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Net-Proton Number Fluctuation of Mixed Zr+Zr and Ru+Ru Collisions at $\sqrt{s_{NN}} = 200$ GeV with the RHIC-STAR Detector

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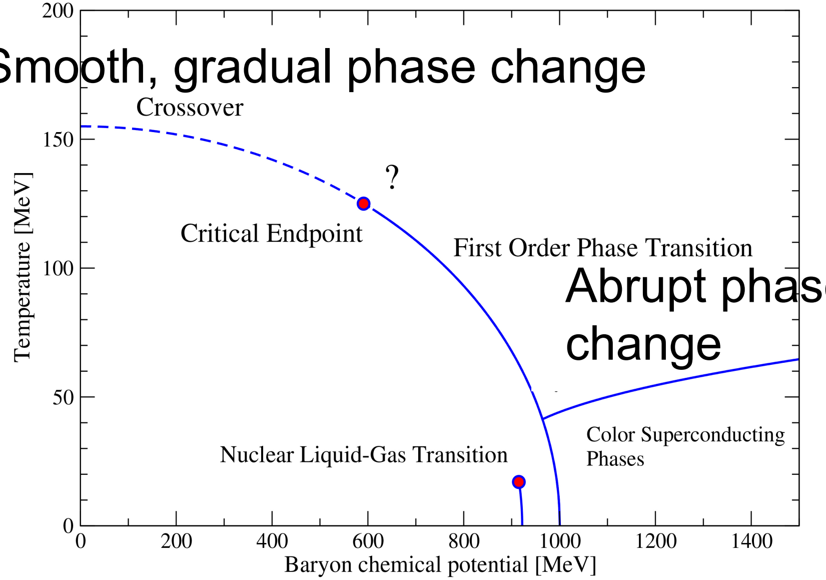
Outline

1) Introduction
2) Previous Results
3) Motivation
4) Analysis Method
5) Data Sets and Early Stage Results

2^{nd} Order Phase Transition Critical Point

QCD Diagram (hypothesis)

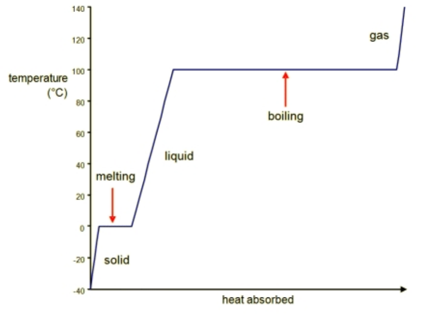
Smooth, gradual phase change



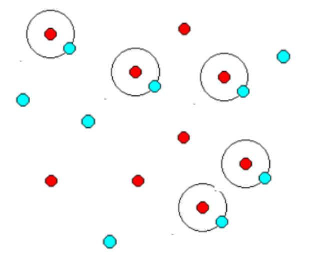
Abrupt phase change

Example:

First order → Ice Water Steam



Crossover → Ionization of gas



Critical point: where two boundaries meet

P. Gunkel et al, 2019, Eur. Phys. J. A 55: 169 | M. Stephanov et al, 1998, Phys. Rev. D. A 60, 114028

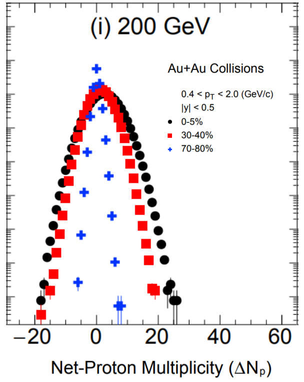
Observable: Net-Proton Cumlants

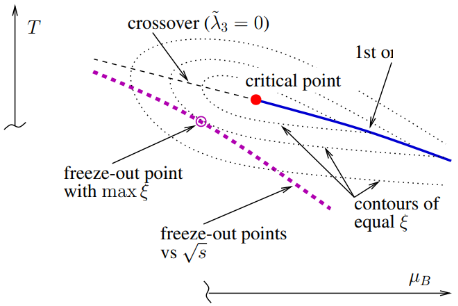
Cumulant: Characterize Probability Distribution of Net-Proton Number

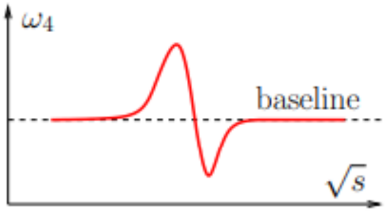
$$C_1 = \langle N \rangle$$
$$C_2 = \langle (\delta N)^2 \rangle$$
$$C_3 = \langle (\delta N)^3 \rangle$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$

