Fluctuations in BES

Yige Huang
for the STAR Collaboration

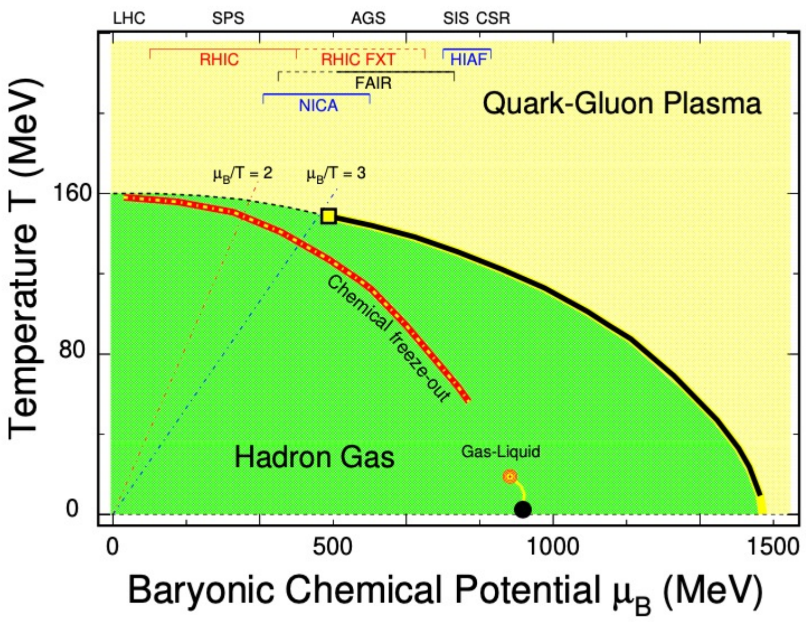
Central China Normal University
GSI Helmholtzzentrum für Schwerionenforschung

Supported in part by
U.S. DEPARTMENT OF ENERGY

Outline

- **Critical End Point and Beam Energy Scan**
- STAR Experiment
- Selected Results
- Summary and Outlook

Critical End Point and Beam Energy Scan



X. Luo, S. Shi, N. Xu, Y. Zhang: Particles 3 (2020) 2, 278-307

QCD Phase Diagram

1. Study of strongly interacting matter: describe QGP and hadronic phase;
2. Lattice QCD: smooth crossover at low μ_B;
3. First order phase transition at high μ_B and low temperature region as well as **Critical End Point** are conjectured

Beam Energy Scan Program

1. By tuning beam energy and centrality, we can vary the μ_B and T;
2. Measurements of various observables characterize the phase diagram: particle yields, collective behaviors, baryon **fluctuations**, …
3. Map out the crossover and/or first order phase boundary, and search for critical end point

Beam Energy Scan Phase-II: Data Sets

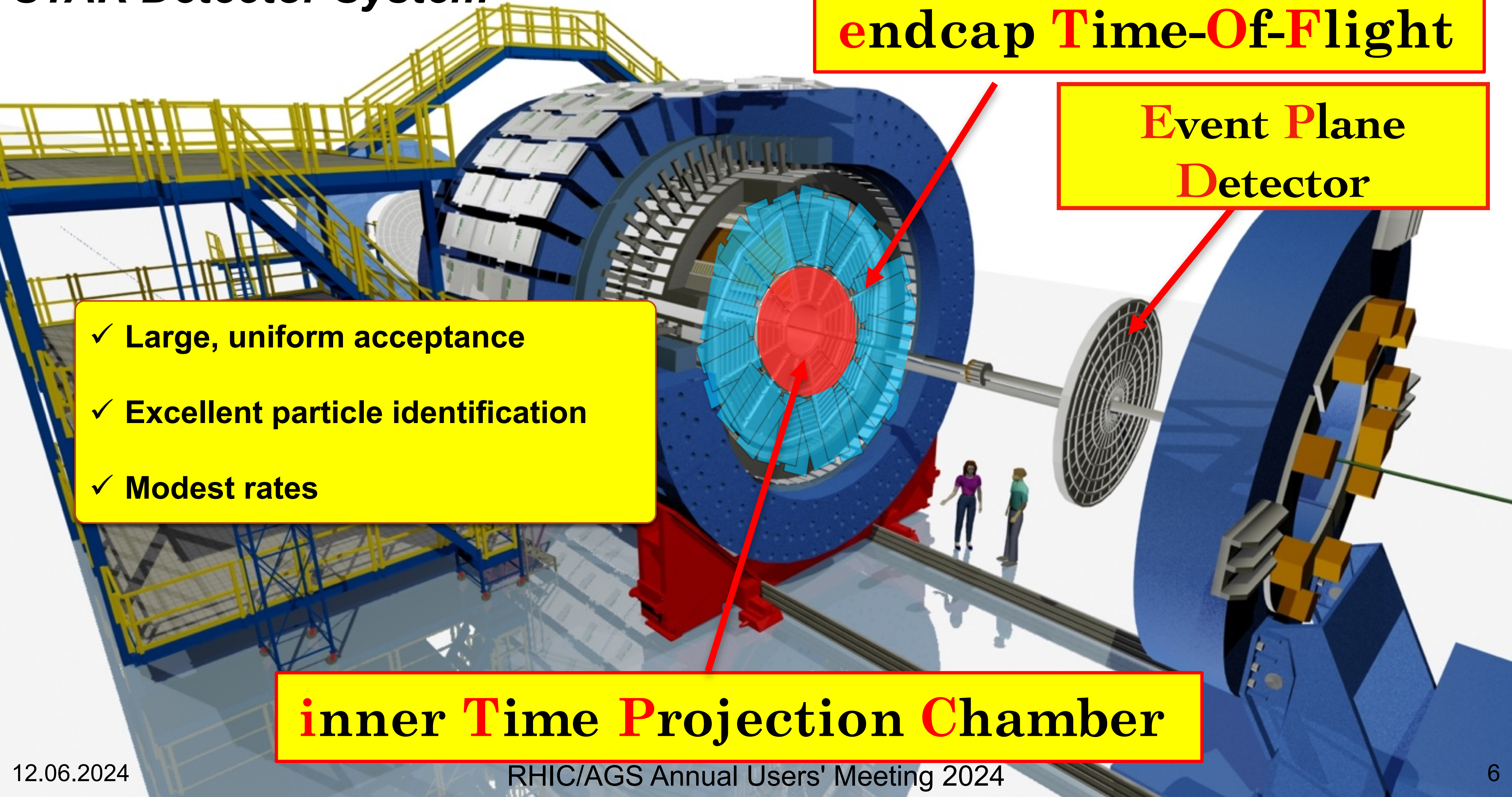
Au+Au Collisions at RHIC							
Collider Runs				**Fixed-Target Runs**			
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B
1	**200**	380 M	**25** MeV	**1**	13.7 (100)	50 M	280 MeV
2	62.4	46 M	75 MeV	**2**	11.5 (70)	50 M	316 MeV
3	54.4	1200 M	85 MeV	**3**	9.2 (44.5)	50 M	372 MeV
4	39	86 M	112 MeV	**4**	7.7 (31.2)	260 M	420 MeV
5	27	585 M	156 MeV	**5**	7.2 (26.5)	470 M	440 MeV
6	19.6	595 M	206 MeV	**6**	6.2 (19.5)	120 M	490 MeV
7	17.3	256 M	230 MeV	**7**	5.2 (13.5)	100 M	540 MeV
8	14.6	340 M	262 MeV	**8**	4.5 (9.8)	110 M	590 MeV
9	11.5	257 M	316 MeV	**9**	3.9 (7.3)	120 M	633 MeV
10	9.2	160 M	372 MeV	**10**	3.5 (5.75)	120 M	670 MeV
11	7.7	104 M	420 MeV	**11**	3.2 (4.59)	200 M	699 MeV
				12	**3.0** (3.85)	**260** + 2000 M	**750** MeV

- $3 < \sqrt{s_{NN}} < 200$ GeV → $750 > \mu_B > 25$ MeV: wide μ_B coverage;
- Most precise data to map the QCD phase diagram!

