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

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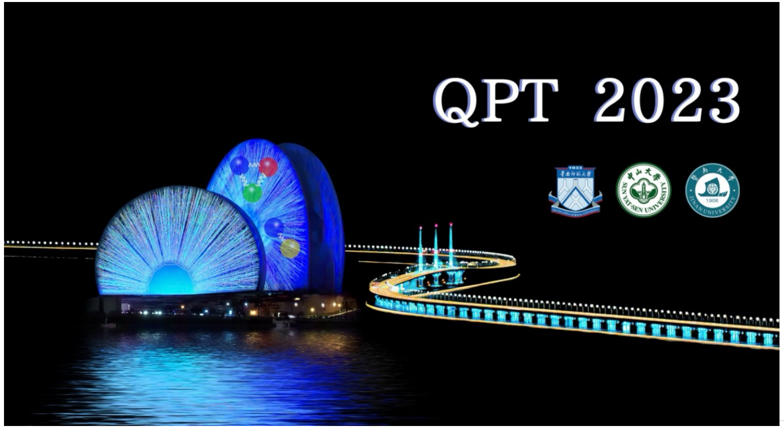
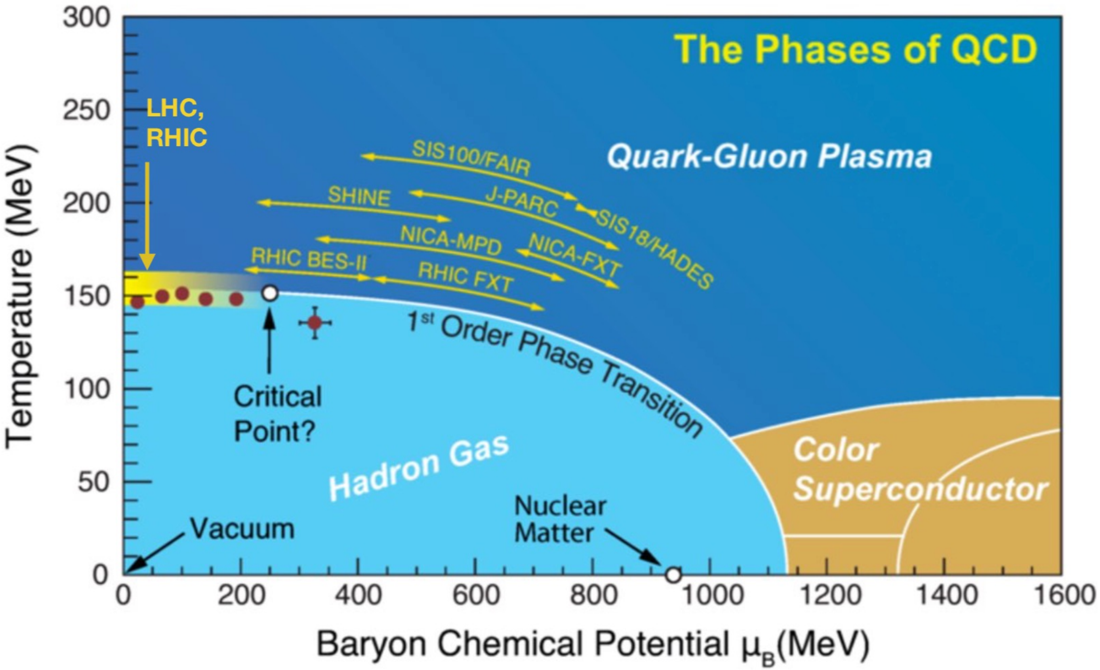


QCD Phase Structure



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

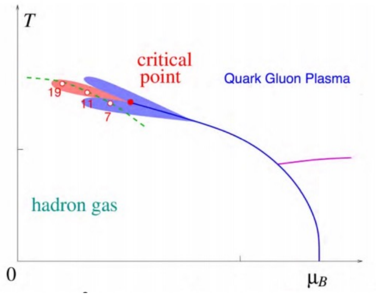
Conserved Charges Fluctuations

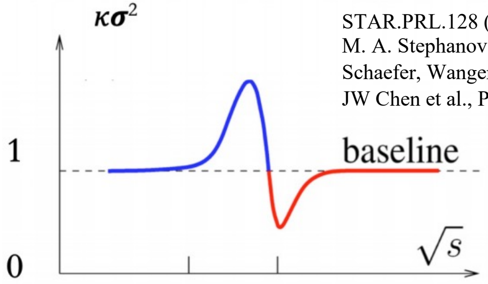
$$\langle(\delta N)^4\rangle \sim \xi^7$$
$$\langle(\delta N)^3\rangle \sim \xi^{4.5}$$

- The correlation length (ξ) of the critical point is diverging

$$\kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} = \frac{\chi_q^{(4)}}{\chi_q^{(2)}}$$
$$S\sigma = \frac{C_{3,q}}{C_{2,q}} = \frac{\chi_q^{(3)}}{\chi_q^{(2)}}$$

