Transport model study of conserved charge fluctuations in high temperature and high density QCD matter

Qian Chen[1,2,3] (陈倩）
Collaborators: Guo-liang Ma[2,3] (马国亮), Wei-jie Fu(付伟杰),Zi-wei Lin(林子威)
1.Guangxi Normal University
2.Fudan University
3.Shanghai Research Center for Theoretical Nuclear Physics

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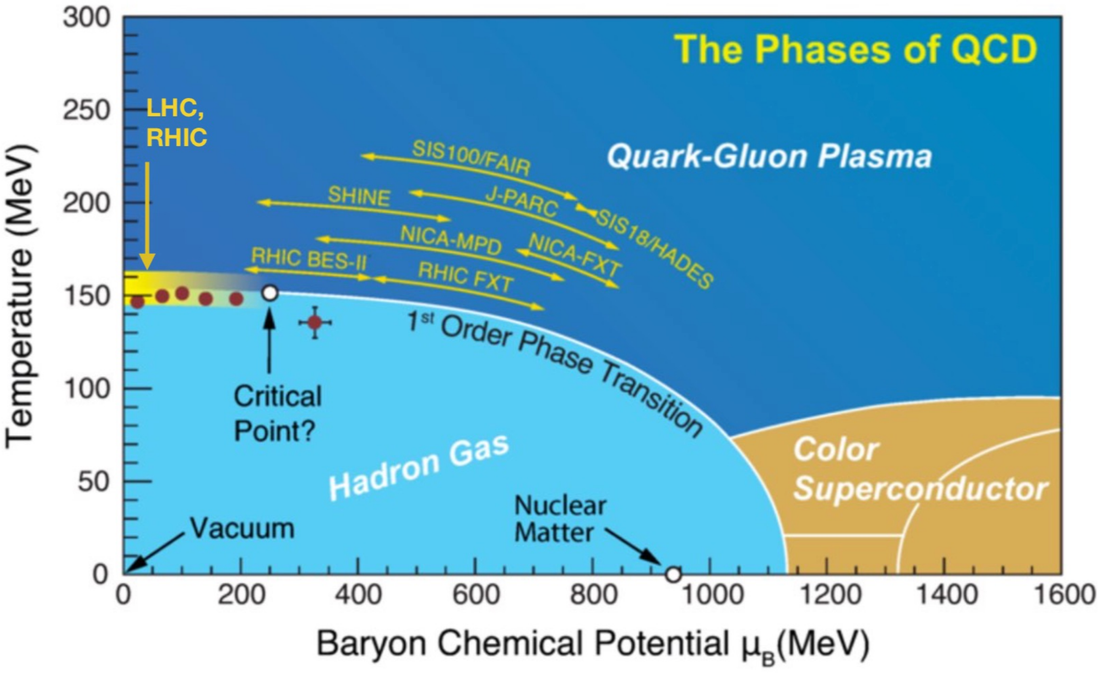
QCD Phase Structure



X. An et al., Nucl.Phys.A 1017 (2022), 122343

- Small baryon chemical potential: Smooth Crossover Transition
- Large baryon chemical potential: First-order Phase Transition
- QCD Critical Endpoint: where the first-order phase transition ends(the key feature of QCD phase structure)
- Increase chemical potential by lowering the beam energy

Fluctuations of Conserved Charges (B, Q, S)

Conserved Charges : net-baryon (B)、 net-charge (Q)、 net-strangeness (S)

Moments and Cumulants: Variance (σ^2、C_2), skewness (S、C_3), kurtosis (κ、C_4)

Measured multiplicity N, $\langle \delta N \rangle = N - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3/C_2^{3/2}$

kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4/C_2^2$

Moments, cumulants and susceptibilities:

2nd order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

3rd order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

4th order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

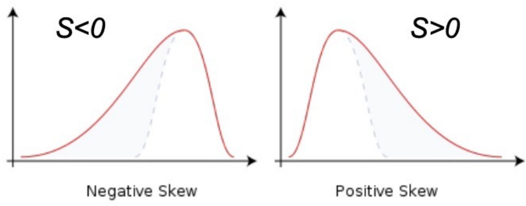
The fluctuations of conserved charges are directly related to the system susceptibility (χ)

$\langle (\delta N)^4 \rangle \sim \xi^7$

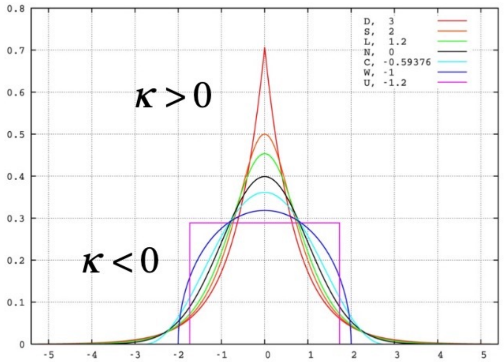
$\langle (\delta N)^3 \rangle \sim \xi^{4.5}$

