Seventh and eighth order cumulants of net-proton number distributions in heavy-ion collisions at RHIC-STAR

Ashish Pandav for the STAR Collaboration
National Institute of Science Education and Research, HBNI, India

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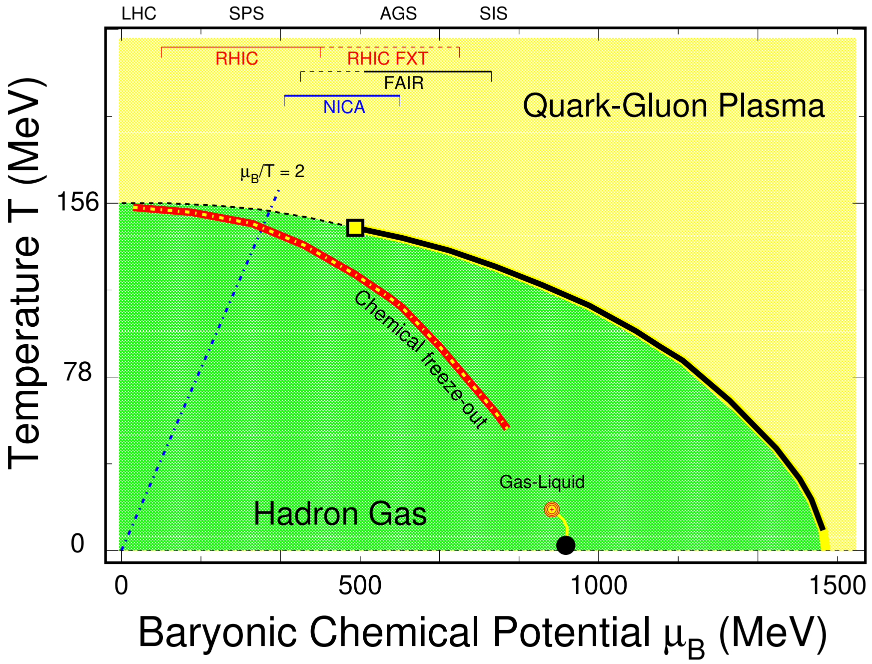
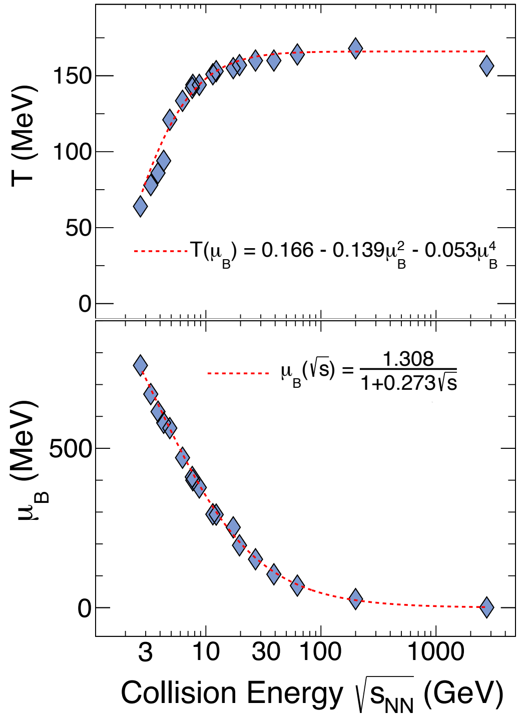
Outline

1. Introduction
2. Physics Motivation
3. Data Analysis
4. Results

Introduction: QCD Phase Diagram



B. Mohanty, N. Xu, arXiv:2101.09210
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)



Goal: Study the phase diagram of QCD.
Varying beam energy varies Temperature (T) and Baryon Chemical Potential (μ_B).
Fluctuations of conserved quantities are sensitive to phase transition and critical point.

Observables

- Hyper-order cumulants of net-proton distributions (proxy for net-baryon).

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

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

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

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

$$C_7 = \langle(\delta N)^7\rangle - 21\langle(\delta N)^5\rangle\langle(\delta N)^2\rangle - 35\langle(\delta N)^4\rangle\langle(\delta N)^3\rangle + 210\langle(\delta N)^3\rangle\langle(\delta N)^2\rangle^2$$

$$C_8 = \langle(\delta N)^8\rangle - 28\langle(\delta N)^6\rangle\langle(\delta N)^2\rangle - 56\langle(\delta N)^5\rangle\langle(\delta N)^3\rangle - 35\langle(\delta N)^4\rangle^2 + 420\langle(\delta N)^4\rangle\langle(\delta N)^2\rangle^2 + 560\langle(\delta N)^2\rangle\langle(\delta N)^3\rangle^2 - 630\langle(\delta N)^2\rangle^4$$

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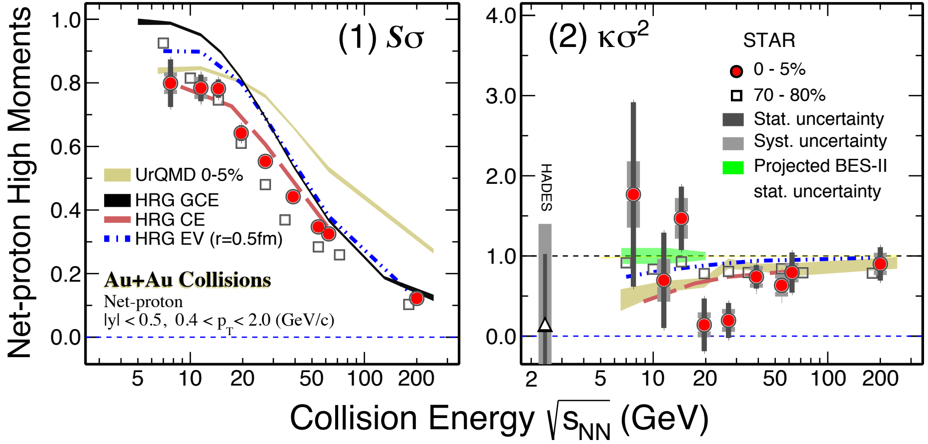
- Hyper-order cumulants (order 5 or higher) probe the nature of phase transition.