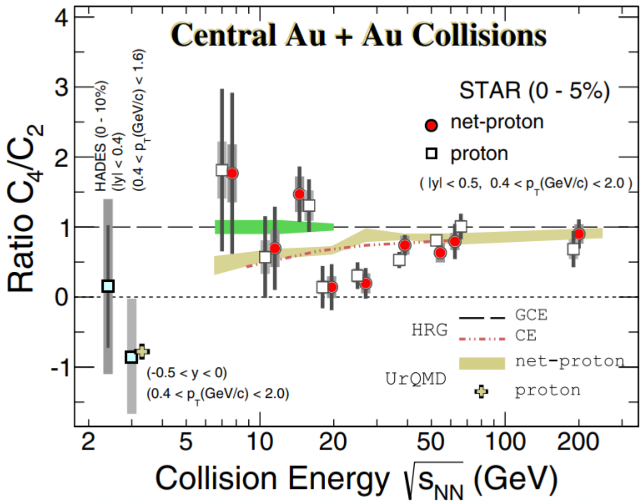
- The fluctuations of conserved charges are directly related to the system susceptibility (χ)





STAR.PRL.128 (2022) 20, 202303
M. A. Stephanov, PRL 107.052301(2011).
Schaefer, Wanger, PRD 85, 034027 (2012)
JW Chen et al., PRD 93, 034037 (2016);

Fluctuations measured by STAR

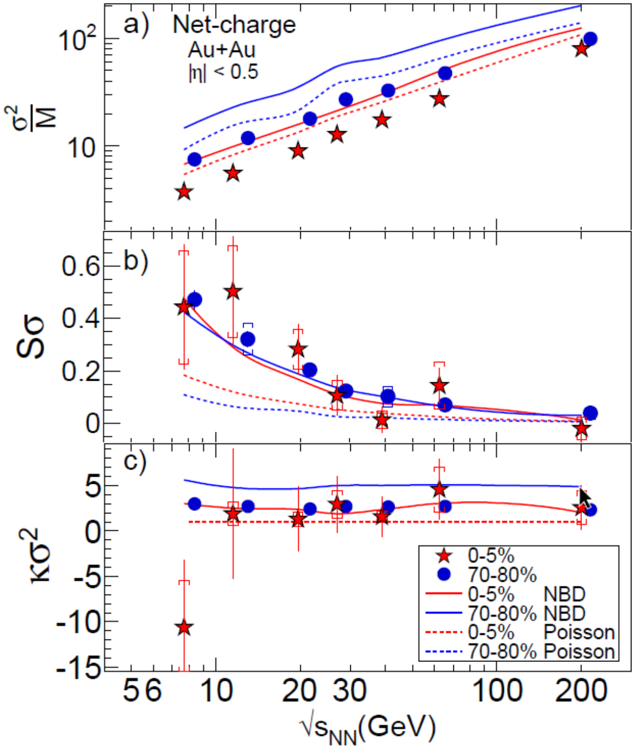


Non-monotonic energy dependence of the $\kappa\sigma^2$

hint of entering critical region.

Conserved Charges Fluctuations

net-charge cumulants ratio

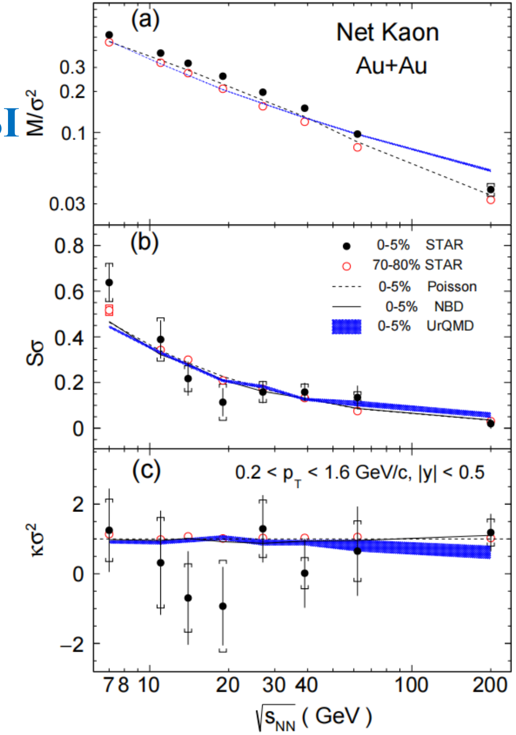


STAR, PRL. 113.092301(2014)

Fluctuations measured by RHIC-BESI

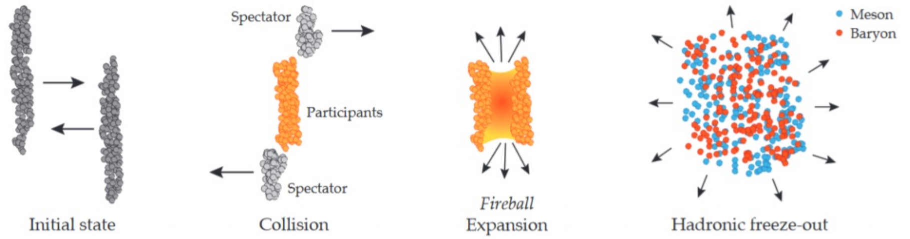
no non-monotonic behavior of the $\kappa\sigma^2$

