Collision energy dependence of C_5 and C_6 of net-proton distributions at RHIC-STAR

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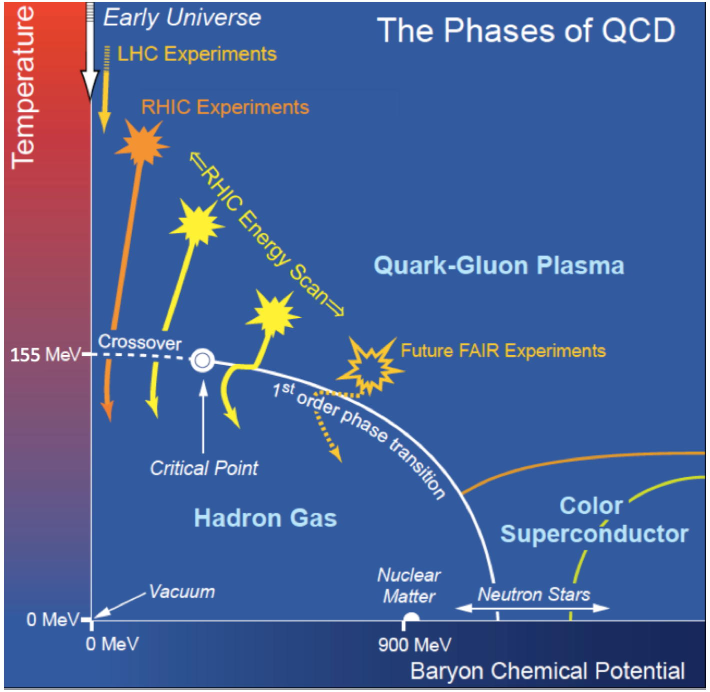
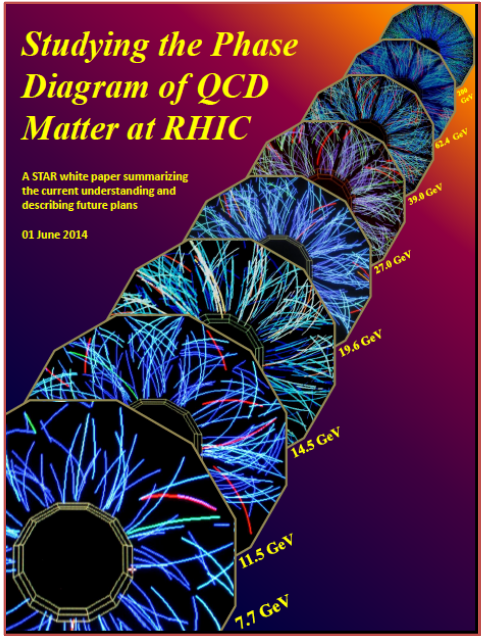
3. The STAR Experiment
4. Analysis
5. Results
6. Summary

Introduction: QCD Phase Diagram & BES





https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/files/BES_WPII_ver6.9_Cover.pdf

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

Results from Au+Au collisions at all BES-I energies

Observables

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

$C_1 = < N >$

$C_2 = < (\delta N)^2 >$

$C_3 = < (\delta N)^3 >$

$C_4 = < (\delta N)^4 > -3 < (\delta N)^2 >^2$

$C_5 = < (\delta N)^5 > -5 < (\delta N)^3 > < (\delta N)^2 >$

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

Here, $\delta N = N -< N >$

$\frac{C_3}{C_2} = S\sigma$

$\frac{C_4}{C_2} = \kappa\sigma^2$

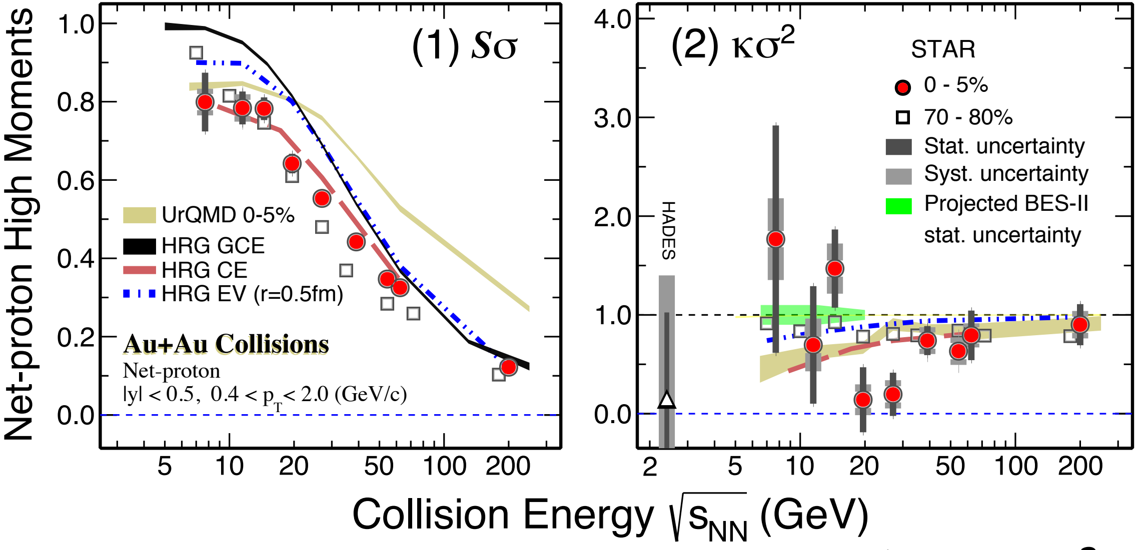
- Higher order cumulants probe the nature of phase transition.