The correlation length (ξ) of the critical point is divergent

Skewness (S) → asymmetry



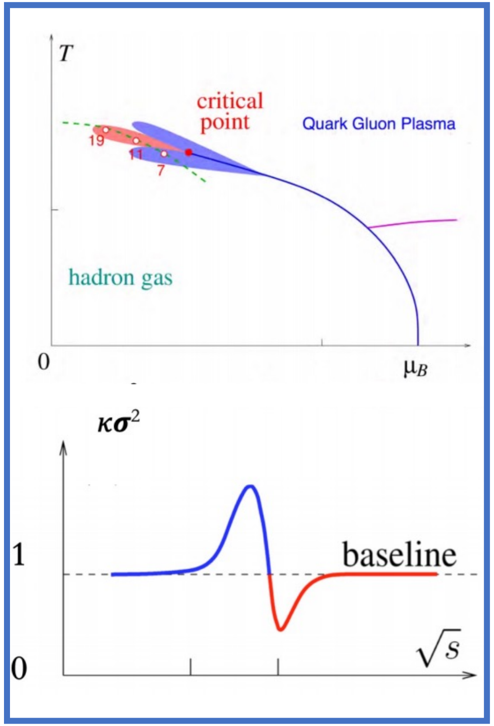
Kurtosis (κ) → Sharpness

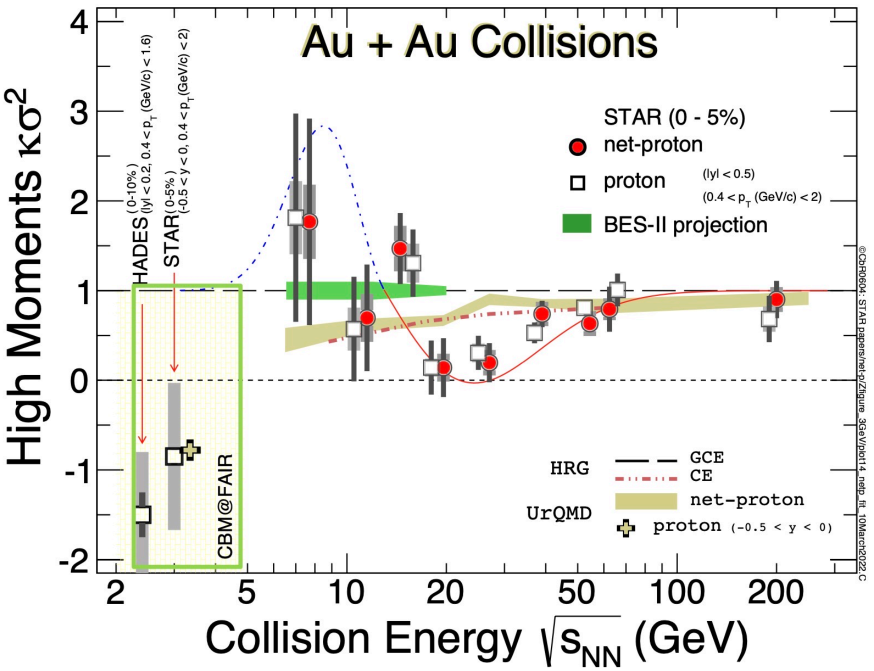


Cheng et al, PRD (2009) 074505. F. Karsch and K. Redlich, PLB 695, 136 (2011). B. Friman et al, EPJC 71 (2011) 1694.S. Gupta, X. Luo et al, Science, 332, 1525(2012). A. Bazavov et al, PRL109, 192302(12)/s. Borsanyi et al, PRL111, 062005(13)

Fluctuations of Conserved Charges (B)

Fluctuations measured by STAR





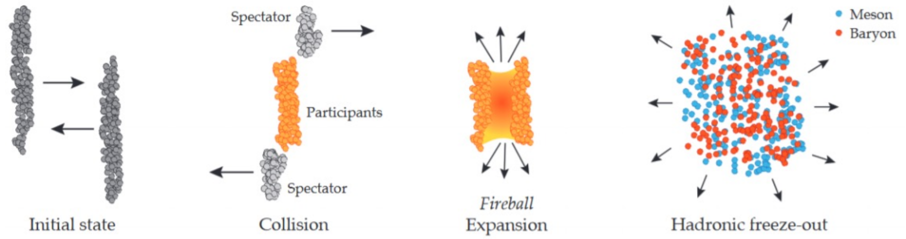
1） Non-monotonic energy dependence: **hint of entering critical region.**

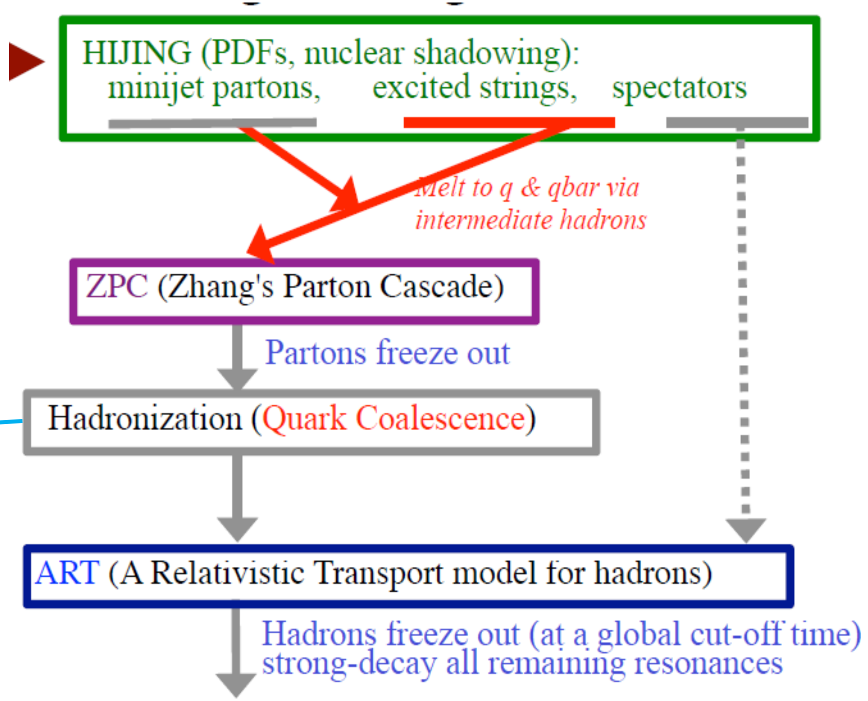
2） 3 GeV proton high moments data：**Hadronic interaction dominant!**

3） Energy gap between 3 and 7.7 GeV, important for **Critical Point search.**

STAR:PRL126,92301(2021)PRL128,202303(2022)HADES: PRC102, 024914(2020)

Extended AMPT Model





new quark coalescence:

quark to form either a meson or a baryon depending on the distance to its coalescence partner(s)(r_{BM})

