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

Lawrence Berkeley National Laboratory

Ho-San Ko

for the STAR Collaboration

Supported by

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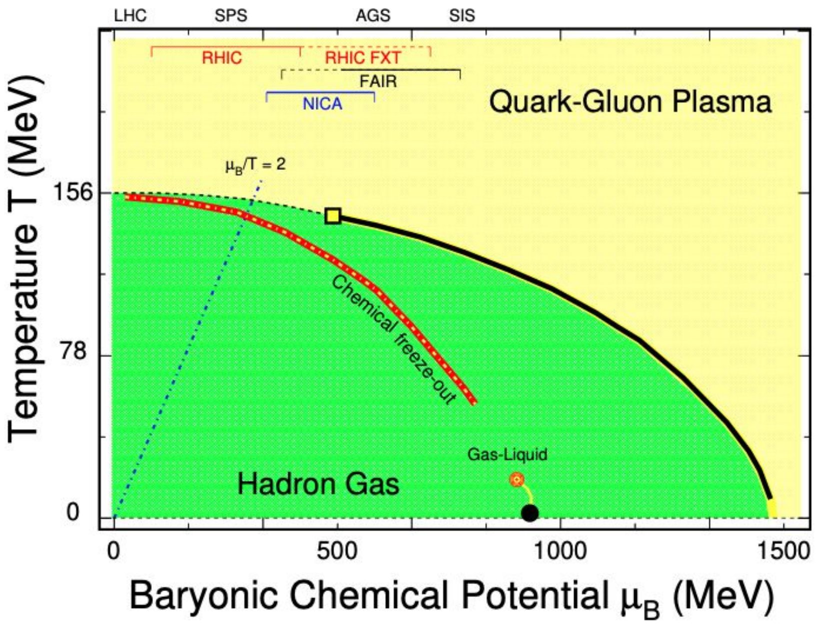
Outline

- Introduction & motivation
- Analysis information
  - $\sqrt{s_{NN}}$ = 200 GeV isobaric collisions **(mixed Ru and Zr data)**
- Corrections
- Net-proton cumulants & cumulant ratios
- Summary

QCD phase diagram



<<arXiv:2001.02852>>

- QCD calculation
  - Cross over at μ_B~0 [1] and T~ 150 MeV [2~4]
  - A critical point followed by first-order phase transition at high μ_B
- Search for the possible signature of critical point by scanning T vs μ_B:
  - By varying collision energy in heavy-ion collisions

[1] Nature 443, 675 (2006)
[2] JHEP 06, 088 (2009)
[3] Phys. Rev. D 85, 054503 (2012)
[4] Science 332, 1525 (2011)

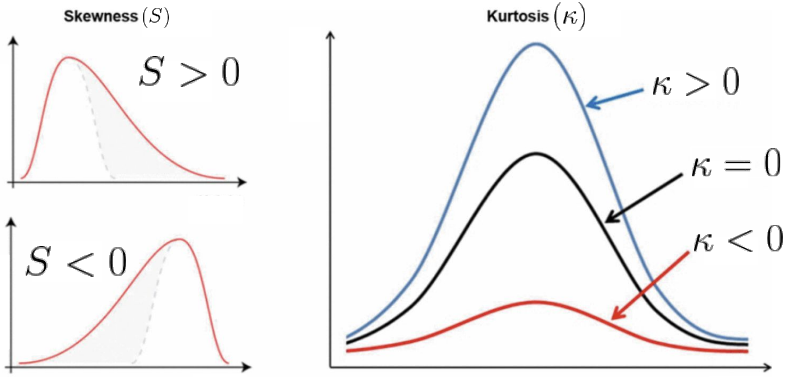
Fluctuation of conserved quantities

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

$$\delta N = N - \langle N \rangle \quad C_1 = \langle N \rangle, C_2 = \left\langle (\delta N)^2 \right\rangle$$

$$C_3 = \left\langle (\delta N)^3 \right\rangle, C_4 = \left\langle (\delta N)^4 \right\rangle - 3\left\langle (\delta N)^2 \right\rangle^2$$

