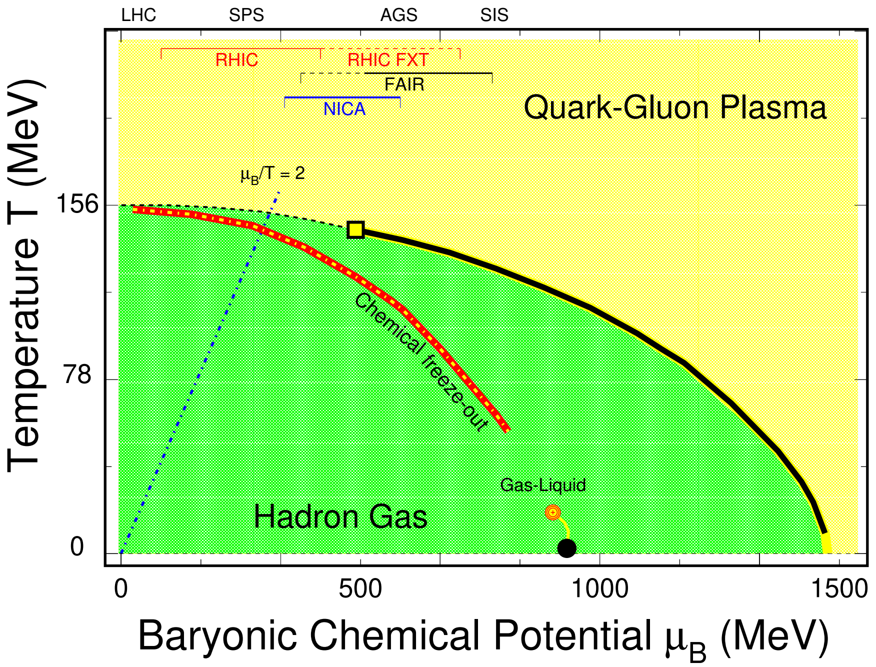
Probing the QCD Phase Diagram via Higher Order Net-particle Fluctuation Measurements from STAR-BES

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

In part supported by

Outline
1. Introduction
2. Observable
3. The STAR Experiment
4. Analysis
5. Results
6. Summary

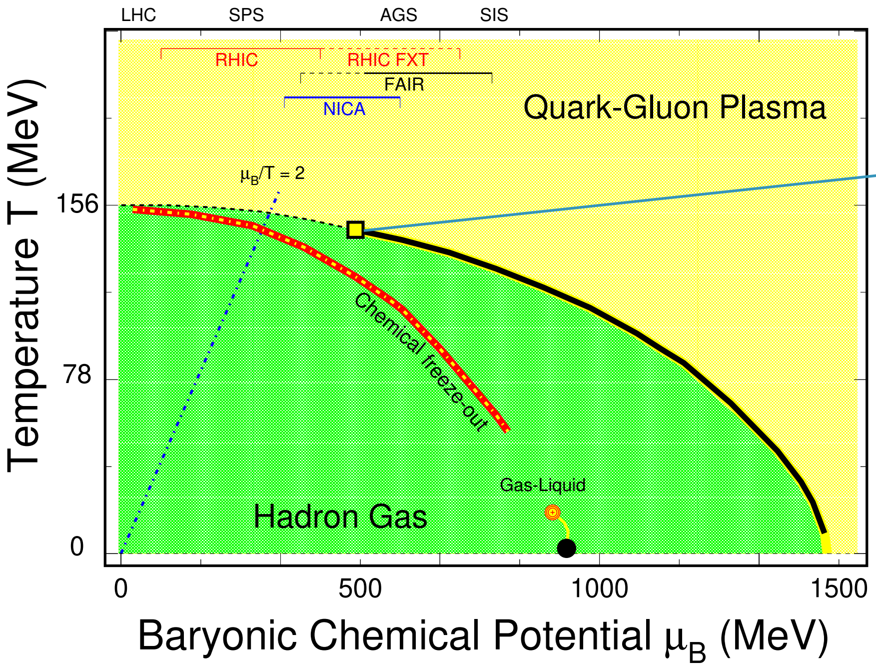
Introduction: QCD Phase Diagram



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



B. Mohanty, N. Xu, arXiv:2101.09210
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Is there a critical point?

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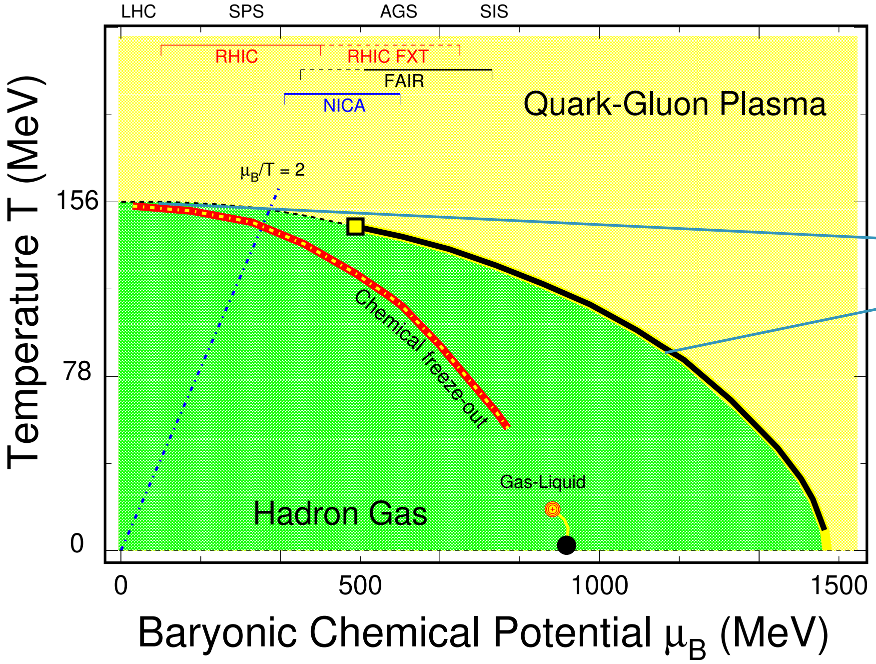


