Higher-Order Cumulants of Net-Proton Multiplicity Distributions in Zr+Zr and Ru+Ru Collisions at $\sqrt{s_{NN}}$ = 200 GeV

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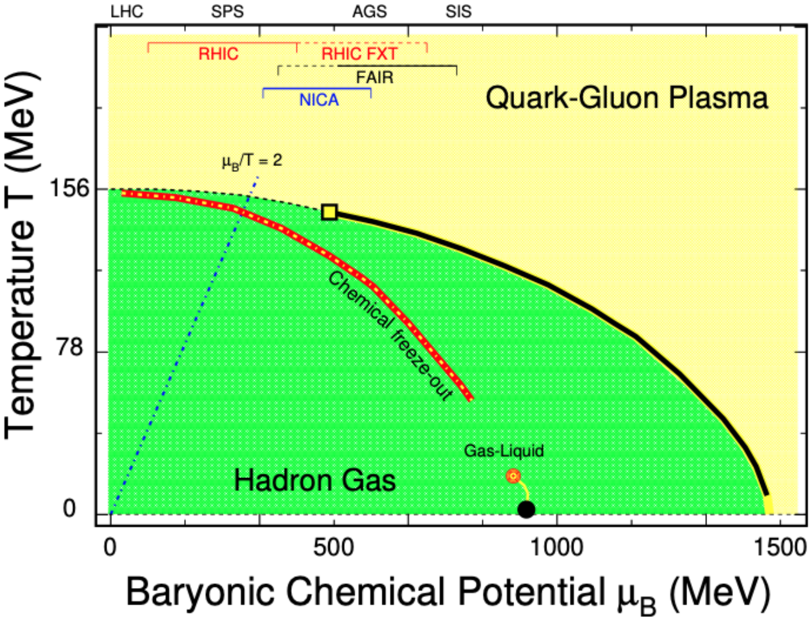
Outline

1. Introduction & motivation
2. Analysis of $\sqrt{s_{NN}}$ = 200 GeV isobaric collisions (Zr+Zr & Ru+Ru)
3. Net-proton cumulants & cumulant ratios
4. Summary & outlook

QCD phase diagram



STAR, Phys. Rev. Lett. 126, 092301 (2021)

1. QCD calculation and model
   a. Lattice QCD: Cross over at μ_B= 0 [1] and T = 156.5 ± 1.5 MeV [2~5]
   b. QCD based Model: A critical point followed by first-order phase transition at high μ_B [6]
2. Search for the possible signature of critical point by scanning T vs μ_B:
   - by varying collision energy in heavy-ion collisions

[1] Y. Aoki, Nature 443, 675 (2006)
[2] Y. Aoki, JHEP 06, 088 (2009)
[3] HotQCD, Phys. Rev. D 85, 054503 (2012)
[4] S. Gupta, Science 332, 1525 (2011)
[5] HotQCD, Phys. Lett. B 795, 15 (2019)
[6] M. A. Halasz, Phys. Rev. D 58, 096007 (1998)

Fluctuation of conserved quantities

1. Cumulants of conserved quantities (B, Q, S) are related to correlation length of the system

$$\delta N = N - \langle N \rangle$$

$$S = C_3/(C_2)^{3/2}, \kappa = C_4/(C_2)^2$$

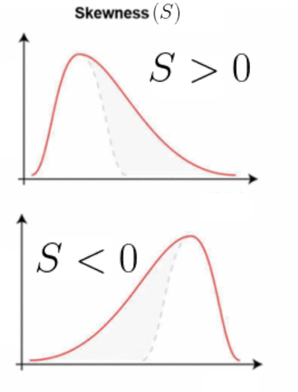
$$C_1 = \langle N \rangle \quad C_2 = \langle (\delta N)^2 \rangle \quad C_3 = \langle (\delta N)^3 \rangle$$

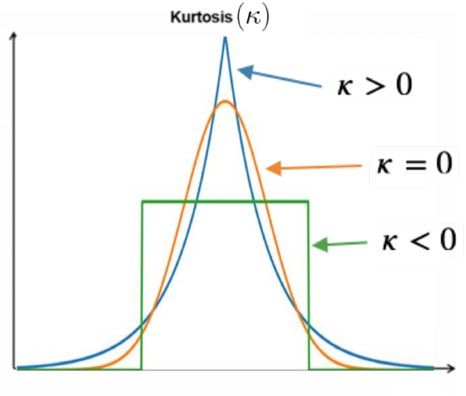
$$C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \quad C_5 = \langle (\delta N)^5 \rangle - 10 \langle (\delta N)^2 \rangle \langle (\delta N)^3 \rangle$$

$$C_6 = \langle (\delta N)^6 \rangle + 30 \langle (\delta N)^2 \rangle^3 - 15 \langle (\delta N)^2 \rangle \langle (\delta N)^4 \rangle - 10 \langle (\delta N)^3 \rangle^2$$