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



- **The higher the order, the more sensitive**

$$C_2 \sim \xi^2, C_3 \sim \xi^{4.5}, C_4 \sim \xi^7$$

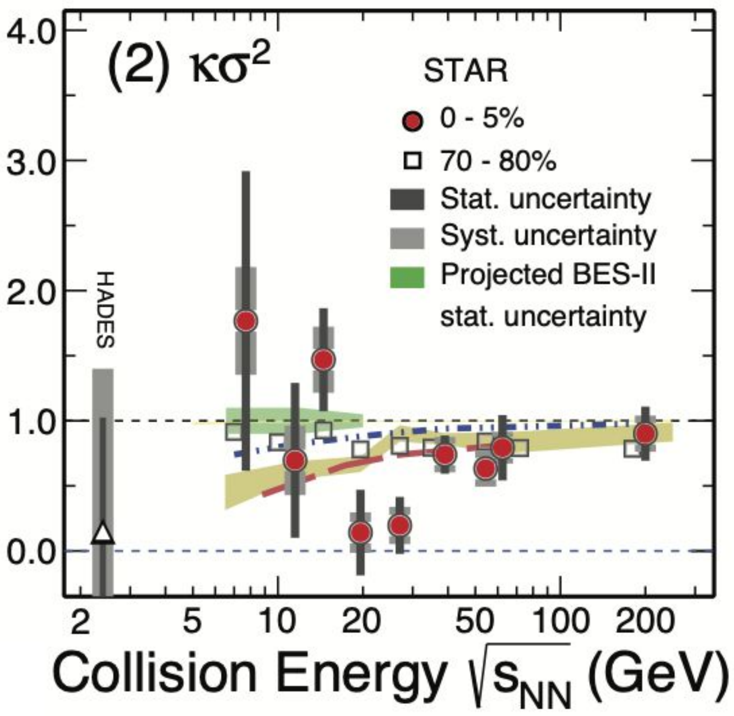
Phys. Rev. Lett. 107, 052301 (2011)

- The cumulant ratios can be directly compared to theoretical calculations

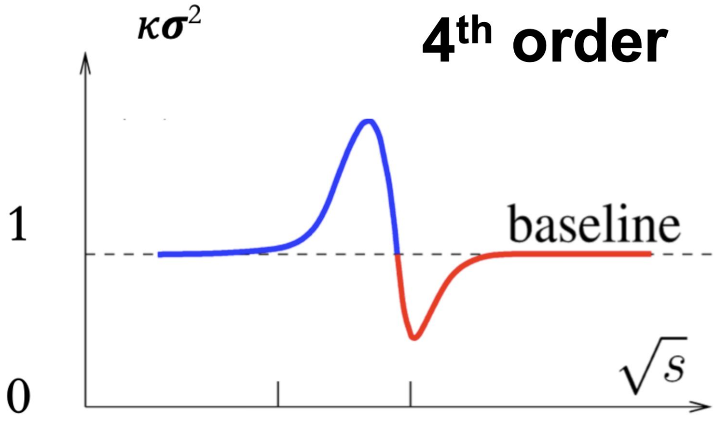
$$\chi_q^{(n)} = \frac{\partial^n (p/T^4)}{\partial(\mu_Q/T)^2} = \frac{1}{VT^3} \times C_q^n$$