$d_B < d_M * r_{BM}$:form a baryon

otherwise: form a meson

Y. He and Z.-W. Lin, Phys. Rev. C 96, 014910 (2017).

Extended AMPT model ensures the conservation of various conserved charges (including electric charge, baryon number, and strangeness) for all hadronic reaction channels during the evolution of hadronic phase

Fluctuations of Conserved Charges (B)

Cumulants:

$$C_1 = \kappa_1,$$
$$C_2 = \kappa_2 + \kappa_1,$$
$$C_3 = \kappa_3 + 3\kappa_2 + \kappa_1,$$
$$C_4 = \kappa_4 + 6\kappa_3 + 7\kappa_2 + \kappa_1.$$

Only for one particle! ! ! →

Correlation Functions:

$$\kappa_1 = C_1 = \langle N \rangle,$$
$$\kappa_2 = -C_1 + C_2,$$
$$\kappa_3 = 2C_1 - 3C_2 + C_3,$$
$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4.$$

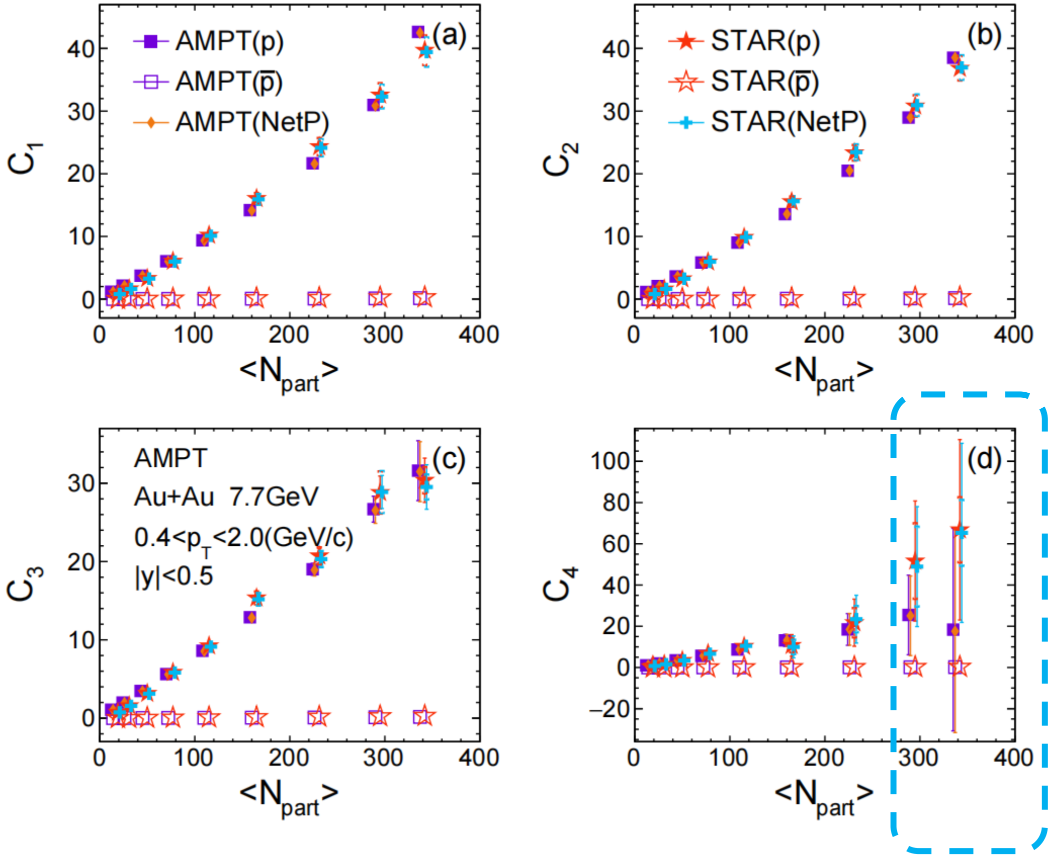
Factorial moments:

$$F_3 = \int dy_1 dy_2 dy_3 \rho_3(y_1, y_2, y_3) = F_1^3 + 3F_1 C_2 + C_3$$

$$\begin{aligned}\rho_3(y_1, y_2, y_3) =& \rho_1(y_1)\rho_1(y_2)\rho_1(y_3) + \rho_1(y_1)\underline{C_2(y_2, y_3)} \\ &+ \rho_1(y_2)\underline{C_2(y_1, y_3)} + \rho_1(y_3)\underline{C_2(y_1, y_2)} \\ &+ \underline{C_3(y_1, y_2, y_3)}\end{aligned}$$

Bzdak, Adam et al. Phys.Rev. C95 (2017)5,054906.