Sign of cumulants sensitive

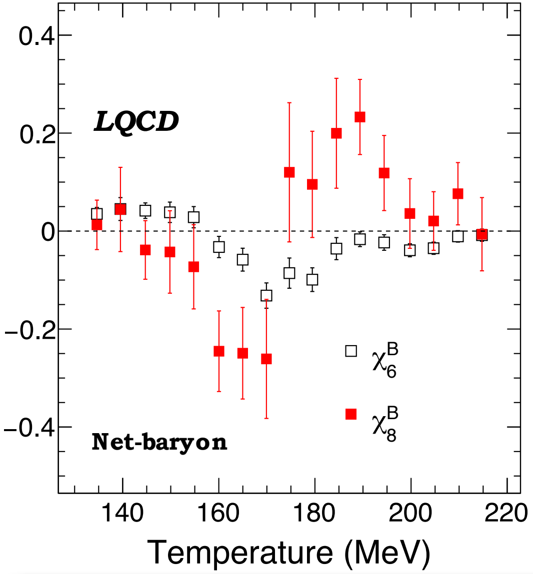
C_2, C_3, C_4: positive for data (7.7-200 GeV) and model (LQCD, FRG, HRG, UrQMD, JAM) – more distinct signatures needed

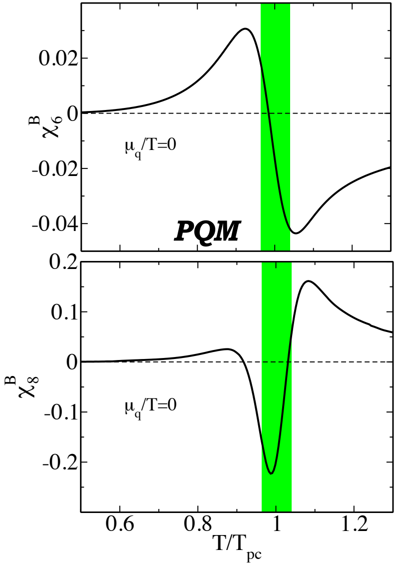
STAR: PRL, 126, 092301 (2021), PRC,104, 024902 (2021)

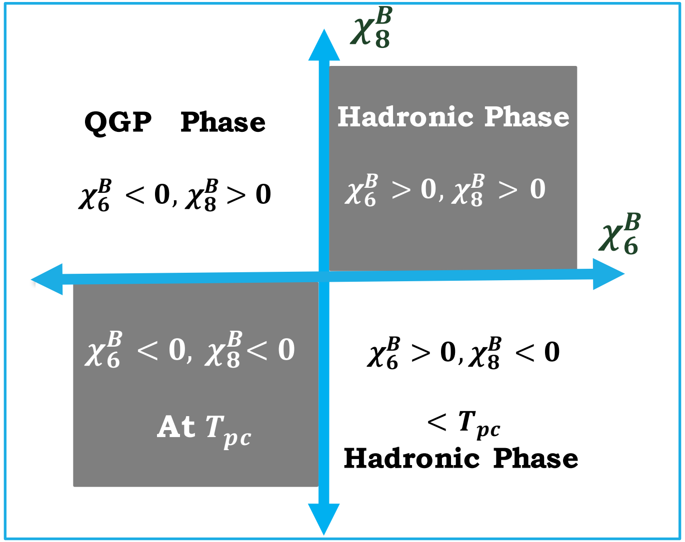


Search for Crossover

Goal: Probing signature of transition between QGP and hadronic phase







- χ_5, χ_6, χ_7, χ_8 (Hyper–order cumulants) < 0 *and* $|\chi_8| > |\chi_6|$, $|\chi_7| > |\chi_5|$ from LQCD, FRG, PQM – more sensitive probes to crossover. Stronger energy dependence.

  LQCD: JHEP10 (2018) 205, PRD101, 074502 (2020), PQM: EPJC71, 1694(2011), FRG: PRD104, 094047 (2021)

- Sign of χ_6 and χ_8 together sensitive to hadronic phase, QGP phase and T_{pc}.

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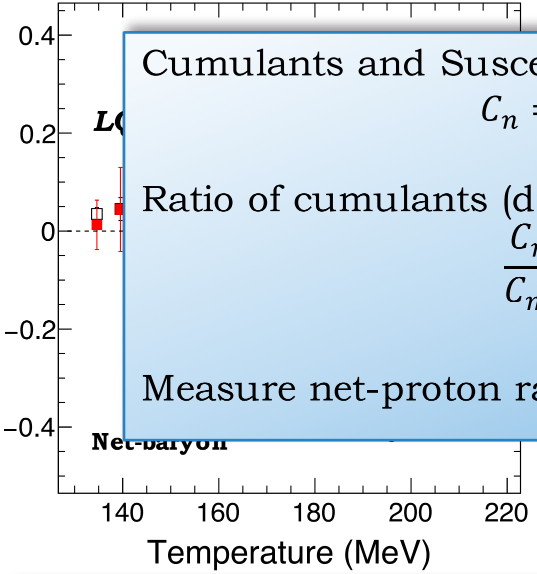
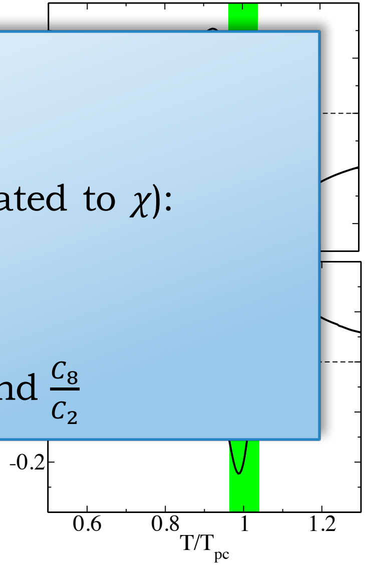




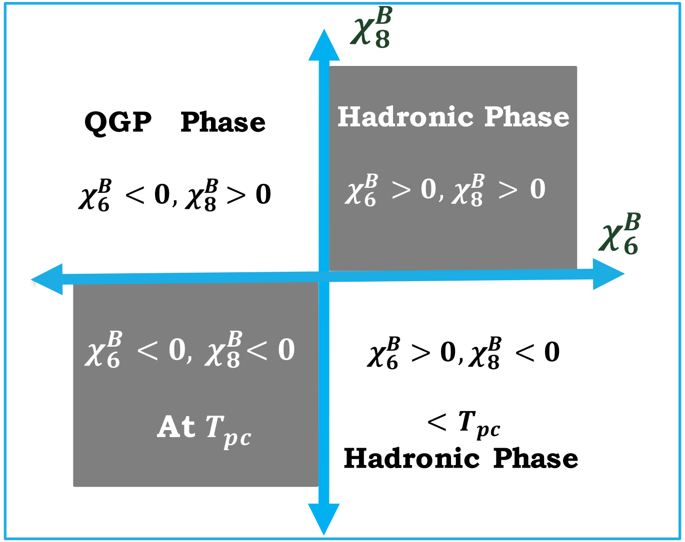
Cumulants and Susceptibilities

$$C_n = VT^3 \chi_n$$

Ratio of cumulants (directly related to χ):

$$\frac{C_n}{C_m} = \frac{\chi_n}{\chi_m}$$

Measure net-proton ratios $\frac{C_7}{C_1}$ and $\frac{C_8}{C_2}$



- $\chi_5, \chi_6, \chi_7, \chi_8$ (Hyper−order cumulants) < 0 *and* $|\chi_8| > |\chi_6|$, $|\chi_7| > |\chi_5|$ from LQCD, FRG, PQM − more sensitive probes to crossover. Stronger energy dependence.