Net-proton number is used as a proxy to net-B number

Fourth-order fluctuations for critical point search



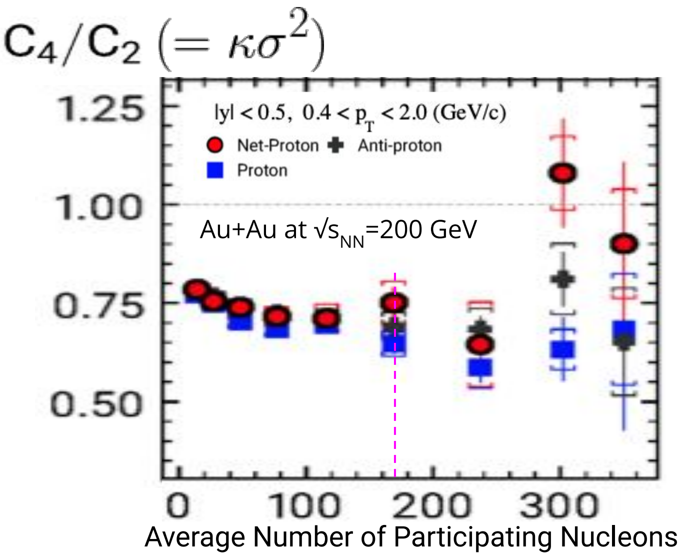
<<Phys. Rev. Lett. 126, 92301 (2021)>>



Phys. Rev. Lett. 107, 052301 (2011)
Phys. Rev. D 85, 034027 (2012)
Phys. Rev. D 93, 034037 (2016)
Phys. Rev. D 95, 014038 (2017)

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

Isobaric (Zr+Zr & Ru+Ru) collision data



C_4/C_2 of net-proton for Au+Au collision at $\sqrt{s_{NN}}$ = 200 GeV

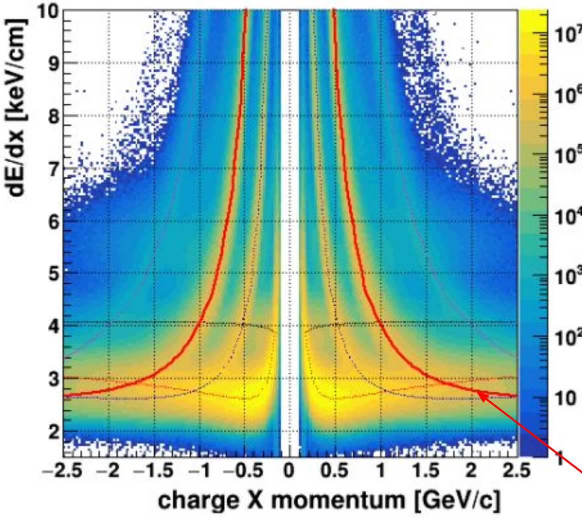
<<Phys. Rev. C 104, 024902 (2021)>>

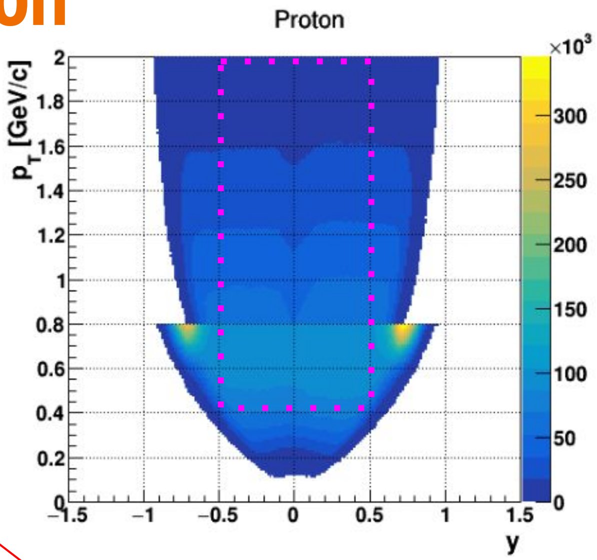
- The number of nucleons per nucleus:
  - Proton: A = 1
  - Isobar (Ru or Zr): A = 96
  - Au: A = 197
- **Expect the same multiplicity dependence in different collision systems at the same collision energy**
- Large statistics: 2.3B Zr+Zr and 2.2B Ru+Ru taken at STAR in 2018