The higher the cumulant order, the more sensitive to the correlation length

$$C_2 \sim \xi^2, C_3 \sim \xi^{4.5}, C_4 \sim \xi^7$$ [1~3]





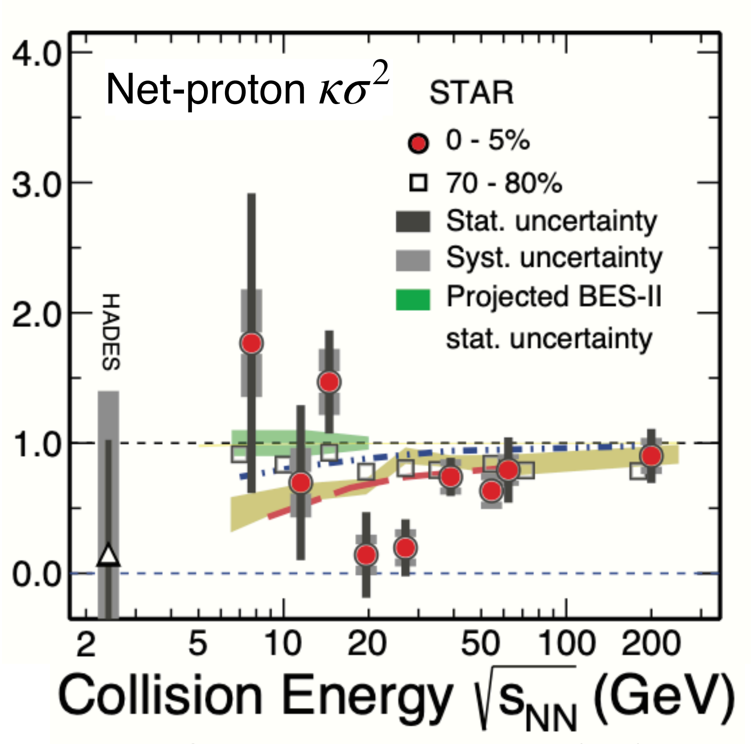
2. The cumulant ratios can be directly compared to theoretical calculations

$$\chi_q^{(n)} = \left(\frac{\partial^n p}{\partial \mu_q^n} \right)_T = \frac{1}{VT^3} \times C_q^n$$

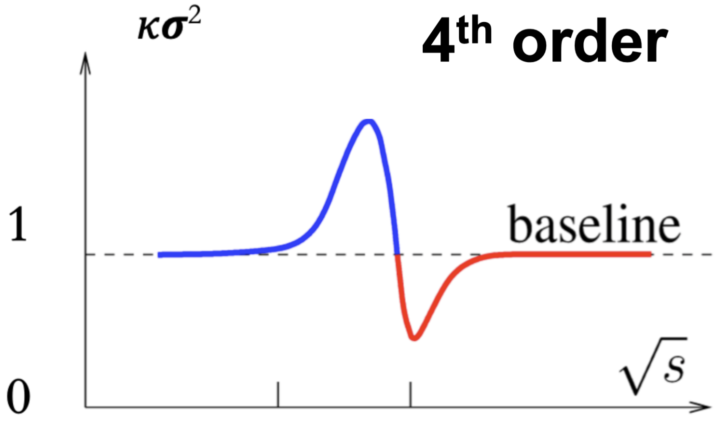
Directly linked to the EoS

[1] M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
[2] M. Asakawa, Phys. Rev. Lett. 103, 262301 (2009)
[3] M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)

Fourth-order cumulant for critical point search



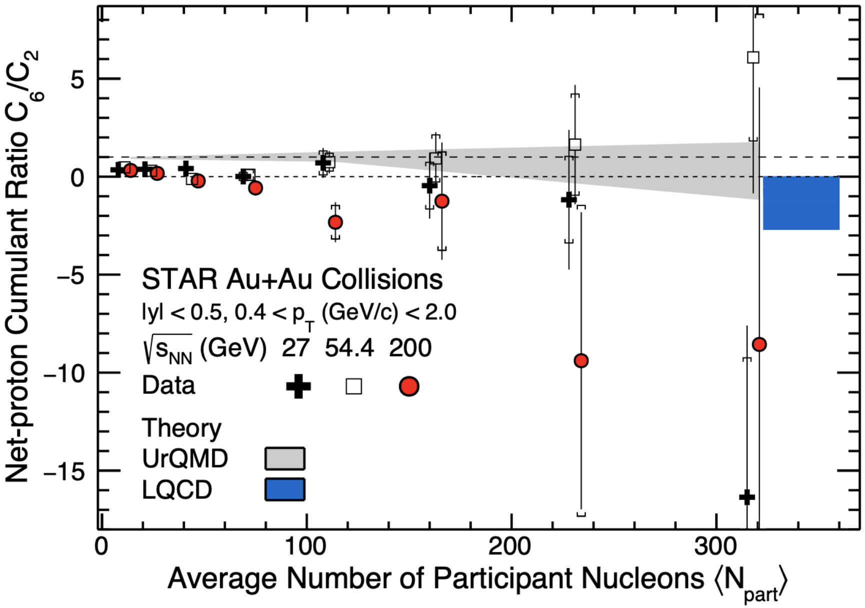
STAR, Phys. Rev. Lett. 126, 092301 (2021)
STAR, Phys.Rev.C 104, 024902 (2021)



