Probing the QCD Phase Diagram via Higher Order Net-particle Fluctuation Measurements from STAR-BES

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National Institute of Science Education and Research, HBNI, India

From RHIC to EIC
At the QCD Frontiers
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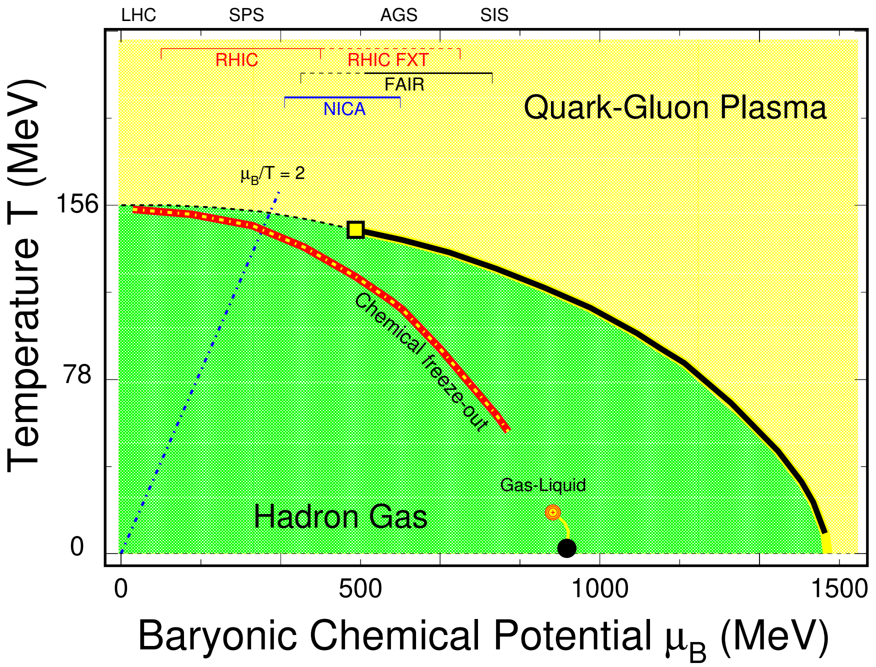
Outline
1. Introduction
2. Physics Motivation
3. Data Analysis
4. Results

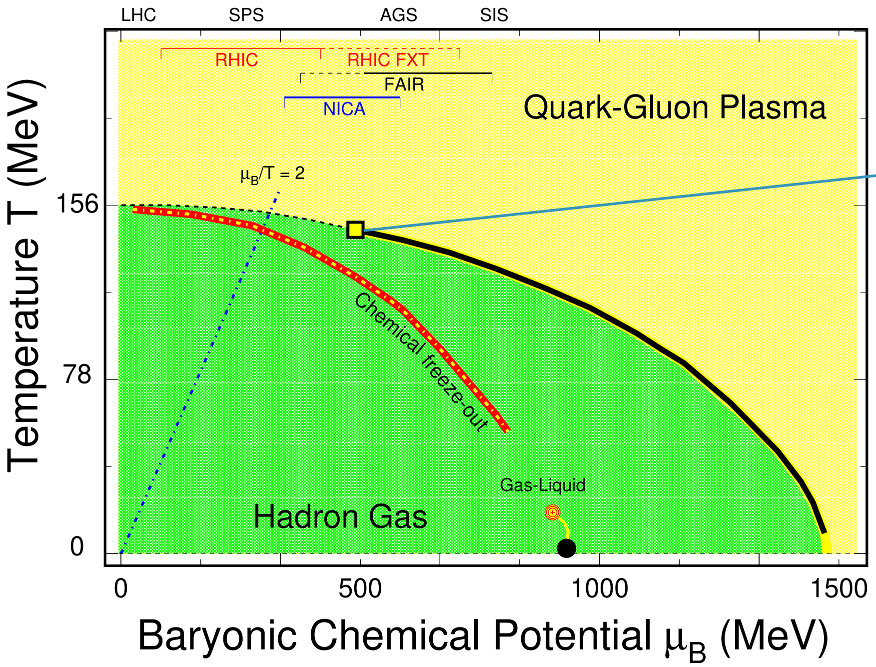
Introduction: QCD Phase Diagram



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

Goal: Study the phase diagram of QCD.

Introduction: QCD Phase Diagram



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Is there a critical point?

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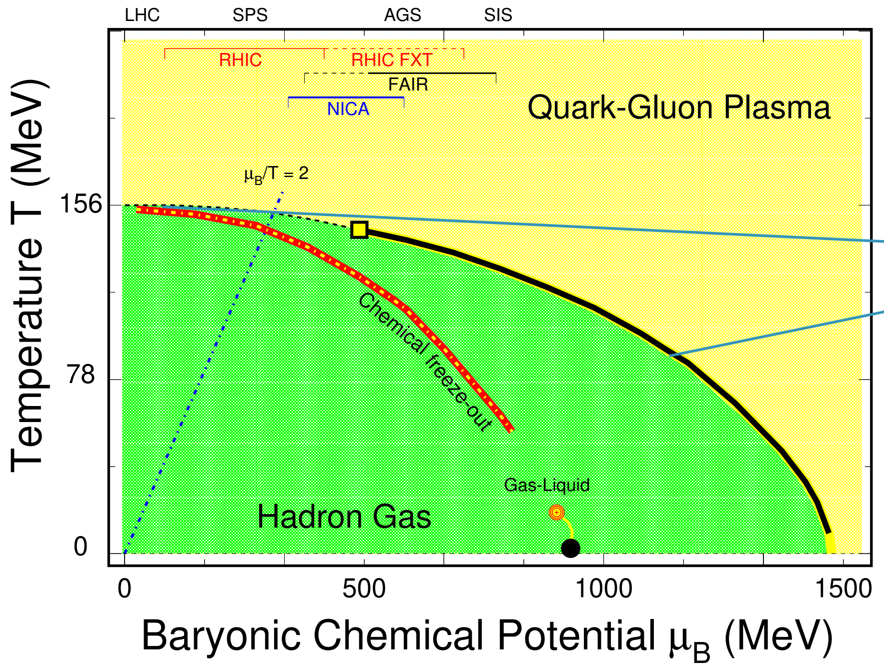