Crossover (small μ_B)

First order (large μ_B)

Key aspect: Sign change of higher order cumulants.

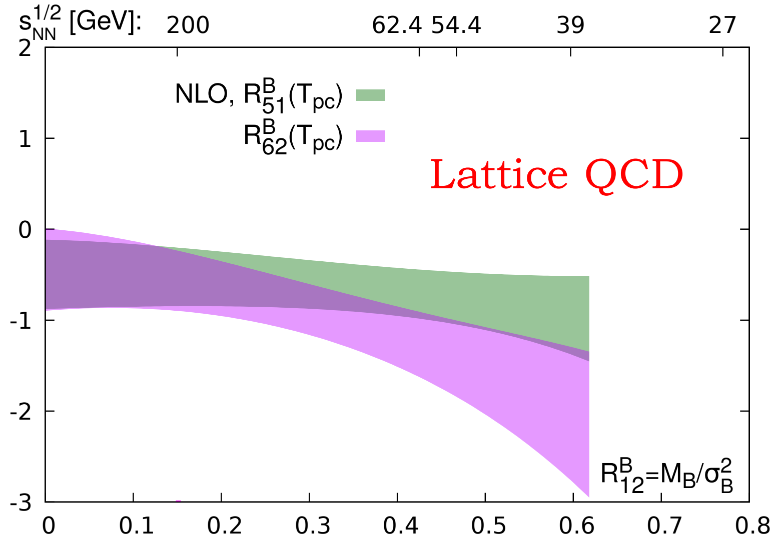
C_2, C_3, C_4: positive for data(7.7-200 GeV) and model(LQCD, FRG, HRG, UrQMD, JAM) – more distinct signatures needed

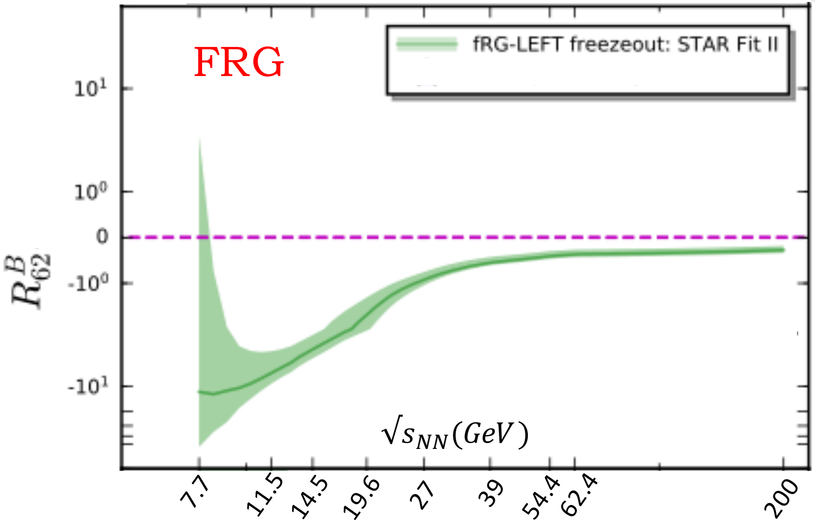


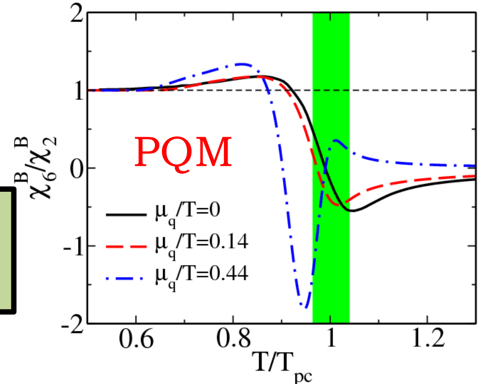
STAR: PRL **126**, 092301 (2021), STAR: arXiv : 2101.12413