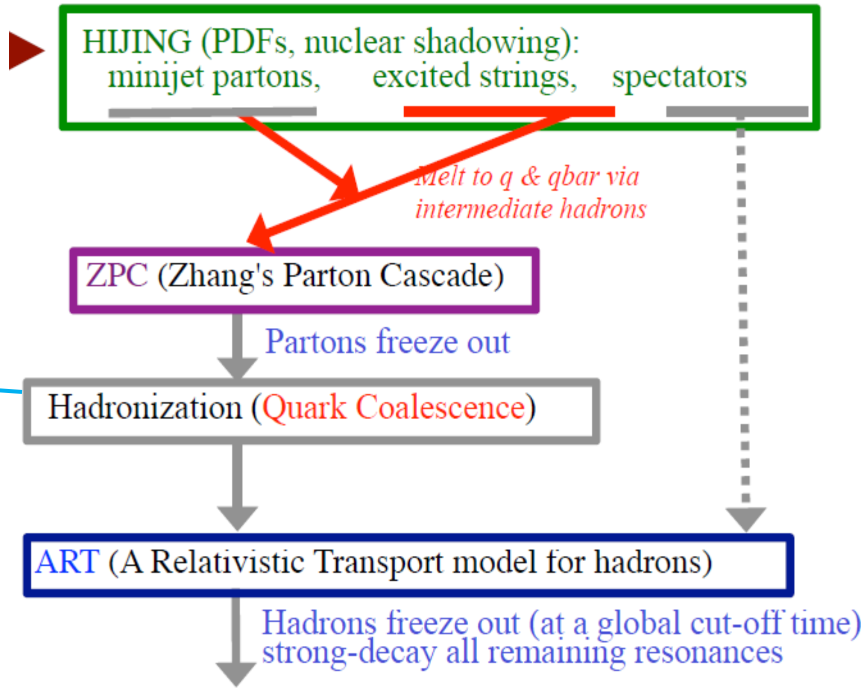
Net-kaon cumulants ratio



STAR, PLB. 785 (2018) 551-560

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

Conserved Charges Fluctuations

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:

$$\kappa_1 = C_1 = \langle N \rangle,$$

$$\kappa_2 = -C_1 + C_2,$$

$$\kappa_3 = 2C_1 - 3C_2 + C_3,$$

$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4.$$

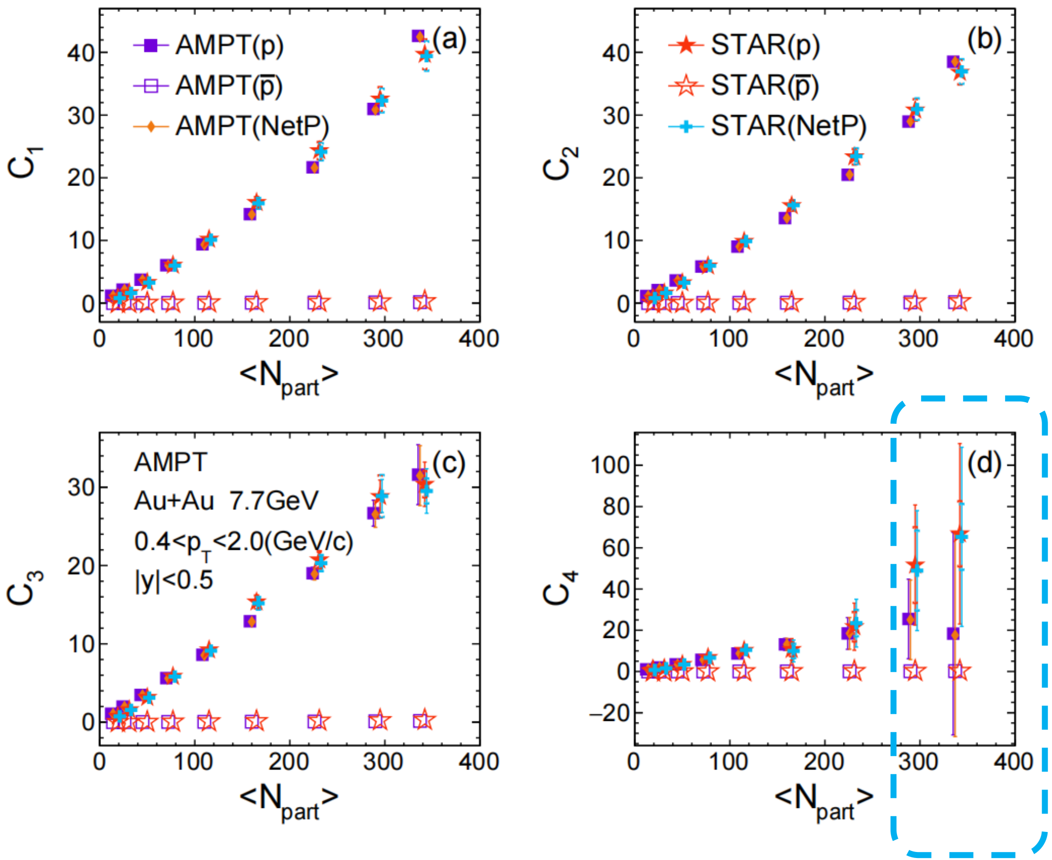
Factorial moments:

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

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

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

AMPT Results On Proton cumulants

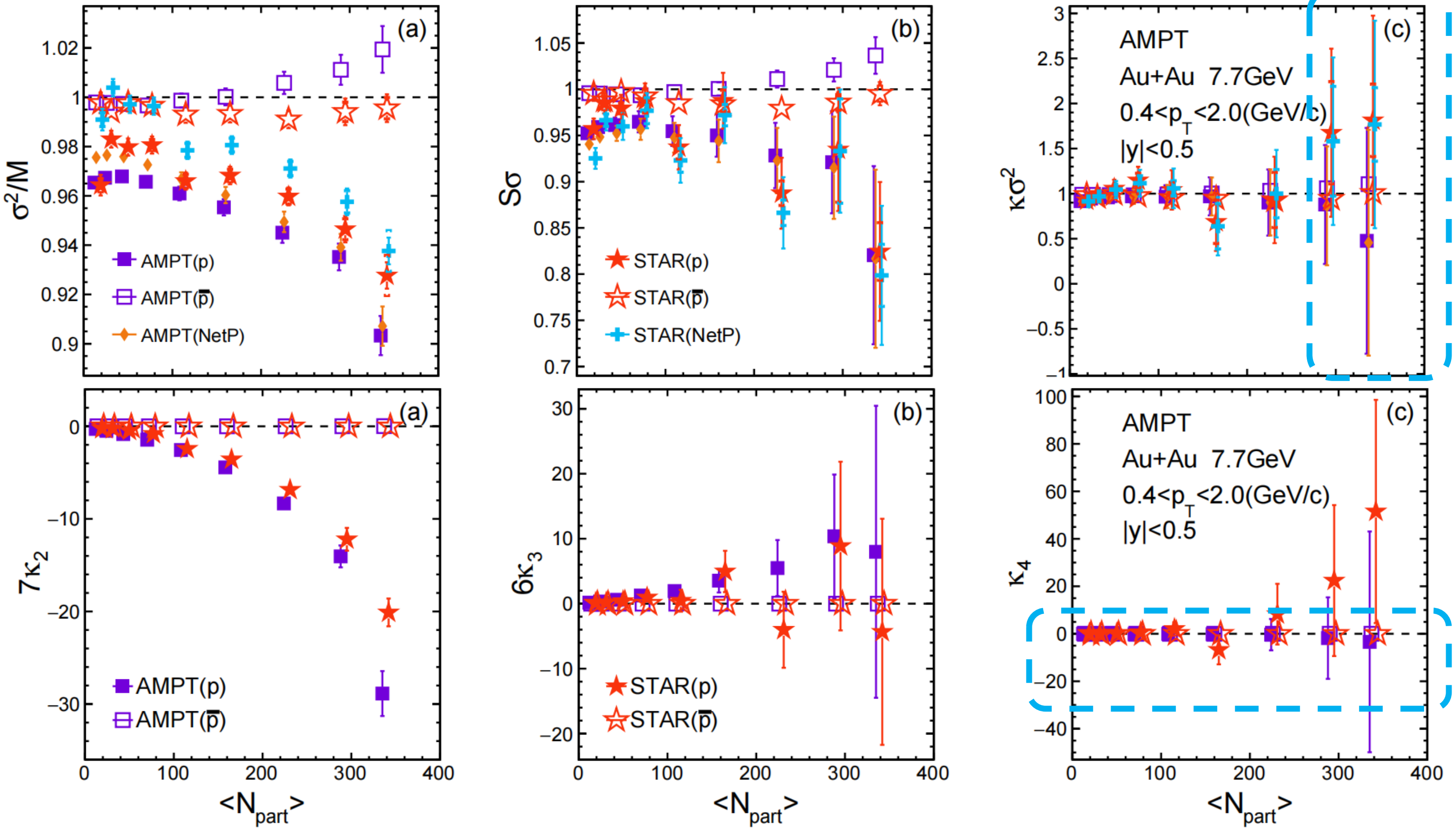


- The cumulants C_n for protons, antiprotons, and net-protons all show a similar increasing dependence on $\langle N_{part} \rangle$
- In the 0-5% and 5-10% centrality ranges, the fourth-order cumulant (C_4) in AMPT notably underestimates STAR's results

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

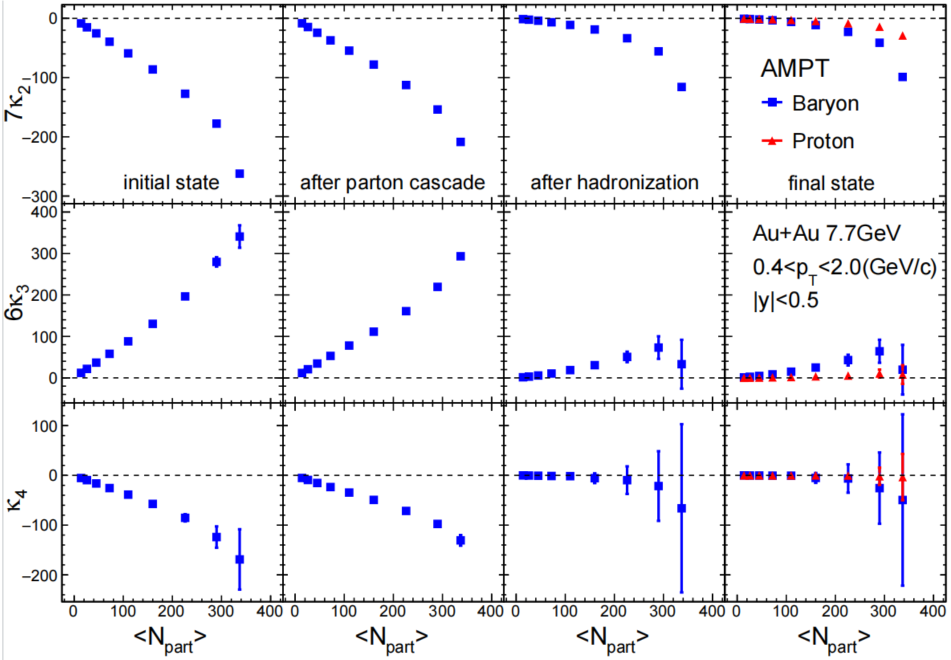


The four-proton correlation from AMPT is very small, consistent with zero.