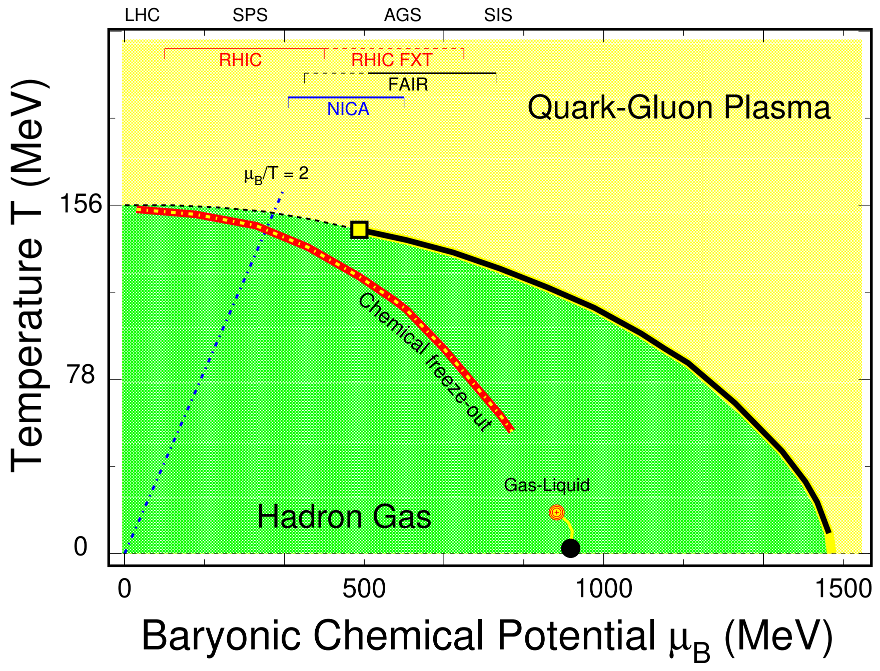
B. Mohanty, N. Xu, arXiv:2101.09210
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

Is there a critical point?

To what extent is the crossover in $T - \mu_B$ plane?
Is there a first-order transition at finite μ_B?

Goal: Study the phase diagram of QCD.

Introduction: QCD Phase Diagram



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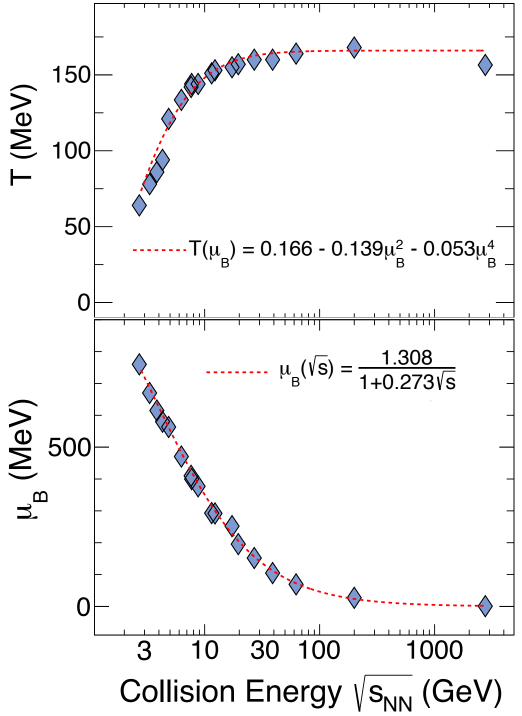

Goal: Study the phase diagram of QCD.
Varying collision energy varies Temperature (T) and Baryon Chemical Potential (μ_B).
Fluctuations in various observables are sensitive to phase transition and critical point.

Observables

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

$$C_1 = < N >$$
$$C_2 = < (\delta N)^2 >$$
Here, $\delta N = N - < N >$
$$C_3 = < (\delta N)^3 >$$
$$C_4 = < (\delta N)^4 > -3 < (\delta N)^2 >^2$$
$$C_5 = < (\delta N)^5 > -10 < (\delta N)^3 > < (\delta N)^2 >$$
$$C_6 = < (\delta N)^6 > -15 < (\delta N)^4 > < (\delta N)^2 > -10 < (\delta N)^3 >^2 +30 < (\delta N)^2 >^3$$

- Higher order cumulants: sensitive probe for CP and the nature of phase transition.

$C_2 \sim \xi^2$ $\quad C_4 \sim \xi^7$ *Quantitative numbers - Model dependent

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

Search for CP

Non-monotonic energy dependence of kurtosis of net-proton in presence of CP

M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301, Y. Hatta et al, Phys.Rev.Lett. 91 (2003) 102003

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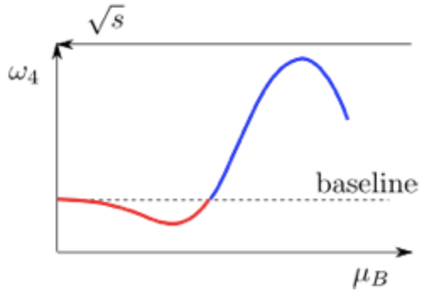
Search for CP