Crossover

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







HotQCD, Phys. Rev. D101,074502 (2020)
Wei-jie Fu et. Al, arXiv:2101.06035
B. Friman et al, Eur.Phys.J. C71 1694 (2011)

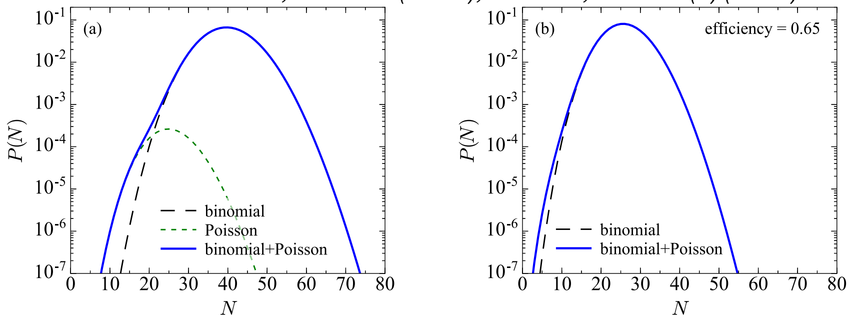
C_5, C_6: negative for LQCD, FRG, PQM – crossover
C_5, C_6: positive for HRG and UrQMD (No QCD transition)

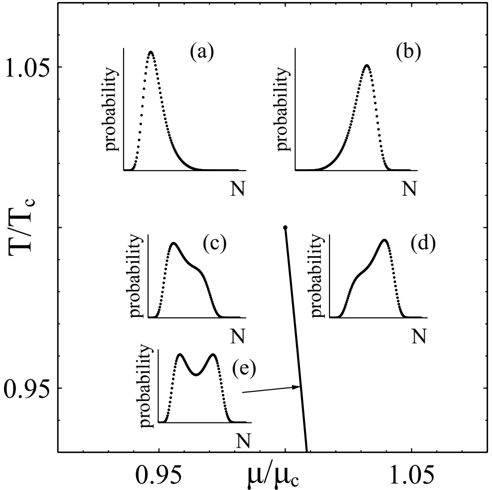
1st order Phase Transition

Multiplicity distribution bi-modal (contribution from two phases)
Ratio of proton factorial cumulant κ_{n+1}/κ_n is negative for higher orders

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

PRC98, 054901 (2018), PRC100, 051902(R) (2019)





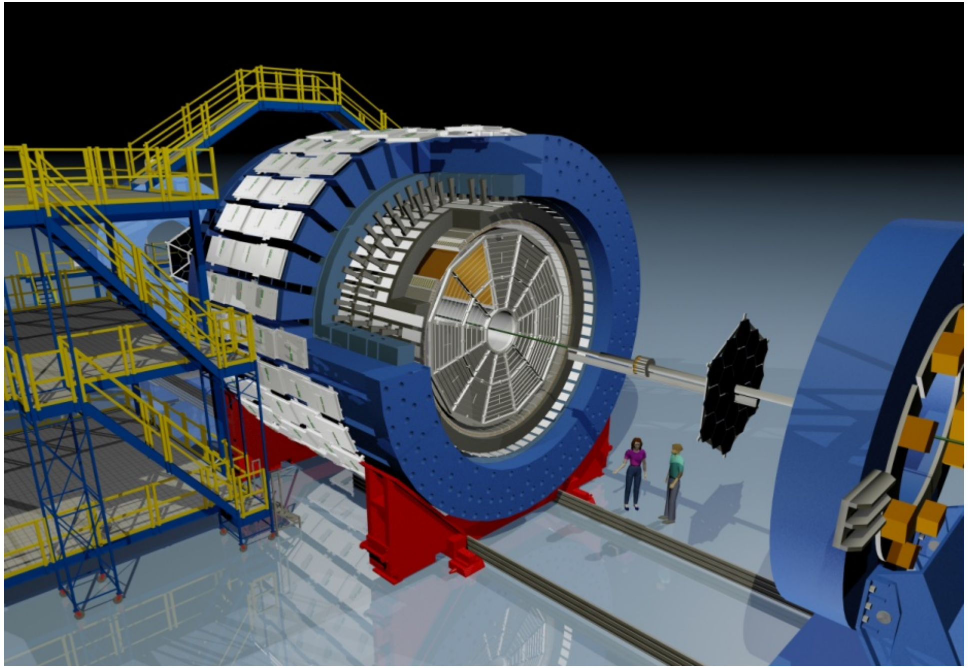
$P(N) = (1-\alpha)P_a(N) + \alpha P_b(N)$: Two Component Model