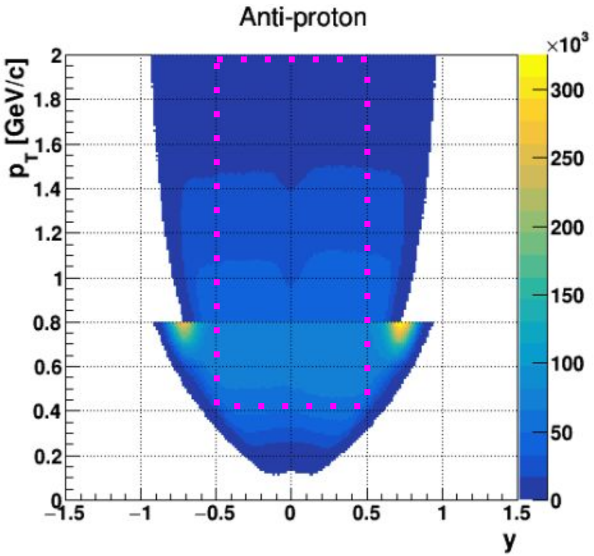
Solenoid Tracker at RHIC (STAR)

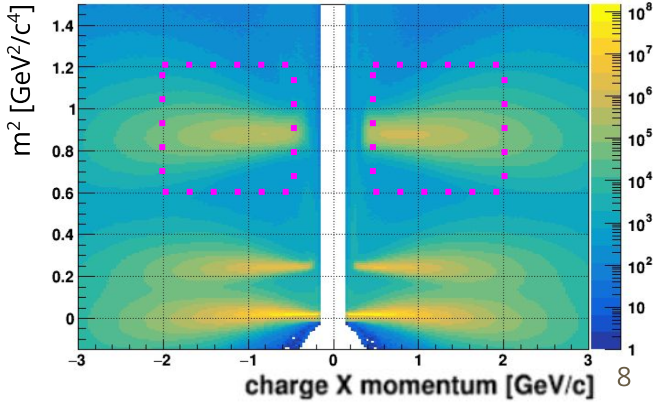
- **Time Projection Chamber (TPC)**: Vertexing & particle identification
- **Time Of Flight (TOF) detector:** Ensures proton purity at $0.8 < p_T < 2.0$ GeV/c

Proton identification









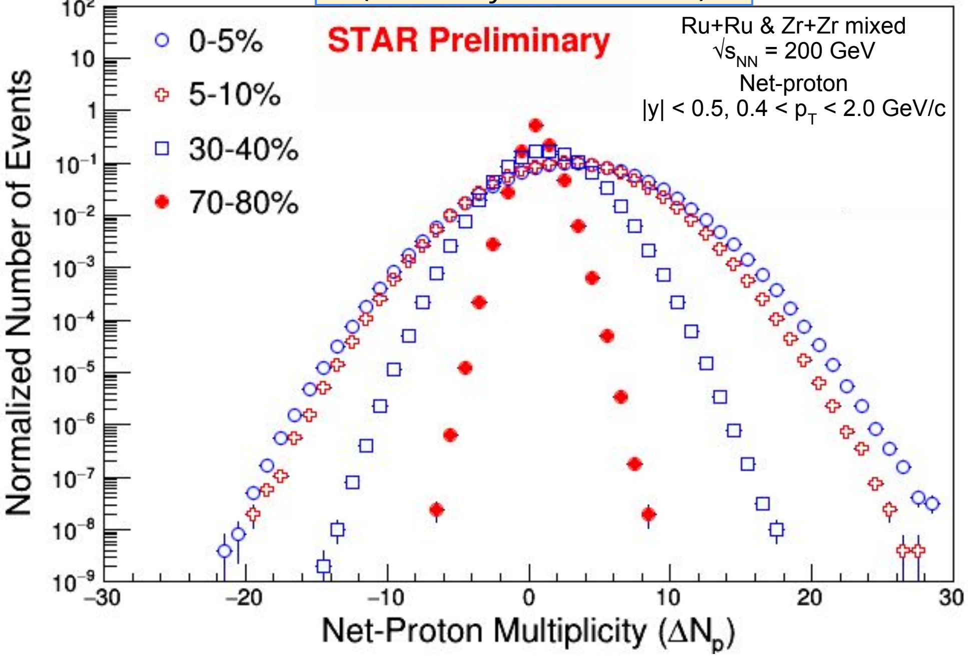
(Anti) Proton identification:

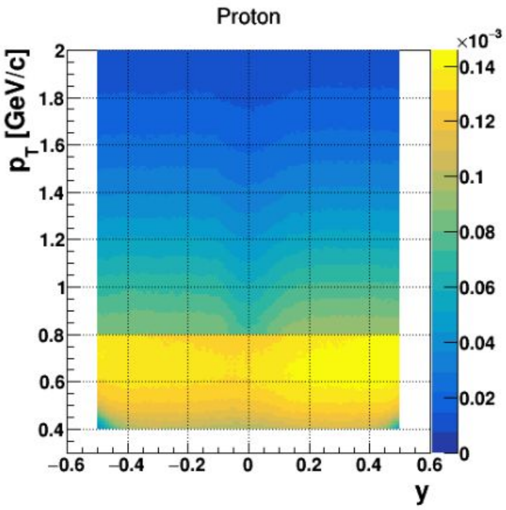
- $0.4 < p_T < 0.8$ GeV/c: deviation from the red line (Bischel) < 2σ
- $0.8 < p_T < 2.0$ GeV/c: red line dev. < 2σ & $0.6 < m^2 < 1.2$ GeV^2/c^4
- Purity: > 99%

Acceptance: $|y| < 0.5$ & $0.4 < p_T < 2.0$ GeV/c

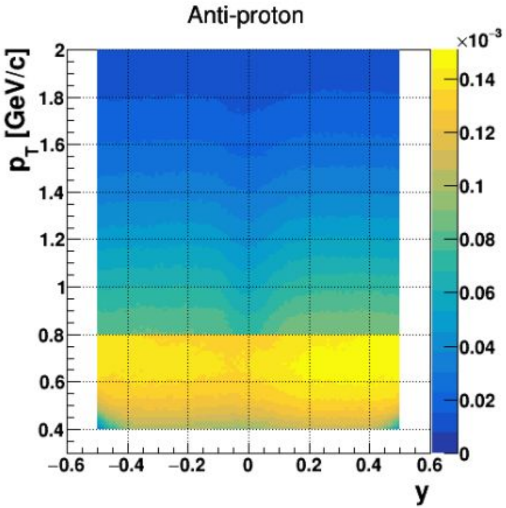
Net-proton distributions

Net-proton distribution
(efficiency un-corrected)





Before detector efficiency correction
z-axis normalized



Before detector efficiency correction
z-axis normalized

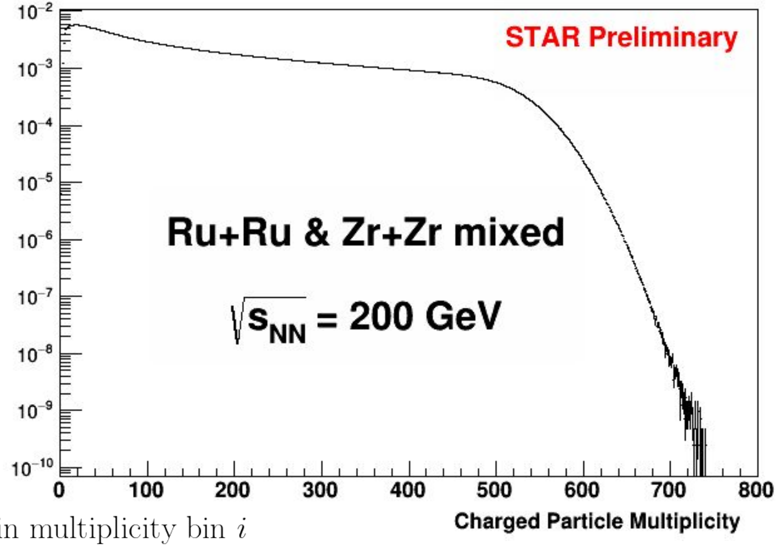
Corrections

Measured | Detector response | Actual distribution

$$p(n) = \sum_N Binomial(n; N, \epsilon) \times P(N)$$

"N" detector bins with efficiency ϵ

- Detector efficiency correction [1~3]
  - Binomial detector efficiency correction
  - Efficiency corrected to each particle track
    - TOF matching + TPC tracking efficiency corrections
- Statistical uncertainty calculated based on Delta theorem [4]
- Centrality bin width correction [5]
  - Corrects finite bin width effect