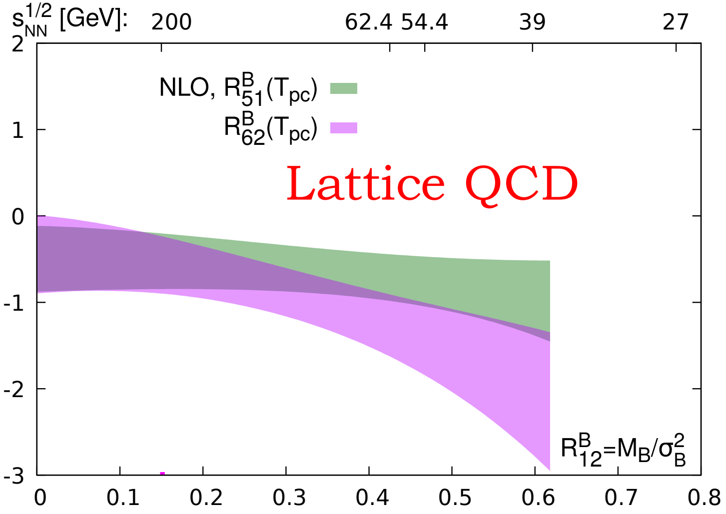


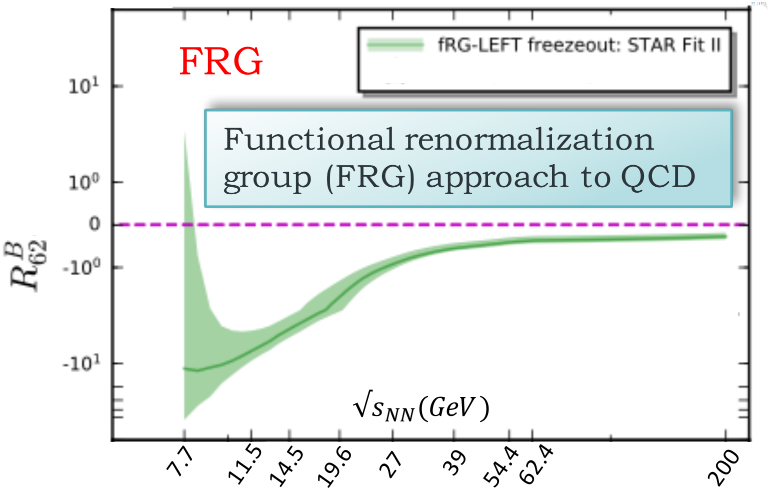
M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301, Y. Hatta et al, Phys.Rev.Lett. 91 (2003) 102003

Search for Crossover

Goal: Identification of O(4) chiral criticality on the phase boundary.

C_5, C_6: negative for LQCD, FRG, PQM – crossover
C_5, C_6: positive for HRG and UrQMD (No QCD transition)





Ordering of ratios : $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$ - LQCD, FRG

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

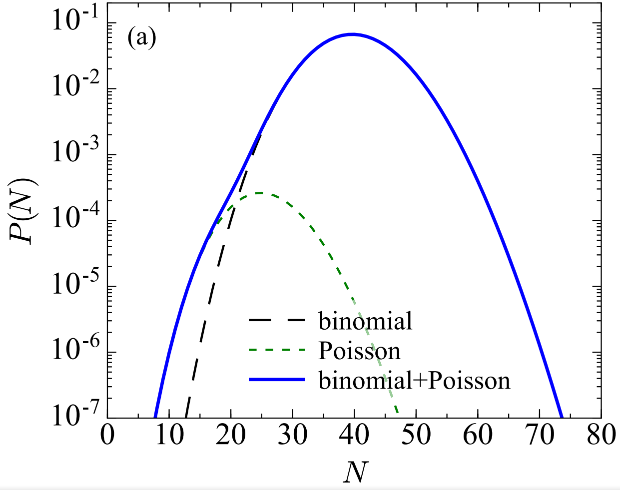
Search for First-order Phase Transition

Multiplicity distribution becomes bi-modal (contribution from two phases)

Proton factorial cumulants κ_n: with increasing order, increase rapidly in magnitude with alternating sign

A. Bzdak et al, PRC98, 054901 (2018), PRC100, 051902(R) (2019)

$$
\begin{aligned}
\kappa_1 &= C_1 \\
\kappa_2 &= -C_1 + C_2 \\
\kappa_3 &= 2C_1 - 3C_2 + C_3 \\
\kappa_4 &= -6C_1 + 11C_2 - 6C_3 + C_4 \\
\kappa_5 &= 24C_1 - 50C_2 + 35C_3 - 10C_4 + C_5 \\
\kappa_6 &= -120C_1 + 274C_2 - 225C_3 + \\
&\quad 85C_4 - 15C_5 + C_6
\end{aligned}
$$



$P(N) = (1-\alpha)P_a(N) + \alpha P_b(N)$: Two Component/Bimodal Distribution

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

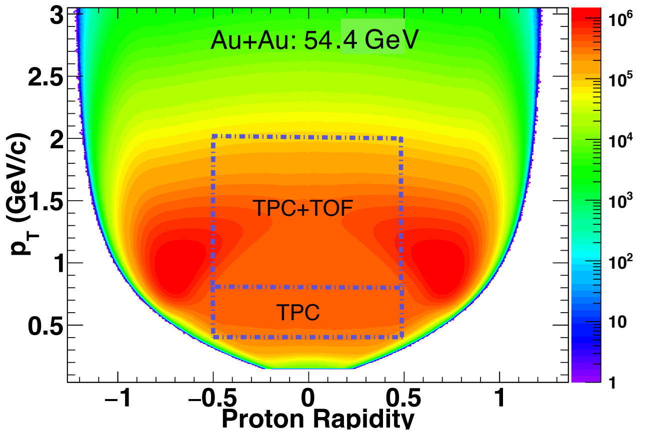
BES-I at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	μ_B (MeV)
200	900	20
62.4	43	73
54.4	550	83
39	92	112
27	31	156
19.6	14	206
14.5	14	264
11.5	7	315
7.7	2.2	420
3	140	750