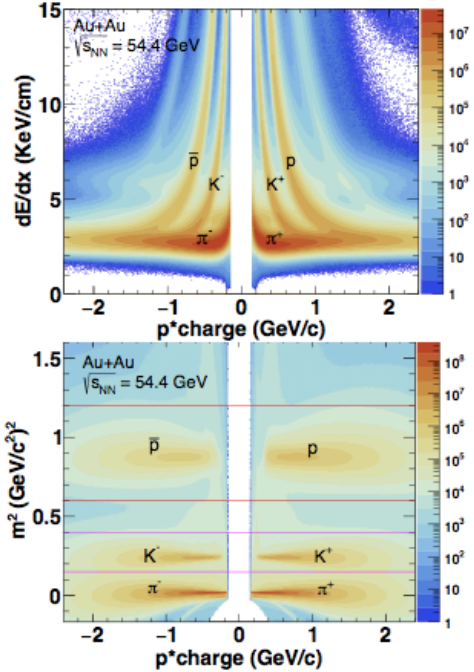
$\kappa_n \approx (-1)^n \alpha \bar{N}^n$ for $\alpha \ll 1,\ n > 1$
where $\bar{N} = \langle N_a \rangle - \langle N_b \rangle$

STAR proton cumulants C_1, C_3, C_4(0-5% centrality) at 7.7 GeV used as input to fix parameters of bimodal distribution.

$$\frac{\kappa_{n+1}}{\kappa_n} \approx -\bar{N} \approx -25$$

The 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)

2010 - 2017: BES-I at RHIC
Data Set Details

STAR

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	μ_B (MeV)
200	900	2010, 2011	25
62.4	43	2010	73
54.4	550	2017	83
39	92	2010	112
27	31	2011	156
19.6	14	2011	206
14.5	14	2014	264
11.5	7	2010	315
7.7	2.2	2010	420

Goal: to map the QCD phase diagram **$25 < \mu_B < 420$MeV**

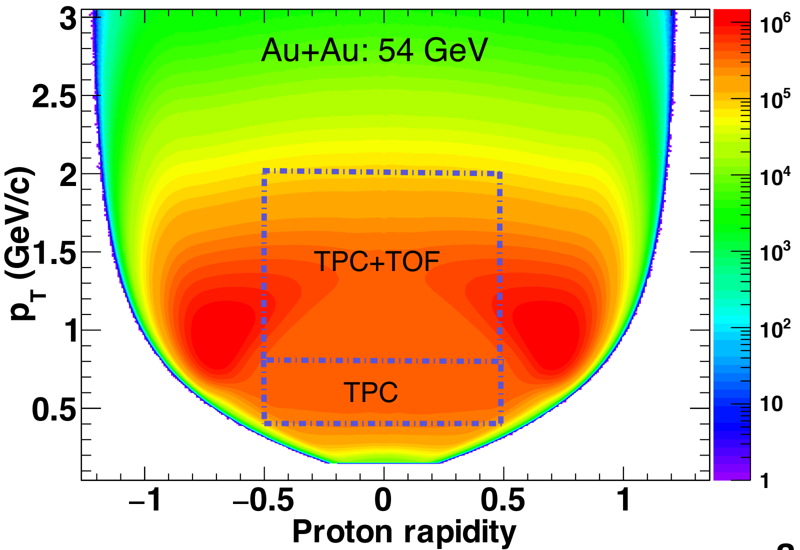
Data Set Details

Collision system and energy	Au+Au at $\sqrt{s_{NN}}$ = 7.7 – 200 GeV
Collision centrality	0-40%, 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