$N \equiv$ number of proton – number of anti-proton

$\delta N \equiv$ deviation from the event averaged N





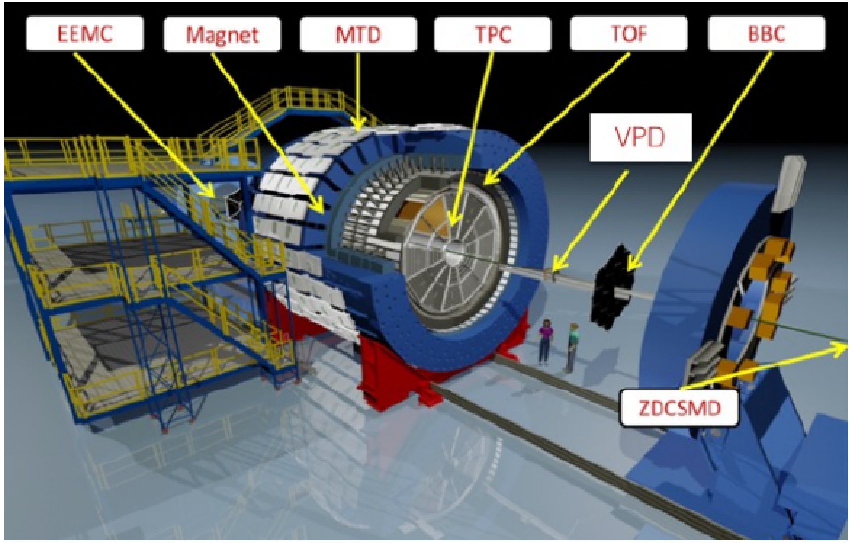


Fluctuation related to the proximity of freeze-out point to the critical point

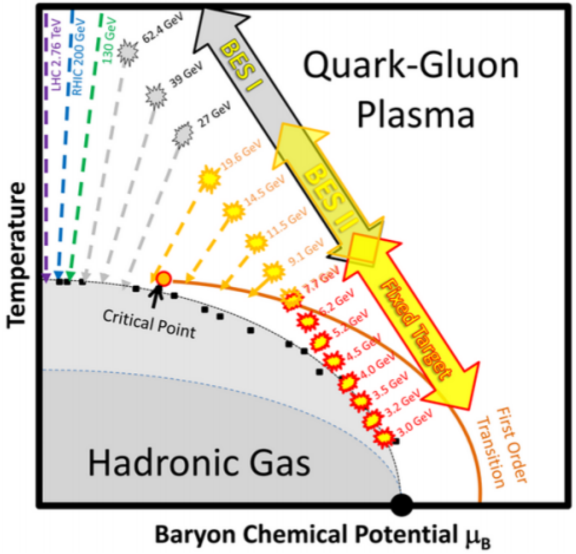
Larger correlation length (ξ) near critical point enhances the net-proton cumulants: $C_2 \propto \xi^2$ $\quad C_3 \propto \xi^{4.5}$ $\quad C_4 \propto \xi^7$

M. Abdallah et al (STAR), 2021, arXiv:2101.12413 | C. Athanasiou, K. Rajagopal, M. Stephanov, 2010, PRD, 82(7) 074008 | Y. Hatta, M. Stephanov, 2003, PRL, 91(10) 102003 | M. Stephanov, 2011, J.Phys.G,38(12),124147

STAR Detector



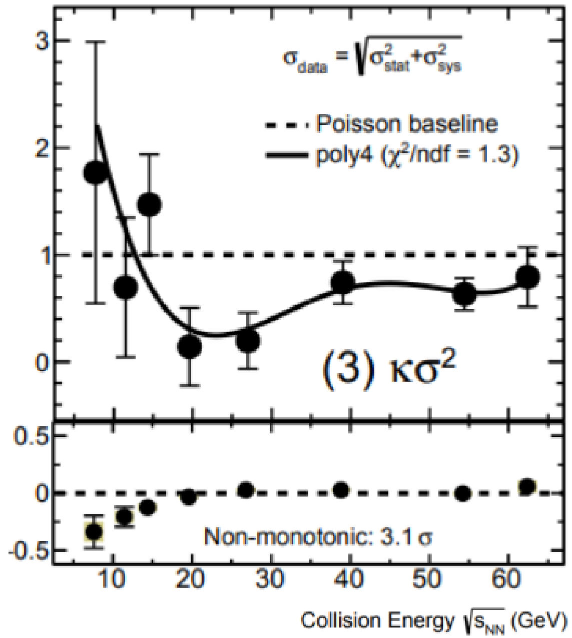
- Large, uniform acceptance at mid-rapidity
- Time Projection Chamber (TPC) and Time of Flight Detector (TOF) for identification of proton and anti-proton