Outline

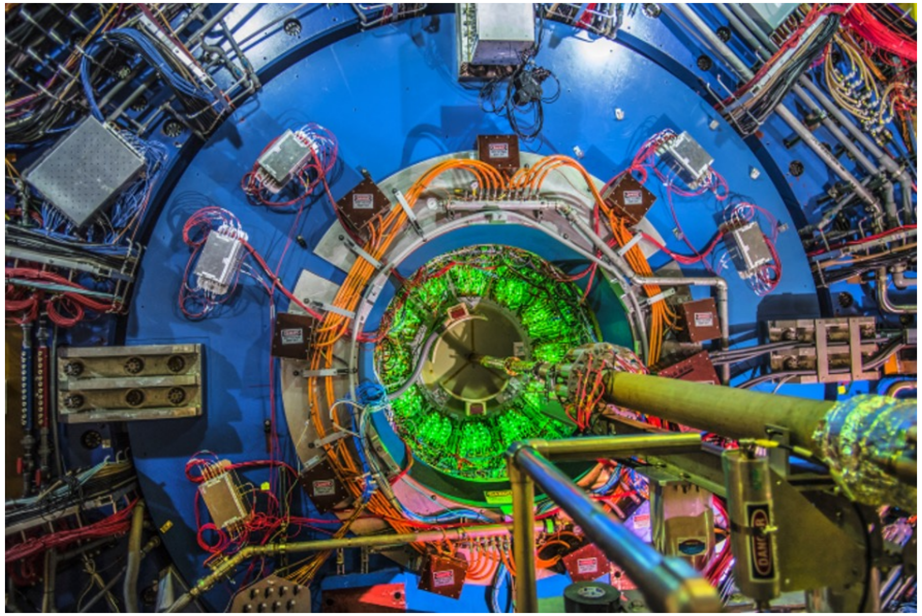
- Critical End Point and Beam Energy Scan
- **STAR Experiment**
- Selected Results
- Summary and Outlook

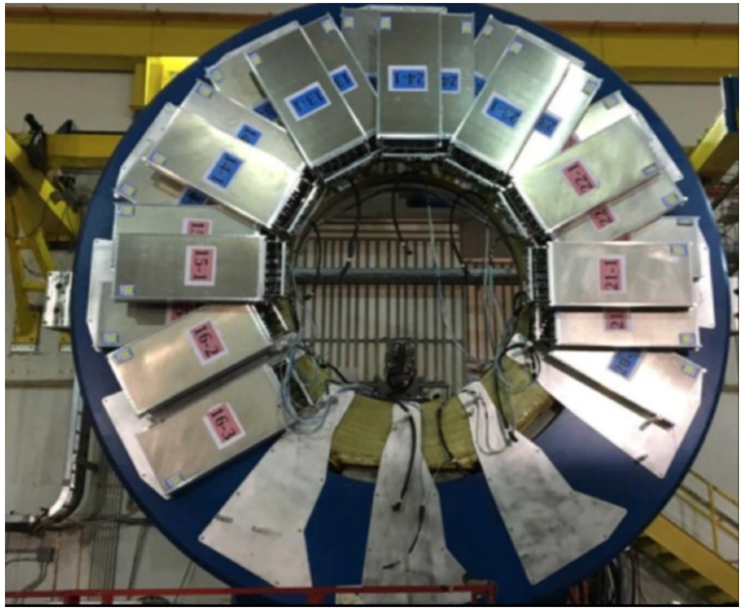
STAR Detector System



- ✓ **Large, uniform acceptance**
- ✓ **Excellent particle identification**
- ✓ **Modest rates**

Major Upgrades for BES-II





iTPC
1. Improves dE/dx
2. Extends η coverage from 1.0 to 1.6
3. Lowers p_T cut-in from 125 to 60 MeV/c

✓ Ready in 2019

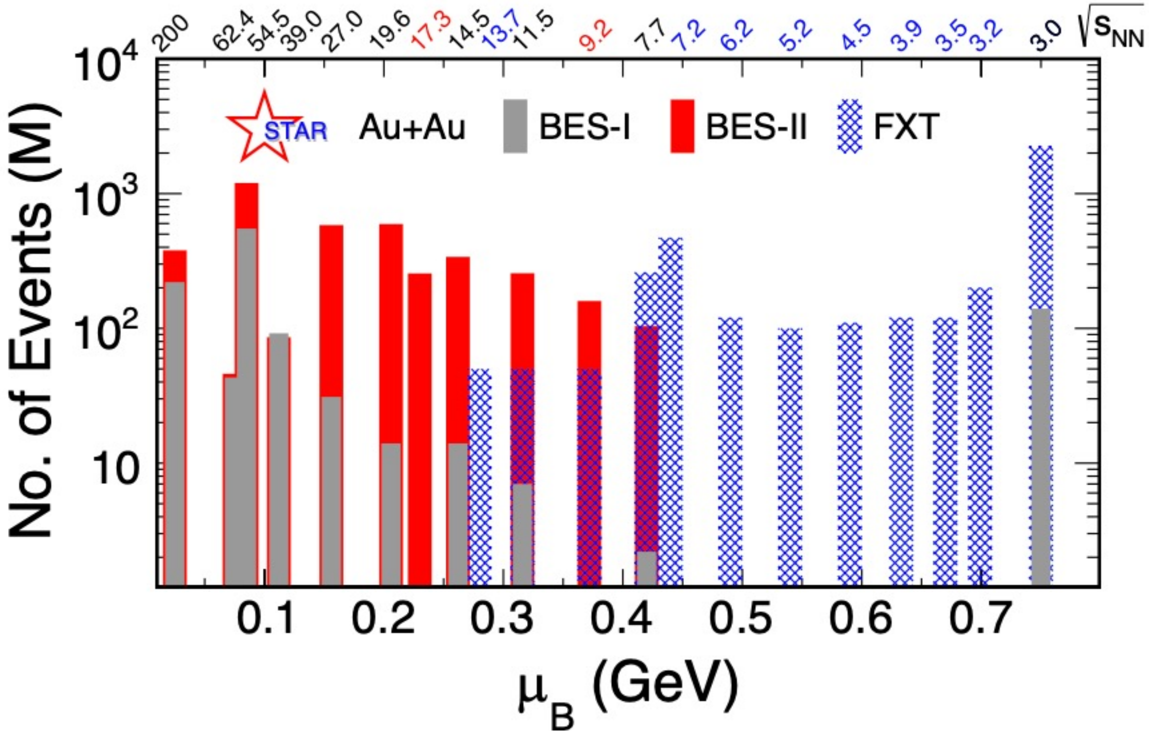
eTOF
1. Forward rapidity coverage
2. PID at η = -1.05 to -1.5
3. Borrowed from FAIR-CBM