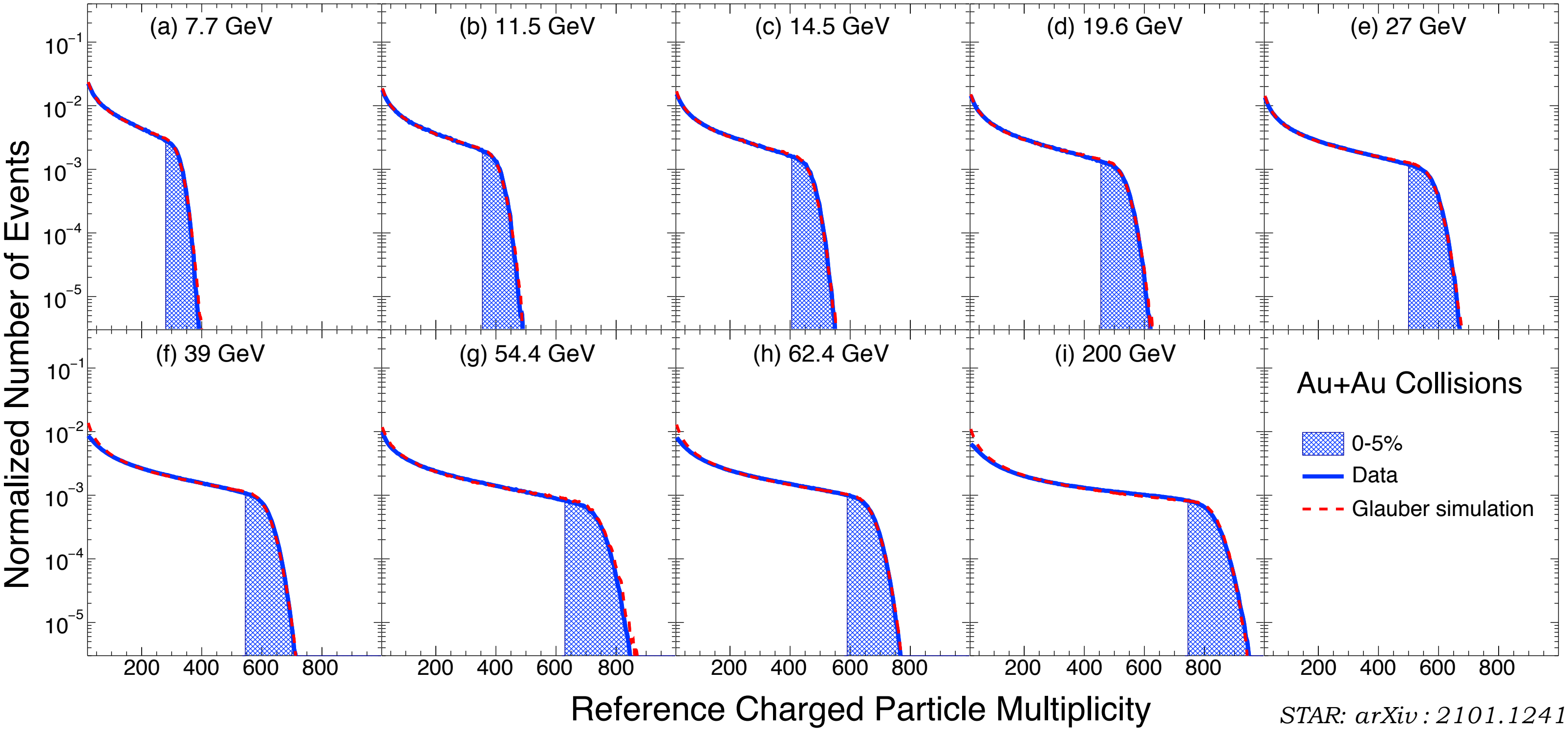
PID Detector	Transverse Momentum Range (p_T)	Rapidity (y)
TPC	0.4 to 0.8 GeV/c	|y| < 0.5
TPC+TOF	0.8 to 2.0 GeV/c	|y| < 0.5

Uniform acceptance in p_T vs. rapidity at midrapidity for all particles.



Centrality Selection

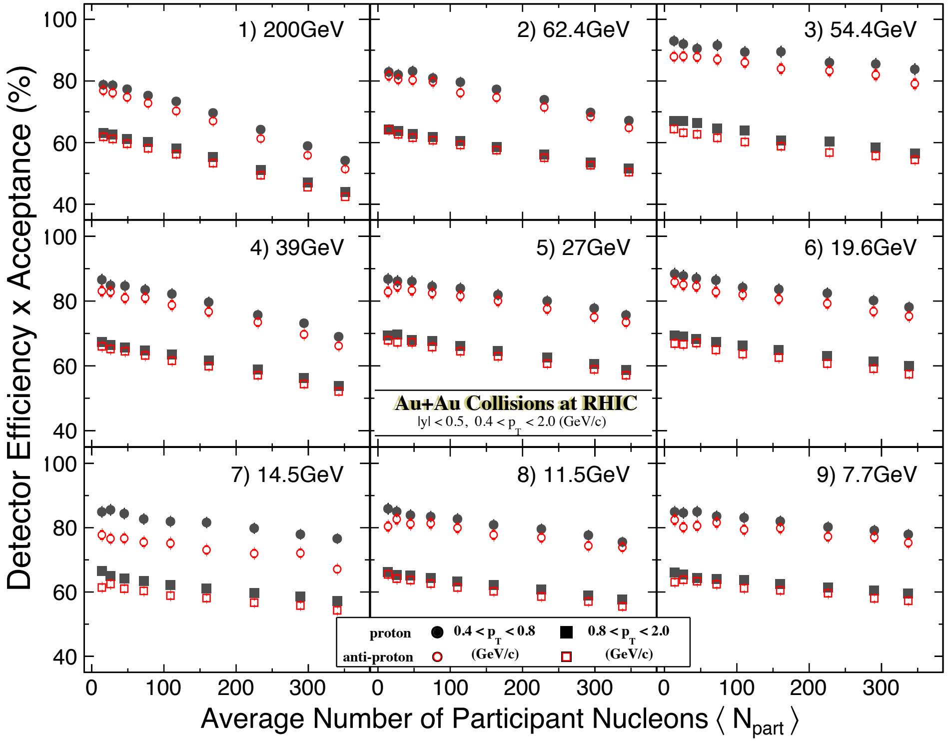
- Use charged particle multiplicity within $|\eta| < 1$, excluding particles of interest to avoid self correlation effects.
- Corrected for luminosity and Z-vertex effects, compared to the MC Glauber model.