AMPT Results On Proton cumulants

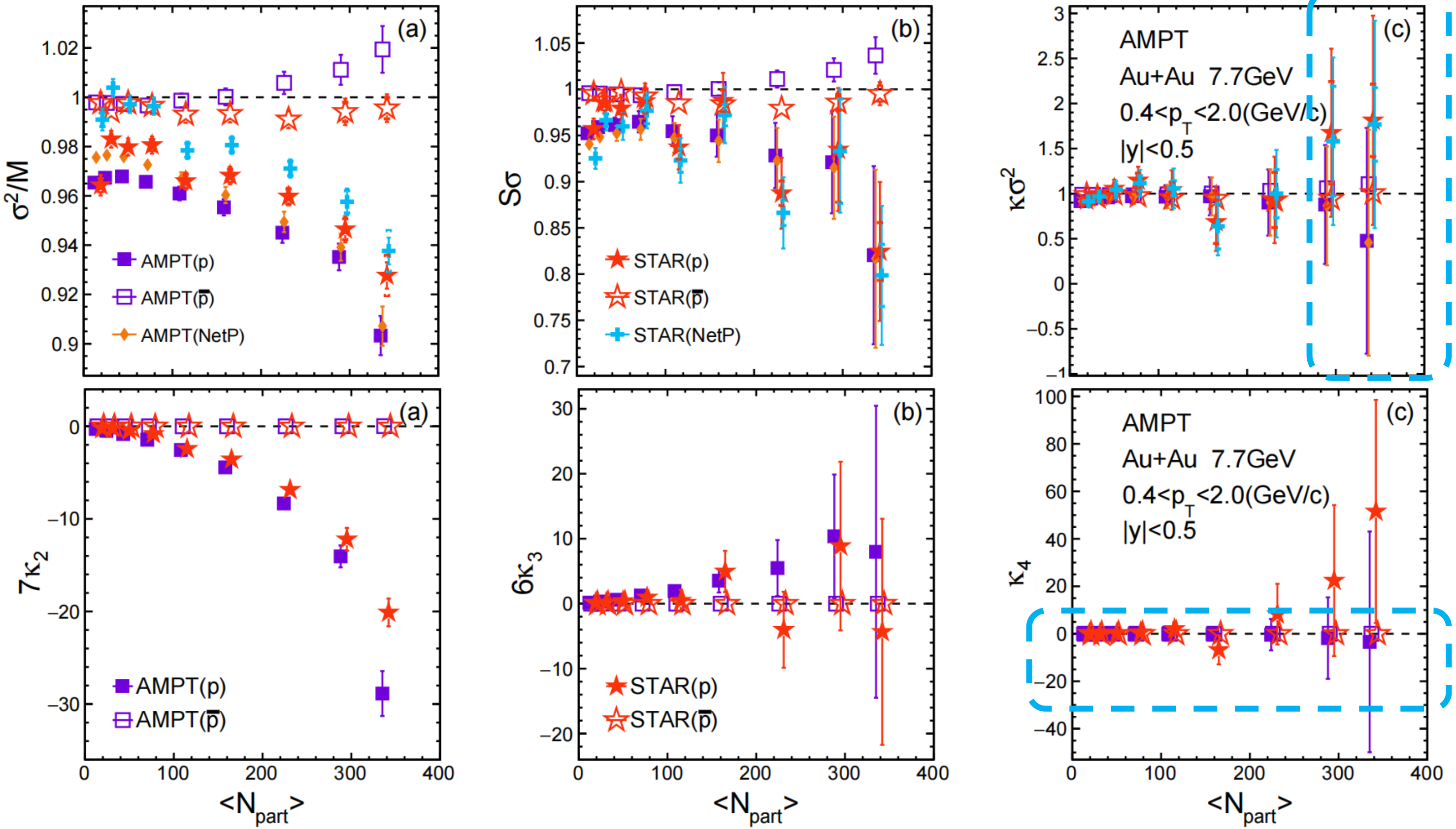


- The cumulants C_n for protons, antiprotons, and net-protons all show a similar increasing dependence on $\langle N_{part} \rangle$
- In the 0-5% and 5-10% centrality ranges, the fourth-order cumulant (C_4) in the AMPT model notably underestimates STAR's results

Qian Chen, Guo-Liang Ma, Phys.Rev.C 106 (2022) 014907

AMPT Results On Proton Cumulant Ratios And Correlations

Qian Chen, Guo-Liang Ma, Phys.Rev.C 106 (2022) 014907

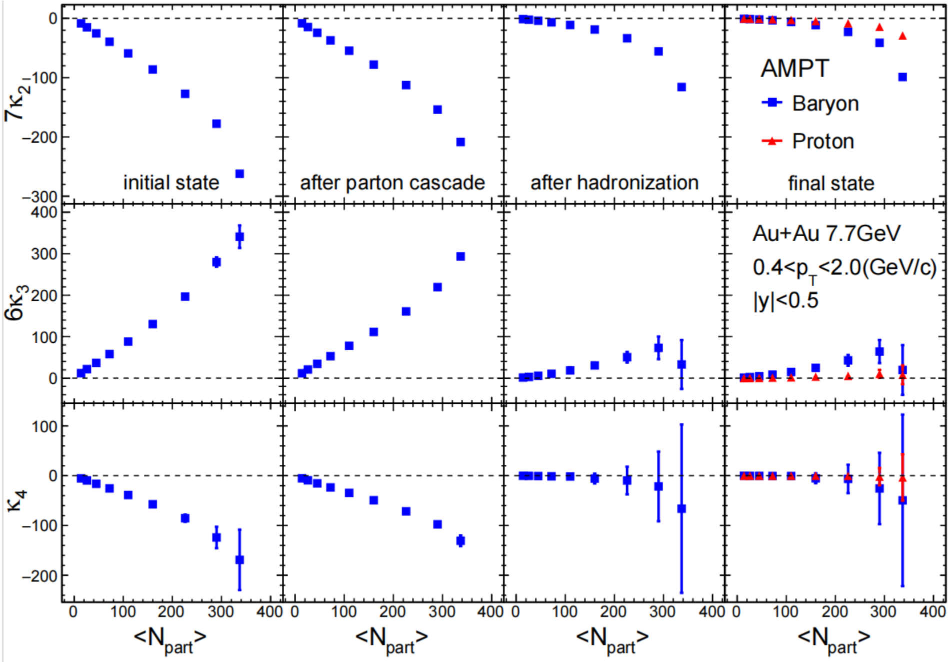


The four-proton correlation from AMPT is very small, consistent with zero.