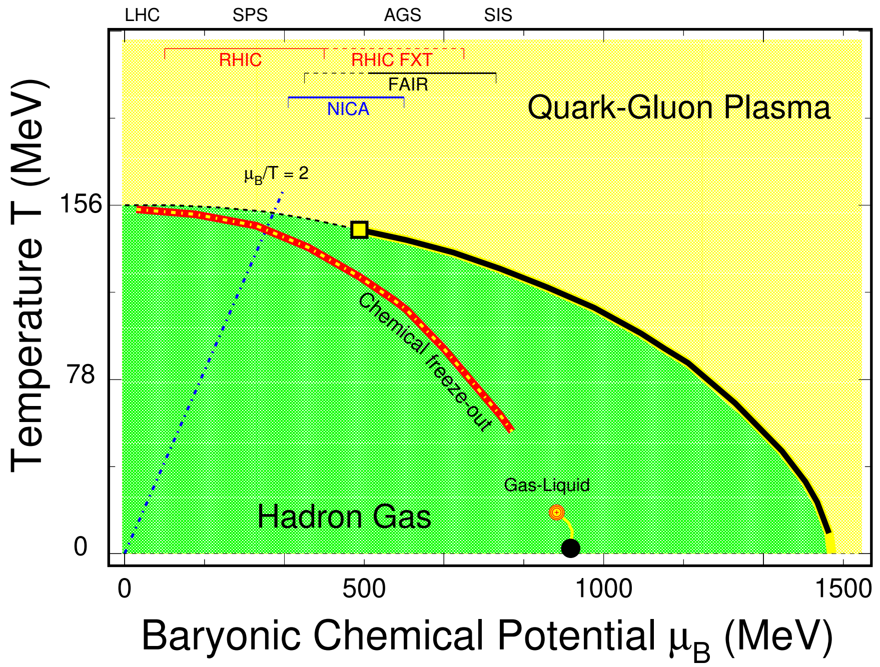
B. Mohanty, N. Xu, arXiv:2101.09210
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

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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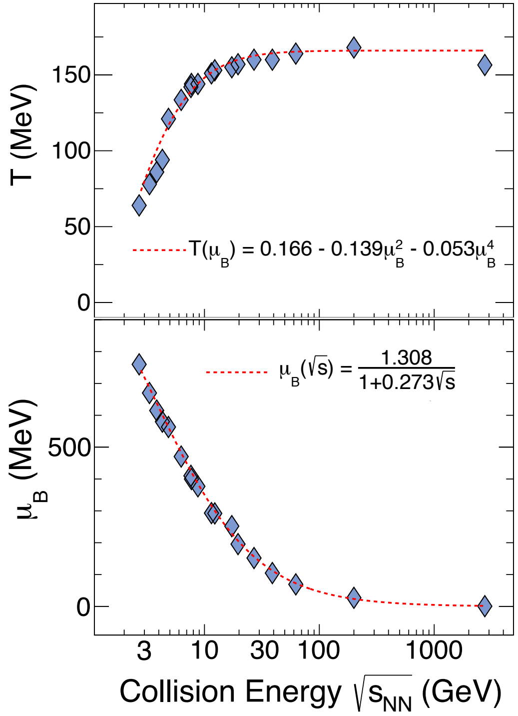

Goal: Study the phase diagram of QCD.
Varying collision energy varies Temperature (T) and Baryon Chemical Potential (μ_B).
Fluctuations in various observables are sensitive to phase transition and critical point.

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.

$C_2 \sim \xi^2$ $C_4 \sim \xi^7$ *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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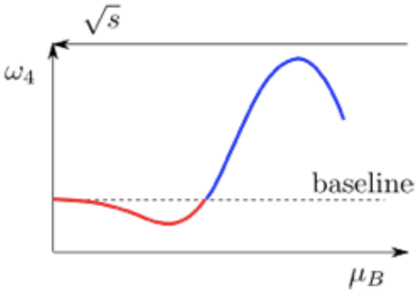
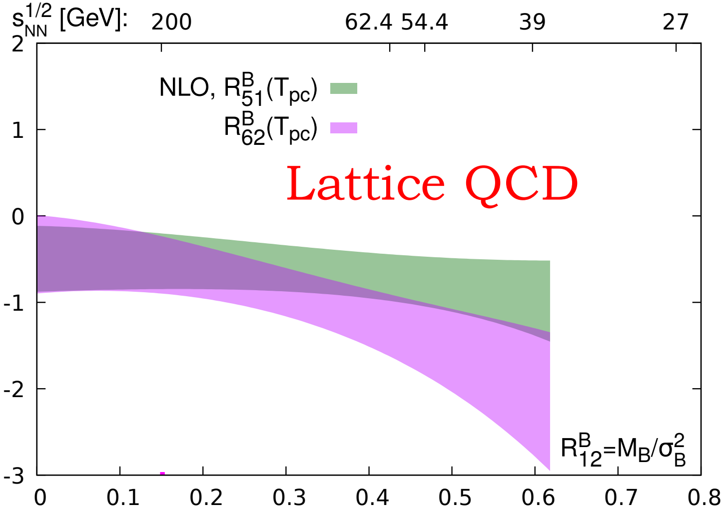


