Measurement of higher moments of net-proton distributions in Au+Au collisions at $\sqrt{s_{NN}}$ =54.4 GeV at RHIC

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Outline
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2. Observable and Data Set
3. The STAR Experiment
4. Higher Moment Analysis
5. Results
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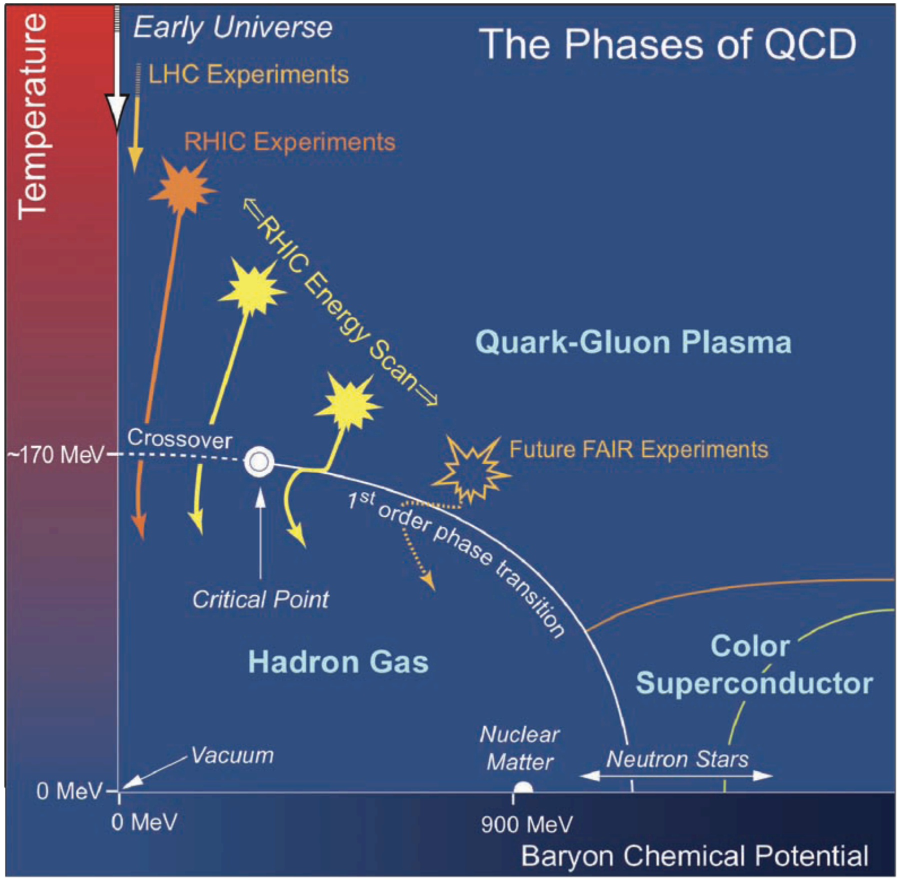
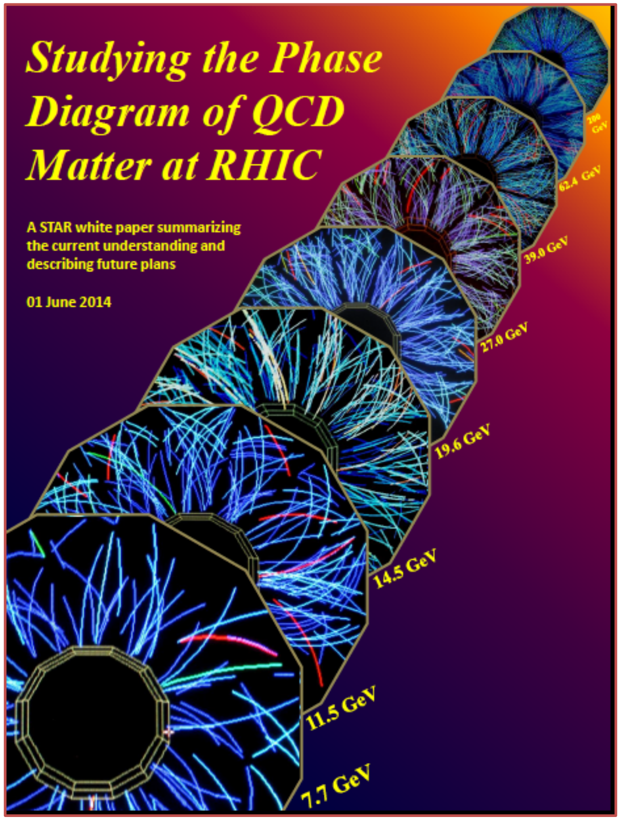
Introduction: QCD Phase Diagram & BES





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 and the phase structure.
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 new data : Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV

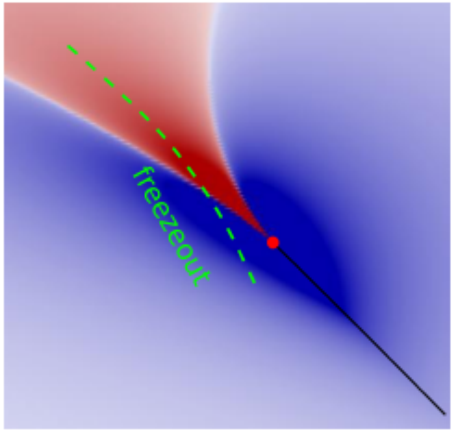
Observables

Higher moments or cumulants of net-particle distributions

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

$$\sigma^2 / M = \frac{C_2}{C_1}$$
$$S\sigma = \frac{C_3}{C_2}$$
$$\kappa\sigma^2 = \frac{C_4}{C_2}$$