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

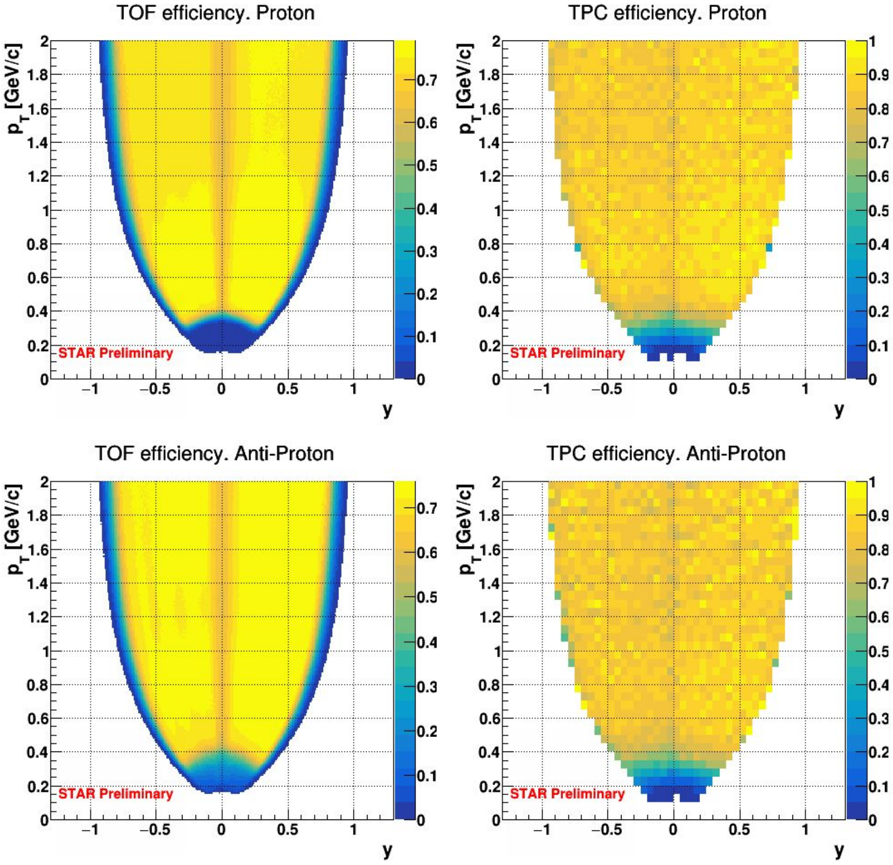
n_i : number of events in multiplicity bin i

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

Centrality: a measure of geometric overlap of two colliding nuclei → determined by charged-particle multiplicity

Charged-particle multiplicity: number of charged particles in $|\eta| < 1$ excluding (anti-)protons per event

