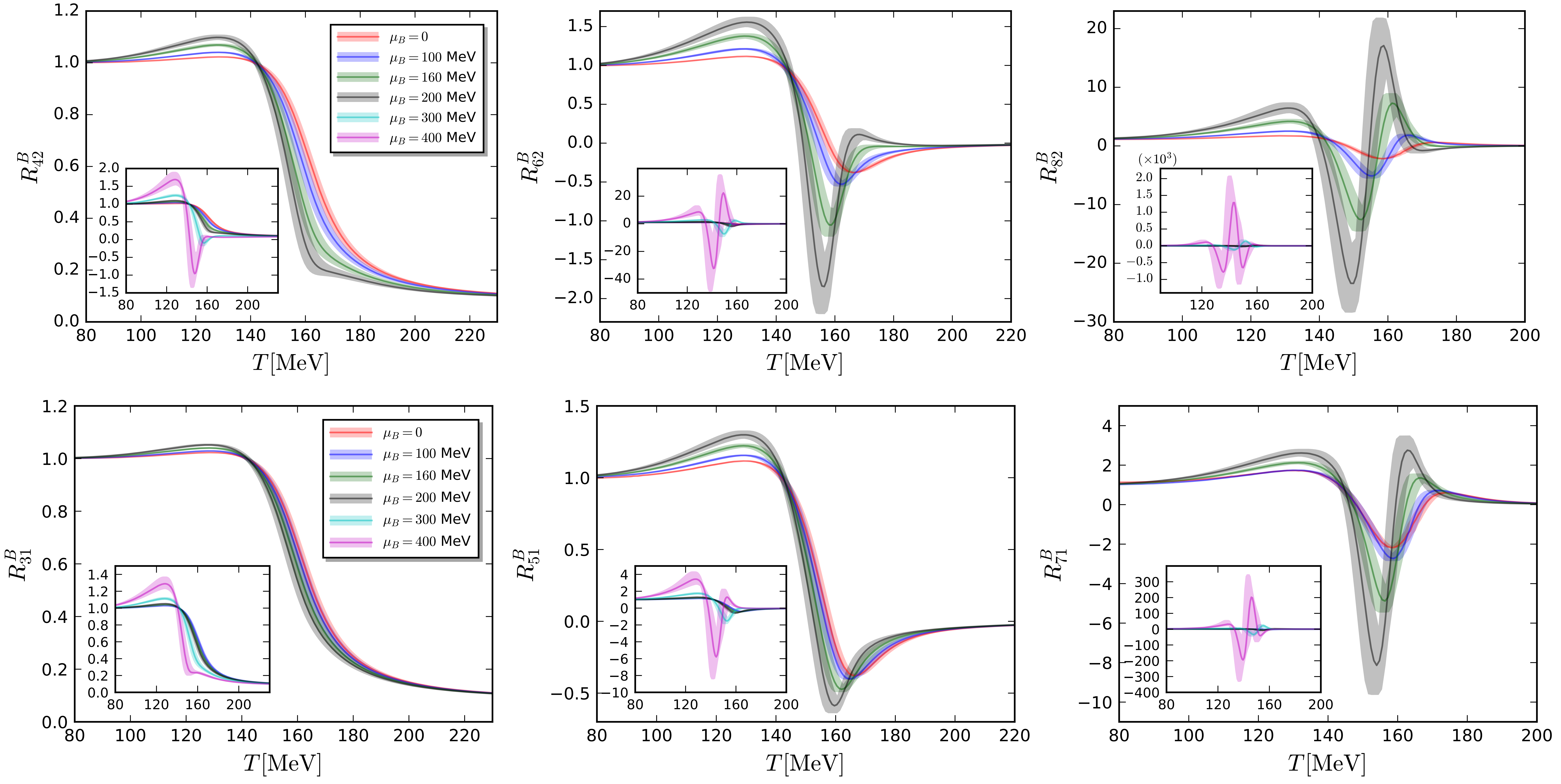
$$T_{LEFT} = c_T T, \quad \mu_{B_{LEFT}} = c_\mu \mu_B$$

$$c_T = \frac{T_{c,LEFT}}{T_{c,QCD}} \simeq 1.247(12) \quad c_{\mu_B} = \frac{\kappa_{LEFT}}{\kappa_{QCD}} \simeq 1.110(66)$$

$$\frac{T_c(\mu_B)}{T_c} = 1 - \kappa\left(\frac{\mu_B}{T_c}\right)^2 + \lambda\left(\frac{\mu_B}{T_c}\right)^4 + \cdots$$