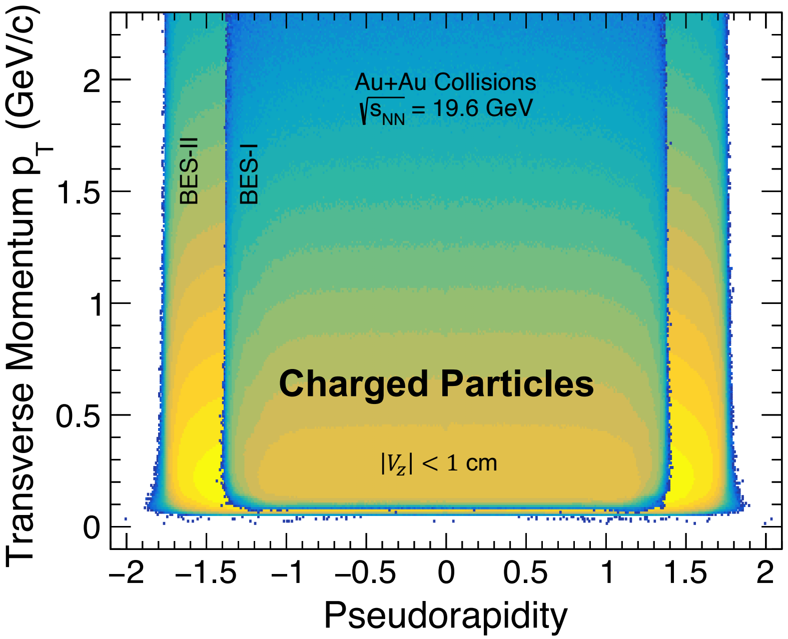
✓ Ready in 2019

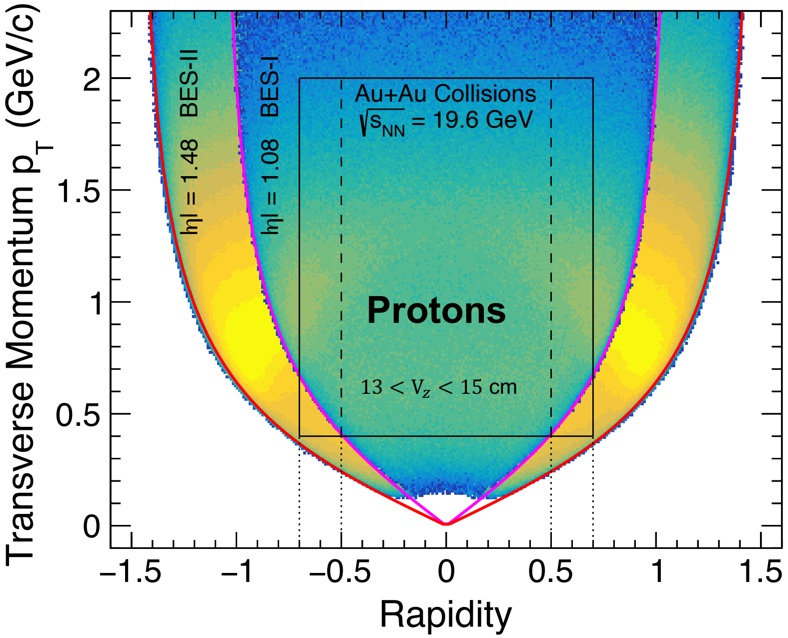
EPD
1. Improves trigger
2. Better centrality and event plane measurements

✓ Ready in 2018

Improvements



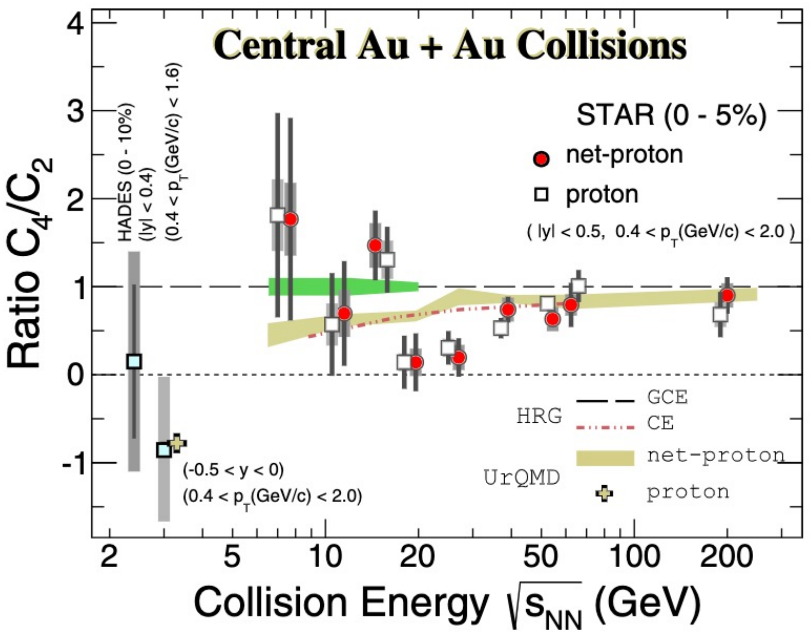




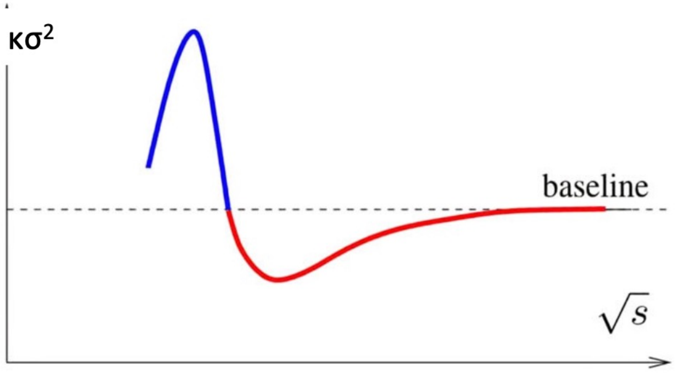
- ✓ Greater statistics
- ✓ Better tracking
- ✓ Larger acceptance
- ✓ Better control on systematics

Outline

- Critical End Point and Beam Energy Scan
- STAR Experiment
- **Selected Results**
- Summary and Outlook



STAR: Phys.Rev.Lett. 128 (2022) 20, 202303



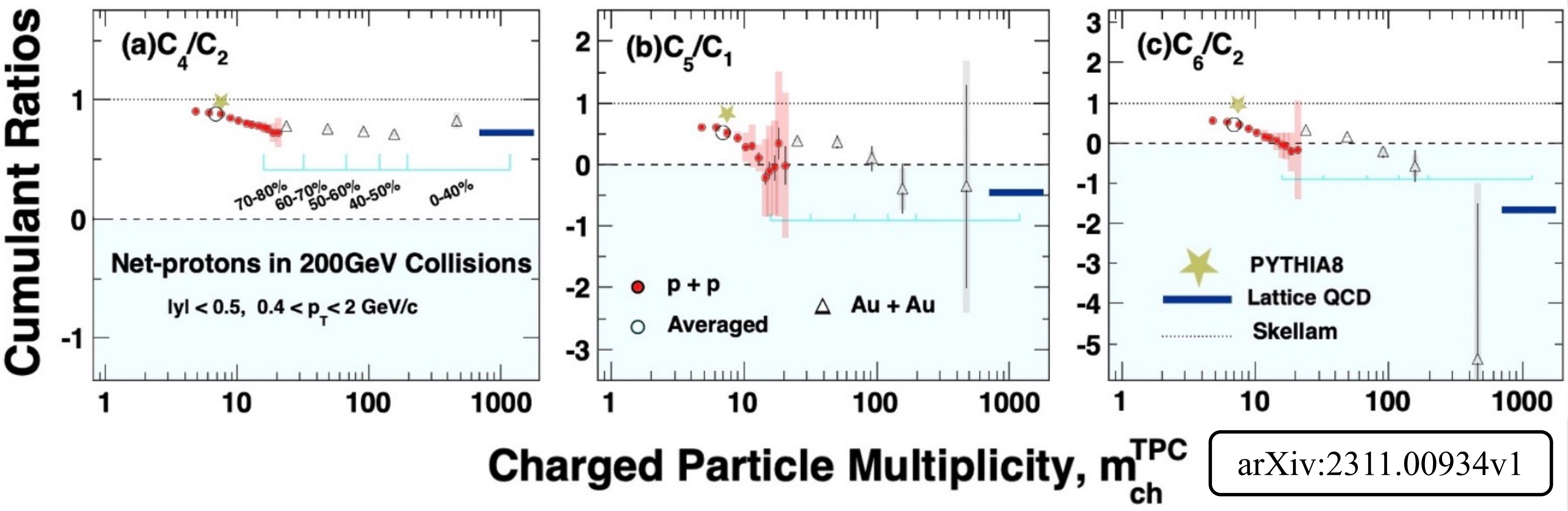
M. Stephanov: Phys.Rev.Lett. 107 (2011) 052301