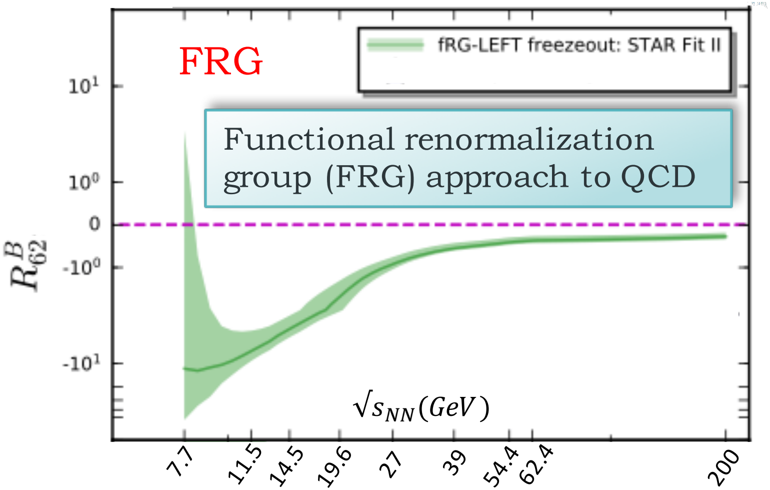
M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301, Y. Hatta et al, Phys.Rev.Lett. 91 (2003) 102003

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)

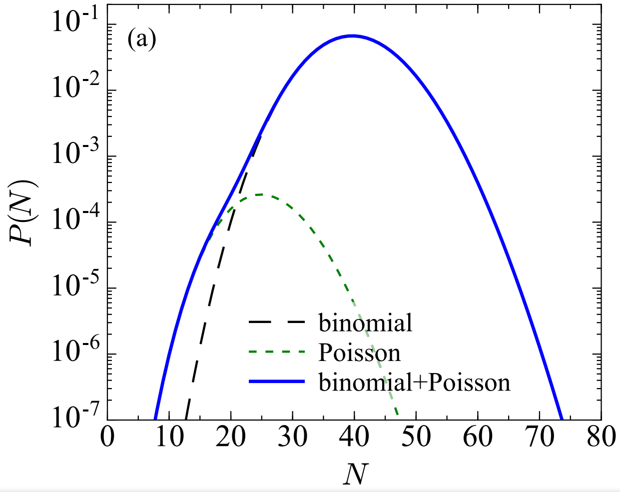
Search for First-order Phase Transition

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

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

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

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



$P(N) = (1-\alpha)P_a(N) + \alpha P_b(N)$: 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