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

Proton PID

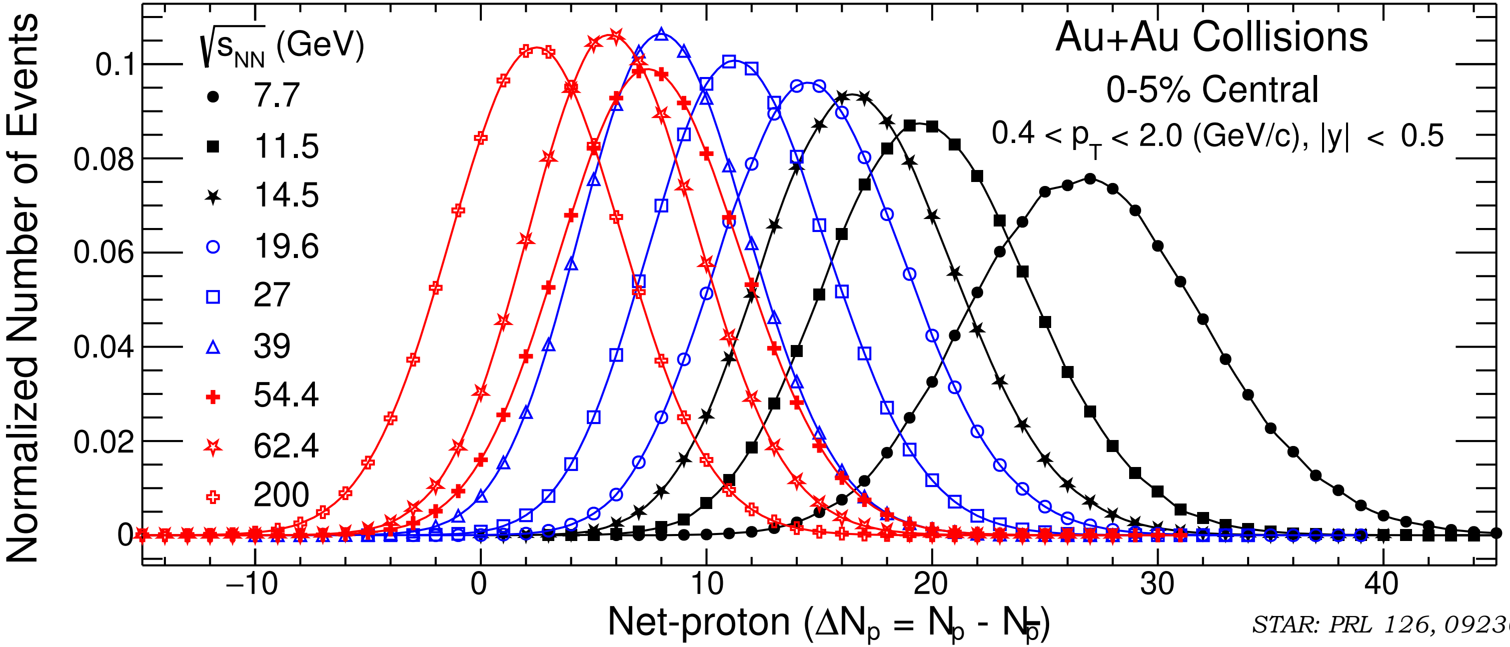
PID Detector	Transverse Momentum Range (p_T)	Rapidity (y)
TPC	0.4 to 0.8 GeV/c	$\lvert y \rvert$ <0.5
TPC+TOF	0.8 to 2.0 GeV/c	$\lvert y \rvert$ <0.5



Centrality: Charge particle multiplicity excluding proton.

Goal: to map the QCD phase diagram **20 < μ_B < 750 MeV**

Event-by-event Raw Net-proton Distributions

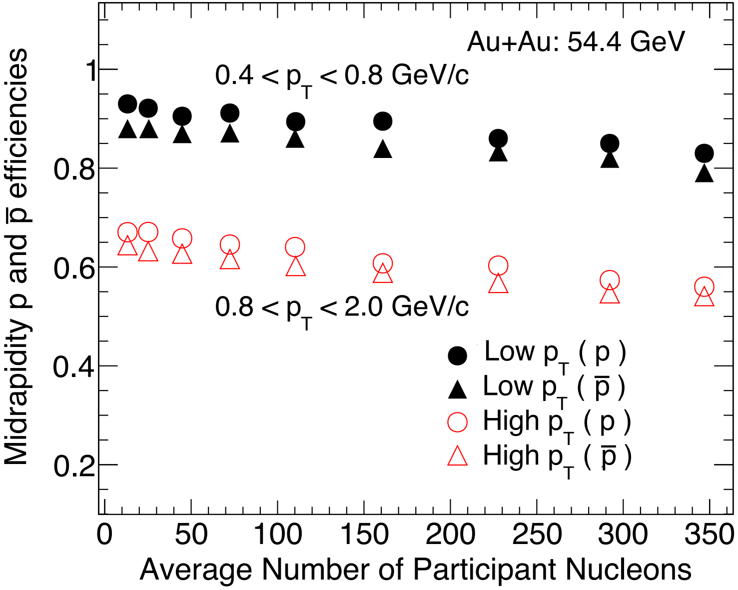


STAR: PRL 126, 092301 (2021)

1) Net-proton distributions, top 5% central collisions, efficiency uncorrected.
2) Values of the mean increase as energy decreases, effect of baryon stopping. Larger width → larger stat. errors: $err(C_r) \propto \frac{\sigma^r}{\sqrt{N_{evts}}}$

Analysis Techniques (Corrections and Uncertainties)

- Reconstruction efficiency



- Statistical uncertainties:
  - Bootstrap method

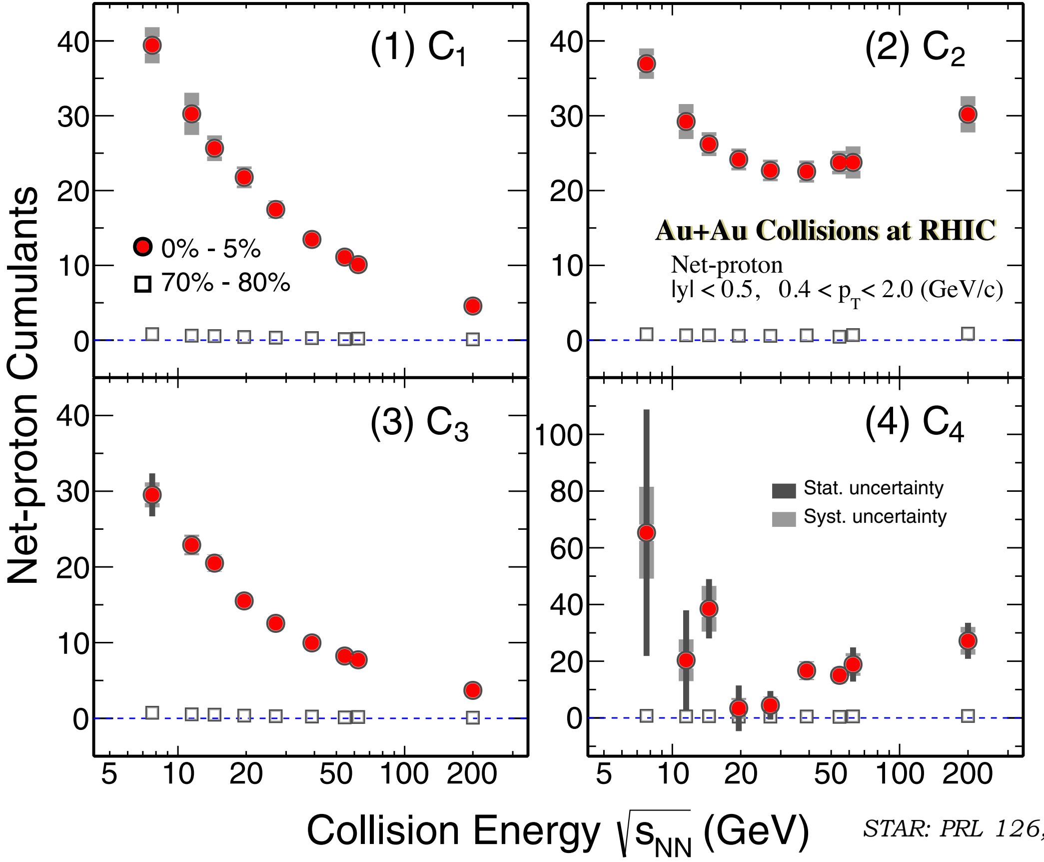
- Sources of systematic uncertainties:
  - Particle identification
  - Background estimates (DCA)
  - Track quality cuts
  - Efficiency variation