$$C_1 = \langle N \rangle \equiv \mu \text{ [mean]}$$
$$C_2 = \langle (N-\mu)^2 \rangle \equiv \sigma^2 \text{ [variance]}$$
$$C_3 = \langle (N-\mu)^3 \rangle$$
$$C_4 = \langle (N-\mu)^4 \rangle - 3\langle (N-\mu)^2 \rangle^2$$

$$S\sigma = C_3/C_2$$
$$\kappa\sigma^2 = C_4/C_2$$

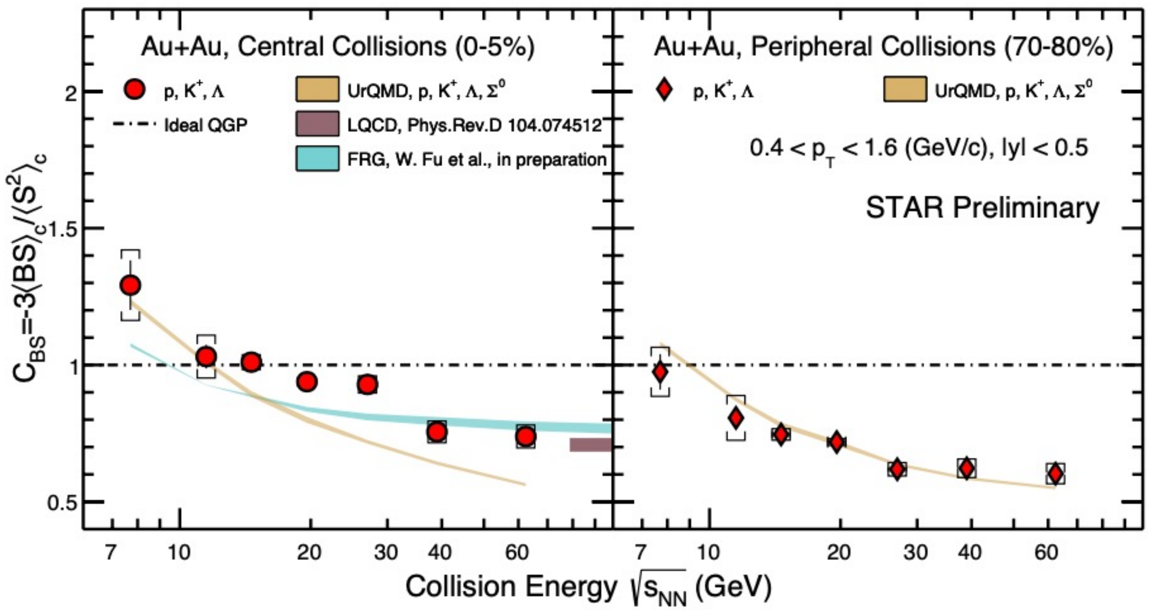
1. Cumulants of conserved charge distributions relate to correlation length of the system: $C_2 \sim \xi^2, C_4 \sim \xi^7$
2. Also related to susceptibilities: $\frac{C_{4,q}}{C_{2,q}} = \frac{\chi_{4,q}}{\chi_{2,q}}, q = B, S, Q$
3. Non-monotonic energy dependence of C_4/C_2 is predicted near critical region;
4. BES-I and 3 GeV FXT results indicate hint of non-monotonic trend but need confirmation with more precise measurement

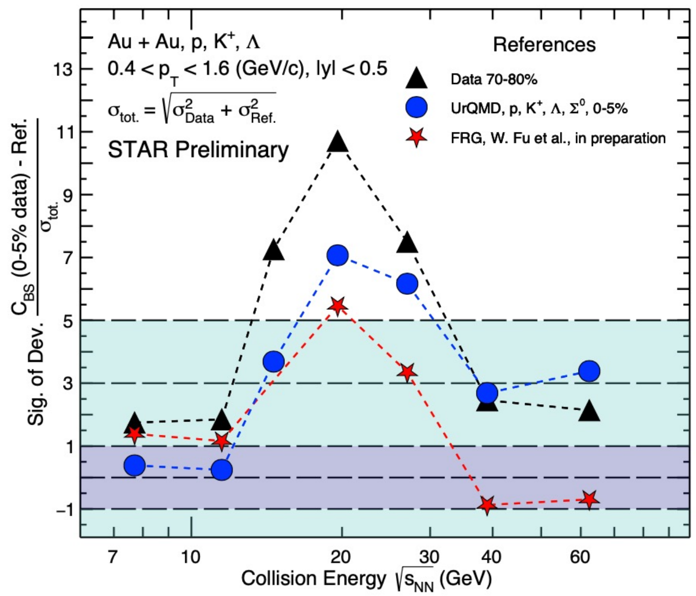
Selected Results: Net-proton Cumulants in p+p collisions at 200 GeV



1. Measurement of net-proton cumulant ratios up to 6th order from p+p collision at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$ is below Skellam expectation;
2. Smoothly connects to the results from Au+Au collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$;
3. Observed trend and sign in C_5/C_1 and C_6/C_2 measurements within large uncertainty may indicate the creation of QGP in high multiplicity events of p+p collisions

Selected Results: Baryon Strangeness Correlation





STAR Preliminary at CPOD

$$C_{BS} = -3\frac{\langle BS\rangle_c}{\langle S^2\rangle_c} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2}$$