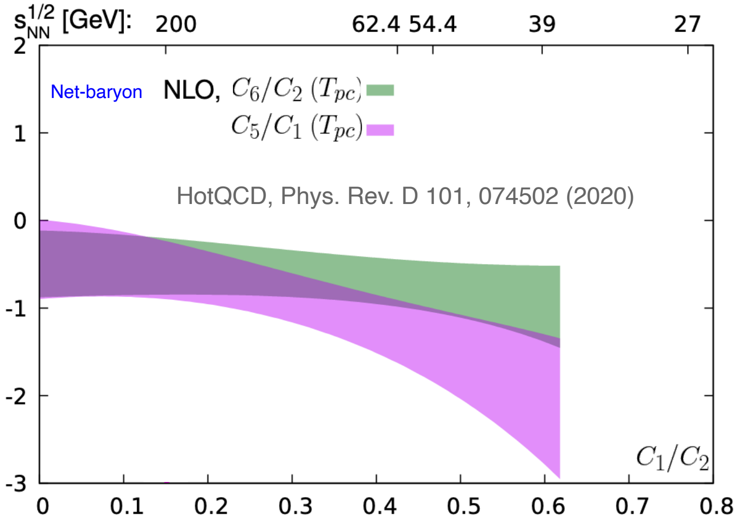
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
B.-J. Schaefer, Phys. Rev. D 85, 034027 (2012)
J.-W. Chen, Phys. Rev. D 93, 034037 (2016)
J.-W. Chen, Phys. Rev. D 95, 014038 (2017)

- 4th order: predicts a non-monotonic energy dependence due to contribution from QCD critical point

Fifth- and Sixth-order cumulant

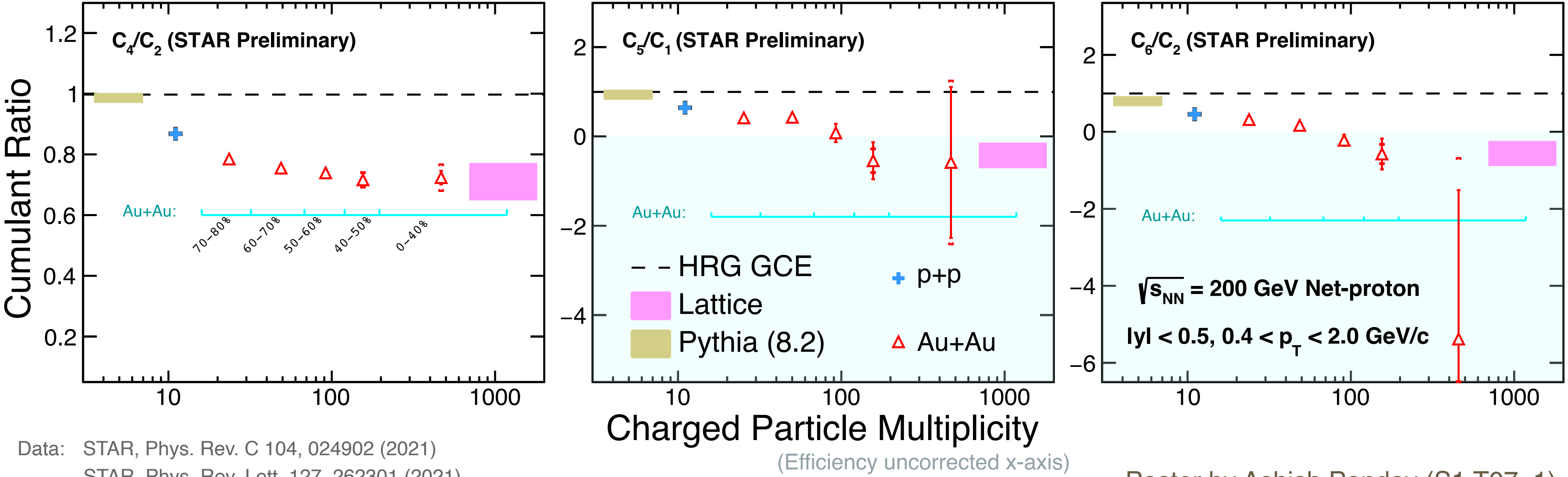


STAR, Phys. Rev. Lett. 127, 262301 (2021)



- Transition from QGP to hadronic matter is smooth crossover at $\mu_B \approx 0$.
  6th order: first principle lattice QCD calculation predicts $C_6/C_2 < 0$