TOF matching efficiency & TPC tracking efficiency maps

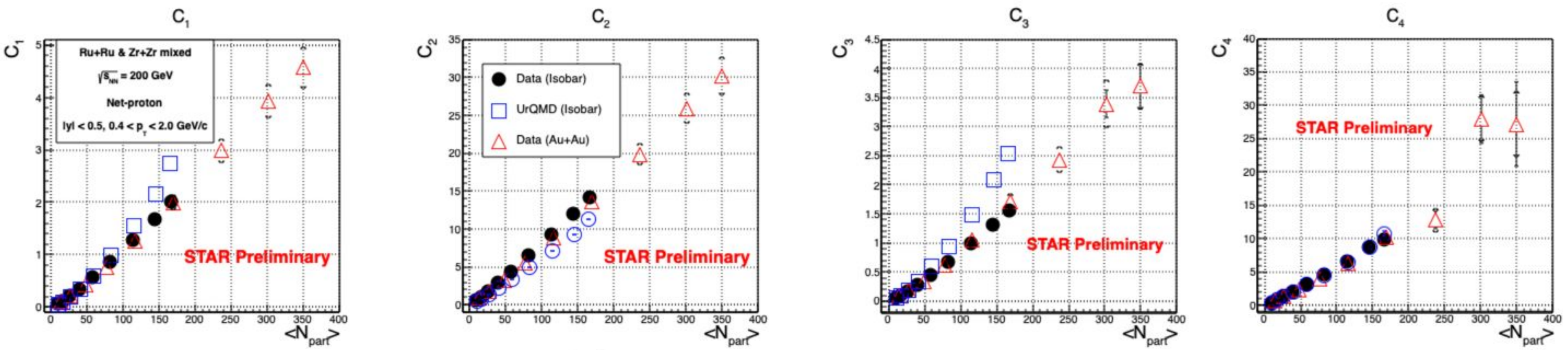


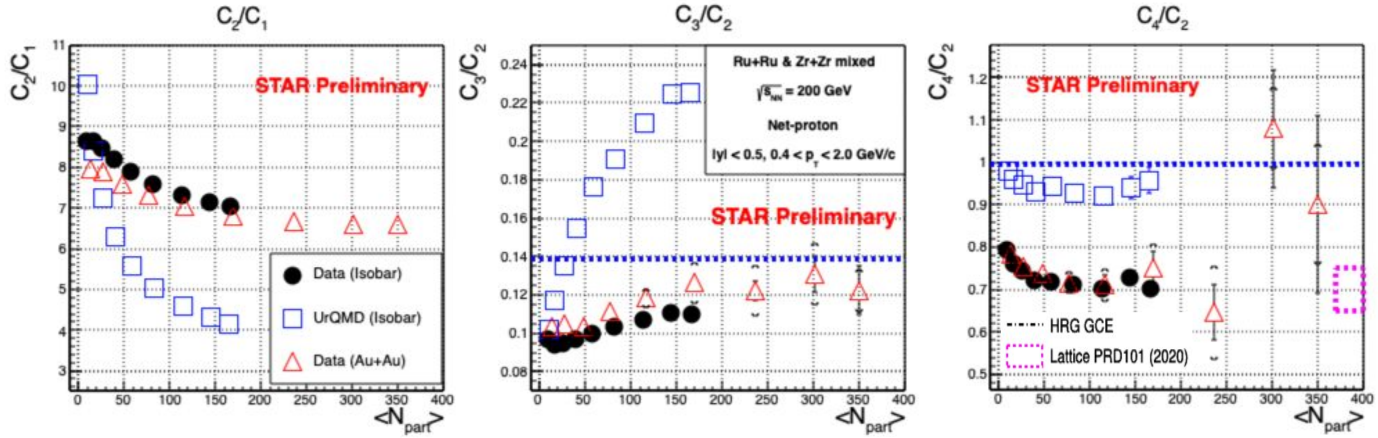
- TOF matching efficiency:
  Number of protons identified by TPC vs TPC+TOF
- TPC tracking efficiency:
  Number of protons identified by TPC vs generated both in MC simulation with realistic geometry (embedding)
- Do interpolation between bins to overcome the low statistics of the MC simulation events