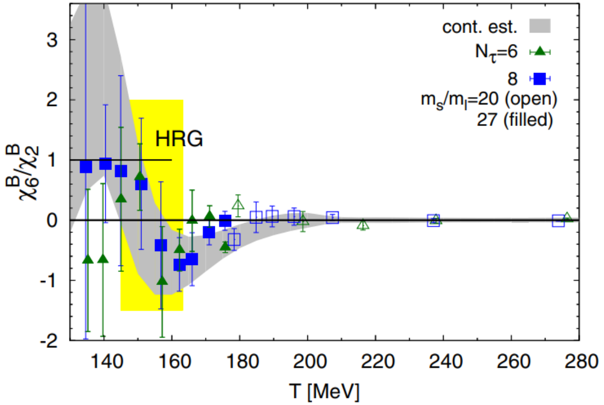
- Wide range of collision energy ⟺ change in μ_B

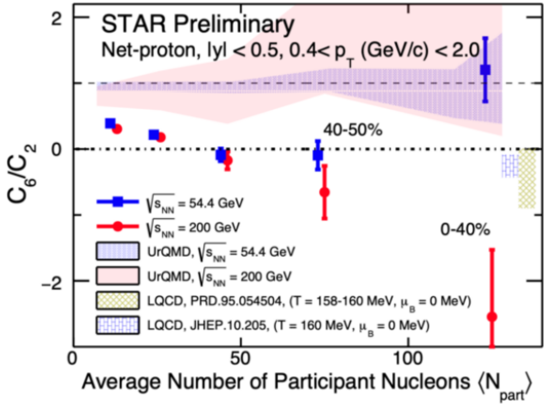
Previous Results from STAR Experiment

Ratio of C_4 over C_2 in Au+Au shows non-monotonic behavior along the collision energy



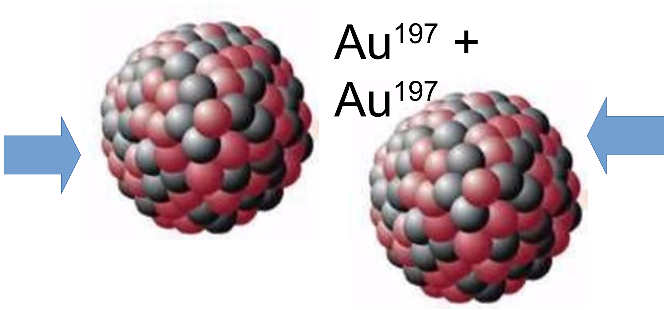
C_6/C_2 has different sign at different energy, could indicate different behaviors in phase transitions

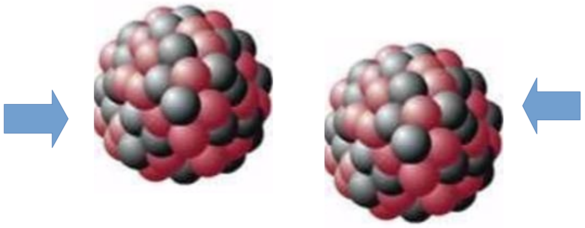




M. Abdallah et al (STAR), 2021, arXiv:2101.12413 | A. Bazavov et al, Phys. Rev. D. 95.054504 | T. Nonaka, 2021, Nuclear Physics A. 1005.121882

System Size Dependence





Zr^{96} + Zr^{96}/ Ru^{96} + Ru^{96}

For nuclei with different sizes

Collisions of same “scale”, quantified by the number of charged particles emitted (multiplicity), have different collision “geometry” or centrality

Freeze-out location could differ

Effects on the net-proton cumulants?

Y. Hatta, M. Stephanov,, 2003, PRL, 91(10) 102003

Methods

Limited detectors efficiencies ➡ probability to detect particle less than 100%

Run computer simulation of detector to extract efficiency.
Use efficiency correction formulae for cumulants, called track by track method.

Centrality fluctuation

To group similar collision “geometry” or centrality to improve statistics, for minimal uncertainty of centrality, average the cumulants with weight of number of events in each mutiplicity bin. This is called Centrality Bin Width Correction.

Auto-Correlation

Cumulants and centrality both depend on multiplicity. To avoid correlation through this dependence, remove protons from multiplicity definition.