- 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

Net-proton Cumulant Measurements

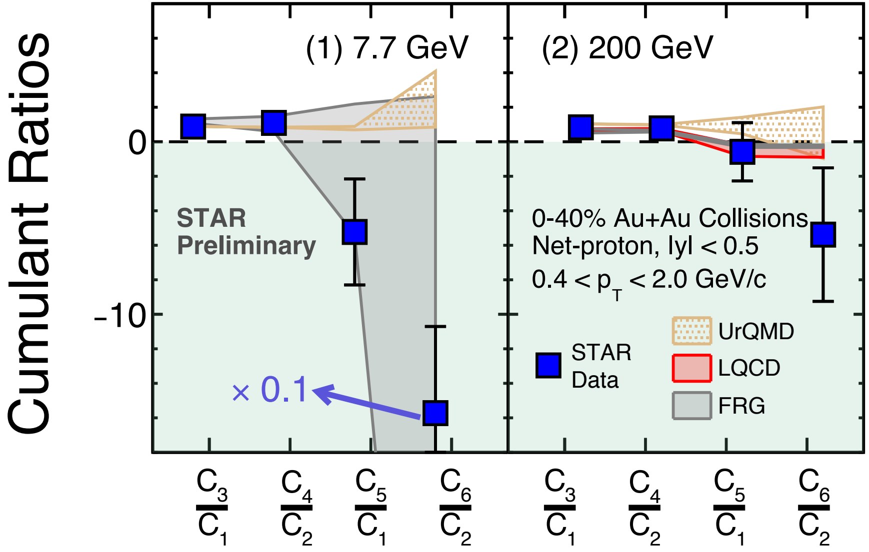


STAR: PRL 126, 092301 (2021)

- Cumulants C_1 and C_3 decrease with collision energy for 0-5% centrality.
- C_2 and C_4 (0-5%) show non-monotonic collision energy dependence.
- Peripheral measurements close to zero.

Measurements and QCD Thermodynamics

Ordering of ratios (Net-baryon): $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$ - LQCD, FRG

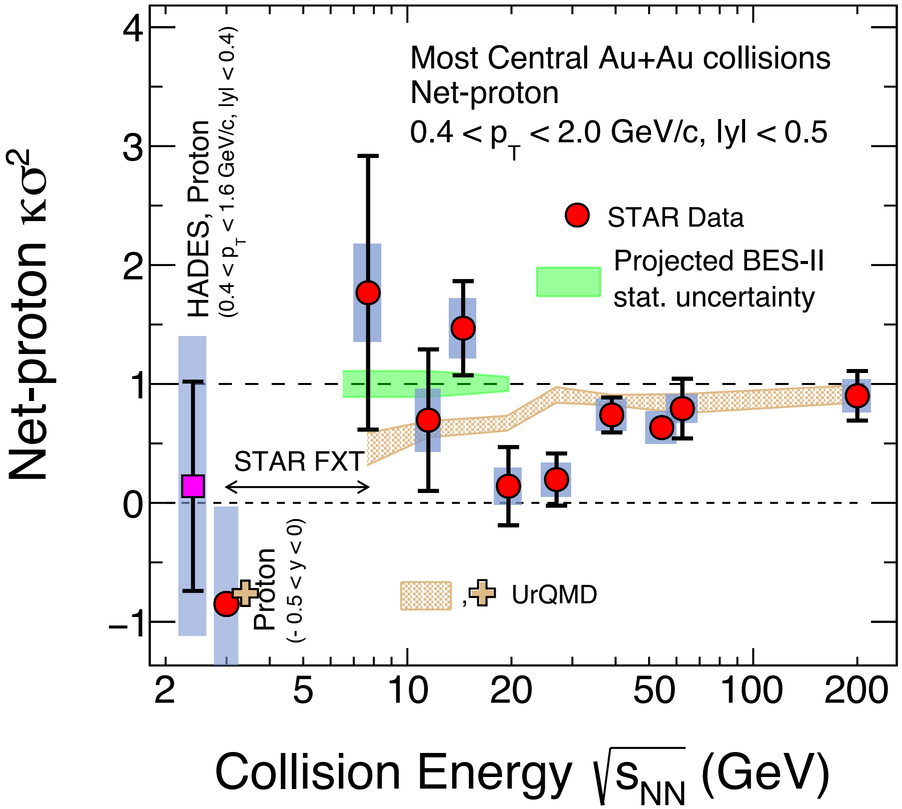


STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)
STAR: PRL 127, 262301 (2021)

Within uncertainties, experimental data consistent with predicted hierarchy.

UrQMD does not follow the ordering. Positive for all the ratios.