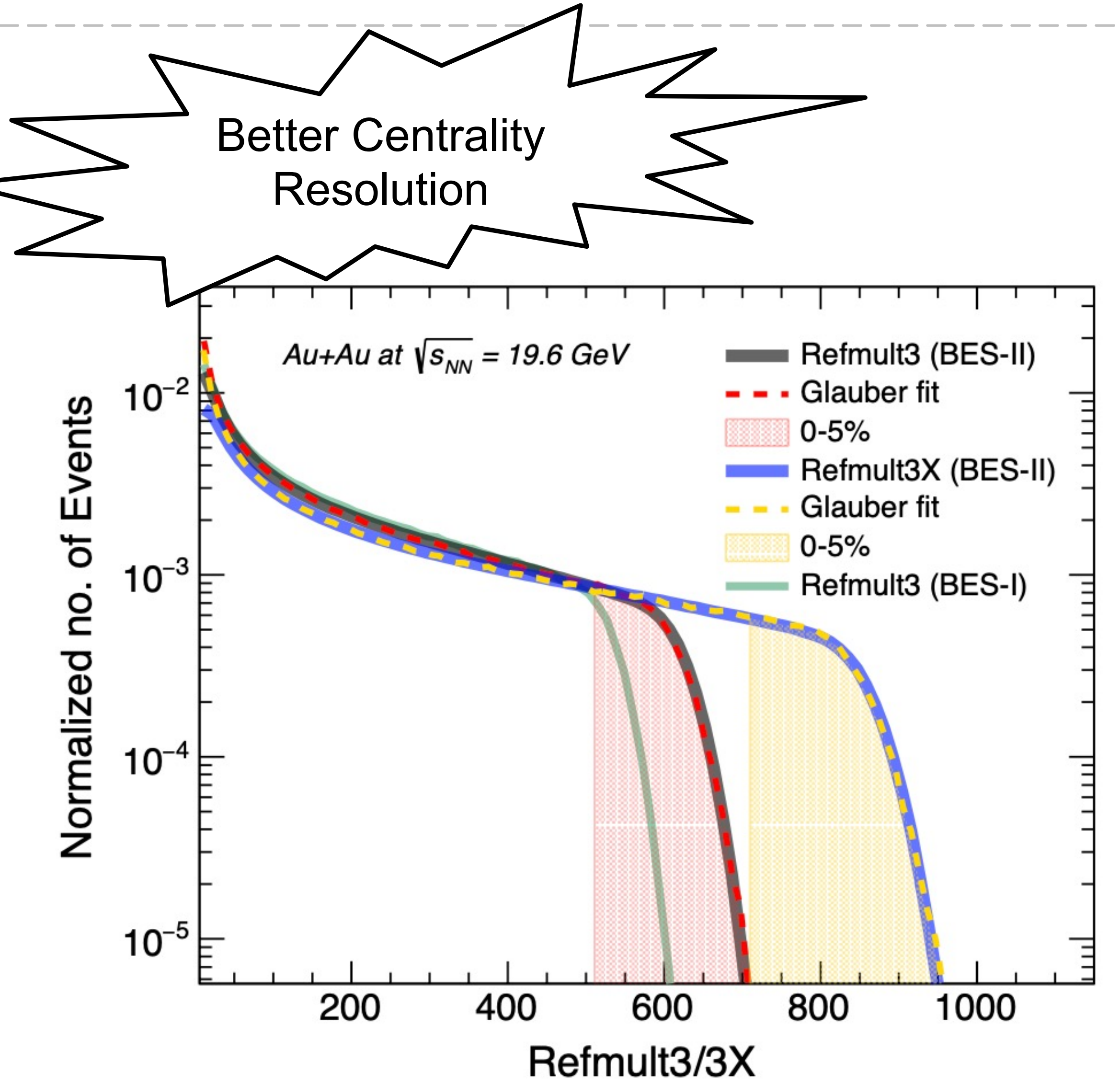
V. Koch, et. al.: Phys.Rev.Lett. 95 (2005) 182301

1. The C_{BS} is proposed as a diagnostic of strongly interacting matter, which behaves distinctly under different degree of freedom;
2. Peripheral collisions can be well described by UrQMD;
3. For central collisions:
   1) At high energy is consistent with FRG and LQCD, and at low energy is reproduced by UrQMD;
   2) Largest deviation at 19.6 GeV is found which is more than 5σ

Outline

- Critical End Point and Beam Energy Scan
- STAR Experiment
- **Selected Results**
  - Precision measurements of cumulants from BES-II
- Summary and Outlook

Centrality Definition

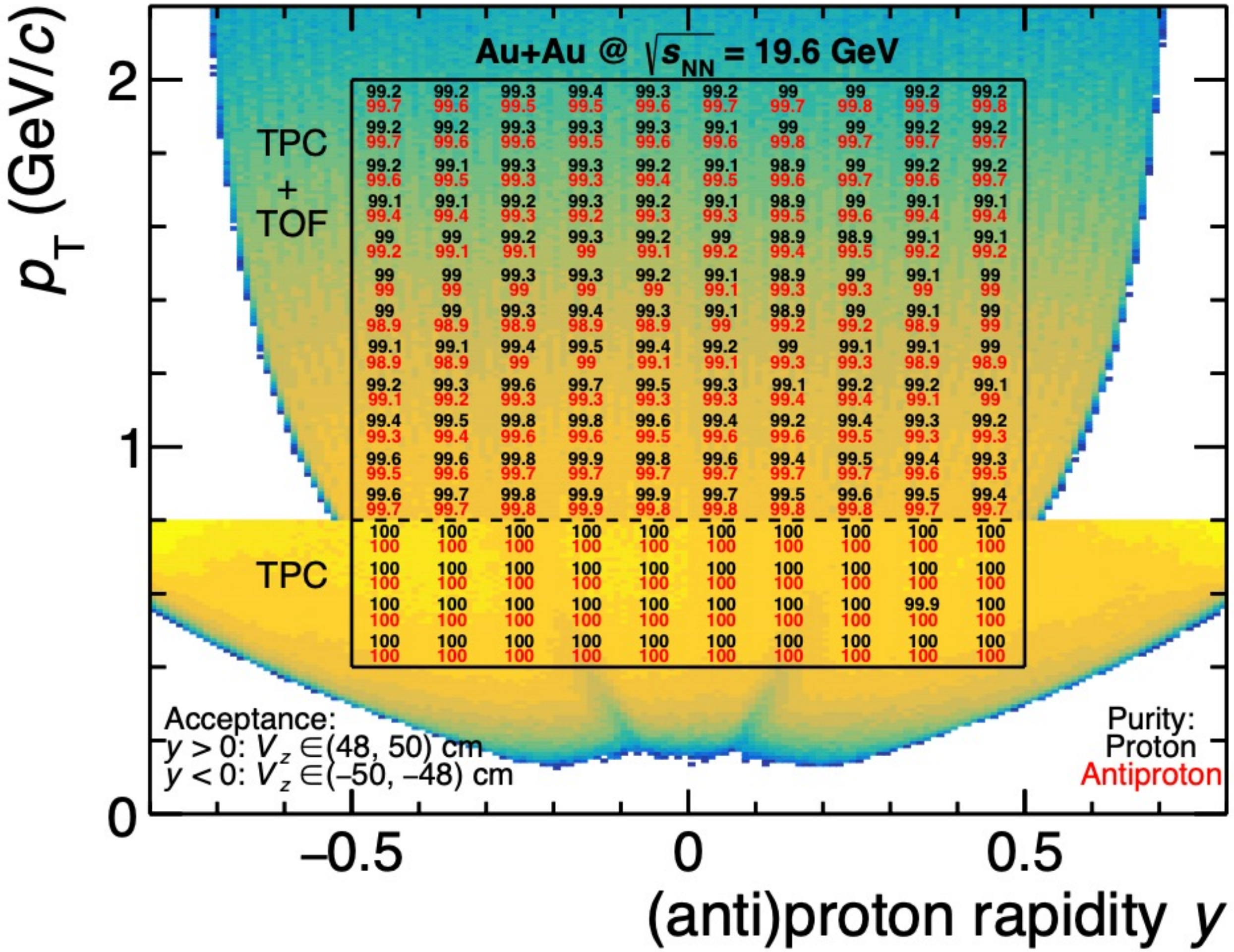


1. Multiplicity of charged particles detected by STAR detector is used for centrality definition;
2. Protons and antiprotons are excluded to avoid self-correlation;

3. Larger acceptance and greater multiplicity lead to better centrality resolution:
   - RefMult3X > RefMult3 > RefMult3 (BES-I)
     w/ iTPC w/ iTPC w/o iTPC