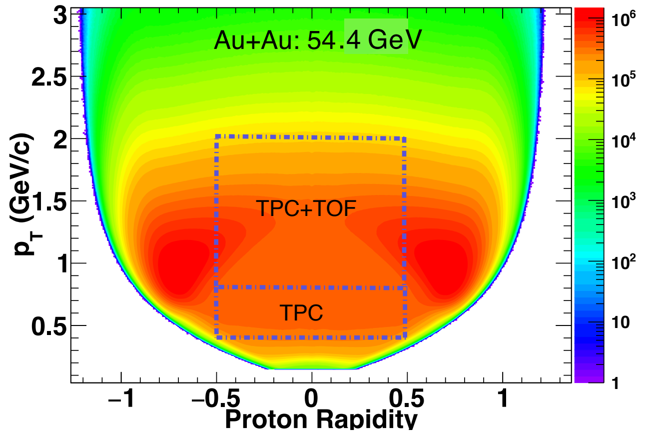
BES-I at RHIC

$\sqrt{s_{NN}}$ (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

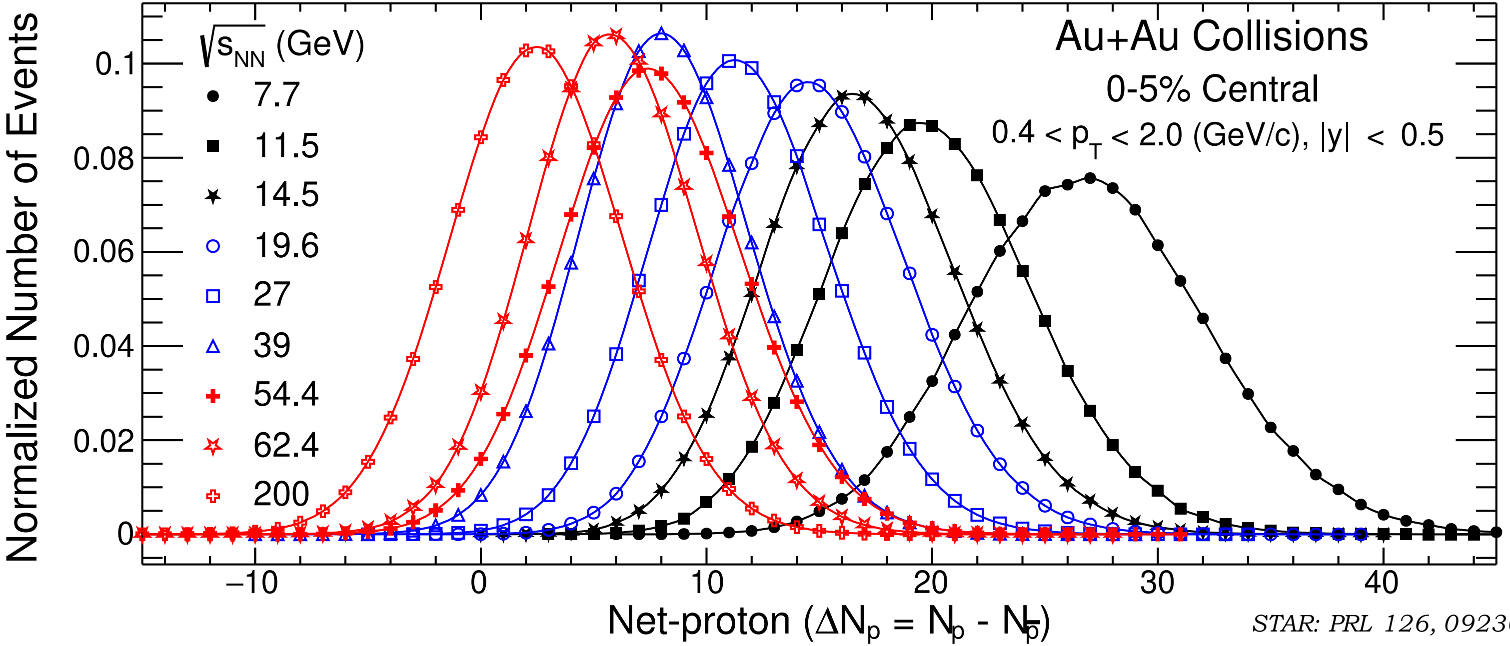
PID Detector	Transverse Momentum Range (p_T)	Rapidity (y)
TPC	0.4 to 0.8 GeV/c	$\|y\|<0.5$
TPC+TOF	0.8 to 2.0 GeV/c	$\|y\|<0.5$



Centrality: Charge particle multiplicity excluding proton.

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

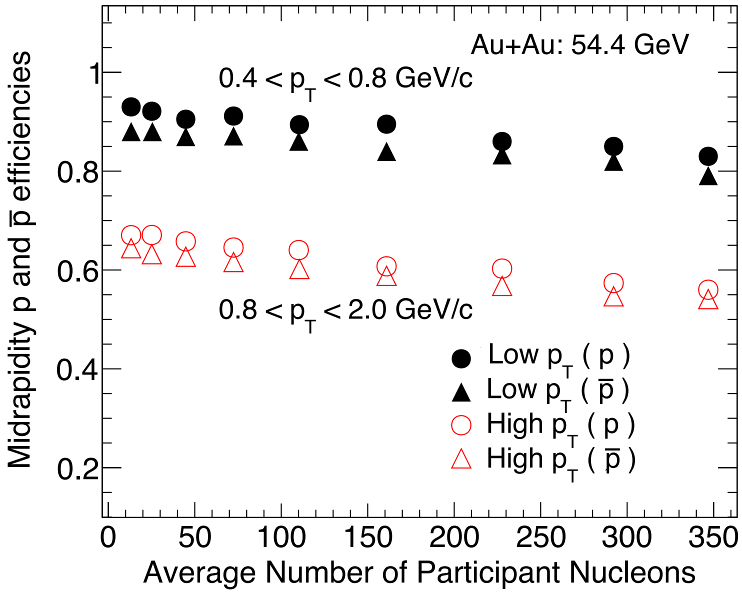
Event-by-event Raw Net-proton Distributions



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

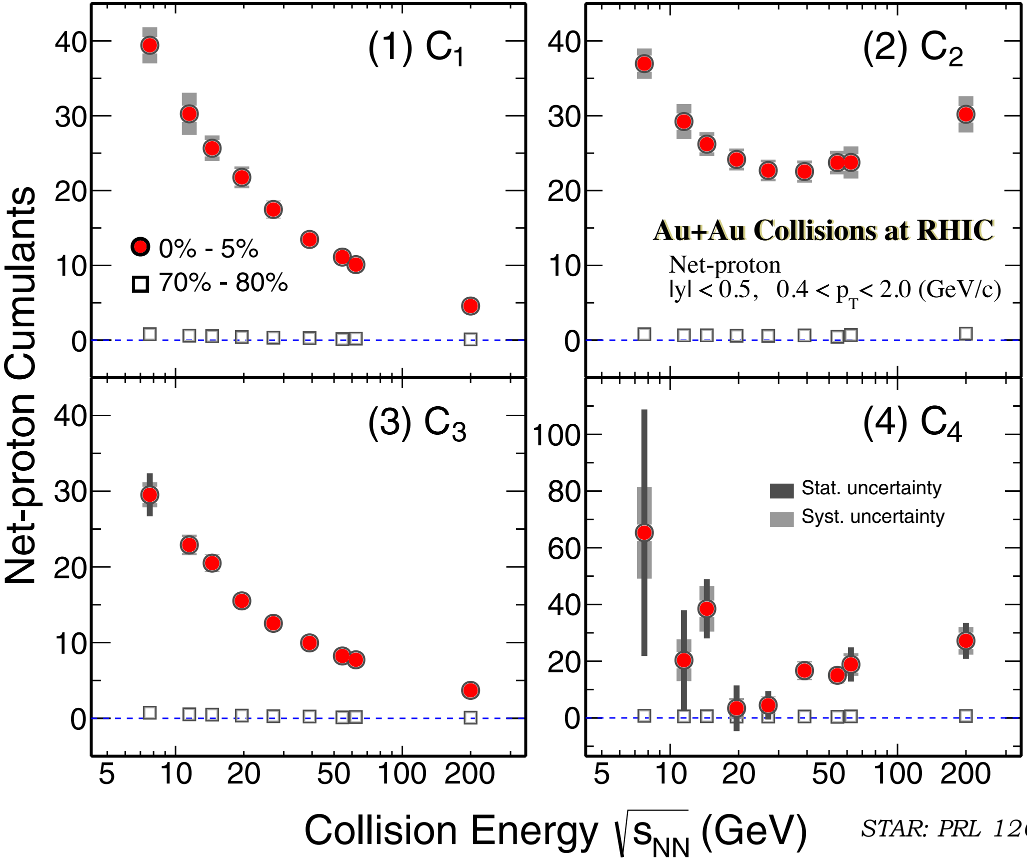
- ❑ Sources of systematic uncertainties:
  - ➢ Particle identification
  - ➢ Background estimates (DCA)
  - ➢ Track quality cuts
  - ➢ Efficiency variation