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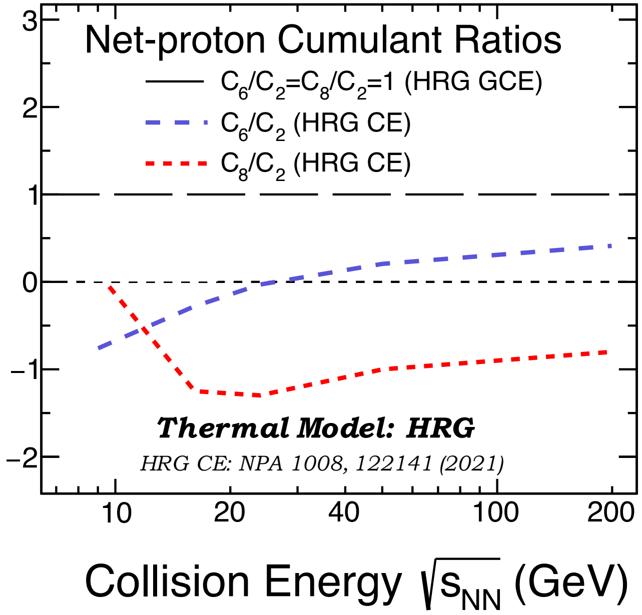
Test of Thermal Model

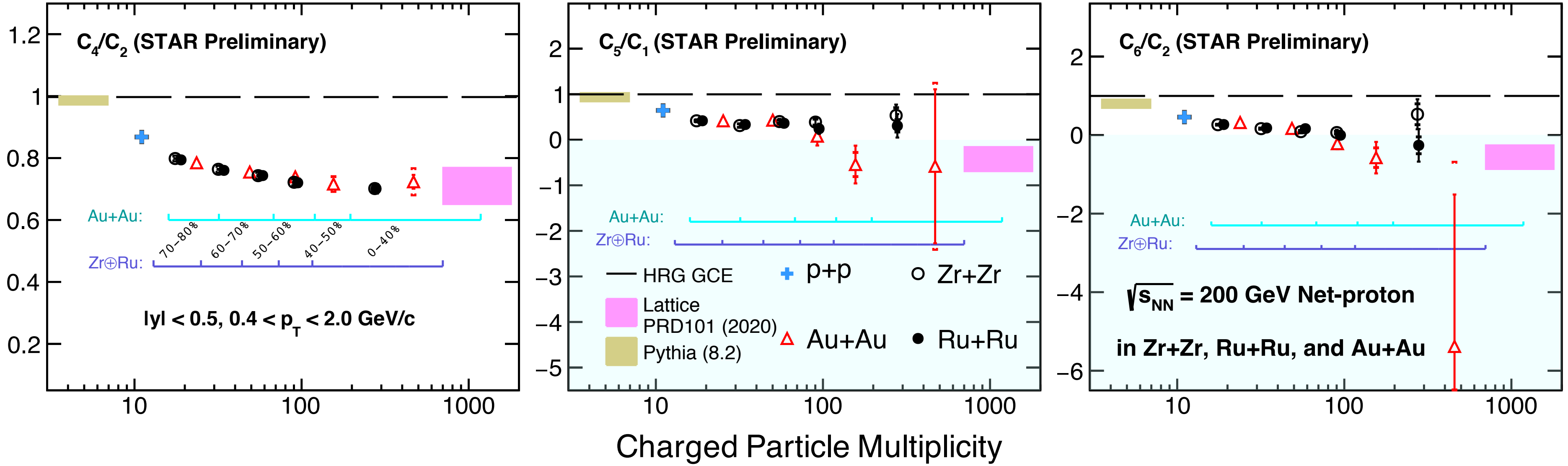


- $C_6/C_2 = C_8/C_2 = 1$ at all $\sqrt{s_{NN}}$ from HRG GCE.
- Deviation from unity observed for HRG CE

Higher-order Cumulants at STAR so far

STAR: PRL 126, 092301 (2021), PRC 104, 024902 (2021), PRL 127, 262301 (2021)

Overview on higher order cumulants:
Ho San Ko (June 15), Plenary Talk



- ❑ STAR has measured net-proton cumulants up to sixth-order so far. (Au+Au, Zr+Zr, Ru+Ru and p+p collisions)