Baryon Number Conservation

Expectation of baryon number conservation:

$$P(N) = \frac{B!}{N!(B-N)!} p^N (1-p)^{(B-N)}$$



Qian Chen, Guo-Liang Ma, Phys.Rev.C 106 (2022) 014907

n-baryon correlations:

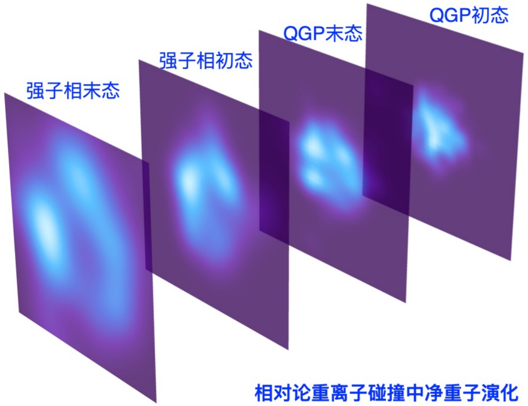
$$\kappa_1 = \langle N \rangle = pB$$

$$\kappa_2 = -\frac{\langle N \rangle^2}{B}$$

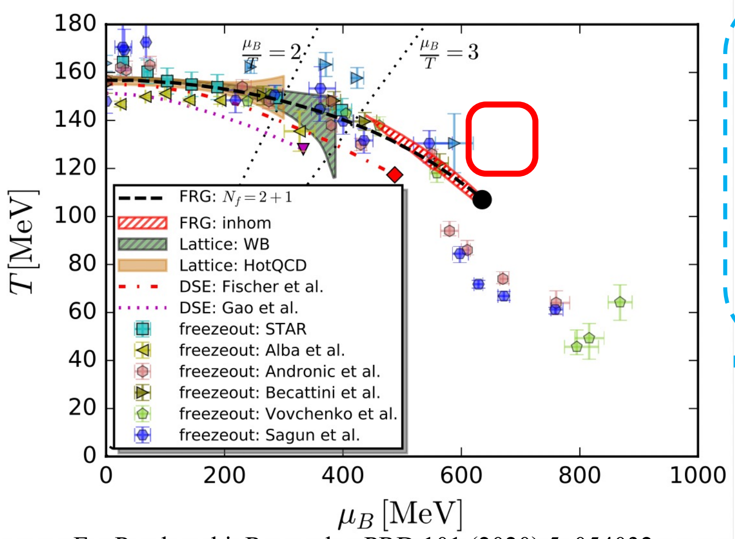
$$\kappa_3 = 2\frac{\langle N \rangle^3}{B^2}$$

$$\kappa_4 = -6\frac{\langle N \rangle^4}{B^3}$$

- Multi-baryon correlations are getting weaker with stage evolution of heavy-ion collisions

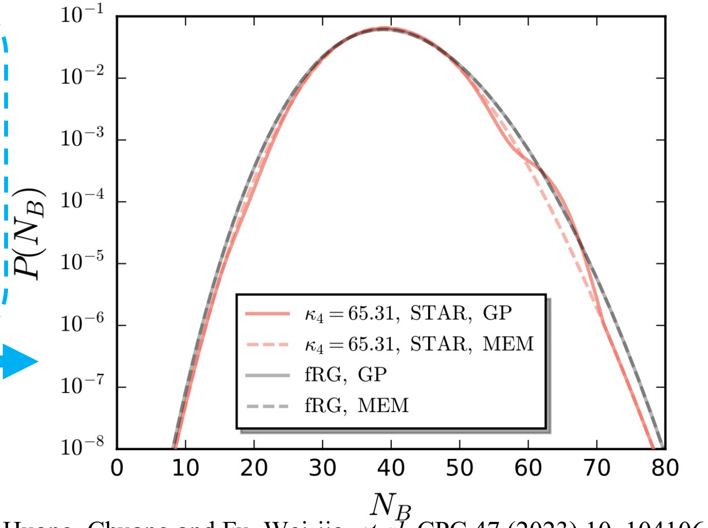


Functional Renormalization Group



Fu, Pawlowski, Rennecke ,PRD 101 (2020) 5, 054032

the baryon number distributions are reconstructed from the cumulants of different orders by means of the maximum entropy method



Huang, Chuang and Fu, Wei-jie, *et al.* CPC 47 (2023) 10, 104106

FRG enables the study of equations of state at both high and low baryon chemical potentials.

FRG with critical fluctuations mechanism without interactions between hadrons and decay processes

Incorporating FRG Into AMPT Model

FRG parameter input:

baryon chemical :

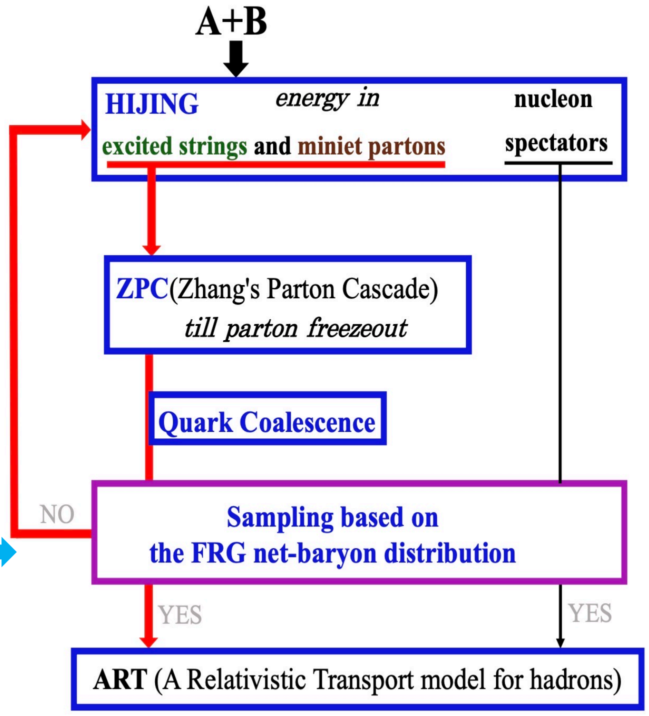
$\mu_B = 399$ MeV;