Net-proton cumulants and ratios

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

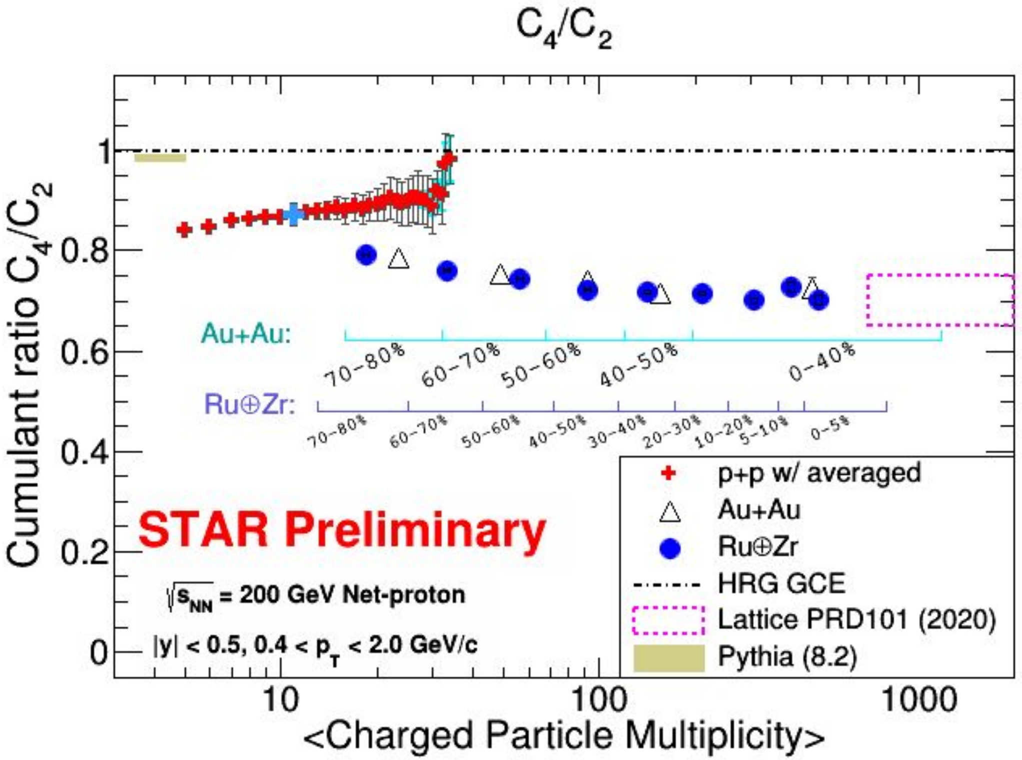
$\langle N_{part} \rangle$: Average Number of participating nucleons per event





- UrQMD: hadronic transport model calculation with the same acceptance of the STAR
- UrQMD results show discrepancies. However, in general, show a similar trend as the data
- Au+Au collision at $\sqrt{s_{NN}}$ = 200 GeV plotted
  - Systematic shift in cumulant ratios
  - Overall trends are consistent

C_4/C_2 (4th-order) net-proton cumulant ratio comparison



p+p: <<CPOD2021 R. Nishitani>>
Au+Au: <<Phys. Rev. C 104, 024902 (2021)>>
LQCD: <<Phys. Rev. D 101, 074502 (2020) >>

1. For p+p collision, the entire centrality classes are merged to one and shown with light blue
   a. p+p collision's multiplicity dependence is the opposite from the heavy-ion collision's
2. Isobaric collisions (Ru+Ru, Zr+Zr combined) fit into the p+p (averaged) and Au+Au collision results at $\sqrt{s_{NN}}$ = 200 GeV
3. C_4/C_2 lowers as the charged particle multiplicity → consistent with the lattice QCD result at high multiplicity region: approaching thermalized medium in the most central collisions

Summary and outlook

Thank you and good morning!
good afternoon!
good evening!
good night!

1. Net-proton cumulants and their ratios from $\sqrt{s_{NN}}$ = 200 GeV isobaric collisions (mixed Ru and Zr data)
2. Net-proton cumulants and their ratios of the isobaric collision compared with the Au+Au collision results at $\sqrt{s_{NN}}$ = 200 GeV
    a. Systematic shift in cumulant ratios. However, overall trends are consistent
    b. p+p collisions show the opposite multiplicity dependency from the heavy-ion collisions
    c. C_4/C_2 from the different collision systems fit one another in collision centrality dependence
3. Net-proton cumulant ratios compared with HRG, UrQMD models, and lattice QCD
    a. UrQMD results qualitatively show the same trends as the data
    b. C4/C2 consistent with the lattice QCD calculation result at high multiplicity
        i. approaching thermalized medium in the most central collisions
4. **Working on higher order cumulants**