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:

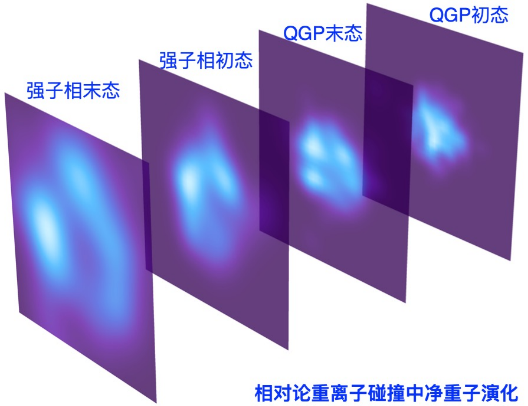
$$\kappa_1 = \langle N \rangle = pB$$

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

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

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

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



Conserved Charges Fluctuations

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！！！

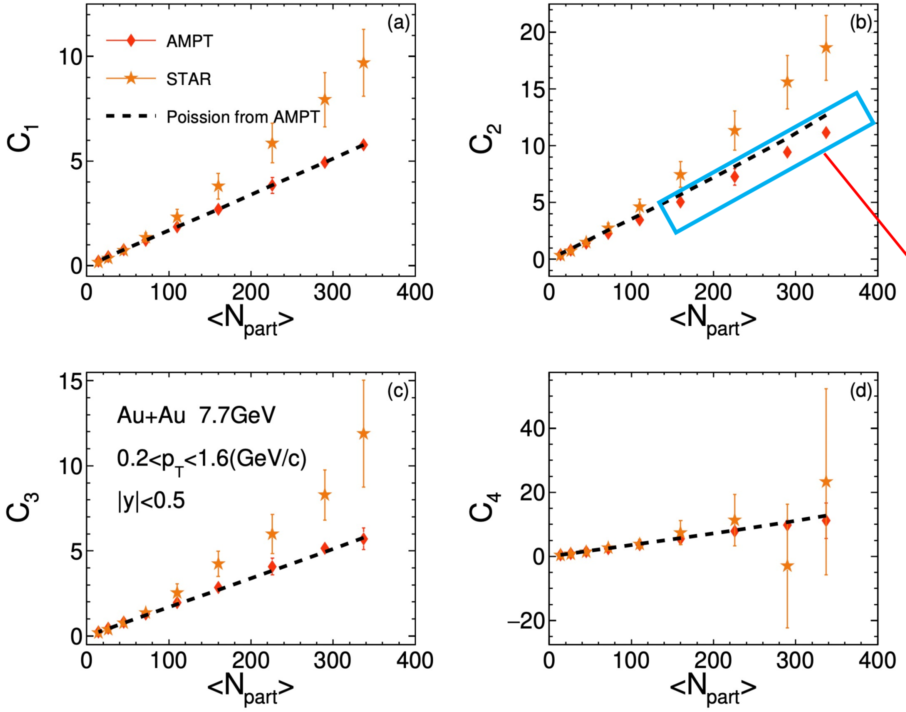
Factorial moments:

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

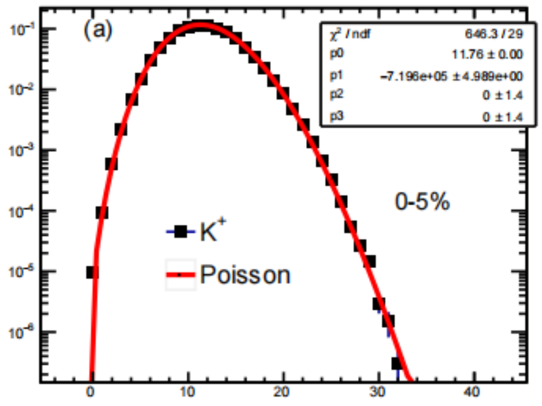
Correlation Functions:

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

AMPT Results On Net-kaon cumulants

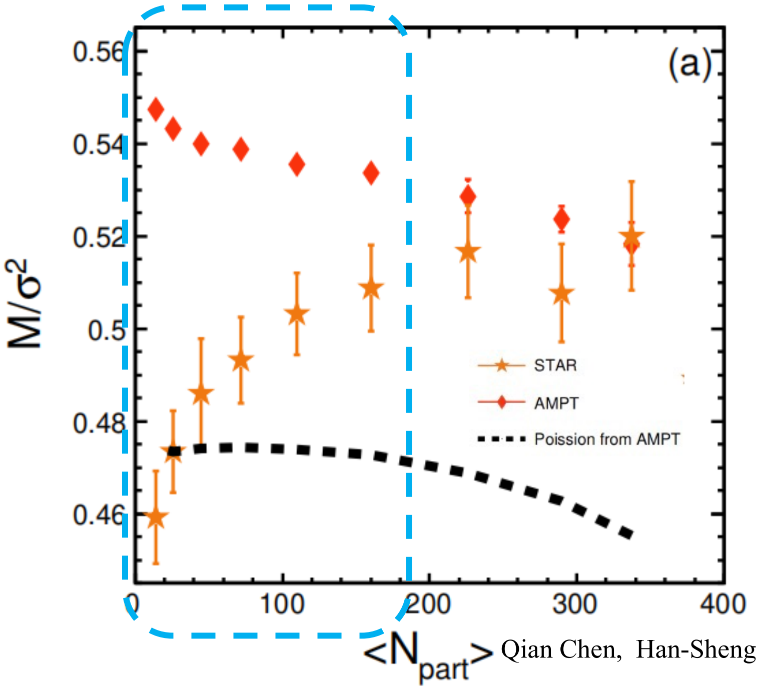


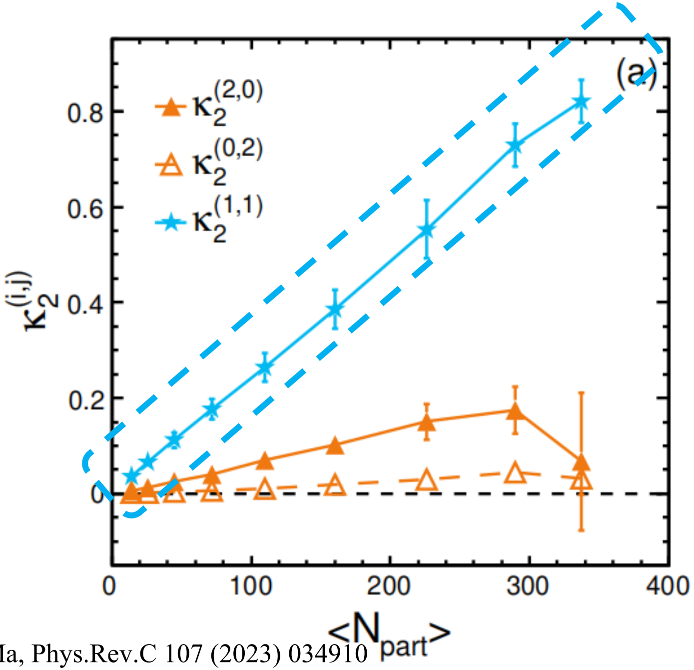
Qian Chen, Han-Sheng Wang, Guo-Liang Ma, Phys.Rev.C 107 (2023) 034910



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

AMPT Results On Net-kaon Cumulant Ratios And Correlations



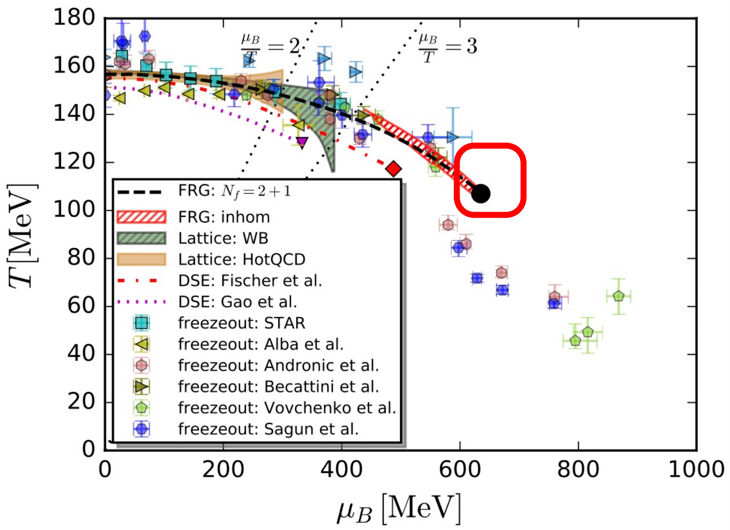


Qian Chen, Han-Sheng Wang, Guo-Liang Ma, Phys.Rev.C 107 (2023) 034910

Caused by the **new quarks coalescence mechanism**

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

Functional Renormalization Group

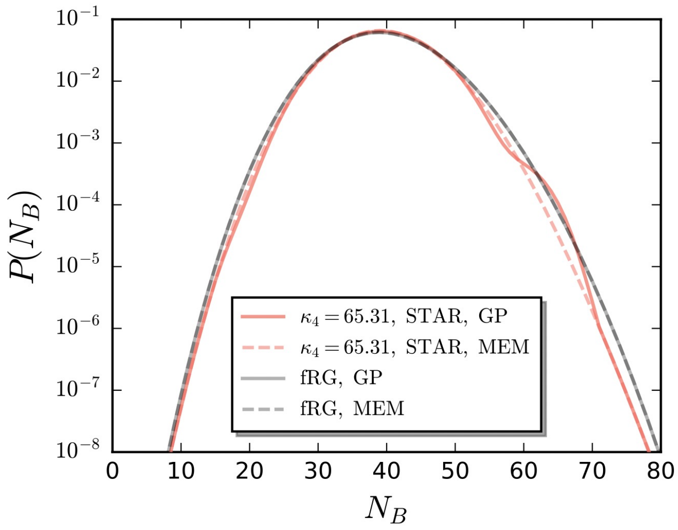


Fu, Pawlowski, Rennecke ,PRD 101 (2020) 5, 054032

$$\left(T_{CEP},\mu_{B_{CEP}}\right)_{N_f=2+1}=\left(107MeV,635MeV\right),$$

$$\left(T_{CEP},\mu_{B_{CEP}}\right)_{N_f=2}=\left(117MeV,630MeV\right)$$

FRG can be applied to high baryon chemical potential(μ_B).