RefMult3	**RefMult3X**
Measured charged particle multiplicity excluding protons and antiprotons within $\|\eta\| < 1.0$	Measured charged particle multiplicity excluding protons and antiprotons within $\|\eta\| < 1.6$

Proton Acceptance, PID and Purity



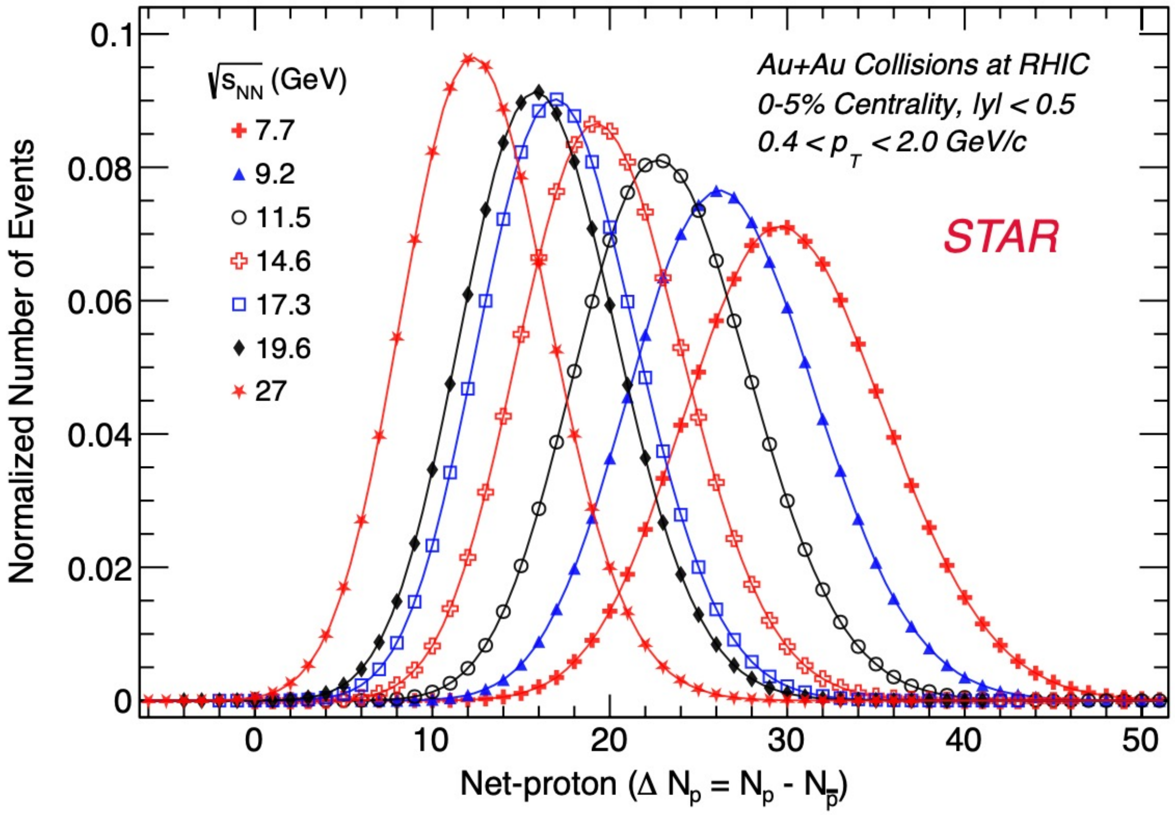
- Identified protons in selected kinetic region are used for analysis:
  $0.4 < p_T < 2.0$ GeV/c and $|y| < 0.5$

- $0.4 < p_T < 0.8$ GeV/c (PID using **TPC**)
  $|n\sigma| < 2$ from dE/dx measurement

- $0.8 < p_T < 2.0$ GeV/c (PID using **TPC+TOF**)
  in addition to TPC, mass square from TOF is used: $0.6 < m^2 < 1.2\ \mathrm{GeV}^2/c^4$

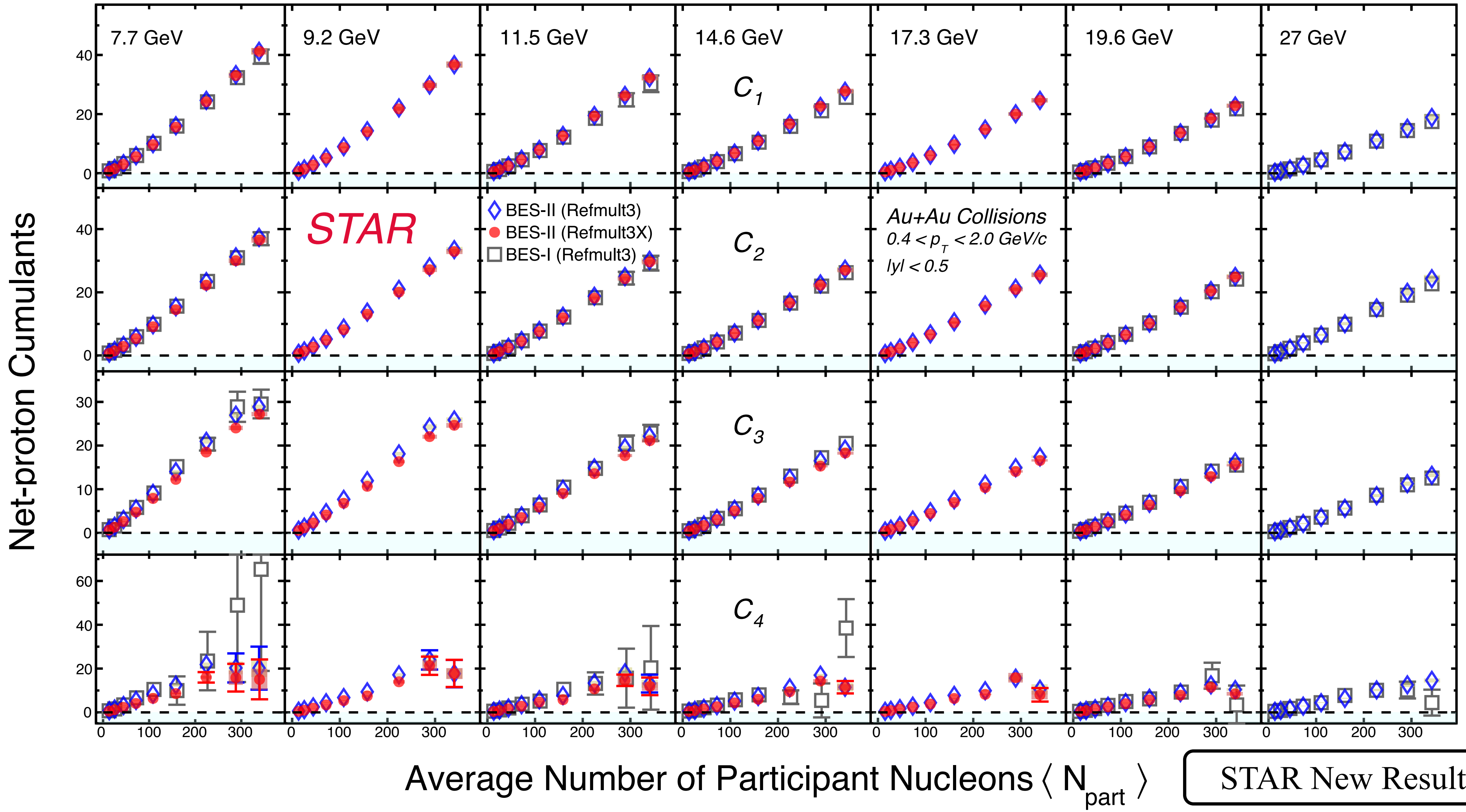
✓ Bin-by-bin proton/antiproton purity > **99%**