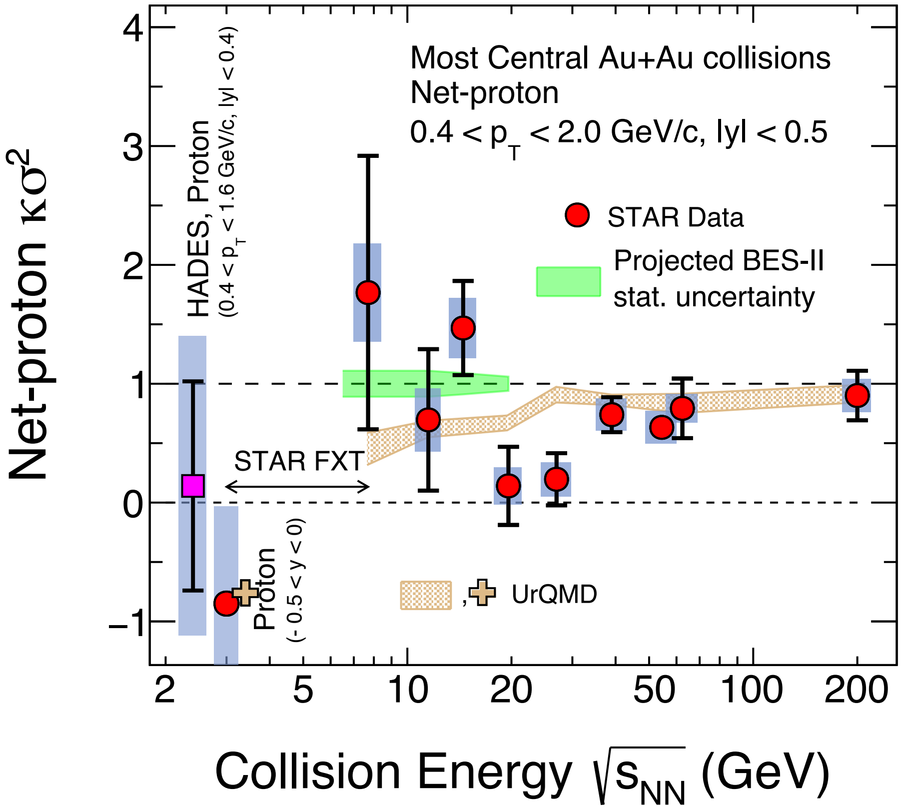
Net-Proton C_4/C_2 – CP Search



STAR: PRL 126, 092301 (2021)
STAR: PRL. 128, 202303 (2022)

- ❑ Non-monotonic collision energy dependence observed.
- ❑ UrQMD model fails to reproduce the observed non-monotonic dependence.

Net-Proton C_4/C_2 – CP Search



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- Non-monotonic collision energy dependence observed

Precision measurements in the range: $7.7 < \sqrt{s_{NN}} < 27$ GeV ongoing at BES-II

the observed non-monotonic dependence.

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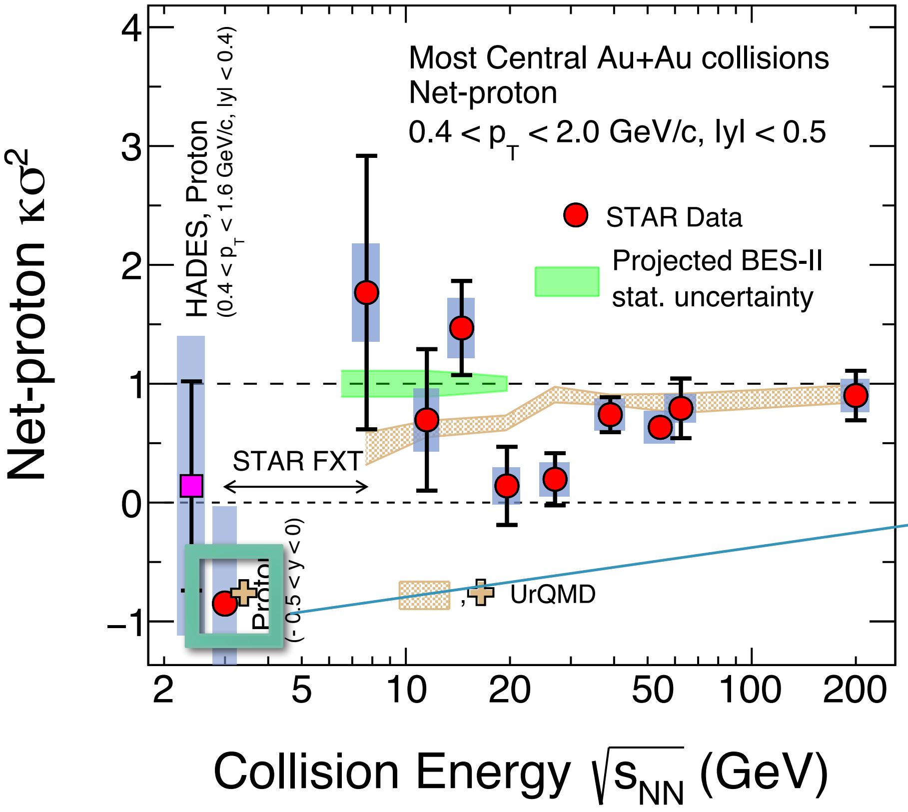

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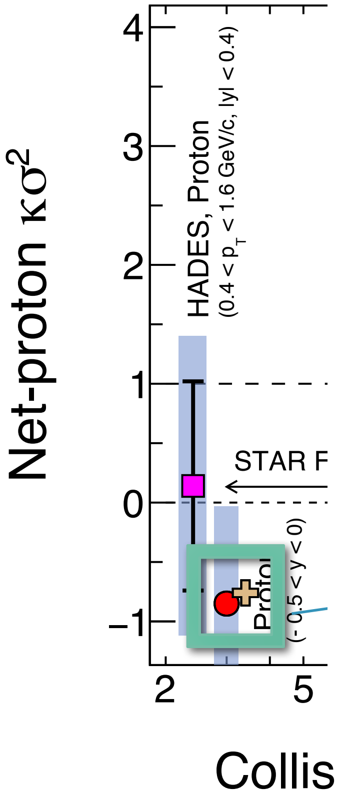
Precision measurements in the range: $7.7 < \sqrt{s_{NN}} < 27$ GeV ongoing at BES-II

New measurement at 3 GeV (μ_B=720 MeV)

- ❑ Consistent with UrQMD.
- ❑ QCD matter is hadronic at 3 GeV.
- ❑ If CP exists, it exists at $\sqrt{s_{NN}} > 3$ GeV.