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

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

Incorporating FRG Into AMPT Model

In preparation

FRG parameter input:

baryon chemical：

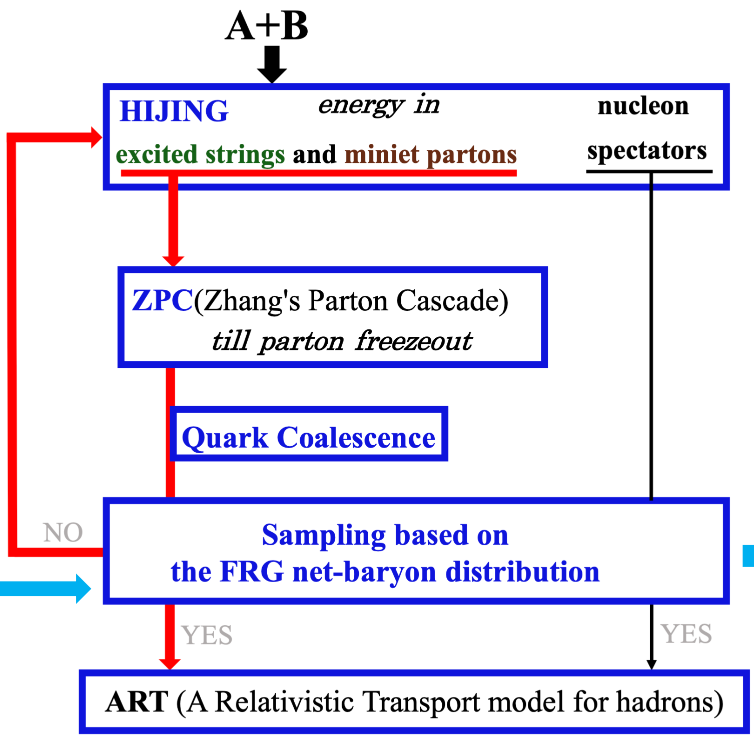
$\mu_B = 399$ MeV;

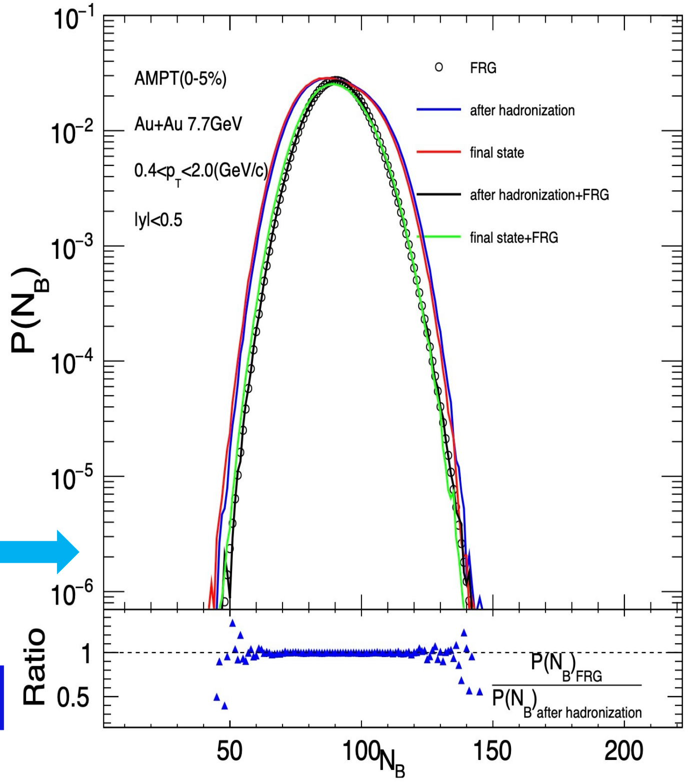
volume of the fire ball：

V = 980 fm^3;

pseudo-critical temperature：

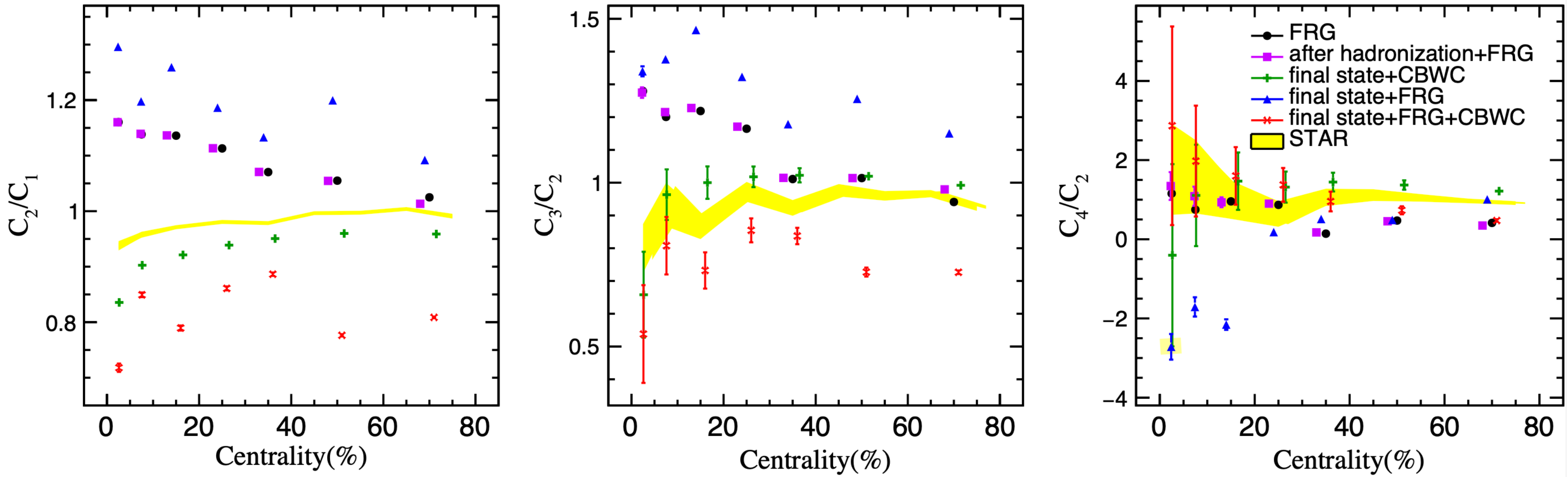
T = 139 MeV;