Net-proton Number Distribution



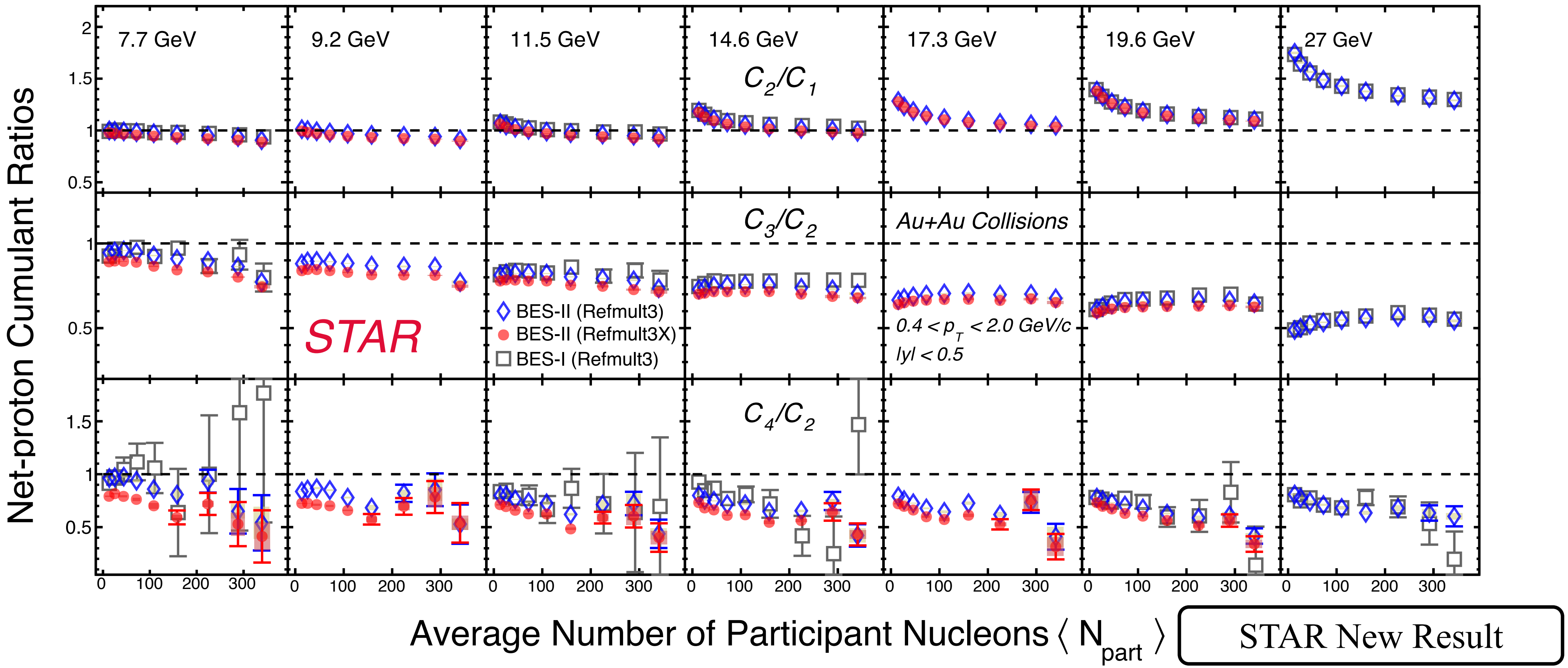
1. Efficiency uncorrected net-proton number distribution from BES-II;
2. Mean increases with decreasing collision energy: effect of baryon stopping;
3. Larger width makes larger statistic uncertainty:
   - Stat. error $C_r \propto \frac{\sigma^r}{\sqrt{N}}$

Centrality Dependence: Net-proton Cumulants



STAR New Result

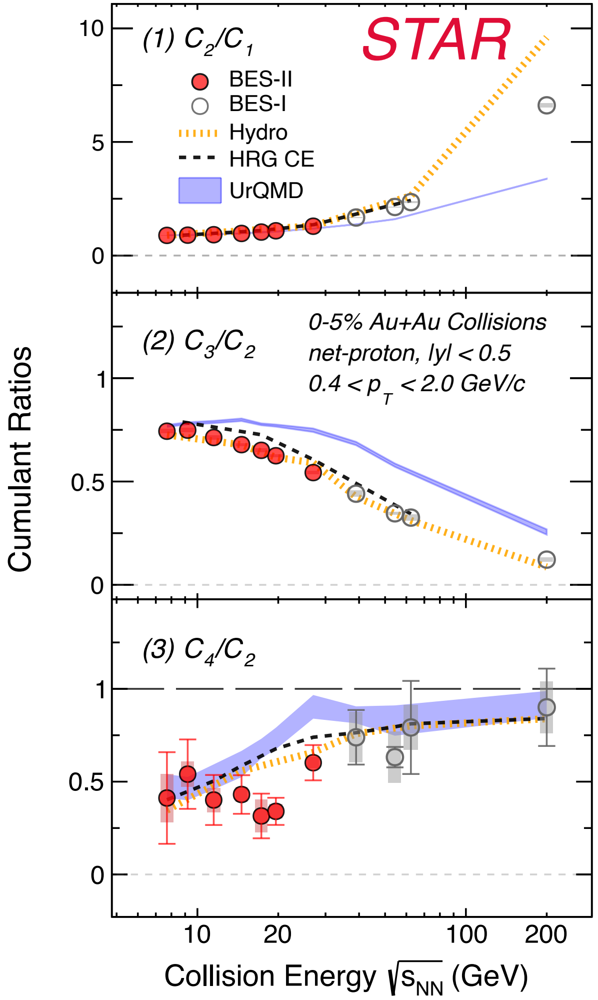
Centrality Dependence: Net-proton Cumulant Ratios



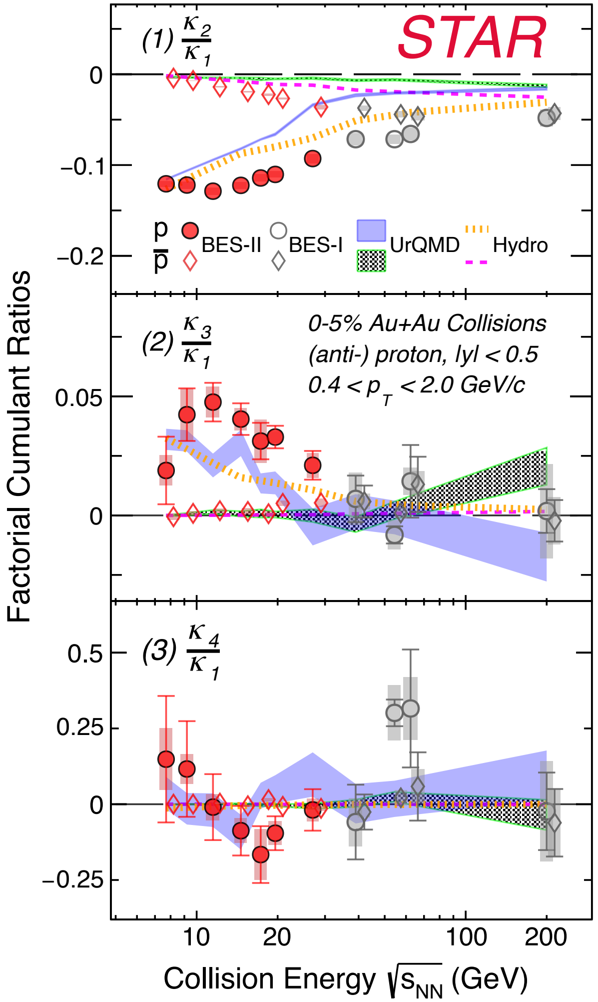
1. Smooth variation across centrality and collision energy is seen from BES-II measurement;
2. Better centrality resolution leads to lower cumulant ratios (especially for mid-central collisions):
   Calculations from RefMult3X < RefMult3 < RefMult3 (BES-I)
3. For 0-5% most central collisions, weak effect of centrality resolution of C_4/C_2 is observed