- ❑ 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

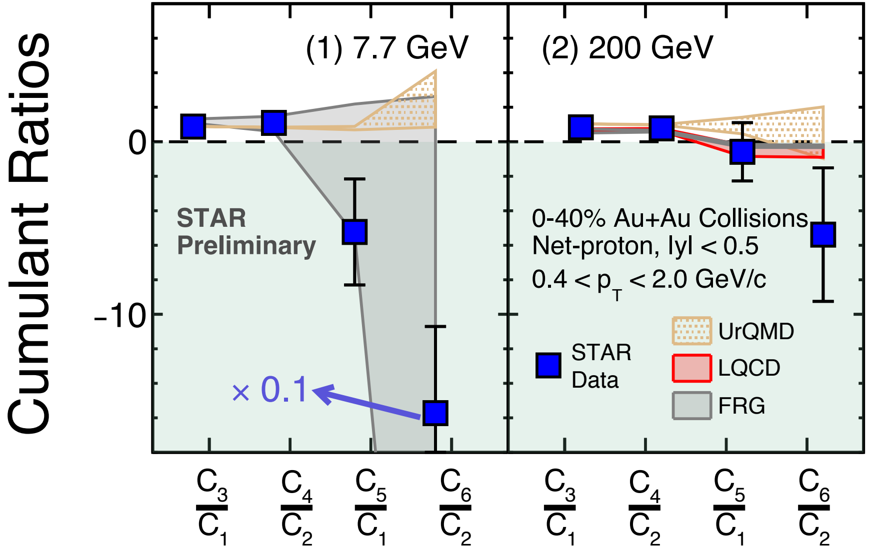


STAR: PRL 126, 092301 (2021)

- 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

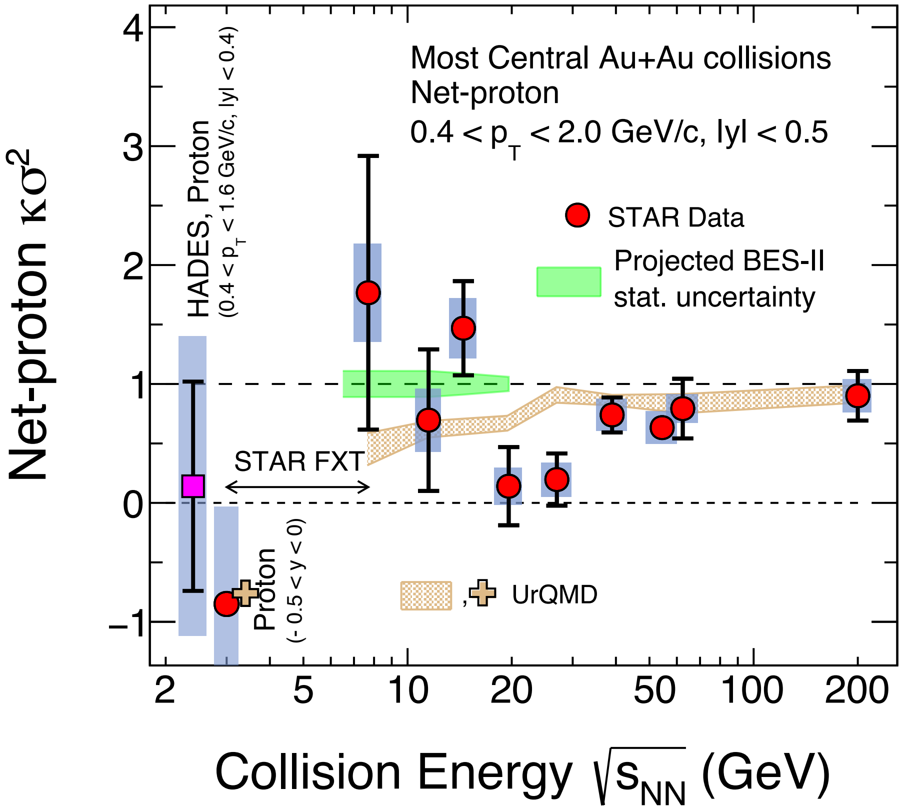


STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)
STAR: PRL 127, 262301 (2021)

Within uncertainties, experimental data consistent with predicted hierarchy.