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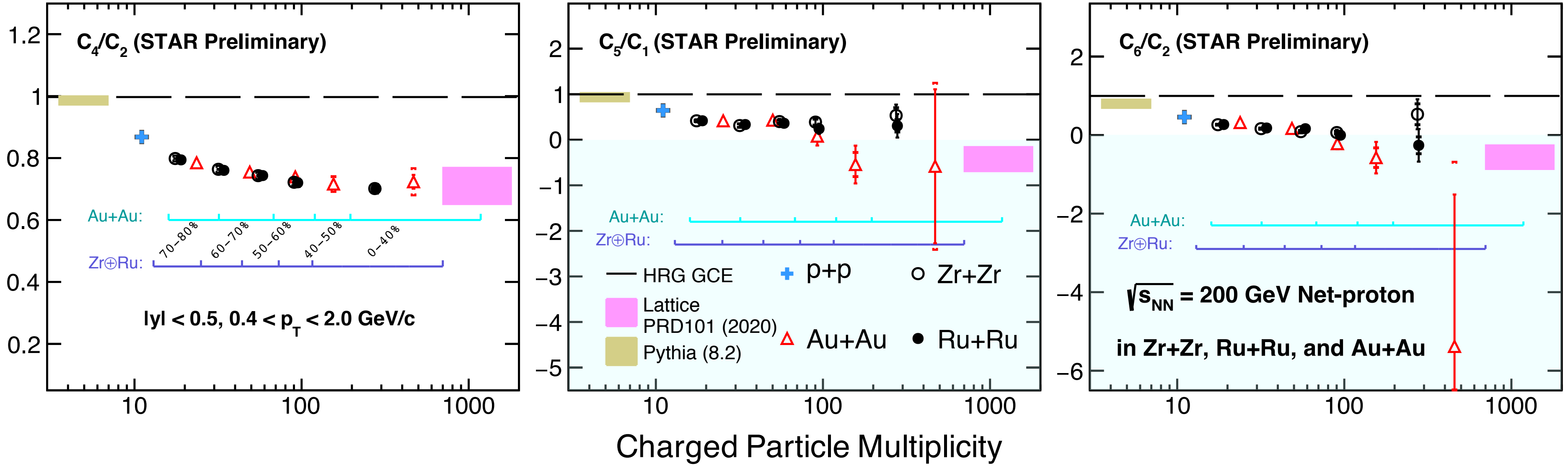
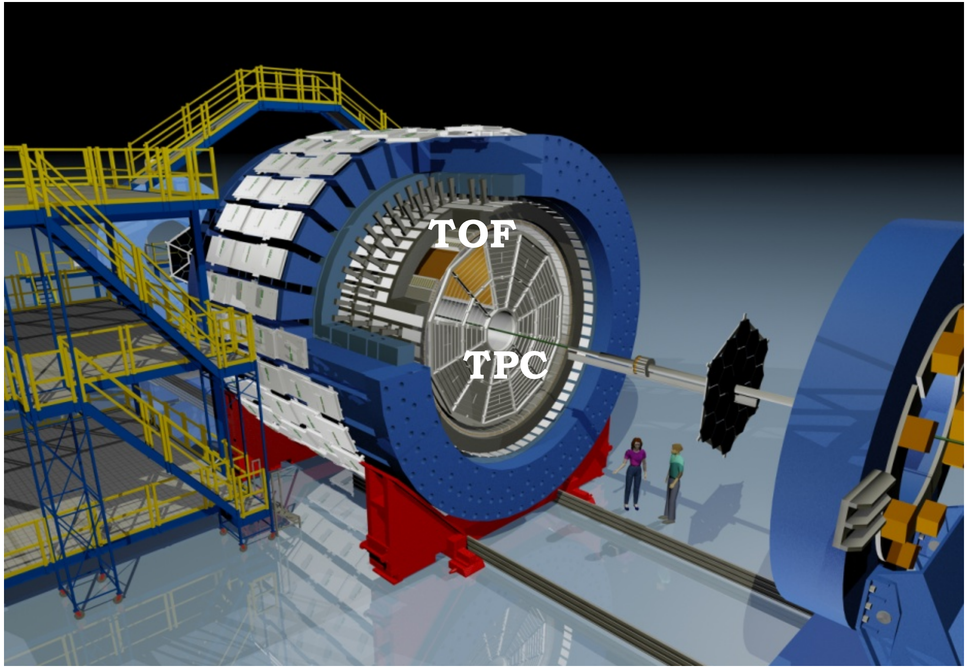
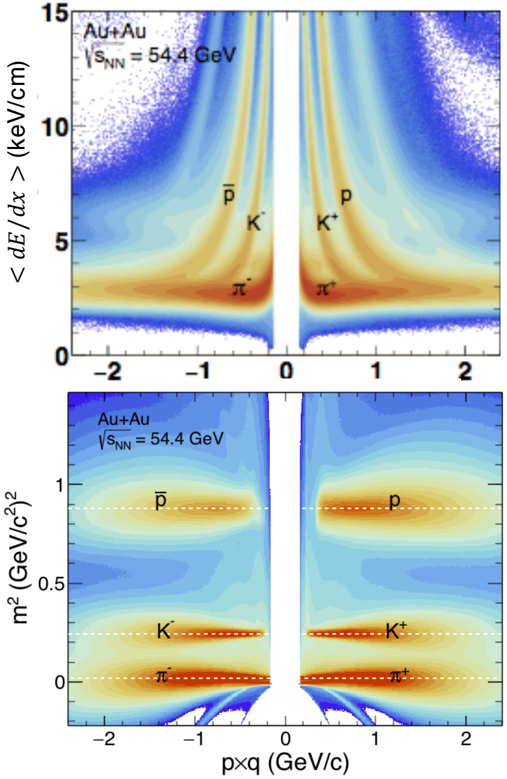


- STAR has measured net-proton cumulants up to sixth-order so far. (Au+Au, Zr+Zr, Ru+Ru and p+p collisions)
- This talk reports measurements on even higher orders: seventh and eighth.

STAR Detector





Main Detectors: Time Projection Chamber and Time-of-Flight.
Full azimuthal angle coverage. $|\eta|<1$ coverage.

K. H. Ackermann et al. Nucl. Instrum. Meth. A 499, 624 (2003)

Analysis Procedure

1/ Event Selection

2/ Centrality Selection

3/ Track selection and PID

4/ Construct Multiplicity Distributions

5/Calculate Cumulants

6/ Correct for Efficiency

7/ Correct for Centrality Bin Width Effect

8/ Compute Statistical Errors

9/ Compute Systematic Errors

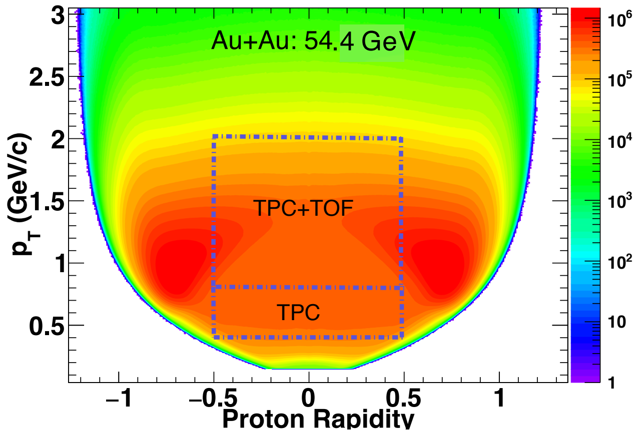
10/ Comparison with models

Dataset Details

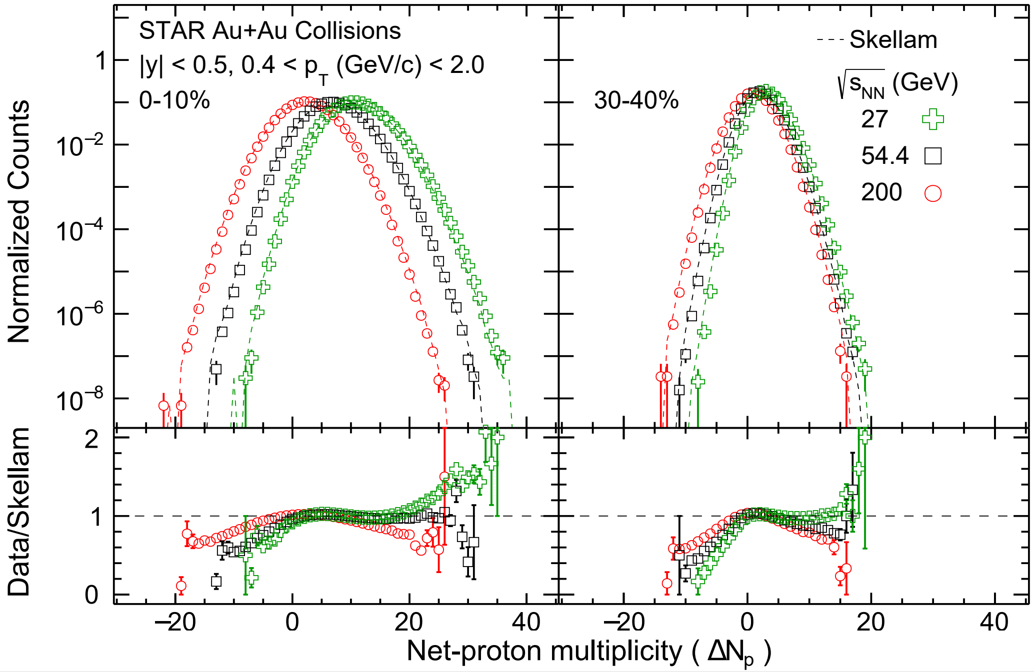
Collision system and energy	Au+Au at $\sqrt{s_{NN}}$ = 27, 54.4, and 200 GeV (300, 550, and 900 million events, respectively.)
Collision centrality	0-40%, 40-50%, 50-60%, 60-70% and 70-80%
Centrality selection	Using charged particle multiplicity excluding protons
Charged Particle Selection	Protons and antiprotons to construct net-protons
Detectors for PID	Time Projection Chamber (TPC) and Time-of Flight (TOF)