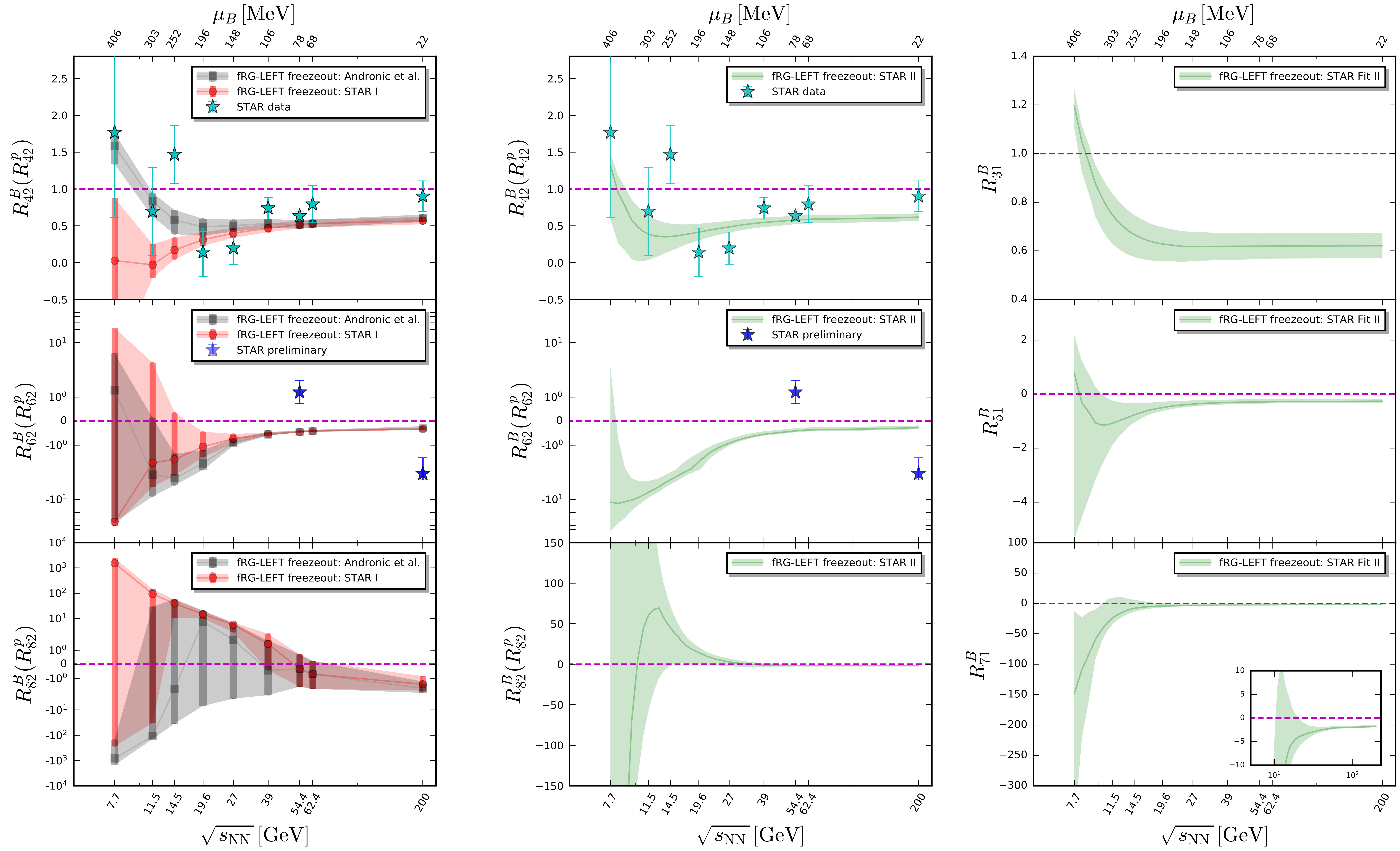
Fu, Luo, Pawlowski, Rennecke, Wen, SY, *PRD* 104 (2021) , 094047