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

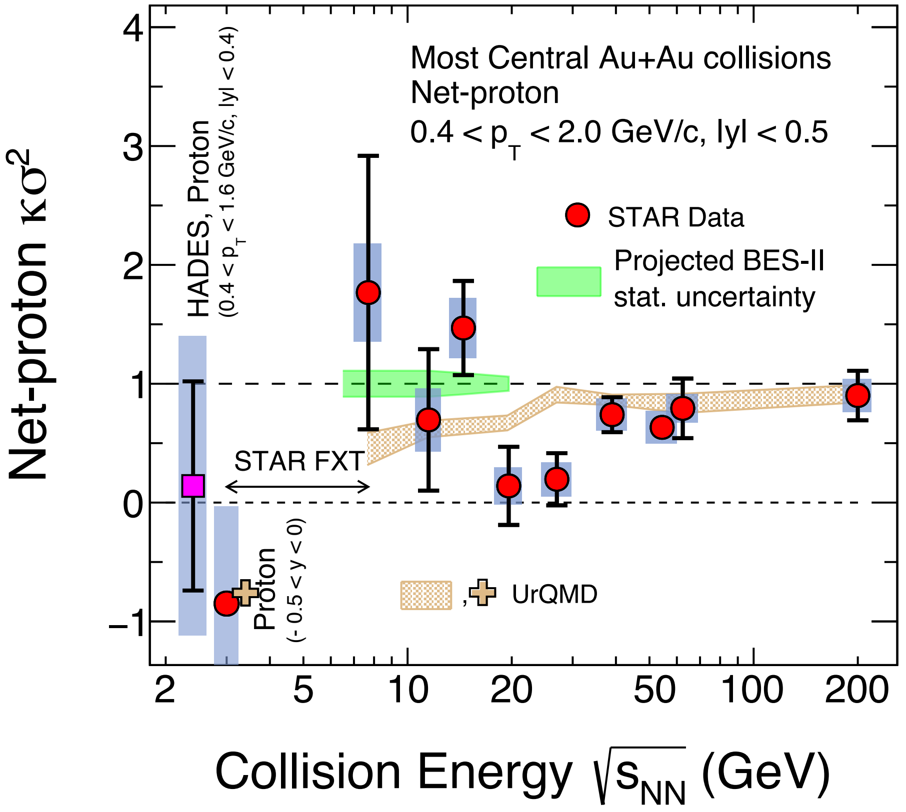
Net-Proton C_4/C_2 – CP Search



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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STAR: PRL. 128, 202303 (2022)

- 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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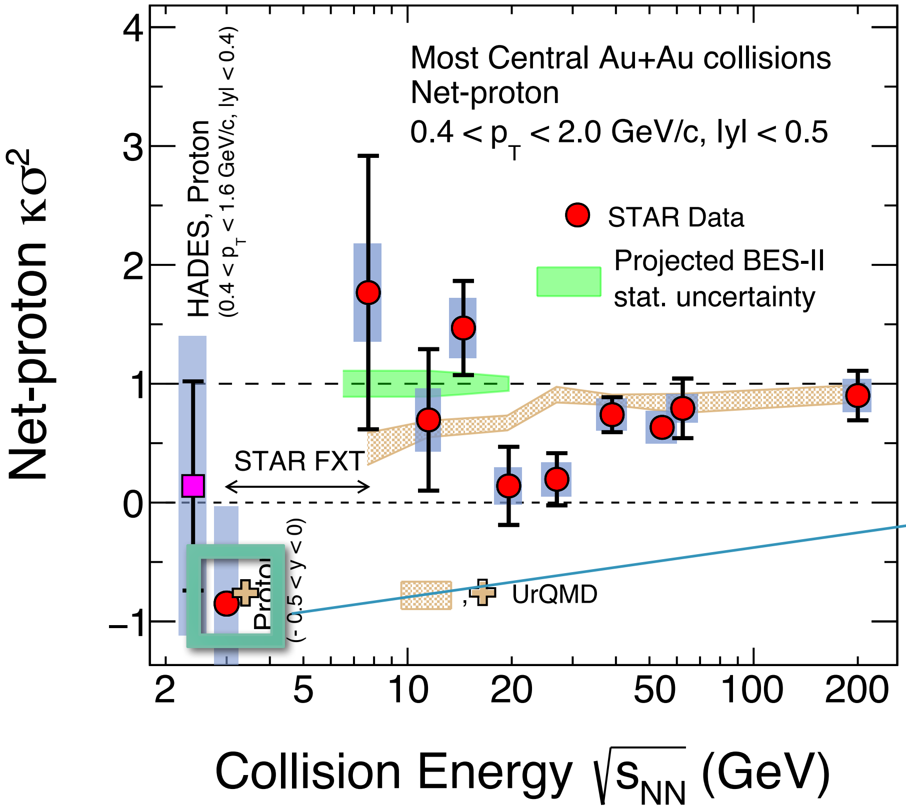

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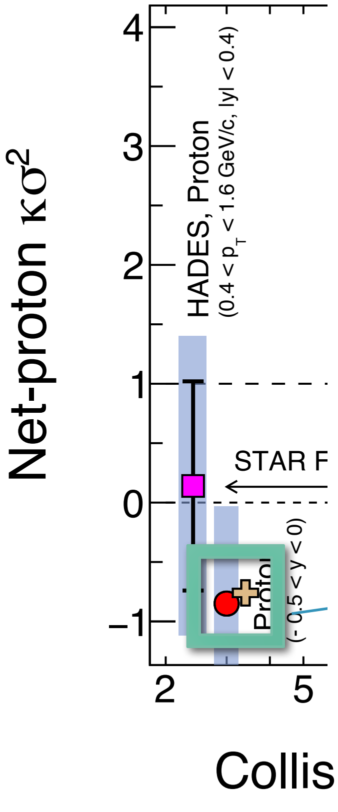
the observed non-monotonic dependence.