Particle multiplicity dependent higher moment analysis

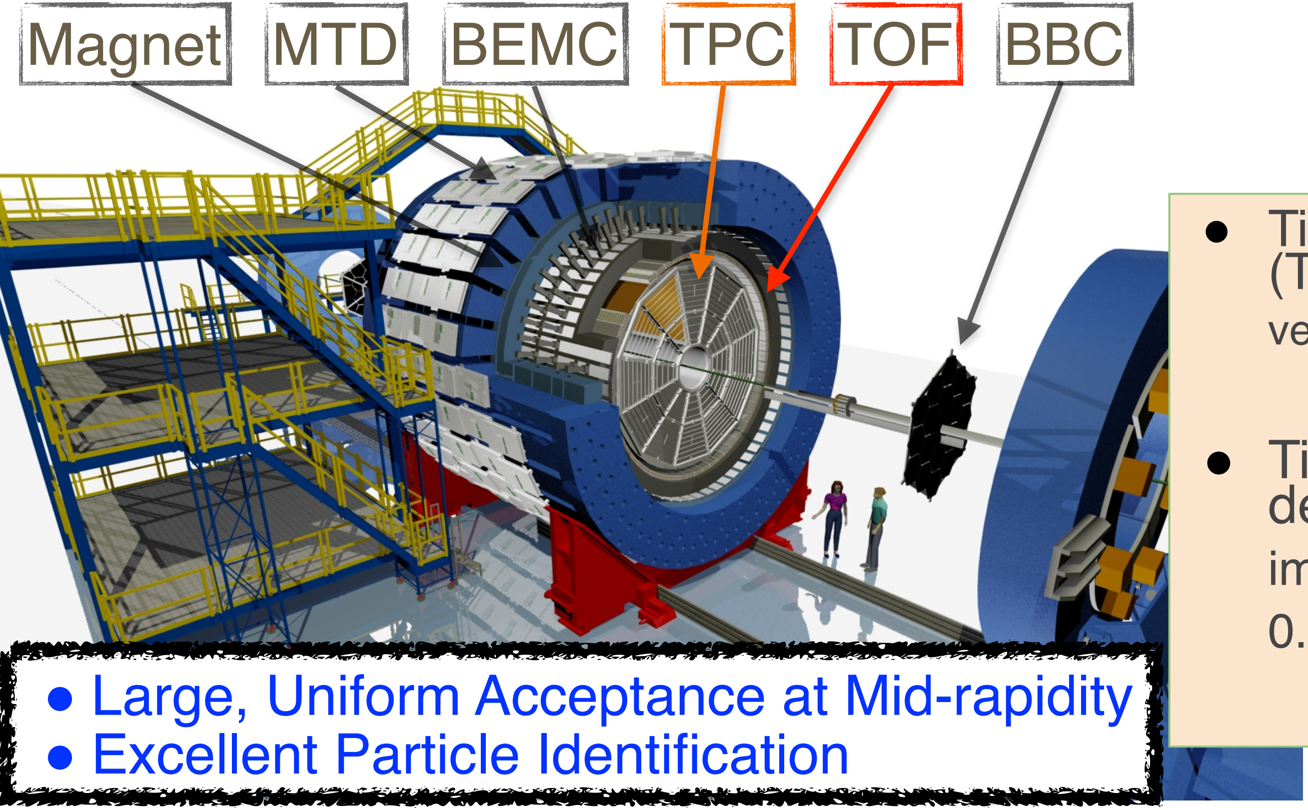


Data: STAR, Phys. Rev. C 104, 024902 (2021)
STAR, Phys. Rev. Lett. 127, 262301 (2021)

Poster by Ashish Pandav (S1 T07_1)

1. At $\sqrt{s_{NN}}$ = 200 GeV: Zr+Zr and Ru+Ru (A = 96), and Au+Au (A=197) with p+p averaged
2. Large statistics: 2.0B Zr+Zr and 1.9B Ru+Ru events taken at STAR in 2018
3. **Inspect the systematic trend of multiplicity dependence of different collision systems (Zr, Ru, and Au) at the same collision energy**

Solenoid Tracker At RHIC (STAR)



- Large, Uniform Acceptance at Mid-rapidity
- Excellent Particle Identification

- Time Projection Chamber (TPC):