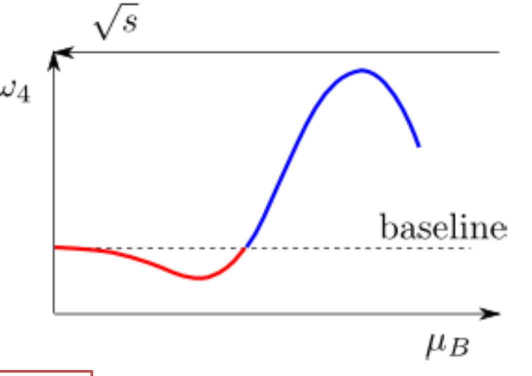
Kurtosis of net-proton in the presence of CP



Higher moments of conserved number distributions are sensitive observables.* Related to the correlation length and susceptibilities.

$$\langle \sigma^2 \rangle \sim \xi^2 \qquad \kappa_4 = \langle \sigma^4 \rangle_c \sim \xi^7$$

*Quantitative numbers
- Model dependent



Phys.Rev.Lett. 107 (2011) 052301
Phys.Rev.Lett. 102 (2009) 032301
Phys.Rev.Lett. 91 (2003) 102003
Phys.Rev.Lett. 81 (1998) 4816-4819
Phys.Rev. D82 (2010) 074008
Phys.Rev. D61 (2000) 105017
Phys.Rev.Lett. 103 (2009) 262301

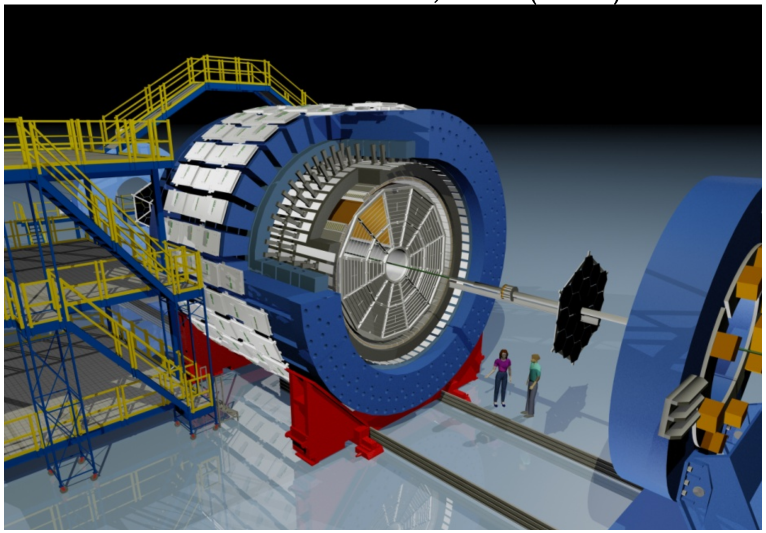
$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}},$$

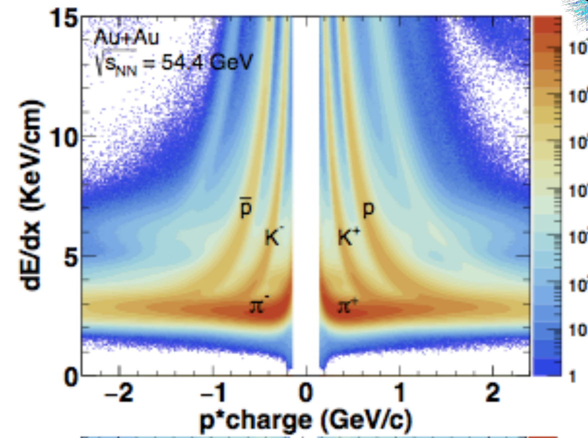
Data Set

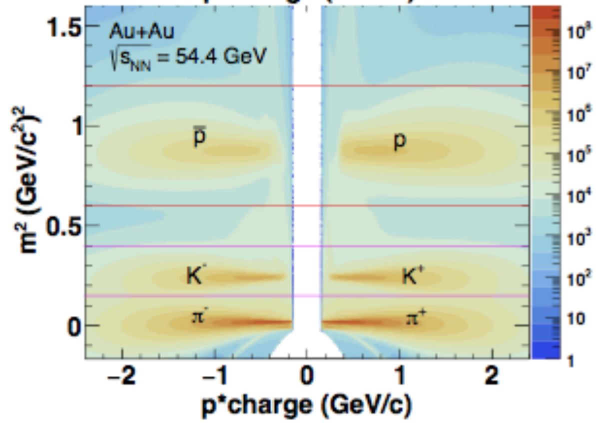
Collision system and energy	Au+Au and 54.4 GeV
Baryon Chemical Potential	~ 90 MeV
No. of events	~ 553 M
Collision centrality	0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%
Centrality	$\|\eta\| < 1$; charged particles other than protons and antiprotons
Z Vertex	+/- 30 cm
Vertex radial position	2 cm
Detectors	Time Projection Chamber and Time-of-Flight
Particle Type	Proton and antiprotons
Rapidity	+/- 0.5
Transverse Momentum Range	0.4 to 2.0 GeV/c
Secondary proton backgrounds	|DCA| < 1cm

The STAR Detector

Nucl. Instrum. Meth. A 499, 624 (2003).







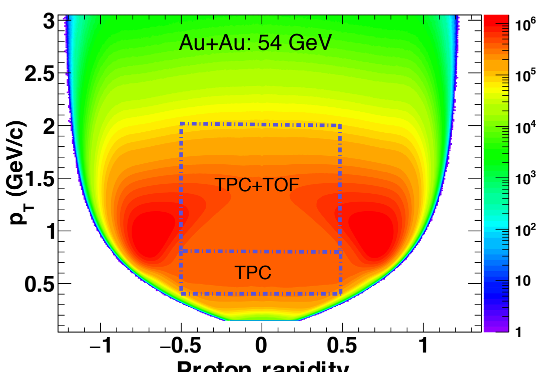
Main Detectors: Time Projection Chamber and Time-of-Flight

One unit rapidity coverage at mid-rapidity.