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.

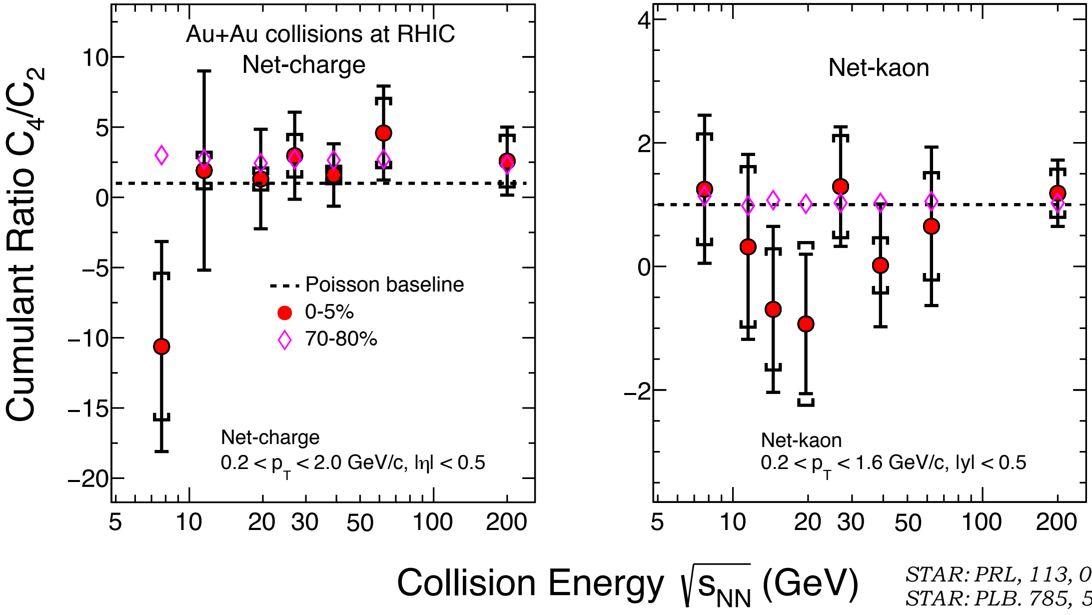
Net-Proton C_4/C_2 – CP Search



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

Net-charge

Net-kaon



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

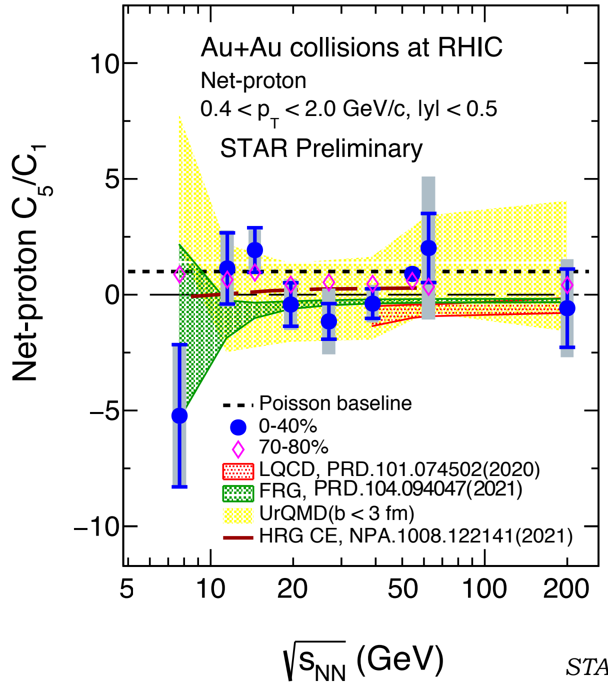
No such non-monotonic trend observed.

Large uncertainties.

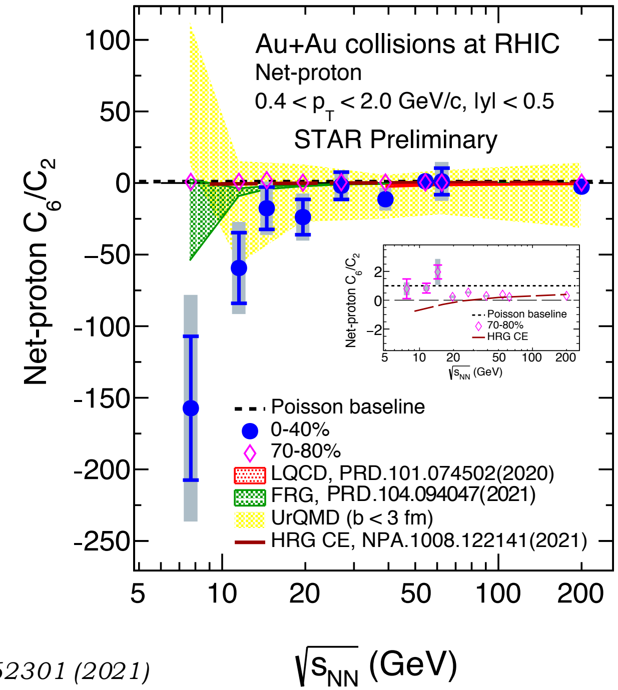
Precision measurement at BES-II needed.