X.Luo,T.Nonaka, 2019, Phys.Rev.C99,044917 | X.Luo et al, 2013, J.Phys.G40,105104

Data set

$Zr^{96} + Zr^{96}$ and $Ru^{96} + Ru^{96}$ at 200 GeV data combined, taken in 2018

Event Selection

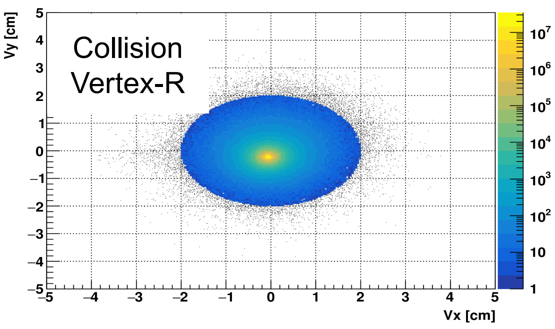
- -35 < TPC-Z-vertex < 25 cm
- | VPD-Z-vertex – TPC-Z-vertex | < 5 cm
- TPC-Z-vertex < 2 cm

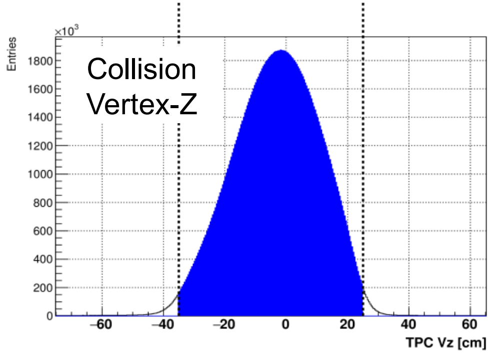
Total event statistics

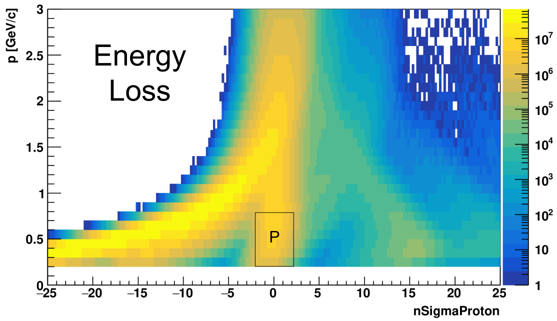
4 billion good events after cut.
(2 billion analyzed)

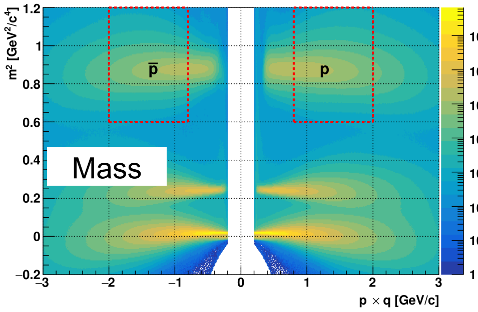
Particle Identification

Require the energy loss per distance traveled and mass measured with TPC and TOF, respectively, to match with that of proton.

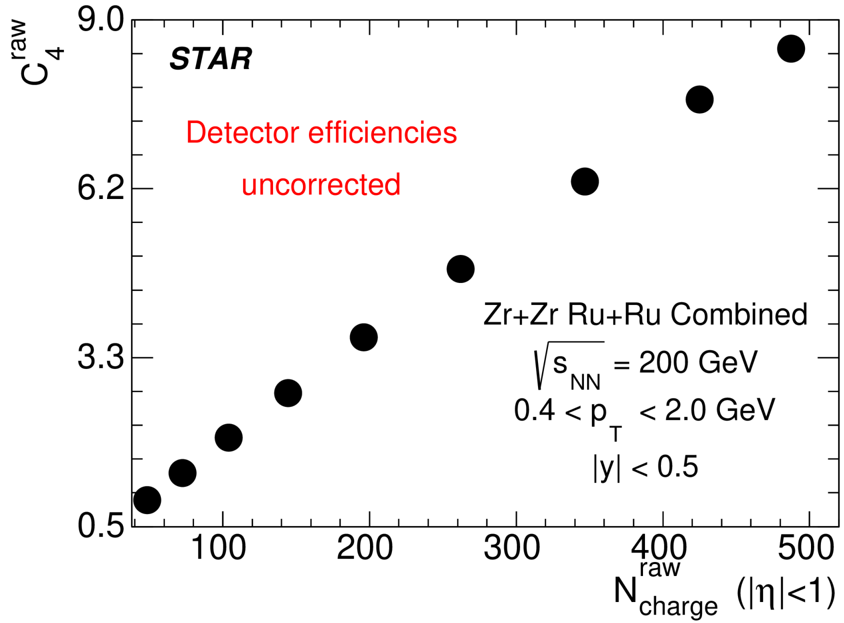








Early Stage Results



- Statistical uncertainty is small as expected for large statistics.
- Detector efficiencies depend on the multiplicity. They are not corrected in the above plot.

Summary and Outlook

- Net-proton cumulants are sensitive to the freeze-out near the critical point. STAR at RHIC is well suited for studying net-proton cumulants and has generated remarkable results.

- We can further study system size dependence of net-proton cumulants with good precision using large-statistics Zr+Zr and Ru+Ru data sets.

- We plan to analyze the net-proton cumulants for Zr+Zr and Ru+Ru up to 6^{th} order.