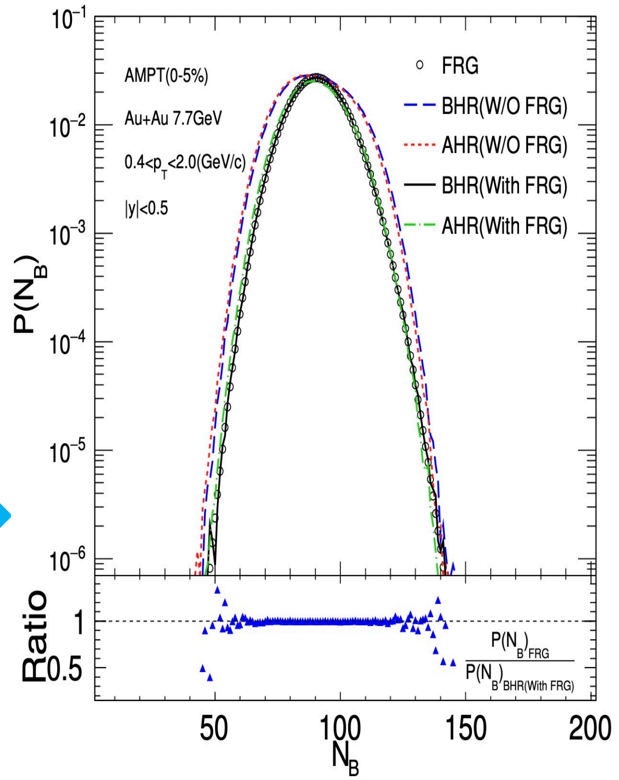
volume of the fire ball :

V = 980 fm^3;

pseudo-critical temperature :

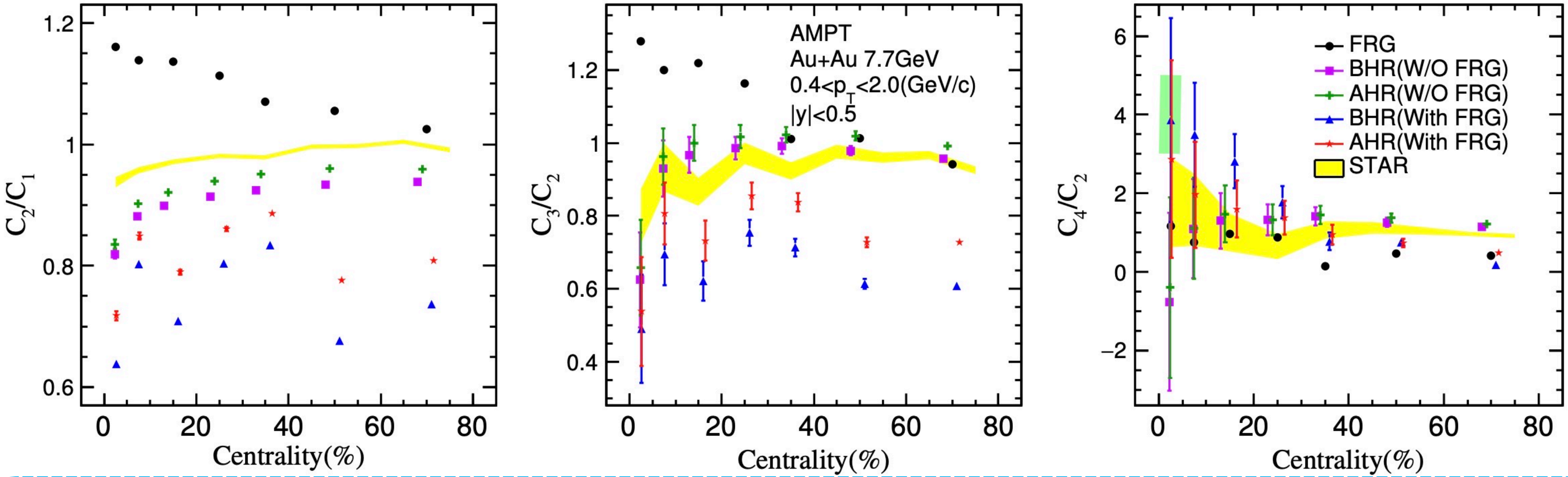
T = 139 MeV;





Qian Chen, Rui Wen, Shi Yin, Wei-jie Fu, Zi-Wei Lin, and Guo-Liang Ma. arXiv:2402.12823.

Incorporating FRG Into AMPT Model



- **The influences of hadronic rescatterings :** increase the cumulant ratios C_2/C_1 and C_3/C_2 , but decrease C_4/C_2 in central collisions and increase C_4/C_2 in peripheral collisions.
- The effect of hadronic rescatterings is more significant for **critical fluctuations** than **dynamical fluctuations**.

Qian Chen, Rui Wen, Shi Yin, Wei-jie Fu, Zi-Wei Lin, and Guo-Liang Ma. arXiv:2402.12823.

Summary and Outlook

Summary：

- The AMPT results are consistent with the expectation from baryon number conservation.
- The incorporation of the FRG into the AMPT model reveals that the hadronic rescatterings process affects different orders of net-baryon cumulant ratios.

Outlook：

- Incorporation of critical fluctuation physics into AMPT： FRG、density fluctuations.
- nuclear thickness effects, coalescence mechanisms, different collision systems, effects of magnetic fields, ...

Thank you for your attentions!

Back Up

- In the old version, only K^+ and K^- were introduced in hadron rescatterings as explicit particles, but K^0 and $\overline{K}^0$ were omitted.

- In the old version, some isospin-averaged cross sections were used, and the charge of the final state particles is chosen randomly from all possible charges, independent of the total charge of the initial state.