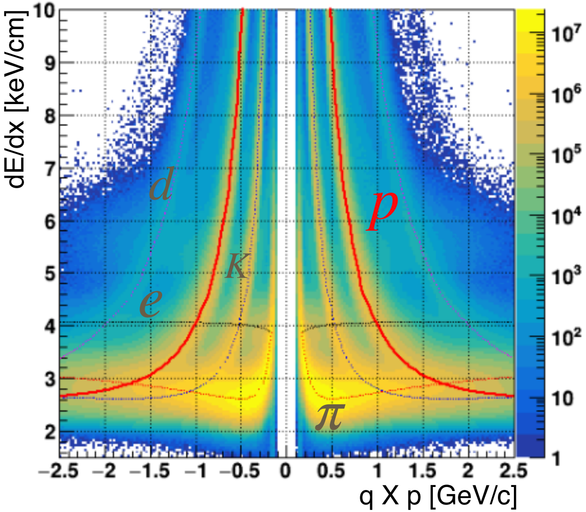
  vertexing & particle identification

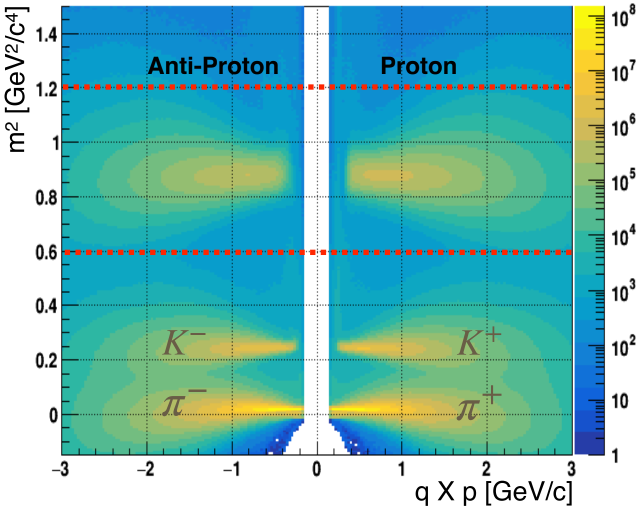
- Time Of Flight (TOF) detector:

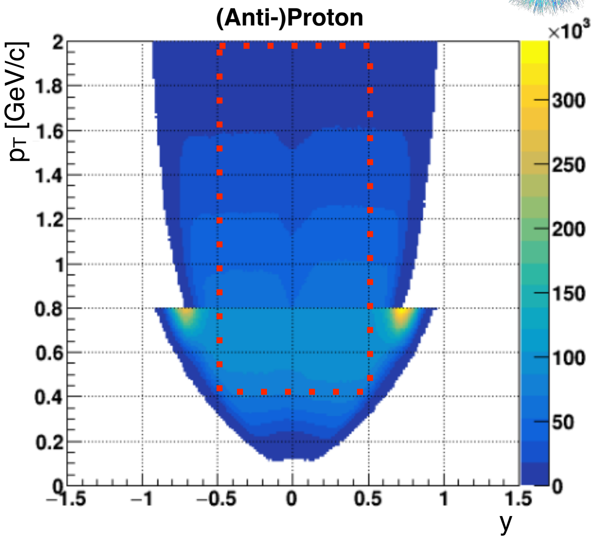
  improves proton purity at

  $0.8 < p_T < 2.0$ GeV/c

Proton identification



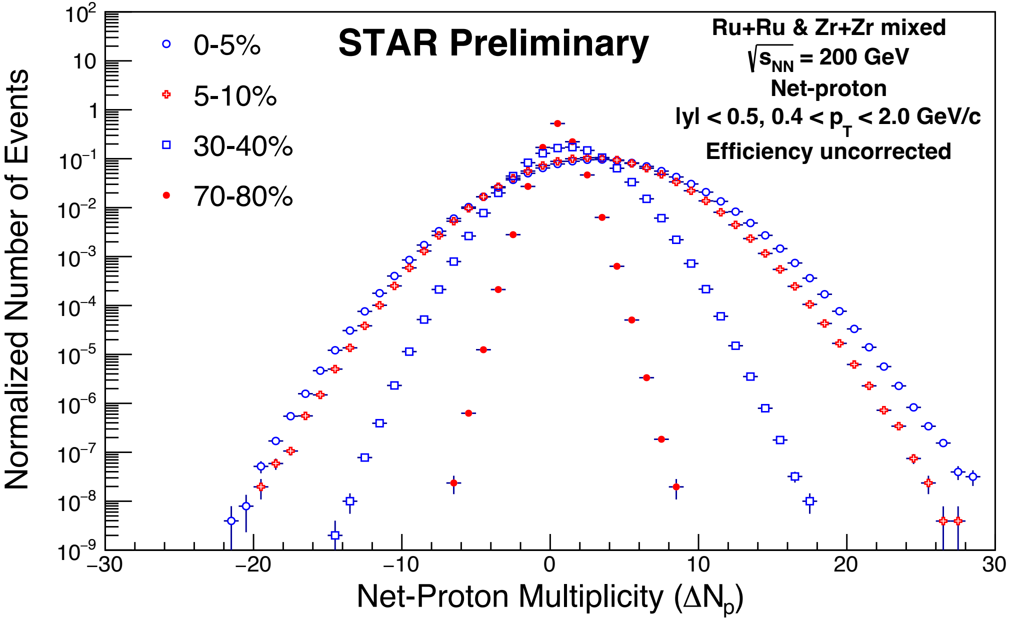


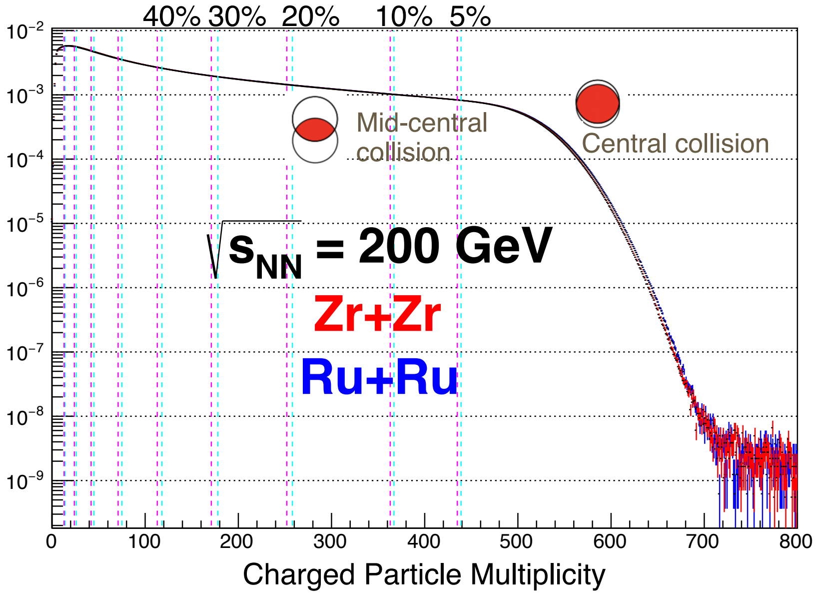


(Anti) Proton identification:

- $0.4 < p_T < 0.8$ GeV/c: deviation from the theoretical expectation red line $< 2\sigma$
- $0.8 \leq p_T < 2.0$ GeV/c: red line dev. $< 2\sigma$ & $0.6 < m^2 < 1.2$ GeV^2/c^4
- Purity: > 99%

Net-proton distributions & multiplicity distributions





Number of charged particles in $|\eta| < 1$ excluding (anti-)protons

Corrections

1. Detector efficiency correction [1~3]
    a. Binomial detector efficiency assumption
    b. TPC & TOF tracks
2. Centrality bin width correction [4]
    - Corrects finite bin width effect
3. Statistical uncertainty calculated based on Delta theorem [5]

Measured distribution

Detector response

Actual distribution

$$p(n) = \sum_{N} Binomial(n; N, \epsilon) \times P(N)$$

“*N*” detector bins with efficiency ϵ

n_i : number of events in multiplicity bin i

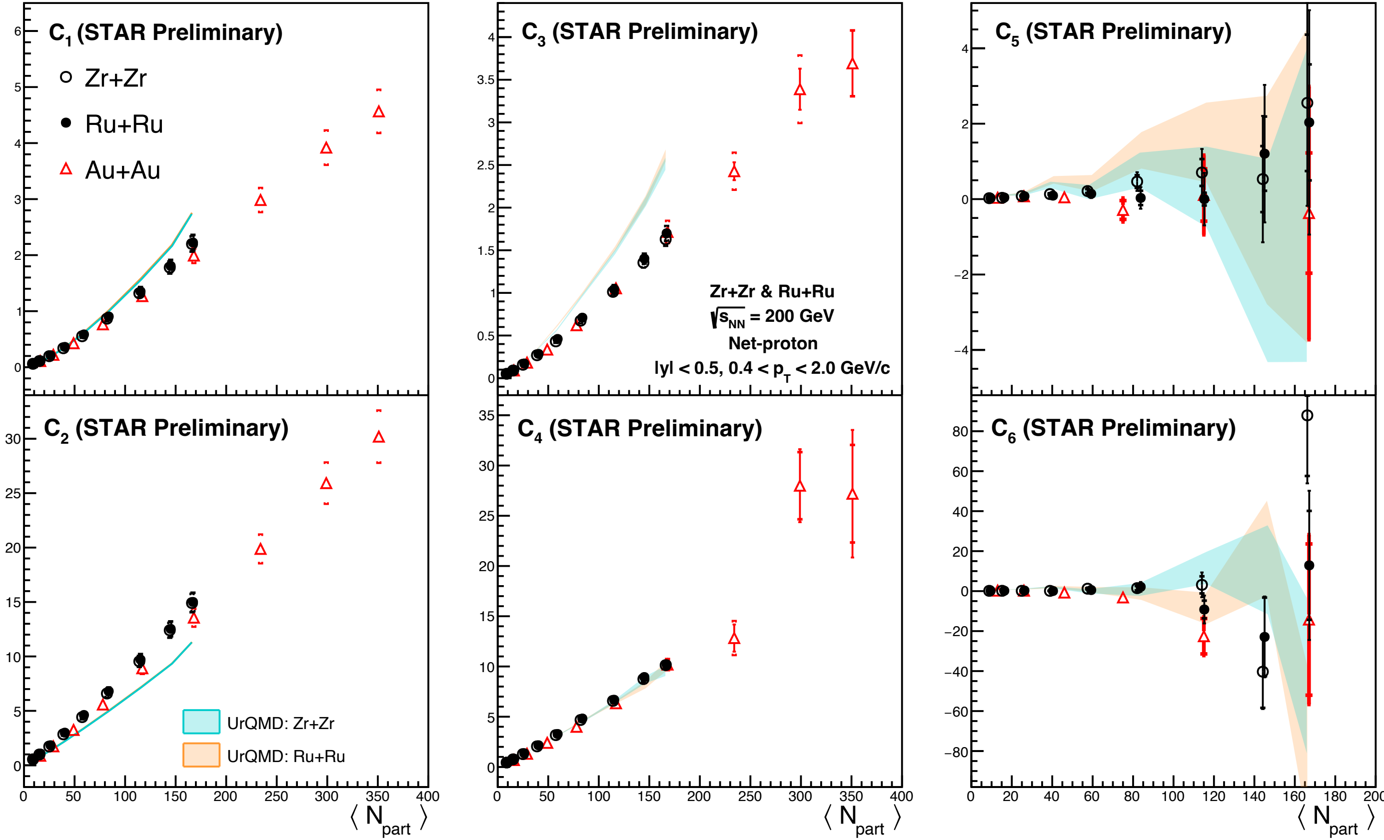
$$C_n^{corr} = \frac{\sum_i n_i C_{n,i}}{\sum_i n_i} = \sum_i \omega_i C_{n,i}$$