STAR: arXiv : 2101.12413

Analysis Techniques (Corrections And Uncertainties)

- Reconstruction efficiency correction - binomial model



- Statistical uncertainties:
  - Bootstrap method

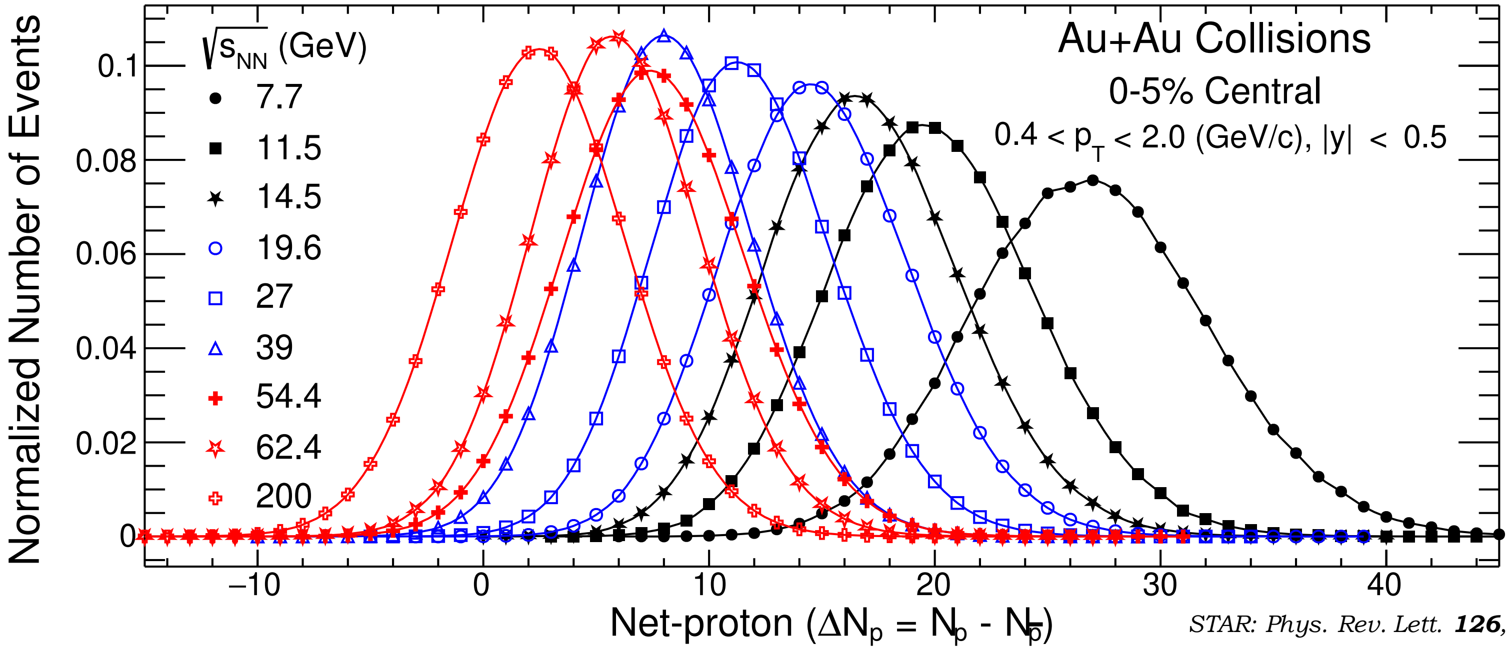
- Sources of systematic uncertainties:
  - Particle identification
  - Background estimates (DCA)
  - Track quality cuts
  - Efficiency variation