For example:

$$1)\ \pi^+ + \pi^+ \to \rho^+ + \rho^+ \quad \checkmark$$

$$2)\ \pi^+ + \pi^+ \to \rho^+ + \rho^- \quad \times$$

$$3)\ \pi^+ + \pi^+ \to \rho^- + \rho^- \quad \times$$

Back Up

Cumulants:

$$C_2 = \langle N \rangle + \langle \bar{N} \rangle + \kappa_2^{(2,0)} + \kappa_2^{(0,2)} - 2\kappa_2^{(1,1)}$$

$$C_3 = \langle N \rangle - \langle \bar{N} \rangle + 3\kappa_2^{(2,0)} - 3\kappa_2^{(0,2)} + \kappa_3^{(3,0)} - \kappa_3^{(0,3)} - 3\kappa_3^{(2,1)} + 3\kappa_3^{(1,2)}$$

$$C_4 = \langle N \rangle + \langle \bar{N} \rangle + 7\kappa_2^{(2,0)} + 7\kappa_2^{(0,2)} - 2\kappa_2^{(1,1)} + 6\kappa_3^{(3,0)} + 6\kappa_3^{(0,3)} - 6\kappa_3^{(2,1)}$$
$$- 6\kappa_3^{(1,2)} + \kappa_4^{(4,0)} + \kappa_4^{(0,4)} - 4\kappa_4^{(3,1)} - 4\kappa_4^{(1,3)} + 6\kappa_4^{(2,2)}$$

Bzdak, Adam et al. Phys.Rev. C86 (2012) 044904

two or more kinds of particles！！！

Factorial moments:

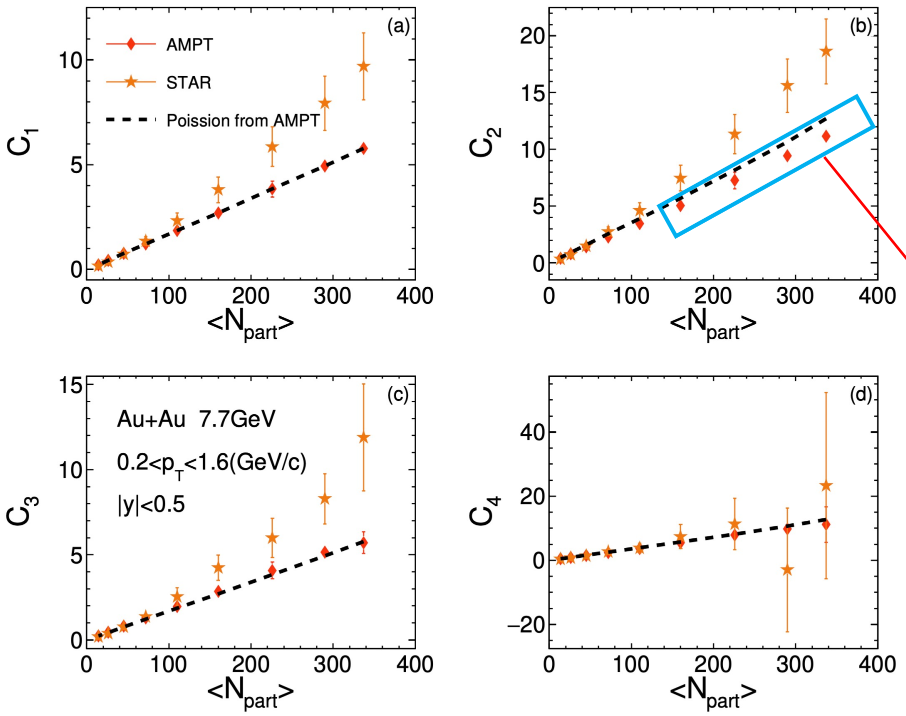
$$F_{i,k} = \left\langle \frac{N!}{(N-i)!} \frac{\bar{N}!}{(\bar{N}-k)!} \right\rangle = \frac{d^i}{dz^i} \frac{d^k}{d\bar{z}^k} H(z,\bar{z})|_{z=\bar{z}=1}$$

Correlation Functions:

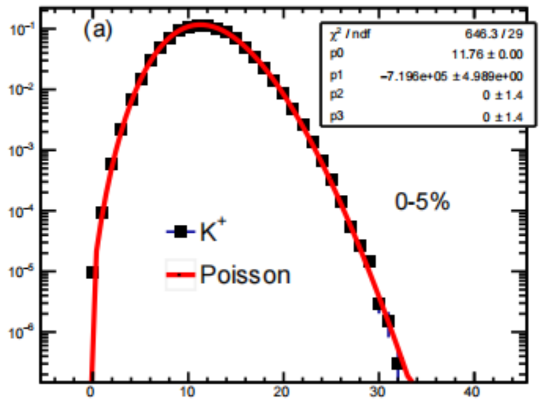
$$\kappa_2^{(2,0)} = -F_{1,0}^2 + F_{2,0},$$