Baryon number fluctuations at finite density



Fu, Luo, Pawlowski, Rennecke, Wen, SY, *PRD* 104 (2021) , 094047

Baryon number fluctuations on the freeze-out curve



Fu, Luo, Pawlowski, Rennecke, Wen, SY, *PRD* 104 (2021) , 094047

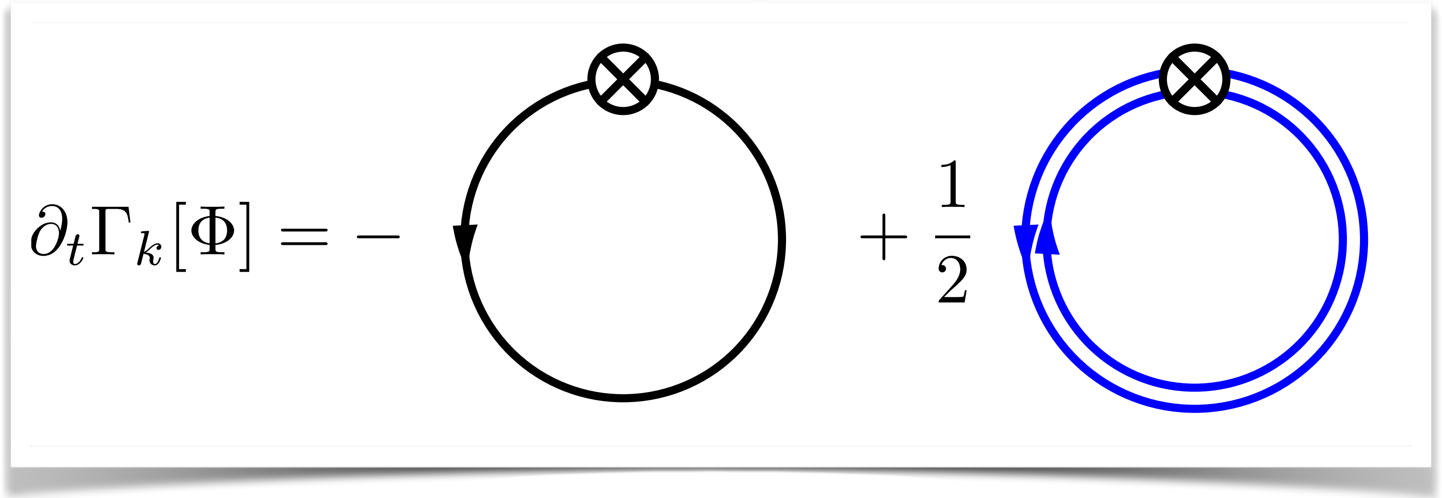
QCD-assisted LEFT within fRG

Effective action:

$$\Gamma_k = \int_x \Big\{ Z_{q,k}\bar{q}\big(\gamma_\mu\partial_\mu - \gamma_0(\mu + igA_0)\big)q + \frac{1}{2}Z_{\phi_k}\left(\partial_\mu\phi\right)^2 + h_k\bar{q}\big(T^0\sigma + i\gamma_5\boldsymbol{T}\cdot\boldsymbol{\pi}\big)q + V_k(\rho) - c\sigma \Big\}$$

h_k is the Yukawa coupling

LEFT flow equation:

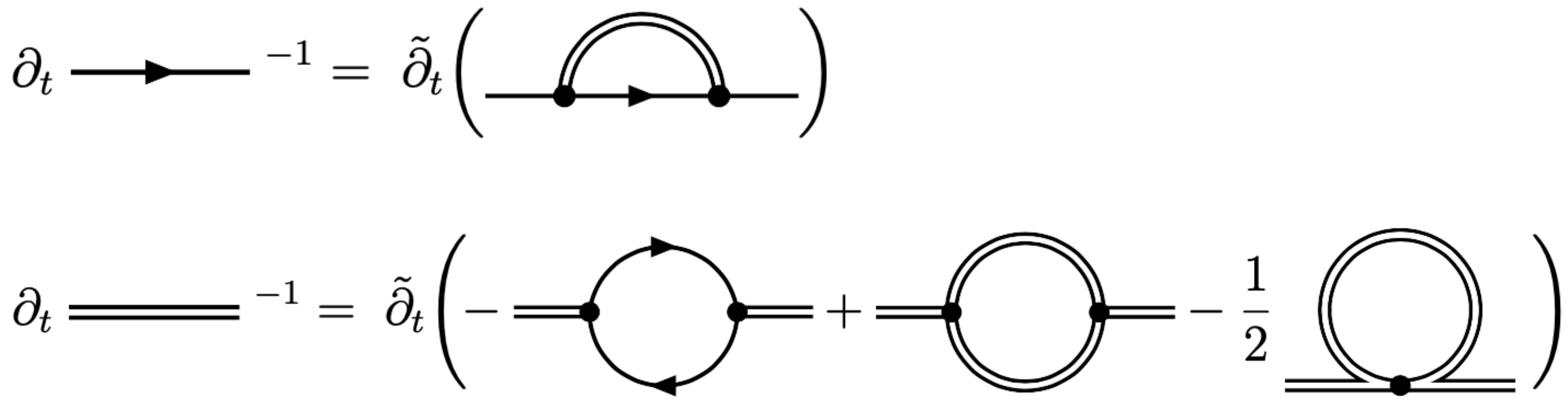


quark meson

⭐ The flow of Yukawa coupling is taken from the fRG-QCD computation.

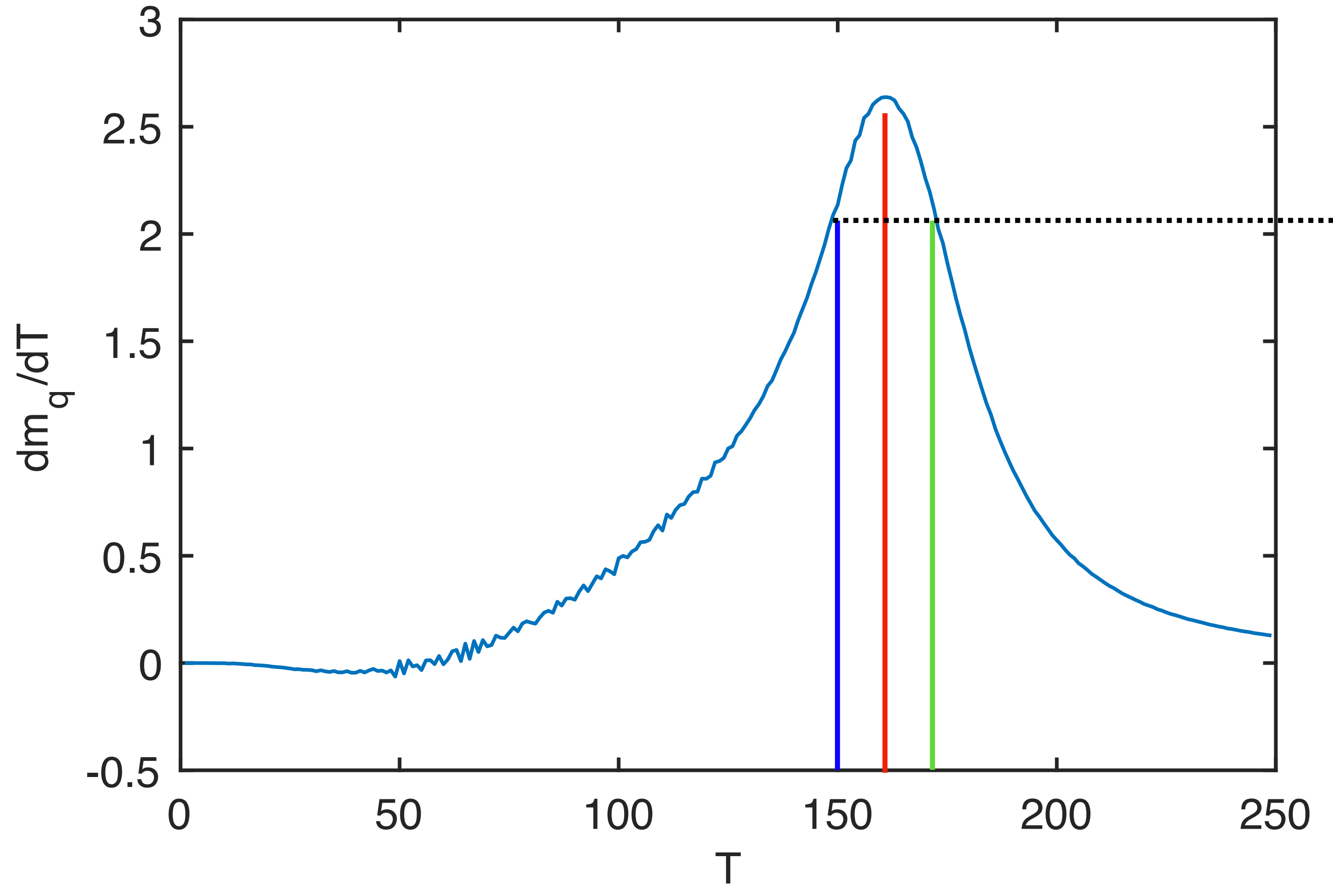
Fu, Pawlowski, Rennecke, *PRD* 101 (2020), 054032