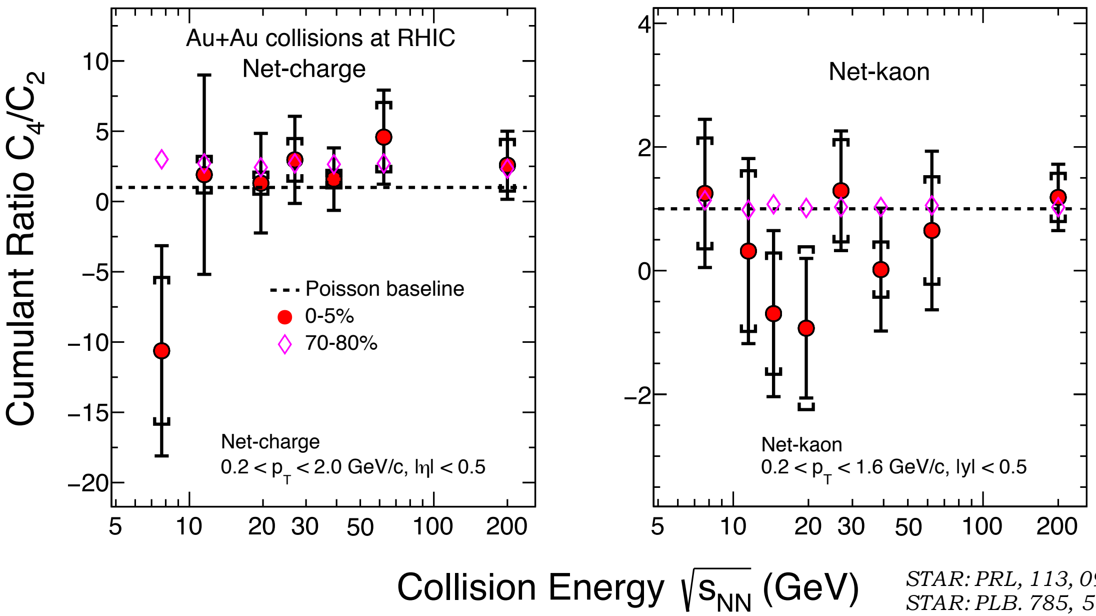
Net-Proton C_4/C_2 – CP Search



STAR: PRL 126, 092301 (2021)
STAR: PRL. 128, 202303 (2022)

Net-charge

Net-kaon



STAR: PRL, 113, 092301 (2014)
STAR: PLB. 785, 551 (2018)

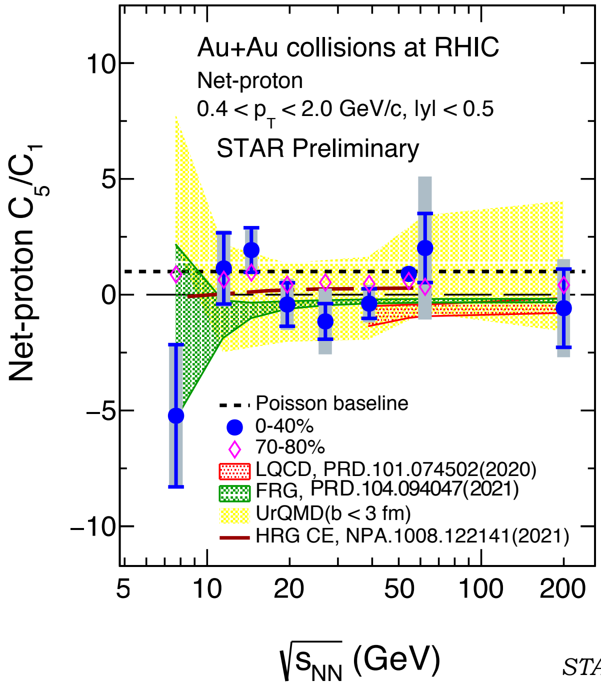
No such non-monotonic trend observed.

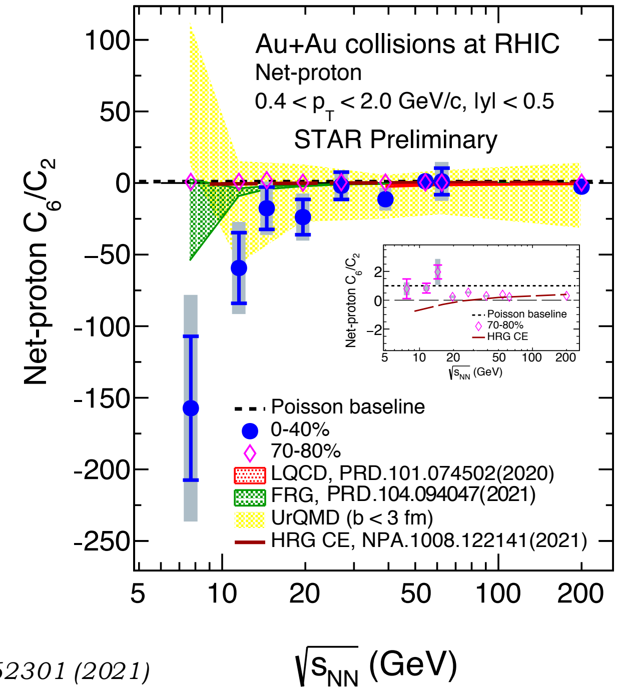
Large uncertainties.

Precision measurement at BES-II needed.

- ❑ If CP exists, it exists at $\sqrt{s_{NN}} > 3$ GeV.

Net-Proton C_5/C_1 and C_6/C_2 – Search for Crossover



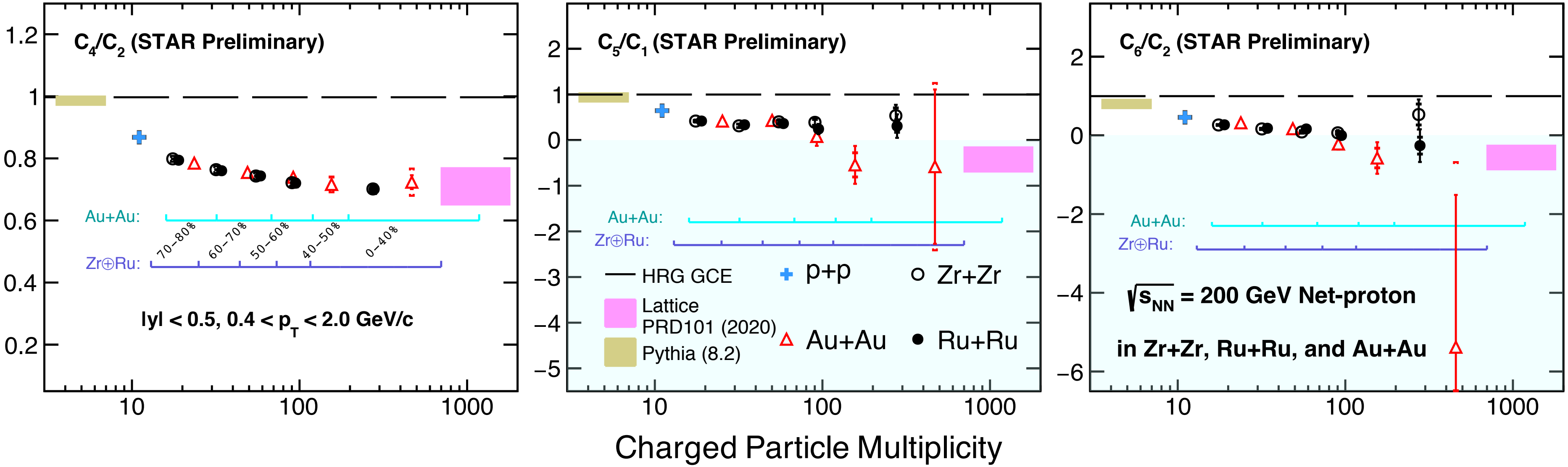


STAR: PRL 127, 262301 (2021)