$$\kappa_2^{(1,1)} = -F_{1,0}F_{0,1} + F_{1,1},$$

Back Up

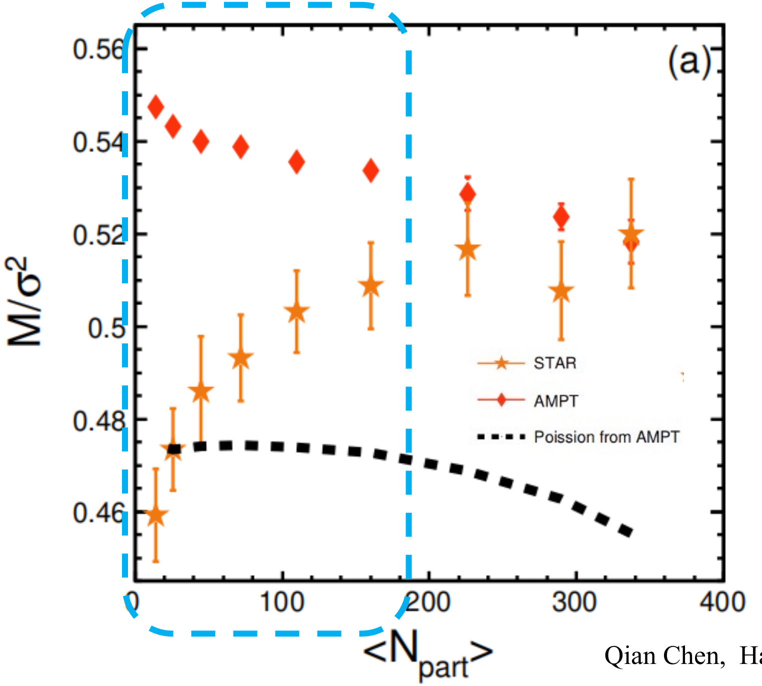


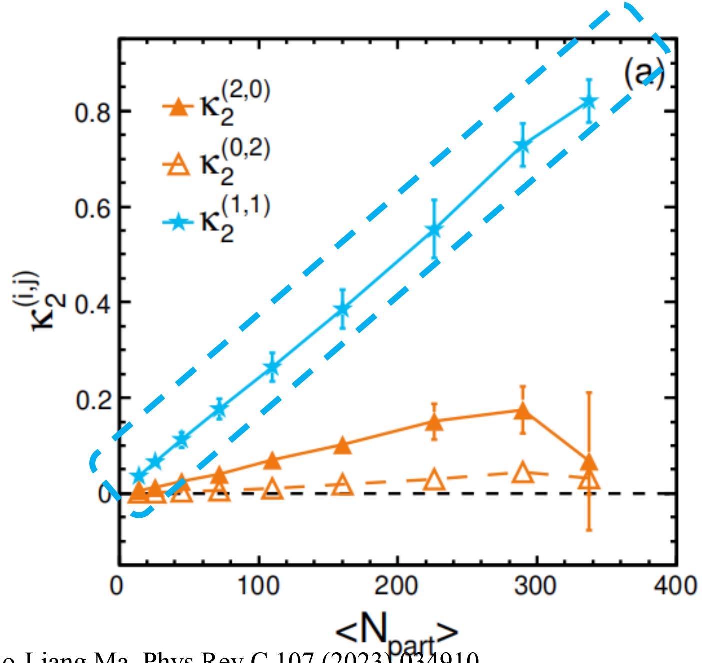
Qian Chen, Han-Sheng Wang, Guo-Liang Ma, Phys.Rev.C 107 (2023) 034910



The C_2 for AMPT is slightly lower than **Poisson baseline** based on its mean multiplicity, suggesting a correlation between $K^+$and K^-

Back Up



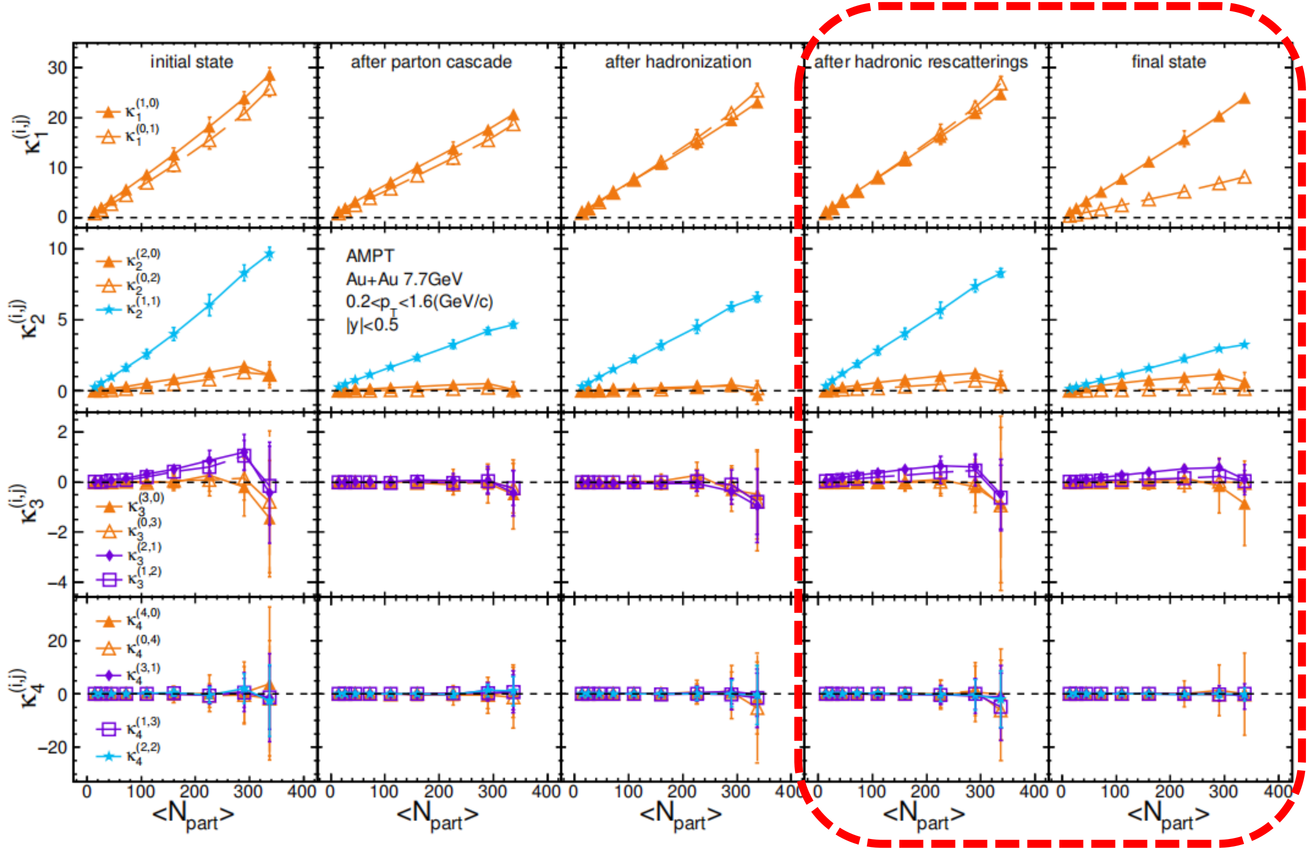


Qian Chen, Han-Sheng Wang, Guo-Liang Ma, Phys.Rev.C 107 (2023) 034910

Caused by the **new quarks coalescence mechanism**

Two-particle correlation function between the K^+ and K^- [$\kappa_2^{(1,1)}$] is dominants——**pair production**

Back Up



- The fluctuations of strangeness are notably influenced during the weak decay evolution stage