Full azimuthal angle coverage.

Track-by-track PID in each event

Purity > 96% for studied p_T range.



Collider: **Uniform acceptance** in p_T vs. rapidity at mid-rapidity for all particles.

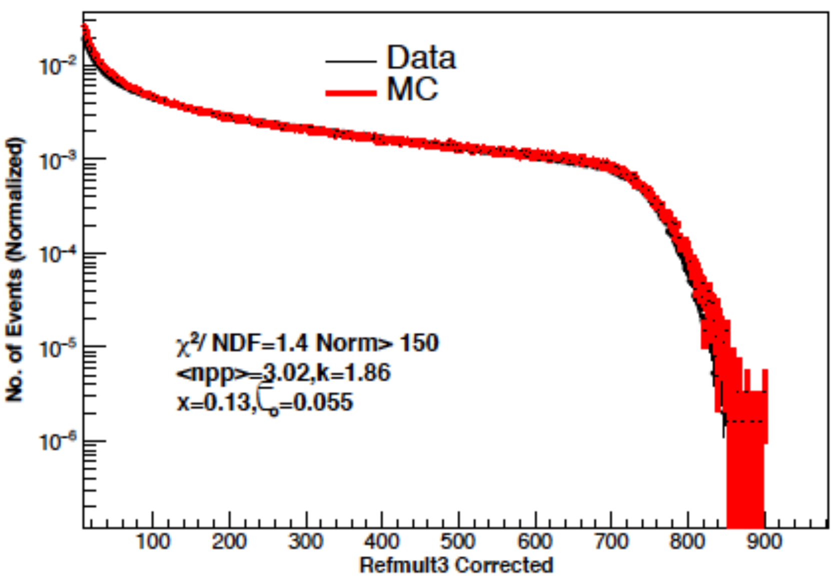
STAR: Phys.Rev. C88 (2013) 014902
Phys.Rev. C81 (2010) 024911

Centrality Selection

Use charged particles other than protons and antiprotons within $|\eta| < 1.0$. Avoids auto-correlation effects

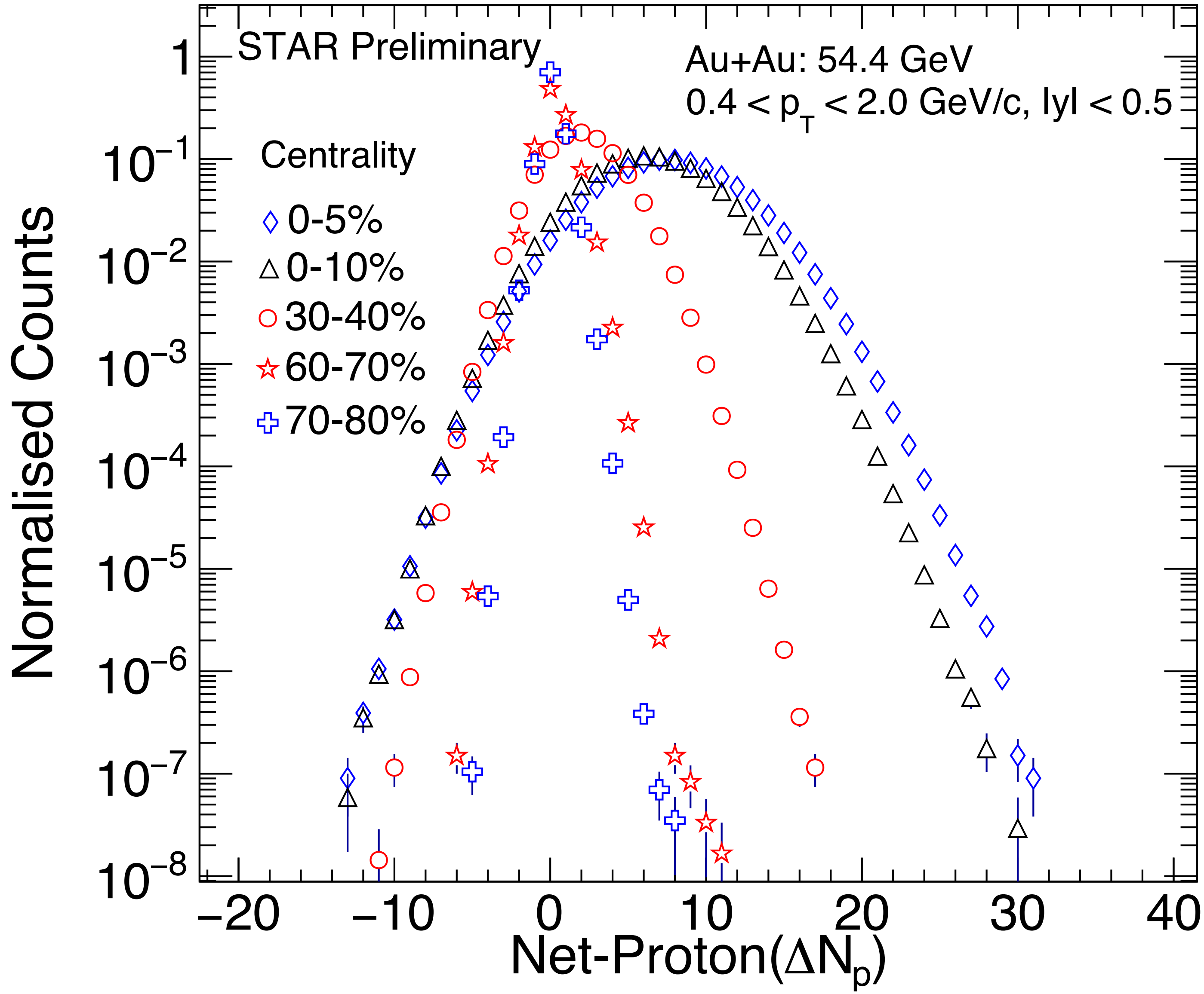
Corrected for luminosity and Z-vertex effects.