- 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

STAR: arXiv : 2101.12413
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

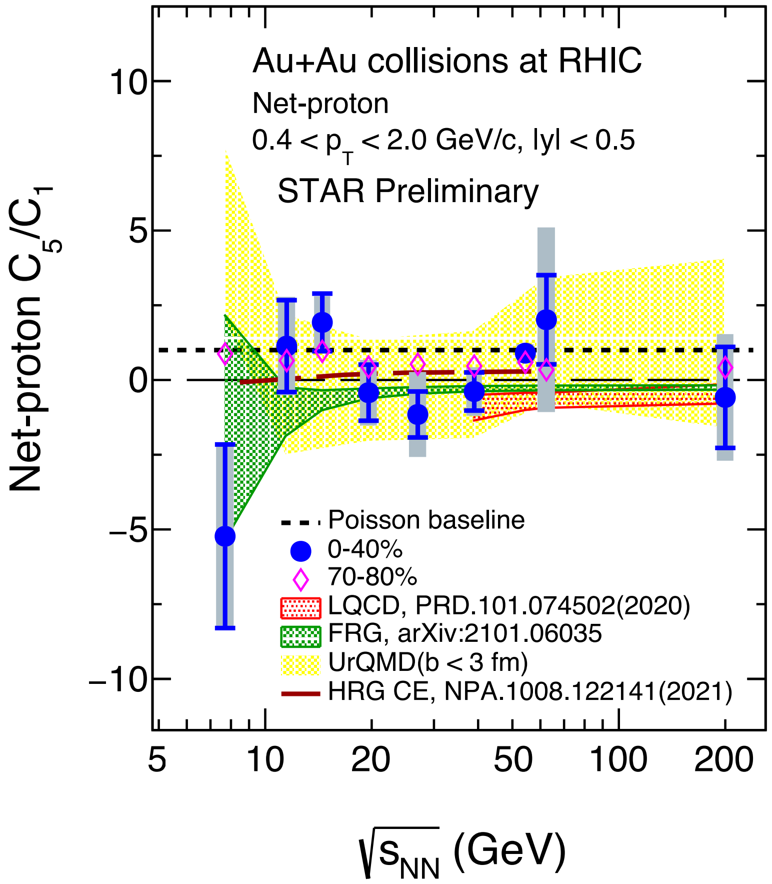
Energy dependence of net-proton distributions



STAR: Phys. Rev. Lett. ***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: $err(C_r) \propto \frac{\sigma^r}{\sqrt{N_{evts}}}$

Beam Energy Dependence of Net-Proton C_5/C_1



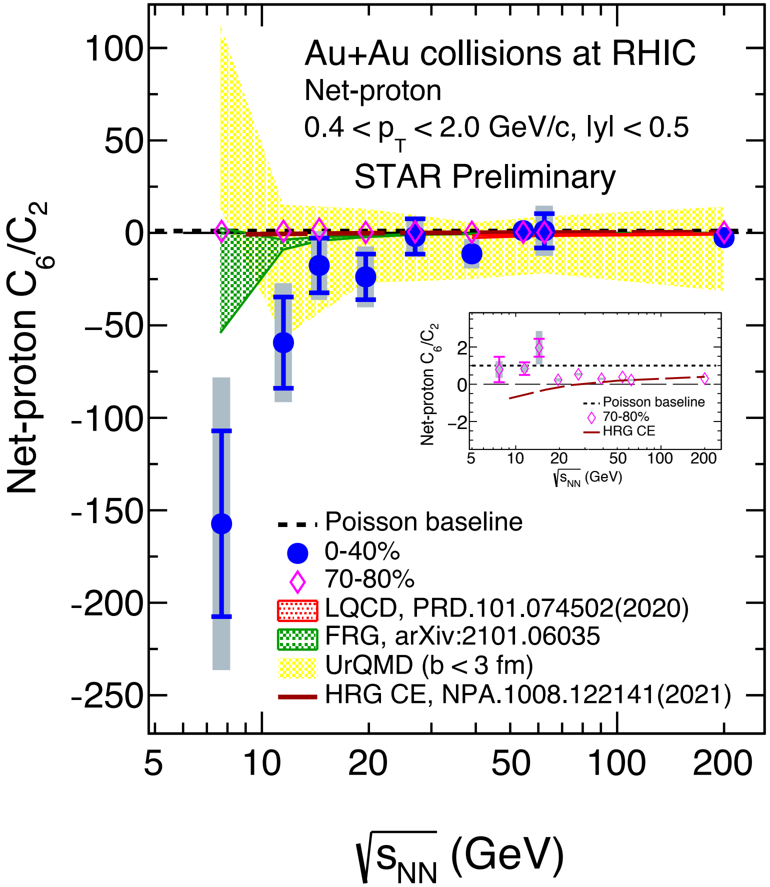
Weak collision energy dependence observed for most central(0-40%) C_5/C_1.