Flow equations of two-point functions:



Determination of Critical point

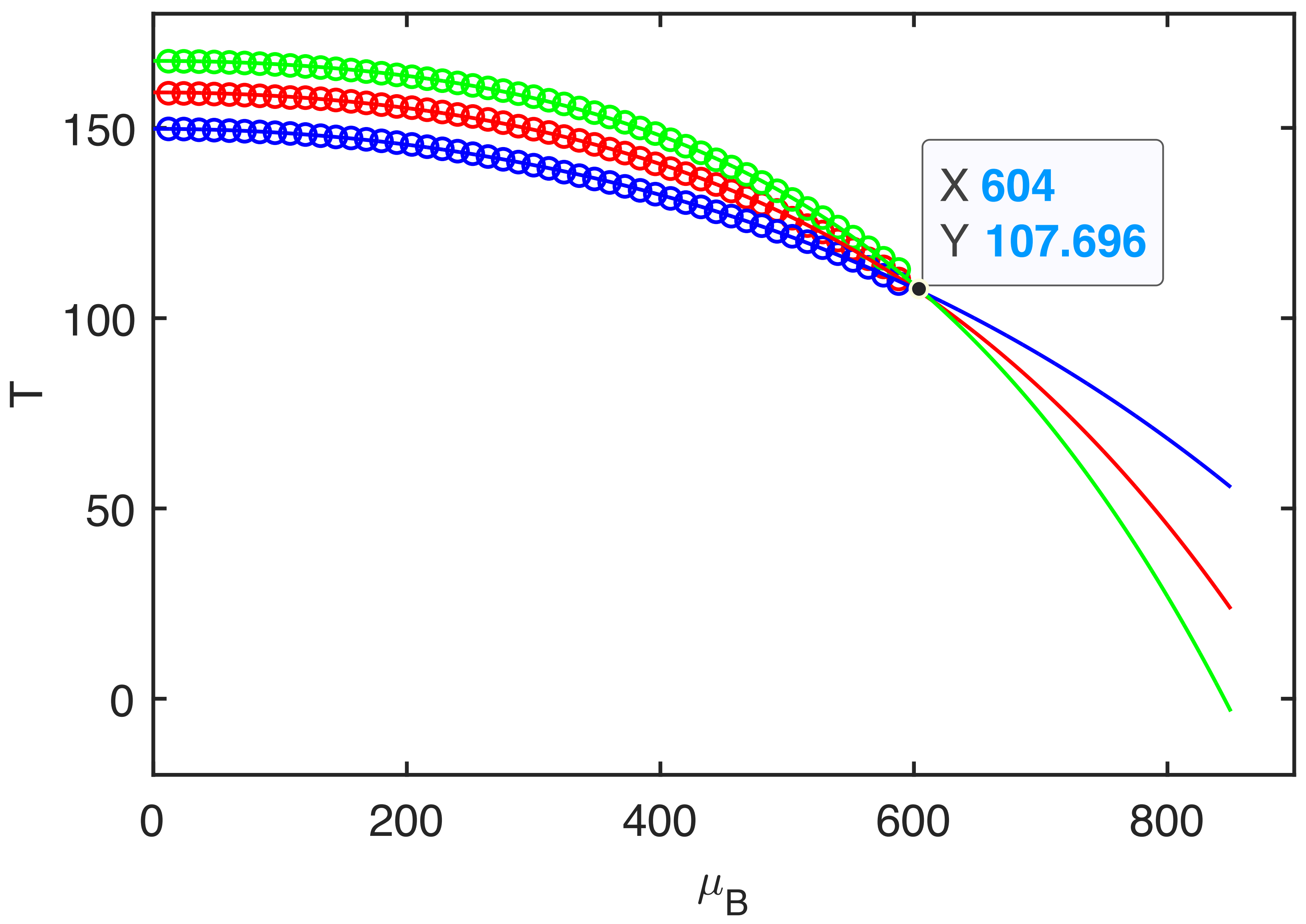
Here we use the thermal derivative of the quark mass to determine the phase boundary and critical point.