Compared to the MC Glauber model



Centrality	Refmult	Npart	Events (Millions)
0-5%	621	346	33
5-10%	516	292	34
10-20%	354	228	70
20-30%	237	161	69
30-40%	151	111	69
40-50%	90	73	67
50-60%	50	45	64
60-70%	24	26	60
70-80%	10	13	57

Event-by-Event Distribution



Corrections and Uncertainties

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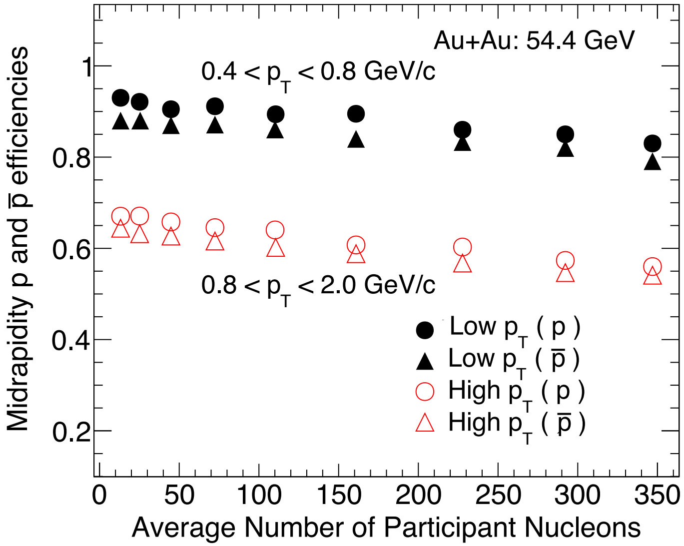
Centrality Bin Width Correction



Reconstruction Efficiency Correction - Binomial model

Statistical Uncertainties: Boot Strap Method

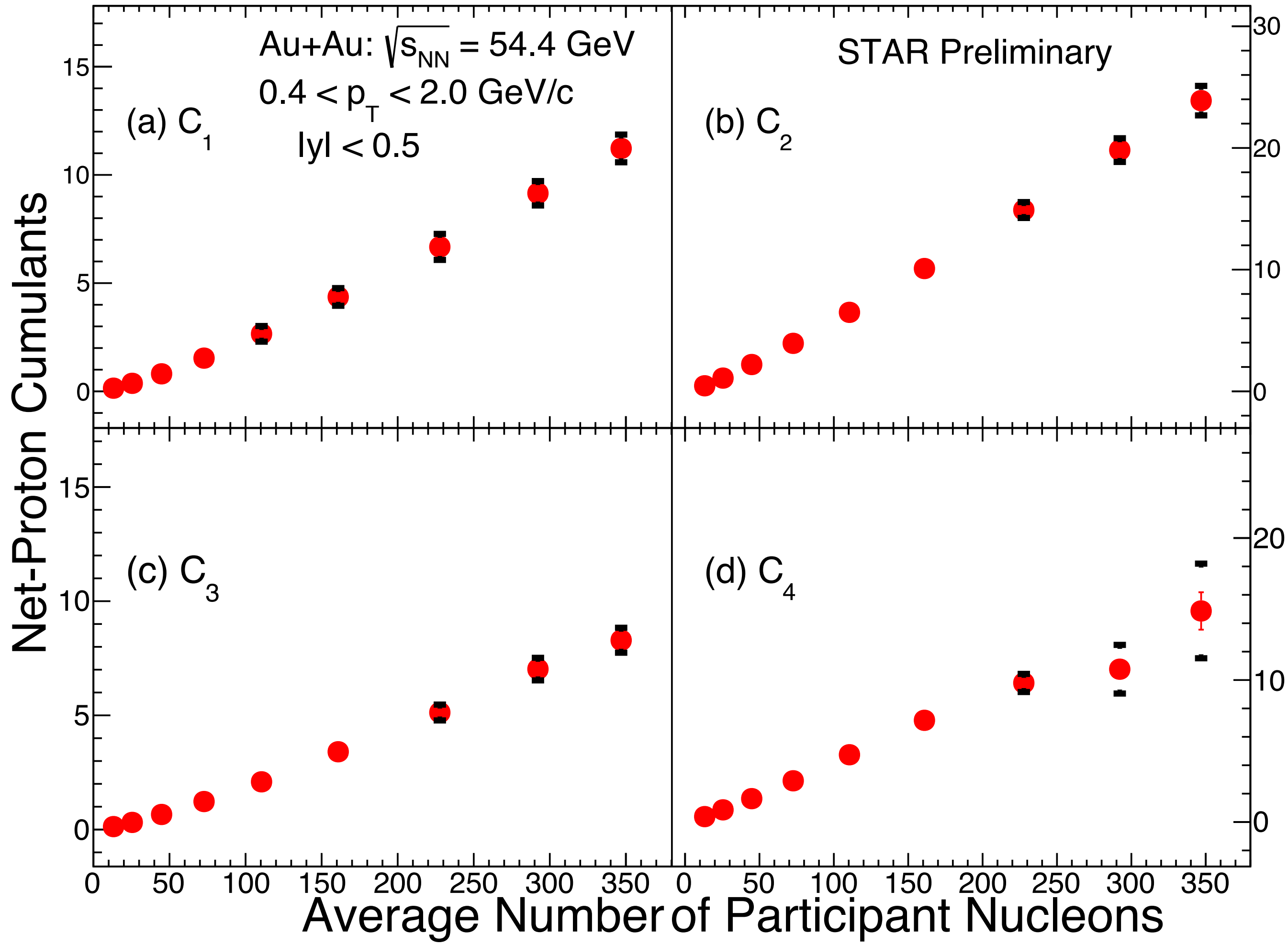
Cumulant	Stat. Uncertainties (0-5%)
C_1	0.008%
C_2	0.04%
C_3	1%
C_4	9%