[1] X. Luo, Phys. Rev. C 91, 034907 (2015)
[2] T. Nonaka, Phys. Rev. C 95, 064912 (2017)
[3] X. Luo, Phys. Rev. C 99, 044917 (2019)
[4] X. Luo, J. Phys. G: Nucl. Part. Phys. 40, 105104 (2013)
[5] X. Luo, J. Phys. G: Nucl. Part. Phys. 39, 025008 (2012)

Net-proton cumulants

UrQMD centrality determined in a similar way to the data: measure charged-pion & charged-kaon multiplicity

$\langle N_{part} \rangle$: Average number of participating nucleons



UrQMD: hadronic transport model. Calculated in the STAR acceptance

1. The cumulants of net-proton in Zr+Zr, Ru+Ru and Au+Au collisions follow the same $\langle N_{part} \rangle$ trend at $\sqrt{s_{NN}}$ = 200 GeV
2. UrQMD overpredicts C_1 and C_3 while underpredicts C_2. In general, it shows a similar trend as the data

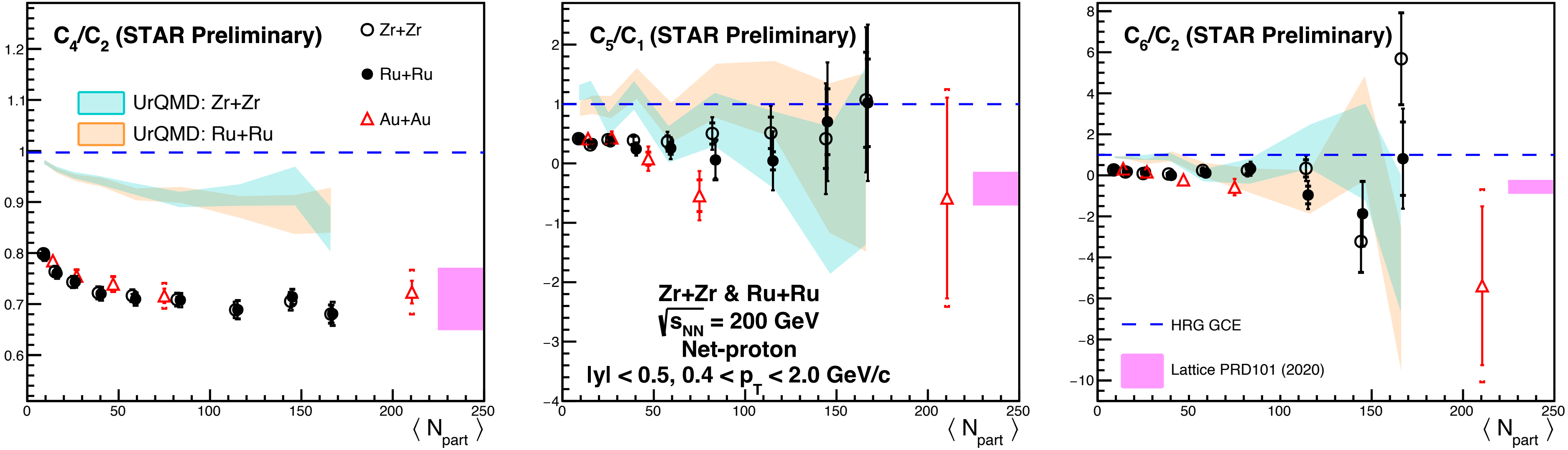
Au+Au C1 ~ C4:
STAR, Phys. Rev. C 104, 024902 (2021)