Phase Space Coverage

PID Detector	Transverse Momentum Range (p_T)	Rapidity (y)
TPC	0.4 to 0.8 GeV/c	$\|y\| < 0.5$
TPC+TOF	0.8 to 2.0 GeV/c	$\|y\| < 0.5$



Event-by-event Raw Net-proton Distributions



STAR: PRL 127, 262301 (2021)

1) Net-proton distributions, 0-10% and 30-40% centrality, efficiency uncorrected.
2) Values of the mean increase as energy decreases, effect of baryon stopping.
   Larger width → larger stat. errors: $err(C_r) \propto \frac{\sigma^r}{\sqrt{N_{evts}}}$

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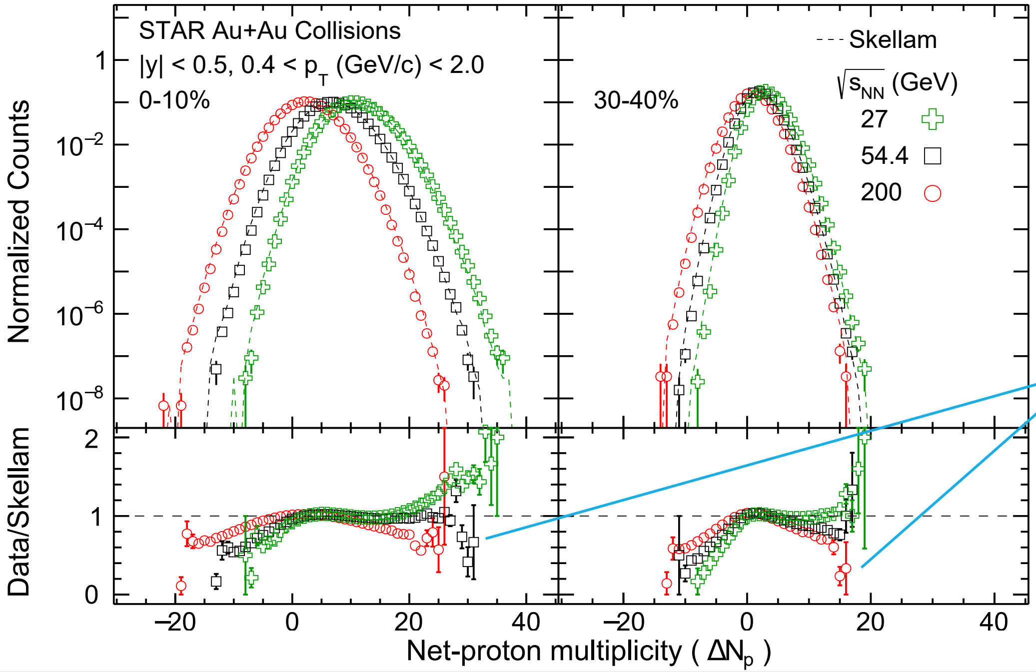

- Deviation from Skellam observed towards the tail of the distribution.

STAR: PRL 127, 262301 (2021)

1) Net-proton distributions, 0-10% and 30-40% collisions, efficiency uncorrected.
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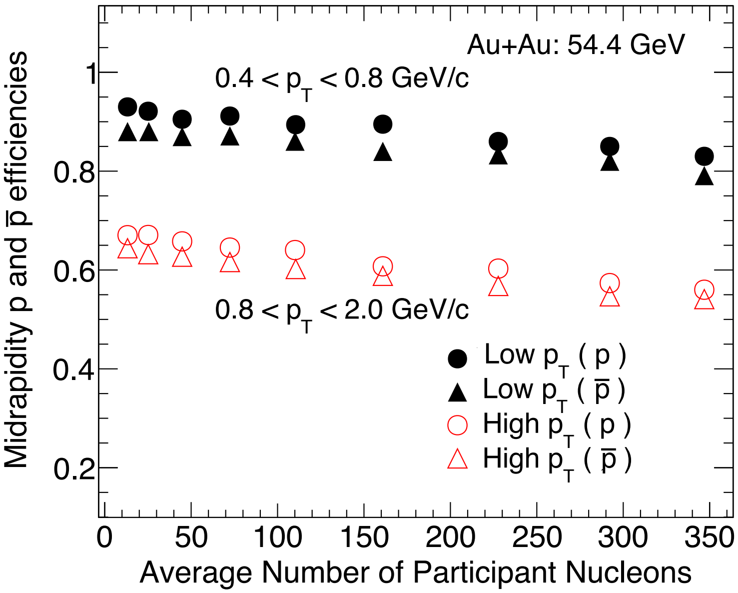
Analysis Techniques (Corrections and Uncertainties)

- Reconstruction efficiency



- Statistical uncertainties:
  - Bootstrap method

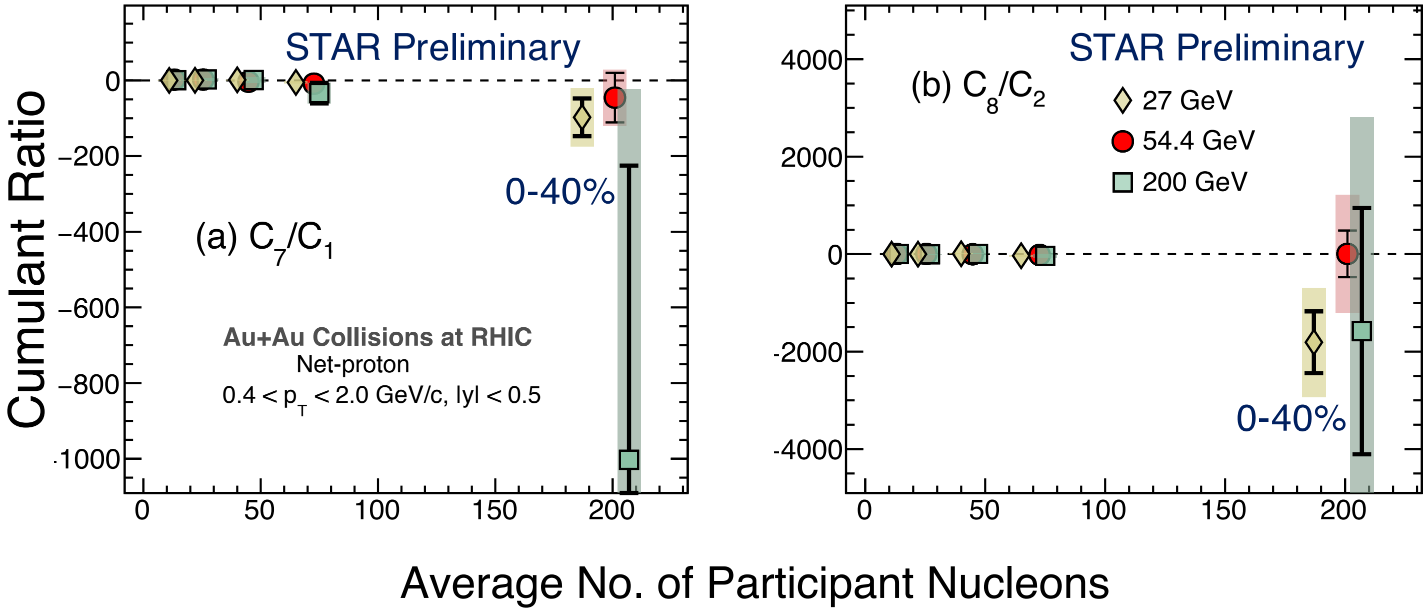
- Sources of systematic uncertainties:
  - Particle identification
  - Background estimates (DCA)
  - Track quality cuts
  - Efficiency variation