Sources of Systematic Uncertainties:

Particle Identification
Track Quality Cuts
Background Estimates (DCA)

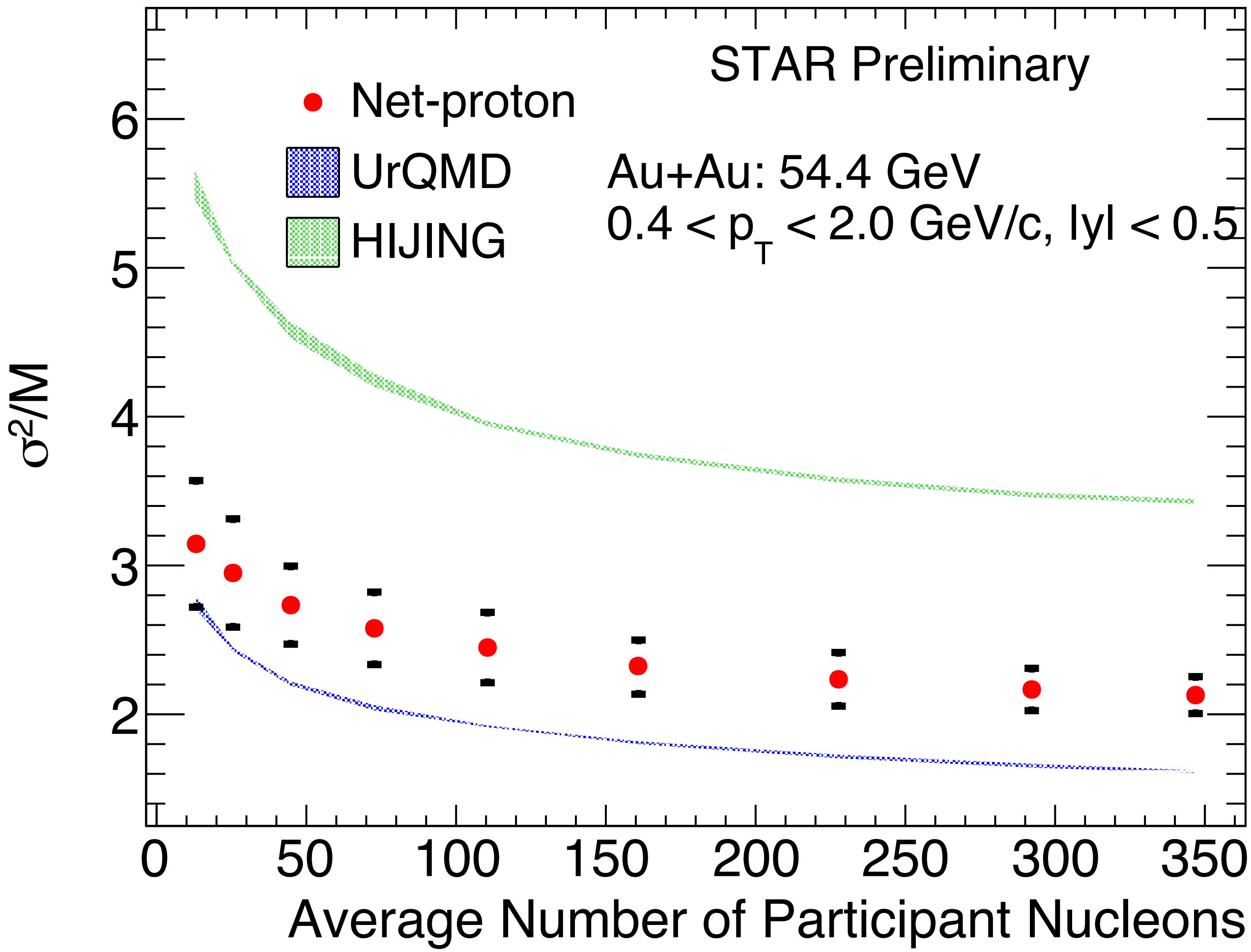
Cumulant	Sys. Uncertainties (0-5%)
C_1	6%
C_2	5%
C_3	7%
C_4	22%