C_5/C_1(0-40%) deviates from zero at a level of $\lesssim 2\sigma$.

C_5/C_1(70-80%) >0 for all energies.

Blue bars: statistical uncertainties
Grey shaded bands: systematic uncertainties

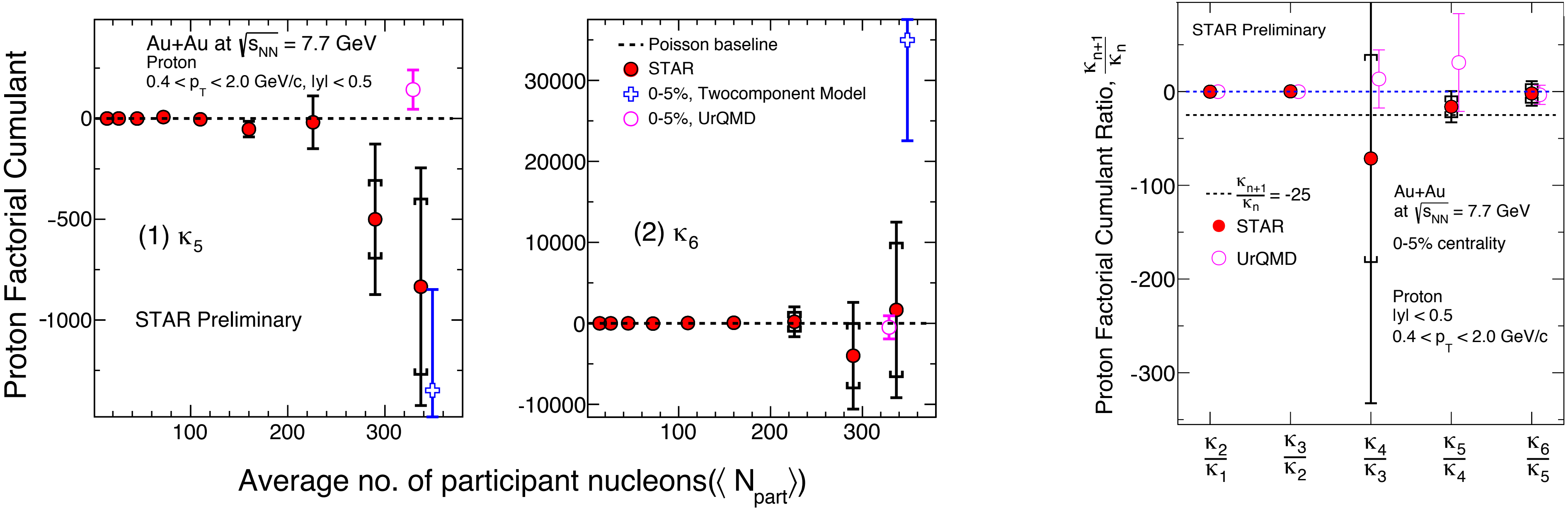
Beam Energy Dependence of Net-Proton C_6/C_2



Deviations from zero at a level of $\lesssim 2\sigma$ observed for most central(0-40%) C_6/C_2.

C_6/C_2(70-80%) >0 for all energies.

Proton Factorial Cumulant κ_5 and κ_6 at 7.7 GeV



PHYSICAL REVIEW C100, 051902(R) (2019)

κ_5 (0-5%) consistent with two component model expectation within uncertainties while κ_6 (0-5%) remains 1.8σ away. The ratios κ_5/κ_4 and κ_6/κ_5 (0-5%) consistent with zero.

Summary

- Beam energy dependence of net-proton C_5/C_1 and C_6/C_2 are presented for all BES-I energies. Centrality dependence of proton factorial cumulants (κ_5, κ_6) at 7.7 GeV are also shown.
- Some intriguing trends were observed, most central (0-40%) net-proton C_5/C_1 and C_6/C_2 show deviations from zero at a level of $\lesssim 2\sigma$.
- LQCD predicts negative C_5/C_1 and C_6/C_2 for QCD matter. Positive values for peripheral collisions (70-80%) and (tentatively) negative values for central collisions (0-40%) observed in measurements.
- The proton factorial cumulant κ_5 at 7.7 GeV (0-5%) agrees with the expectation from a two component model within uncertainties while κ_6 (0-5%) remains 1.8σ away from expectation from such a model.
- High order fluctuations are crucial for determining the QCD phase structure. Precision measurements are necessary in order to confirm the observed trend in the fifth and sixth order cumulants.

See next talk by Risa: Multiplicity dependence of net-proton C_5 and C_6 at STAR

THANK YOU