- Centrality bin width correction

$C_n = \sum_r w_r C_{n,r}$ where $w_r = n_r / \sum_r n_r$, n=1,2,3,4...
Here, n_r is no. of events in r^{th} multiplicity bin

X. Luo , Phys. Rev. C 91, (2015) 034907
T. Nonaka et al, Phys. Rev. C 95, (2017) 064912
X. Luo et al, J.Phys. G 40, 105104 (2013)
X. Luo, J. Phys. G 39, 025008 (2012)
X.Luo et al, Phys.Rev. C99 (2019) no.4, 044917
A.Pandav et al, Nucl. Phys. A 991, (2019)121608

Centrality Dependence of Net-Proton C_7/C_1 and C_8/C_2



- ❑ Central 0-40% measurements consistent with zero within uncertainties for 54.4 and 200 GeV. Measurement at $\sqrt{s_{NN}}$ = 27 GeV negative with ~1.4σ significance.
- ❑ Peripheral data close to zero for the three energies.

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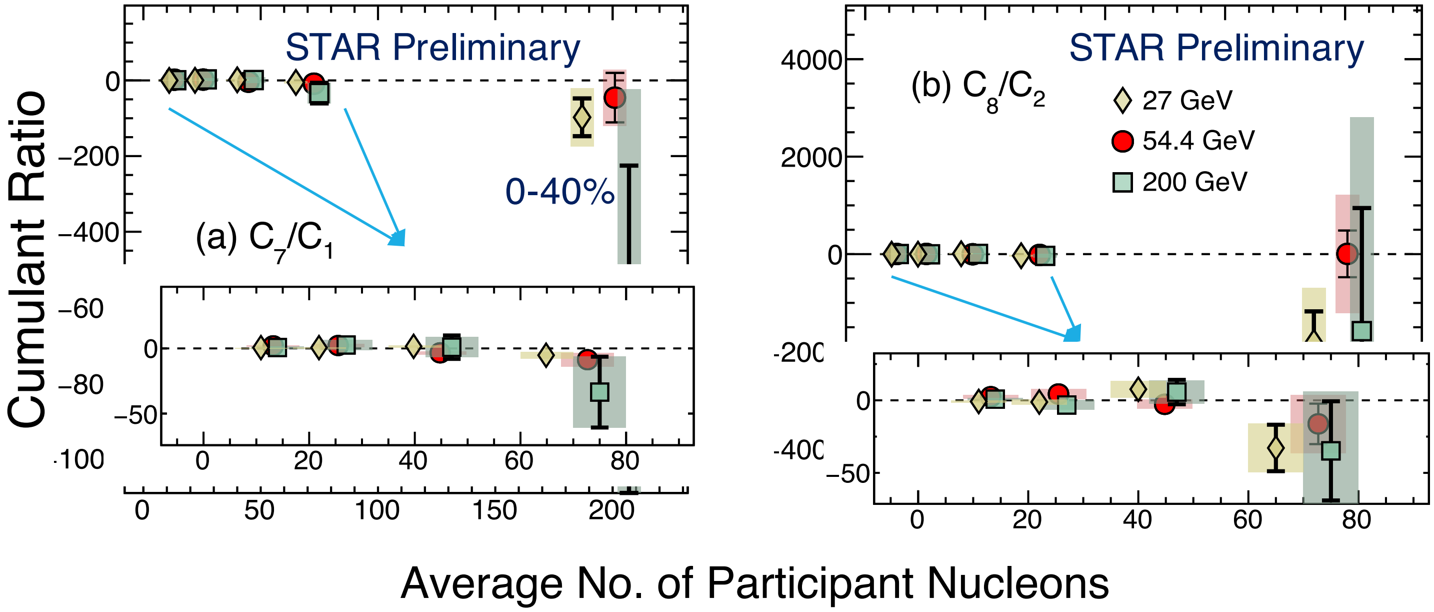