Energy Dependence and Model Comparison

Net-proton Cumulant Ratios



(anti-)Proton Factorial Cumulant Ratios



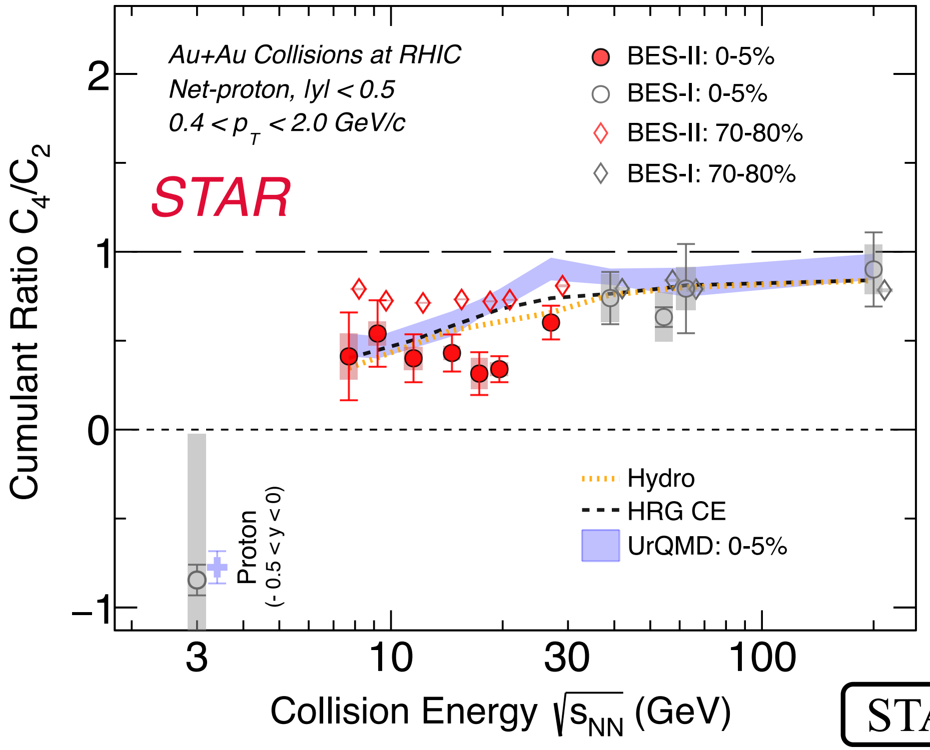
STAR New Result

1. C_2/C_1 and C_3/C_2 change smoothly as a function of collision energy;
2. C_4/C_2 decreases with decreasing $\sqrt{s_{NN}}$;
3. Proton factorial cumulant ratios deviate from Poisson baseline at 0;
4. Antiproton's κ_3/κ_1 and κ_4/κ_1 are close to 0;
5. Non-CP models are used for comparison:
   1) Their trends follow STAR data qualitatively;
   2) Quantitative differences exist between them and STAR measurements

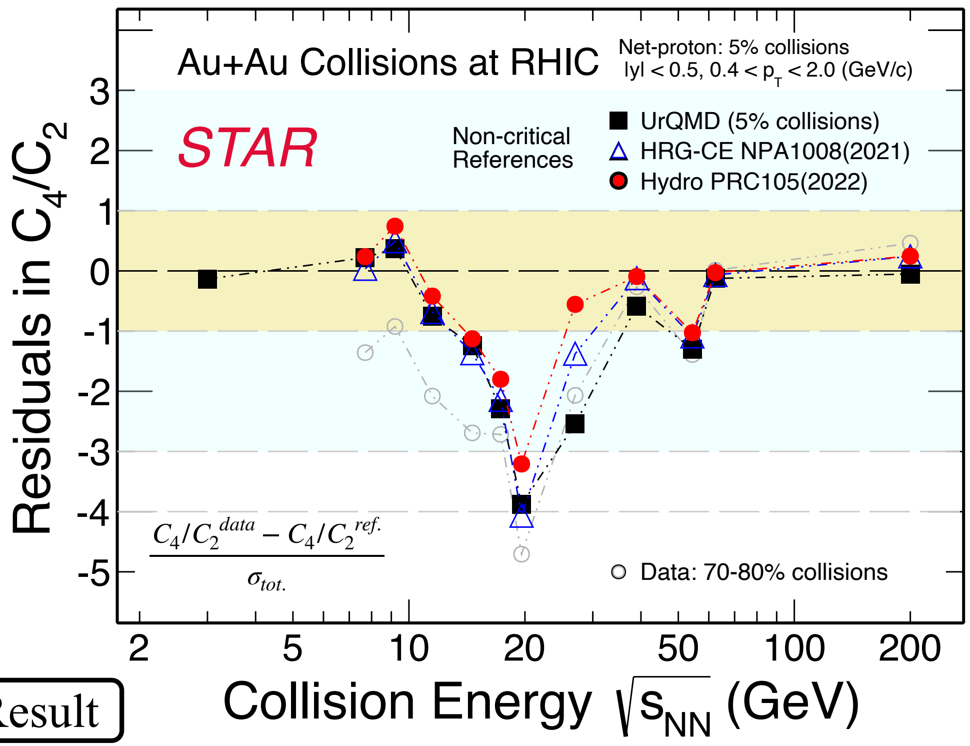
- Hydro: hydrodynamical model
  V. Vovchenko et. al.: Phys. Rev. C 105 (2022) 1, 014904
- HRG CE: thermal model with canonical treatment of baryon charge
  P. Braun-Munzinger et. al.: Nucl.Phys.A 1008 (2021) 122141
- UrQMD: hadronic transport model
  M. Bleicher et. al.: J.Phys.G 25 (1999) 1859-1896

✓Baryon number conservation is included in all models

Energy Dependence of C4/C2



STAR New Result



- Most central C_4/C_2 shows minimum around 20 GeV comparing to non-CP models and 70-80% collisions
  1) Maximum deviation: $3.2 - 4.7\sigma$ at 20 GeV ($1.3 - 2\sigma$ at BES-I)
  2) Overall deviation from $\sqrt{s_{NN}} = 7.7$ to 27 GeV: $1.9 - 5.4\sigma$ ($1.4 - 2.2\sigma$ at BES-I)

Outline

- Critical End Point and Beam Energy Scan
- STAR Experiment
- Selected Results
- **Summary and Outlook**

Summary and Outlook

Summary

1. From p+p collisions at 200 GeV data set, observed net-proton cumulant ratios $C_5/C_1$and C_6/C_2 approach negative values in the highest-multiplicity events may indicate the formation of thermalized QCD matter
2. Baryon strangeness correlation are measured, deviation from references reaches maximum at about 20 GeV;
3. Precision measurements of net-proton number cumulants up to 4th order are presented, $3.2-4.7\sigma$ deviation relative to models without CP are found in most central Au+Au collisions at 20 GeV

Outlook

1. Higher order measurements and acceptance extension of net-proton cumulants from collider energies;

2. Analysis using FXT data sets

Thank You!