Incorporating FRG Into AMPT Model

In preparation



Effect of Hadronic rescatterings processes on cumulant ratios:
C_2/C_1 and C_3/C_2 in **"final state+FRG"** stage results are larger compared to the results from the **FRG**, Conversely, C_4/C_2 is smaller.

Summary and Outlook

Summary:

- The AMPT results are consistent with the expectation from baryon number conservation.
- By analyzing the cumulants and correlation functions of net-strangeness and net-kaon, we found that they originate from pair production.
- 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.
- different collision systems (isobar), effects of magnetic fields, coalescence mechanisms ....

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.

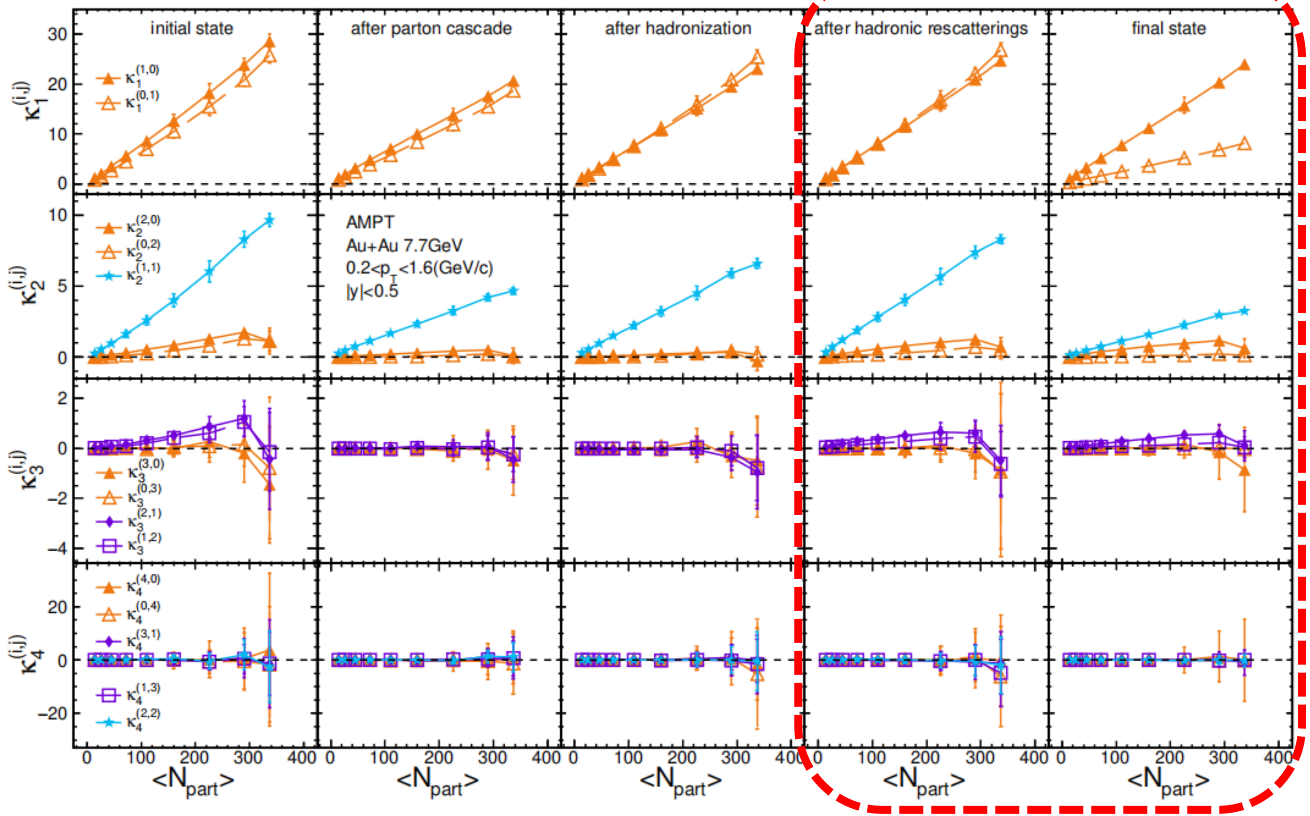
For example:

1) $\pi^+ + \pi^+ \rightarrow \rho^+ + \rho^+$ ✓

2) $\pi^+ + \pi^+ \rightarrow \rho^+ + \rho^-$ ×

3) $\pi^+ + \pi^+ \rightarrow \rho^- + \rho^-$ ×

Back Up



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