Centrality Dependence of Cumulants



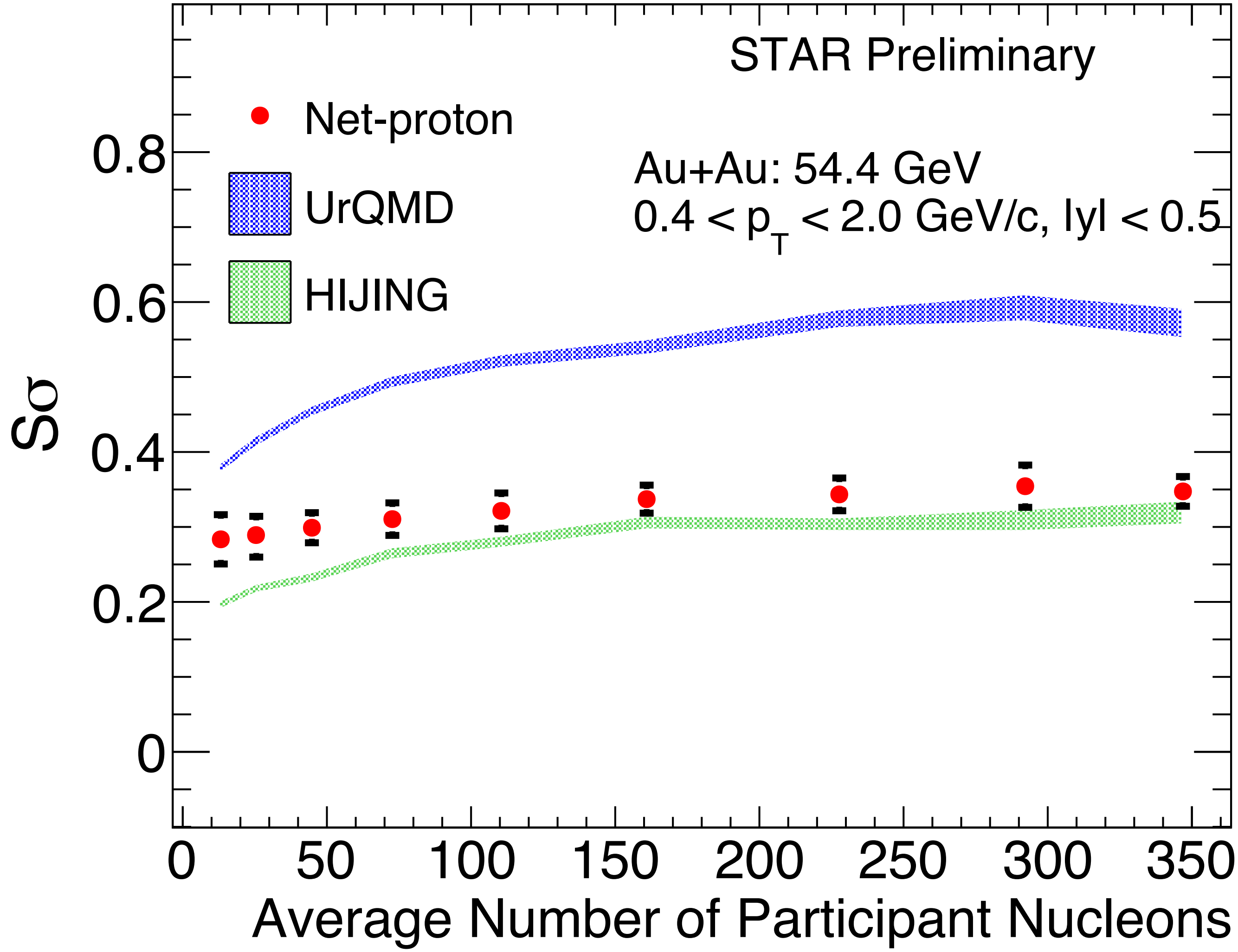
Net-proton cumulants up to the fourth order increases with number of participant nucleons

Centrality Dependence of Cumulants Ratios



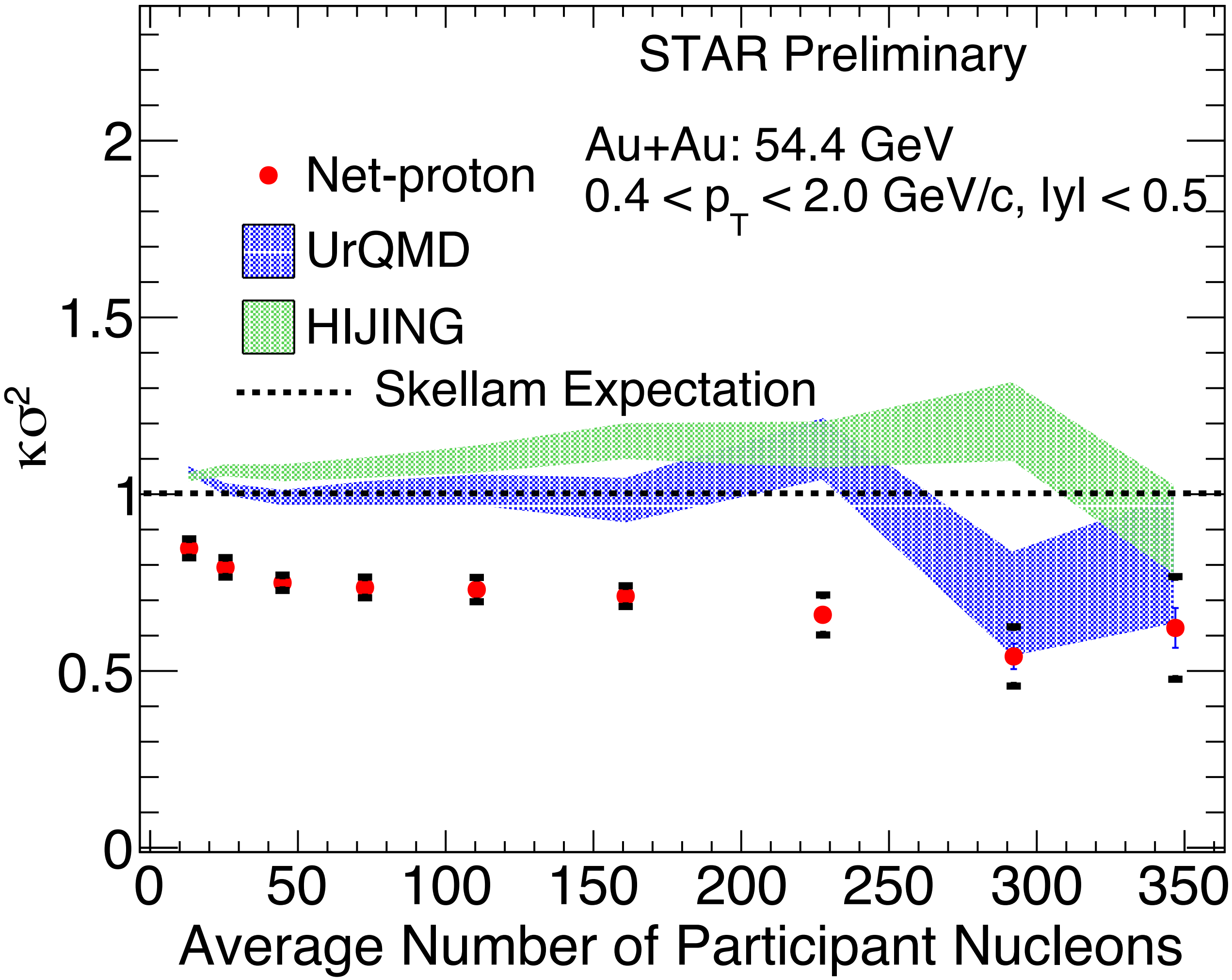
Net-proton cumulants ratio C_2/C_1 variation with number of participant nucleons. Results compared to the UrQMD and HIJING model calculations