Net-proton cumulant ratios

UrQMD centrality determined in a similar way to the data: measure charged-pion & charged-kaon multiplicity

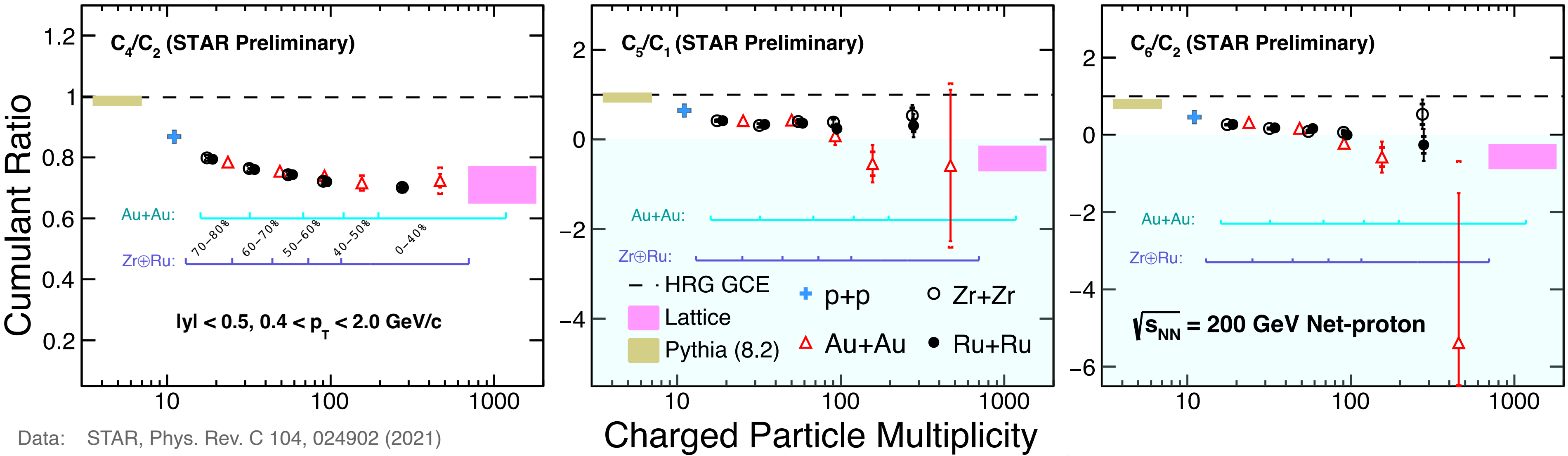
$\langle N_{part} \rangle$: Average number of participating nucleons

UrQMD: hadronic transport model. Calculated in the STAR acceptance



1. The cumulant ratios C_4/C_2, C_5/C_1, and C_6/C_2 of net-proton in Zr+Zr, Ru+Ru and Au+Au collisions show the same $\langle N_{part} \rangle$ trend at $\sqrt{s_{NN}}$ = 200 GeV
2. UrQMD overpredicts C_4/C_2. In general, it shows a similar trend as the data

High-order net-proton cumulant ratio comparison



Data: STAR, Phys. Rev. C 104, 024902 (2021)
STAR, Phys. Rev. Lett. 127, 262301 (2021)

Poster by Ashish Pandav (S1 T07_1)

1. Zr+Zr and Ru+Ru collision results fit into the p+p ⊕ Au+Au results at $\sqrt{s_{NN}}$ = 200 GeV
2. All cumulant ratios C_4/C_2, C_5/C_1, and C_6/C_2 decrease as the multiplicity increases
   —> Most central Au+Au collision results become consistent with Lattice QCD prediction for the formation of thermalized QCD matter and smooth crossover transition

Summary and outlook

1. At $\sqrt{s_{NN}}$ = 200 GeV: the highest precision data of Zr+Zr & Ru+Ru multiplicity-dependent cumulants and their higher order ratios fit into p+p and Au+Au results. All C_4/C_2, C_5/C_1, and C_6/C_2 show decreasing trend as multiplicity increases

2. Comparison with model and lattice QCD calculations
    a. UrQMD over/underpredicts the results and in general, shows a similar trend as the data
    b. Higher order cumulant ratios at high multiplicity (top Au+Au collision centrality) **consistent with the lattice QCD calculation result** (smooth crossover phase transition of thermalized medium)

3. Outlook: mixed cumulant ratios analysis to check a difference of B-field created in two isobar collisions
    a. Expect ~15% difference in the B-field^2 between Zr+Zr & Ru+Ru collisions [1]
    b. Mixed cumulant ratios offer an opportunity to experimentally assess the background B-field in the late stage of heavy-ion collisions [2]

[1] STAR, Phys. Rev. C 105, 014901 (2022)
[2] H.-T. Ding, Eur. Phys. J. A 57, 202 (2021)