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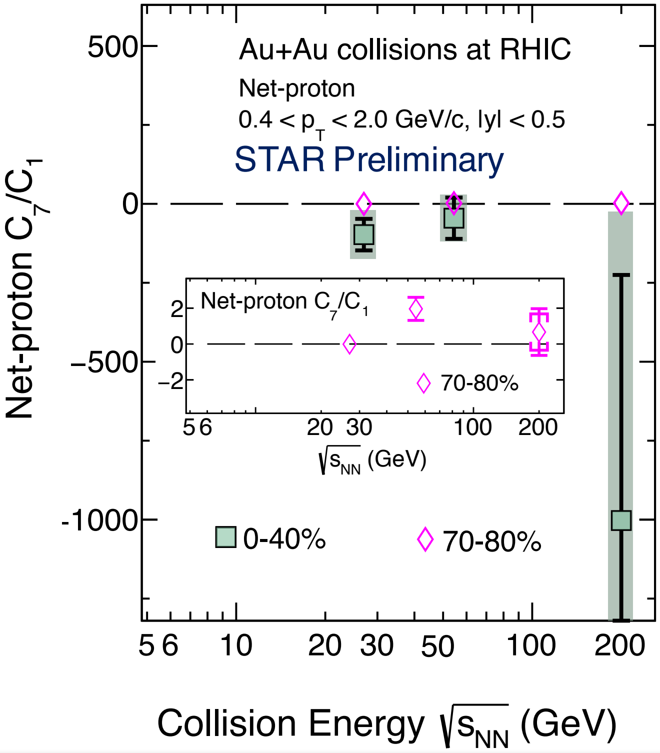
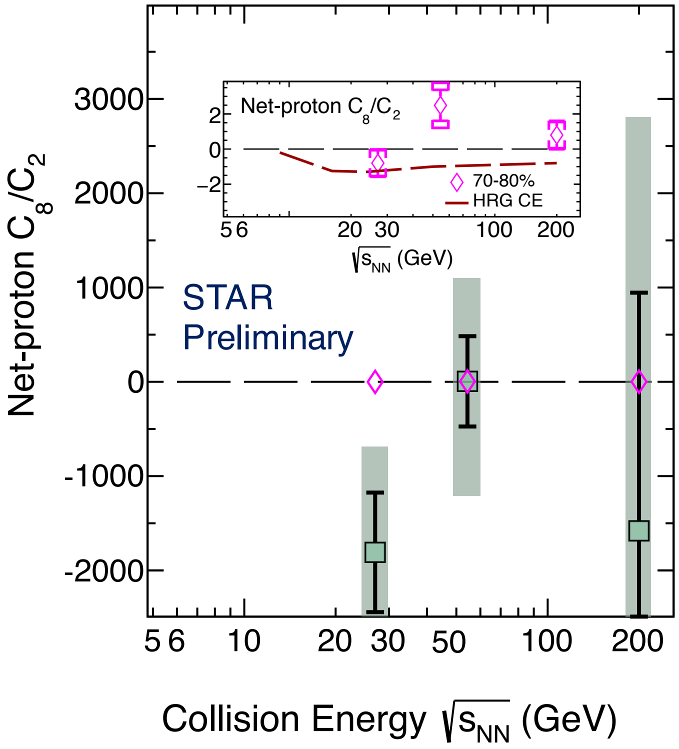
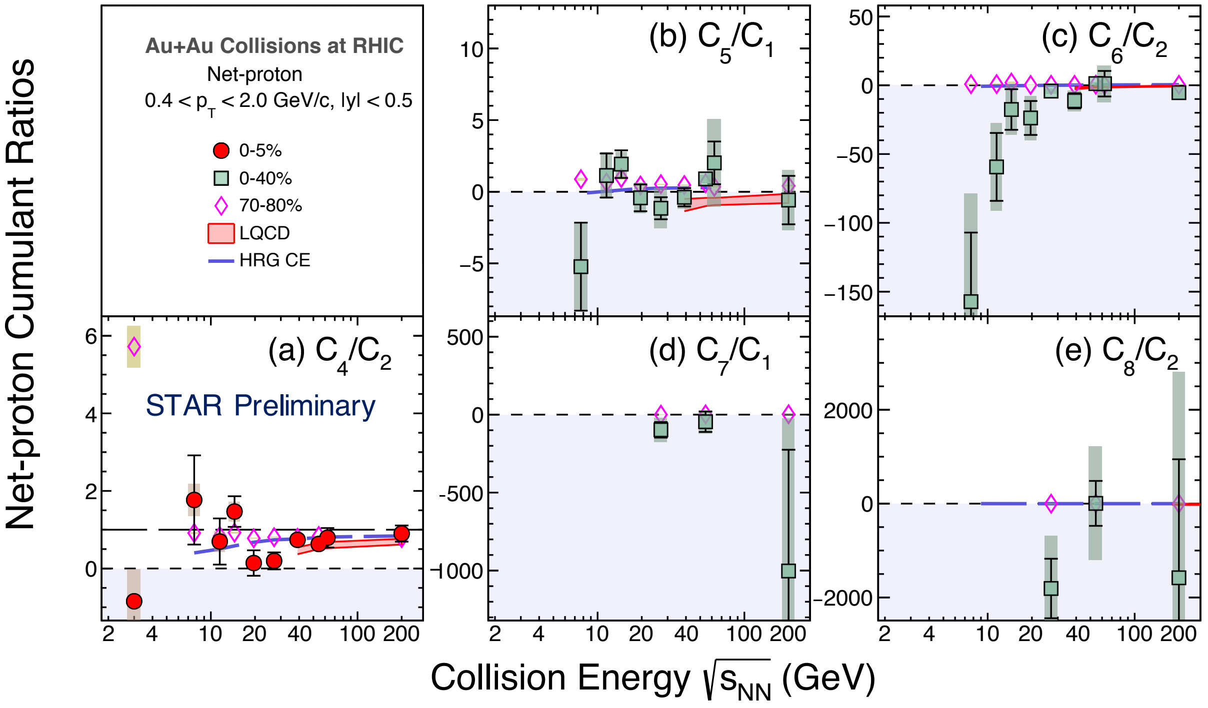
Beam Energy Dependence of Net-Proton C_7/C_1 and C_8/C_2





- 0-40% measurements: No clear energy dependence observed within large uncertainties.
- Peripheral data: either positive or consistent with zero.

Summary Plot:
Beam Energy Dependence of Net-Proton Cumulant Ratios



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LQCD: PRD101, 074502 (2020), HRG CE: NPA 1008, 122141 (2021)

- ❑ Non-monotonic $\sqrt{s_{NN}}$ dependence of C_4/C_2 observed – consistent with CP expectation.
- ❑ C_6/C_2 increasingly negative with decreasing $\sqrt{s_{NN}}$ – consistent with lattice QCD prediction (μ_B < 110 MeV).
- ❑ The new data on C_7/C_1 and C_8/C_2 (0-40%): large uncertainties. Negative ratios at $\sqrt{s_{NN}}$ = 27 GeV at 1.4σ level.
- ❑ Peripheral data ≥ 0 for all ratios.

Summary and Outlook

- Hyper-order cumulants are important observable in the study of QCD phase structure. Combination of signs of hyper-order cumulants are sensitive to hadronic phase, QGP phase and T_{pc}.

- First look at the seventh and eighth order net-proton cumulants at STAR reported.

- Current net-proton C_7/C_1 and C_8/C_2 measurements at 54.4 and 200 GeV are consistent with zero within large uncertainties. Ratios at $\sqrt{s_{NN}}$ = 27 GeV are negative with ~1.4σ significance. Measurements at lower energies will be interesting.

- Measurements with high statistic STAR BES-II data (~10 – 20 times of current statistics) ongoing. Large number of events to be collected for Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: ~ 20 billions (year 2023+2025).