Centrality Dependence of Cumulants Ratios



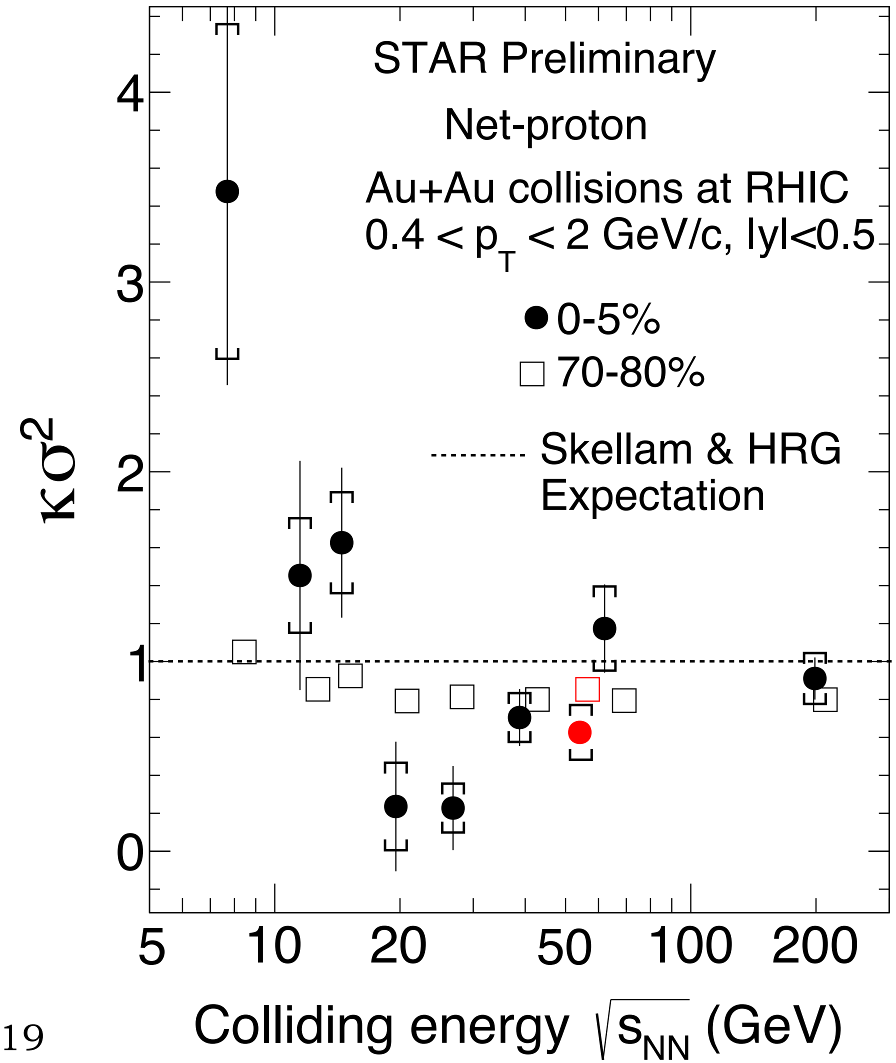
Net-proton cumulants ratio C_3/C_2 variation with number of participant nucleons. Results compared to the UrQMD and HIJING model calculations

Centrality Dependence of Cumulants Ratios



Net-proton cumulants ratio C_4/C_2 variation with number of participant nucleons. Results compared to the UrQMD and HIJING model calculations

Energy Dependence of Cumulant Ratios



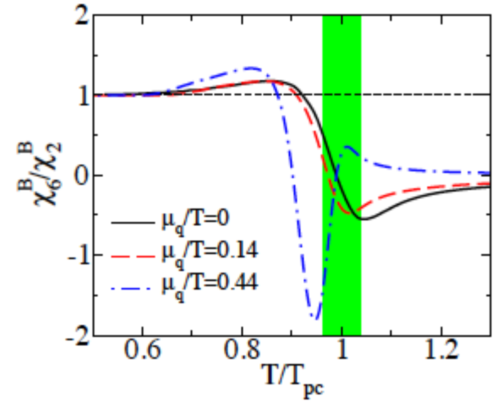
STAR: Xiaofeng Luo,
PoS CPOD2014 (2015) 019

Dependence of net-proton cumulants ratio C_4/C_2 on beam energy including results from 54.4 GeV.