- ❑ C_5/C_1 (0-40%) fluctuates around zero as a function of $\sqrt{s_{NN}}$. C_6/C_2 (0-40%) increasingly negative with decreasing $\sqrt{s_{NN}}$ - consistent with expectation from LQCD, FRG model.
- ❑ Peripheral data, UrQMD, HRG model calculation are positive or consistent with zero.

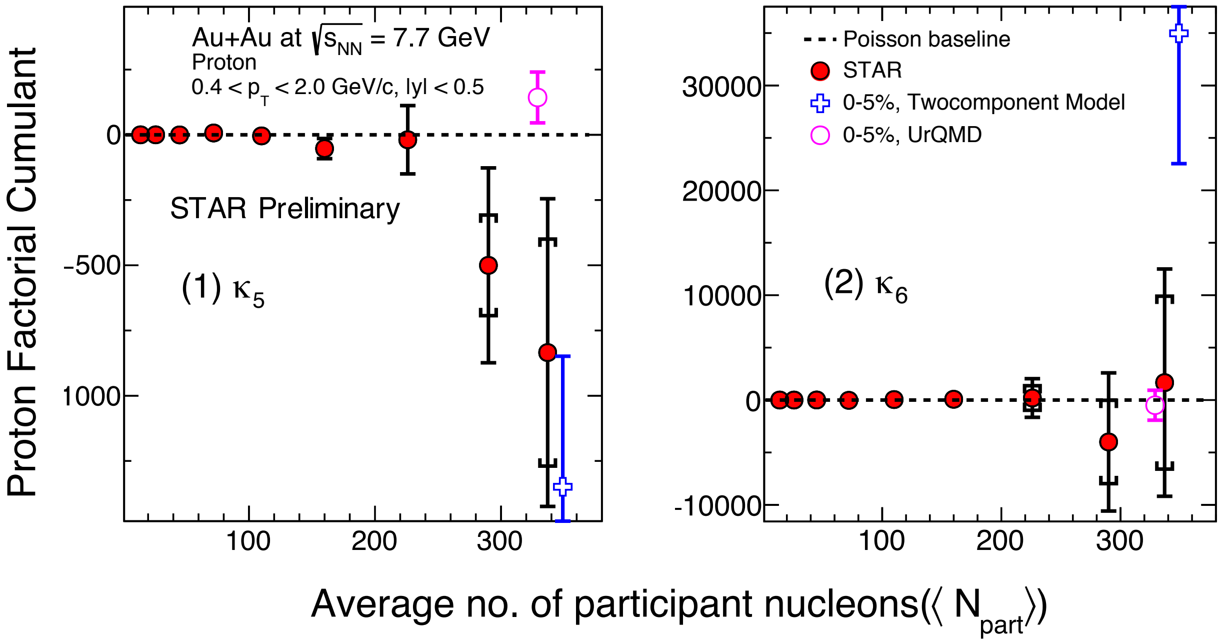
Net-Proton C_5/C_1 and C_6/C_2 at 200 GeV – Search for Crossover

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



- ❑ Zr+Zr and Ru+Ru data follows the multiplicity trend shown by p+p and Au+Au.
- ❑ Cumulant ratios decrease with increasing multiplicity. C_5/C_1 and C_6/C_2 from Au+Au results becomes negative: consistent with LQCD.

Proton κ_5 and κ_6 – Search for First-order Phase Transition



- ❑ κ_5 (0-5%) consistent with two component model expectation within uncertainties while κ_6 (0-5%) remains 1.8σ away.

Summary and Outlook

- Higher-order cumulants are important observable in the study of QCD phase structure. Sensitive to CP, crossover and first-order phase transition.

- Net-proton cumulant ratios seem to follow hierarchy predicted by QCD thermodynamics.

- Non-monotonic collision energy dependence observed for net-proton C_4/C_2. Hint of CP in the collision energy range $7.7 \leq \sqrt{s_{NN}} \leq 27$ GeV. Recent data at 3 GeV suggests QCD matter is hadronic at such low energies, indicating that if critical region is created in heavy-ion collisions, it should exist at $\sqrt{s_{NN}} > 3$ GeV.

- Net-proton C_6/C_2 is increasingly negative with decreasing $\sqrt{s_{NN}}$. Multiplicity dependence studies at $\sqrt{s_{NN}} = 200$ GeV suggest C_6/C_2 becomes negative with increasing multiplicity. Observations are consistent with sign predicted by lattice QCD for crossover.

- Proton κ_n measurement at 7.7 GeV have large uncertainties. Precision measurements at low $\sqrt{s_{NN}}$ from BES-II will be interesting for the search of first-order phase transition.

- Measurements with high statistic BES-II data ($\sim 10 - 20$ times of current statistics) ongoing.

BES-II at RHIC

STAR

High statistics collected for $\sqrt{s_{NN}}$= 7.7 – 27 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.

Collider Mode

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	μ_B (MeV)
7.7	101	420
9.2	162	355
11.5	235	315
14.5	324	264
17.3	256	230
19.6	478	206
27	555	156

FXT Mode

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	μ_B (MeV)
7.7	163	420
6.2	118	487
5.2	103	541
4.5	108	589
3.9	170	633
3.5	116	666
3.2	201	699
3.0	2361	750

STAR Internal Note: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598
T. Nonaka (for STAR Collaboration) : 3rd workshop on Physics performance studies at FAIR and NICA, 2021

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Stay Tuned For BES-II Results

THANK YOU ALL FOR YOUR ATTENTION

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