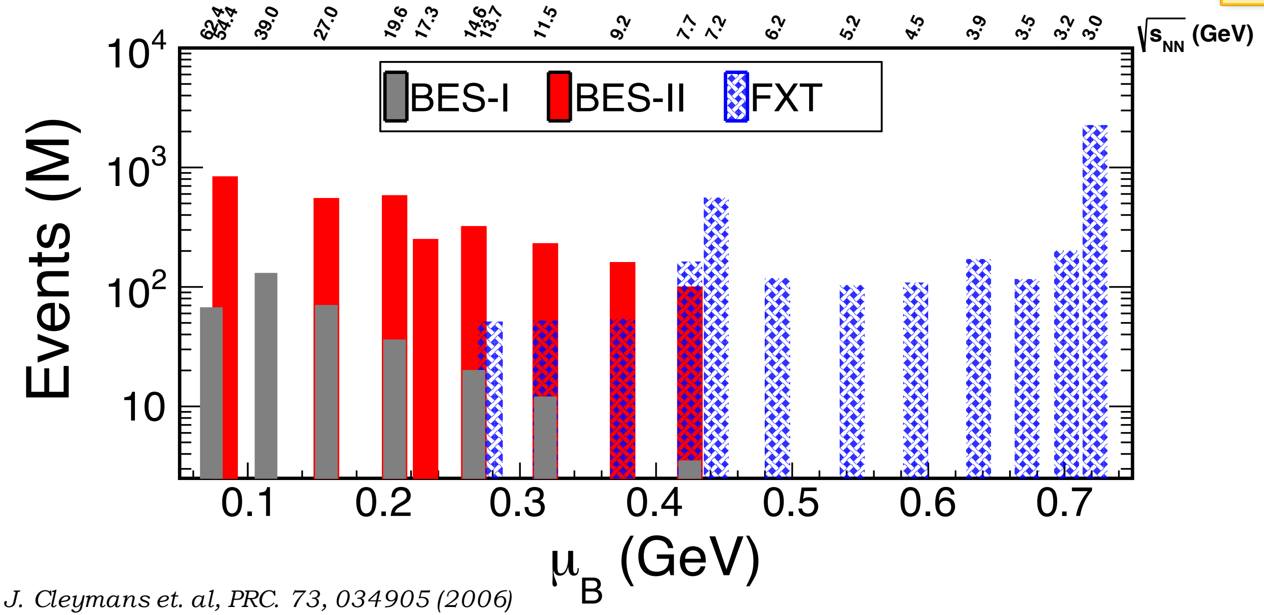
BES-II at RHIC

STAR Internal Note: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

High statistics collected for $\sqrt{s_{NN}}$= 7.7 – 54.4 GeV :Precision measurement

STAR FXT: Extend precision measurements to μ_B=750 MeV

Detector Upgrades: iTPC, eTOF, EPD: Enlarged phase Space coverage.
Crucial for CP search.



J. Cleymans et. al, PRC. 73, 034905 (2006)

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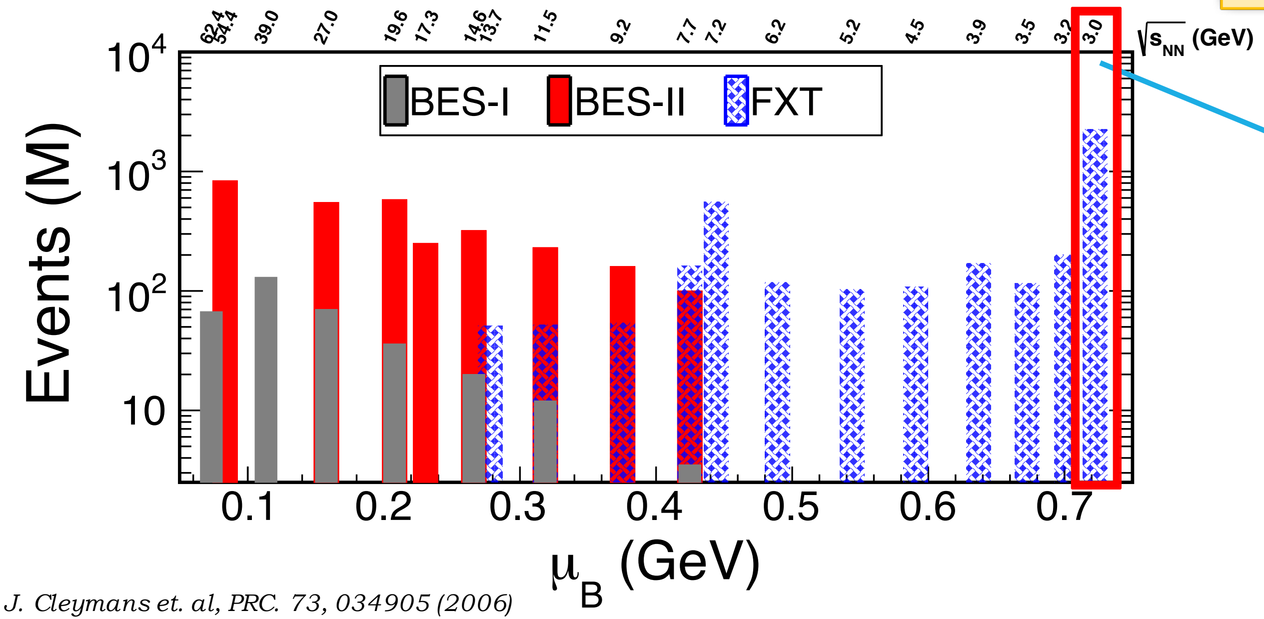

More than 2 billion events at $\sqrt{s_{NN}}$=3 GeV (μ_B= 750 MeV)

J. Cleymans et. al, PRC. 73, 034905 (2006)

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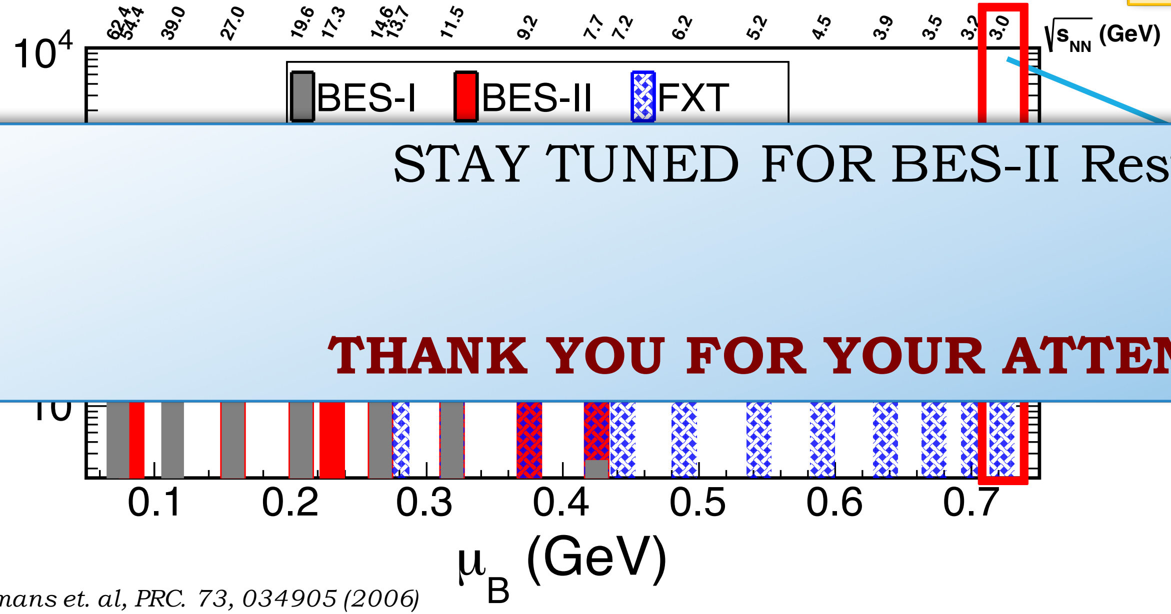

STAY TUNED FOR BES-II Results

THANK YOU FOR YOUR ATTENTION

J. Cleymans et. al, PRC. 73, 034905 (2006)