The Sixth-Order Cumulant

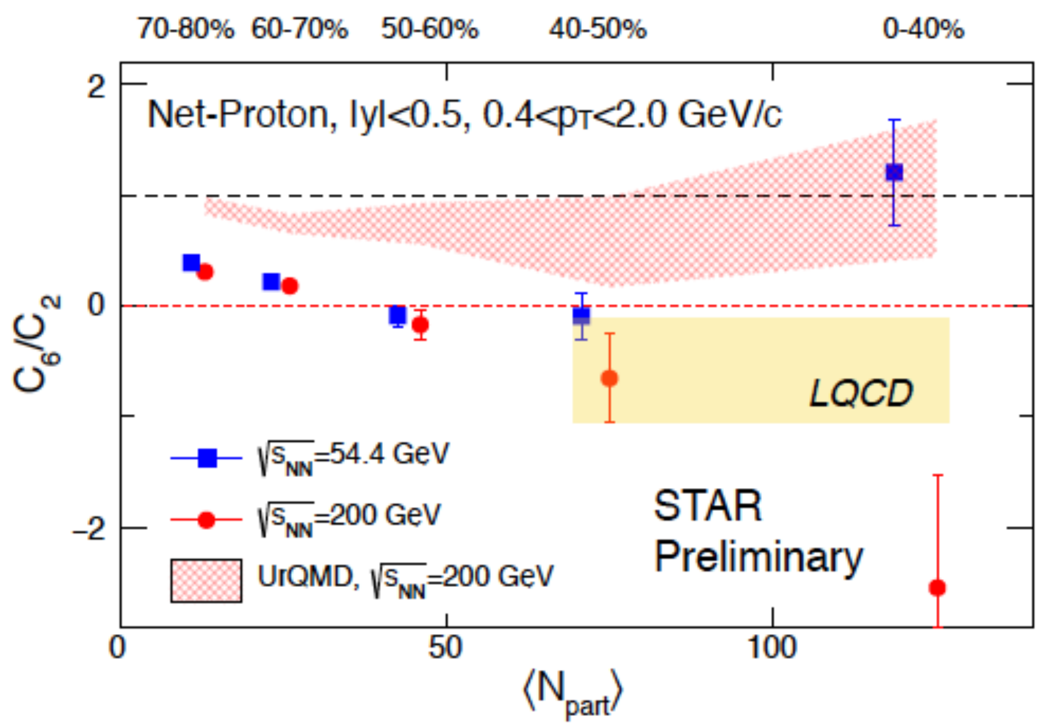
Goal: Identification of O(4) chiral criticality on the phase boundary.

freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~ 2	~ 10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~ 2	~ 10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~ 0.5	< 0	~ 1	< 0



The sixth-order cumulants of baryon number and electric charge fluctuations remain negative at the chiral transition temperature.

Most central value of C_6/C_2
$C_6/C_2 < 0$ for $\sqrt{s_{NN}}$ = 200 GeV
$C_6/C_2 > 0$ for $\sqrt{s_{NN}}$ = 54.4 GeV

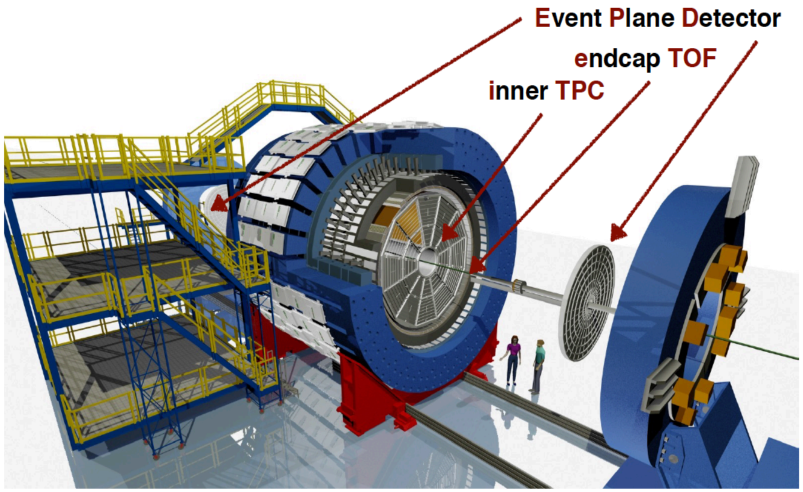


Eur.Phys.J. C71 (2011) 1694
Phys.Rev. D95 (2017) 054504
STAR: Toshihiro Nonaka ATHIC, 2018

Summary

- The first measurements of net-proton cumulants (up to the fourth order) presented for Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV. Measurements carried out at midrapidity ($|y| < 0.5$), wide transverse momentum range ($0.4 < p_T < 2.0$ GeV/c) and nine centrality bins.
- The cumulants monotonically increase with increasing number of participant nucleons.
- The C_2/C_1 shows a strong centrality dependence, whereas C_3/C_2 and C_4/C_2 have a weak centrality dependence.
- The centrality dependence of cumulant ratios is only qualitatively reproduced by the UrQMD and HIJING models. Quantitative differences exist.
- The C_6/C_2 for central Au+Au collisions at 54.4 GeV is positive while that for 200 GeV is negative (with large uncertainties). These have consequences vis-à-vis chiral criticality in QCD.

Beam Energy Scan Phase - II



√s (GeV)	Statistics(Millions) – BES-I	Statistics(Millions) – BES-II
7.7	~4	**~100**
9.1	-	**~160**
11.5	~12	**~230**
14.5	~ 20	**~300**
19.6	~36	**~400**
27	~70	**~500**

iTPC	EPD	eTOF
Larger rapidity coverage $\|\eta\| < 1.5$	$2.1 < \|\eta\| < 5.1$	$-1.6 < \eta < 1.0$
Better dE/dx resolution	Better Centrality determination	PID extended to forward rapidity
Lower momentum acceptance > 0.1 GeV/c	Better event plane resolution	
Physics Impact: Higher moments and Dilepton	Physics Impact: Higher moments, v_n	Physics Impact: Fixed target program and all analysis with PID