- ❑ 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



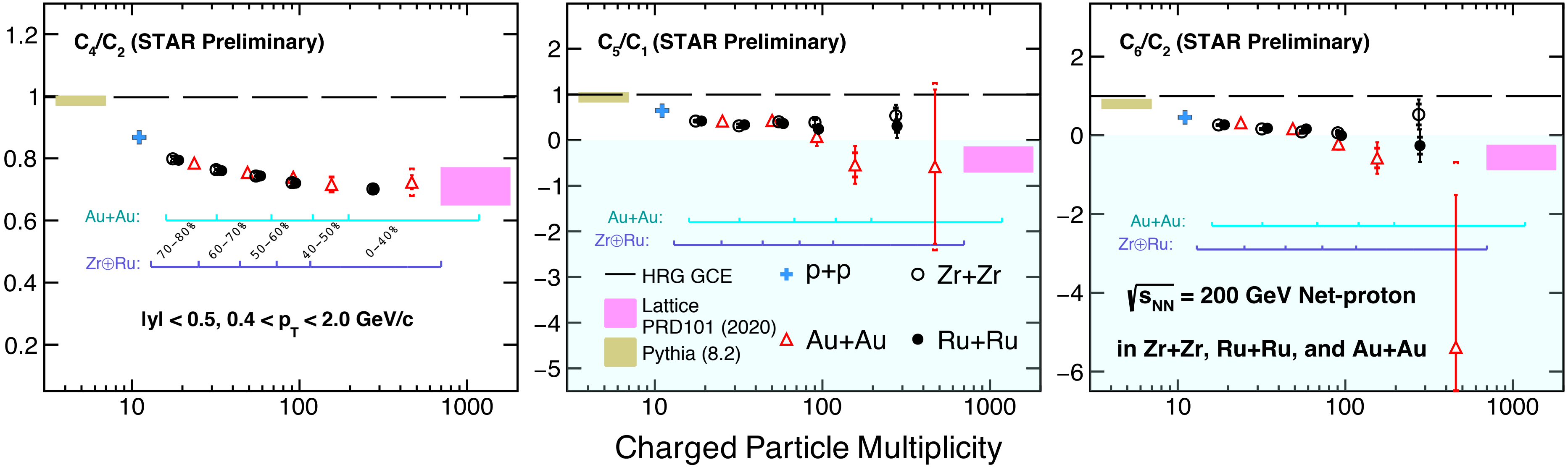
STAR: PRL 127, 262301 (2021)



- ❑ 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.

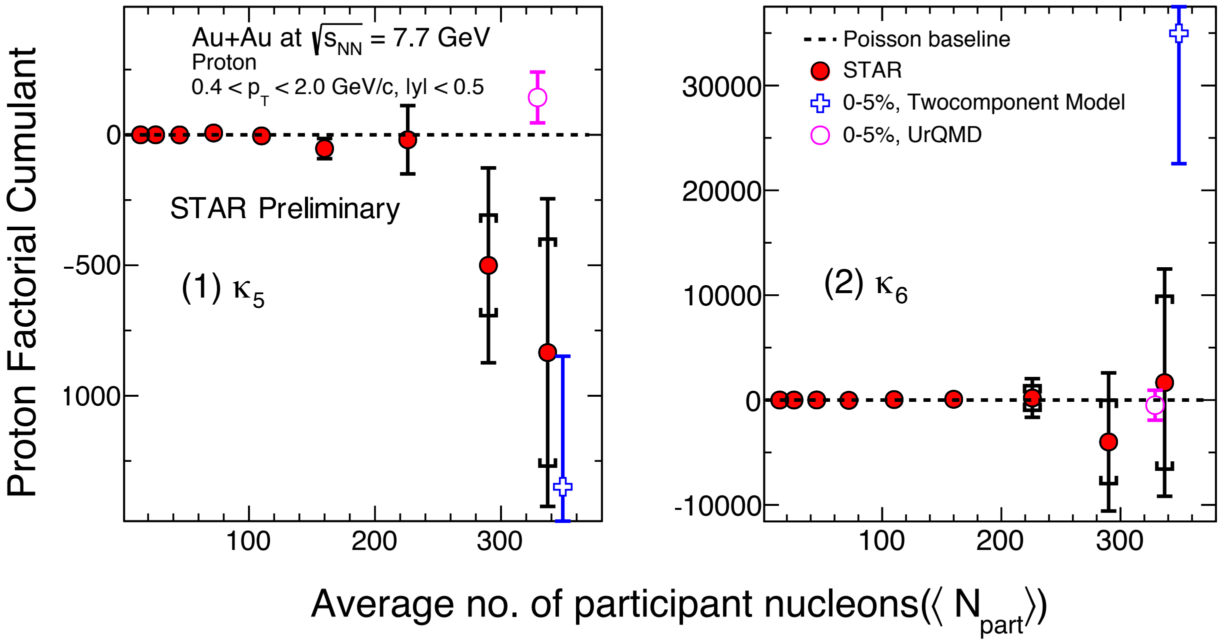
Net-Proton C_5/C_1 and C_6/C_2 at 200 GeV – Search for Crossover

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

STAR

- 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 FOR YOUR ATTENTION

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