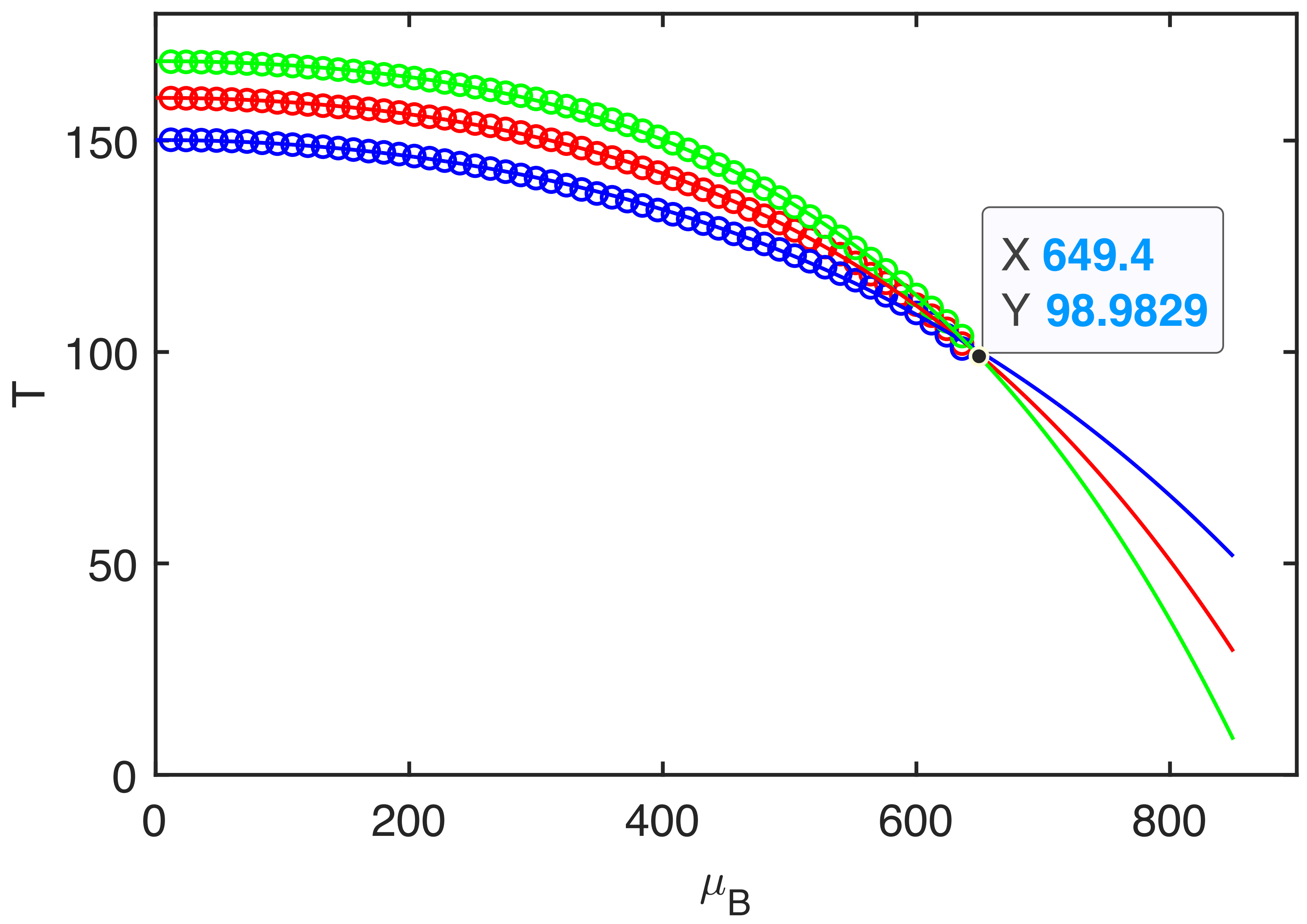


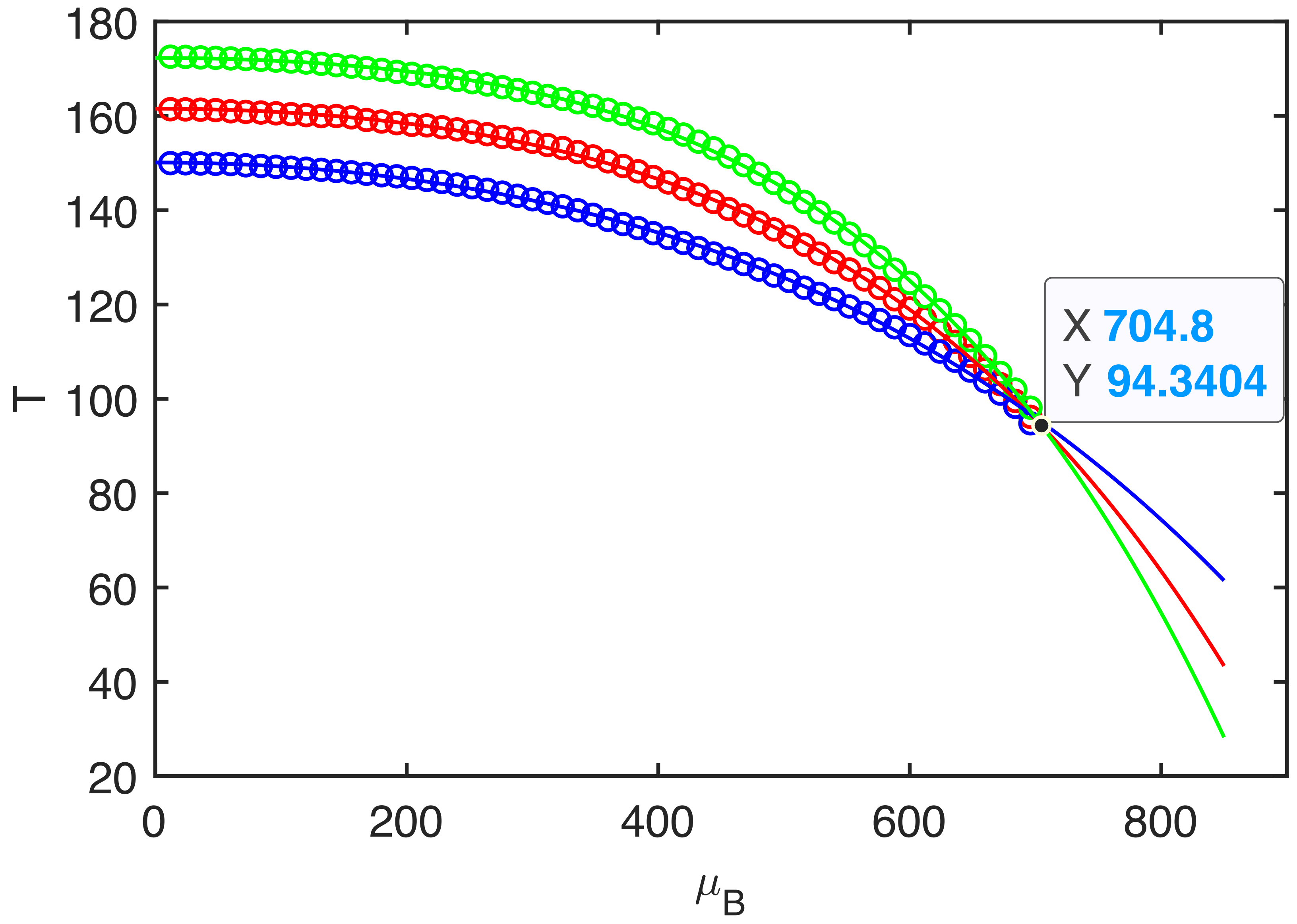
$$80\% \times \frac{\partial m_q(T)}{\partial T}\bigg|_{T=T_c}$$

⭐ Red lines are the temperature of the peak.

⭐ Blue and green lines are temperature of 80% peak height.







Error estimate: freeze-out curve

Fu, Luo, Pawlowski, Rennecke, Wen, SY; in preparation