STAR Regional Workshop
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Precision Measurement of Net-proton Number Fluctuations in Au+Au Collisions at RHIC

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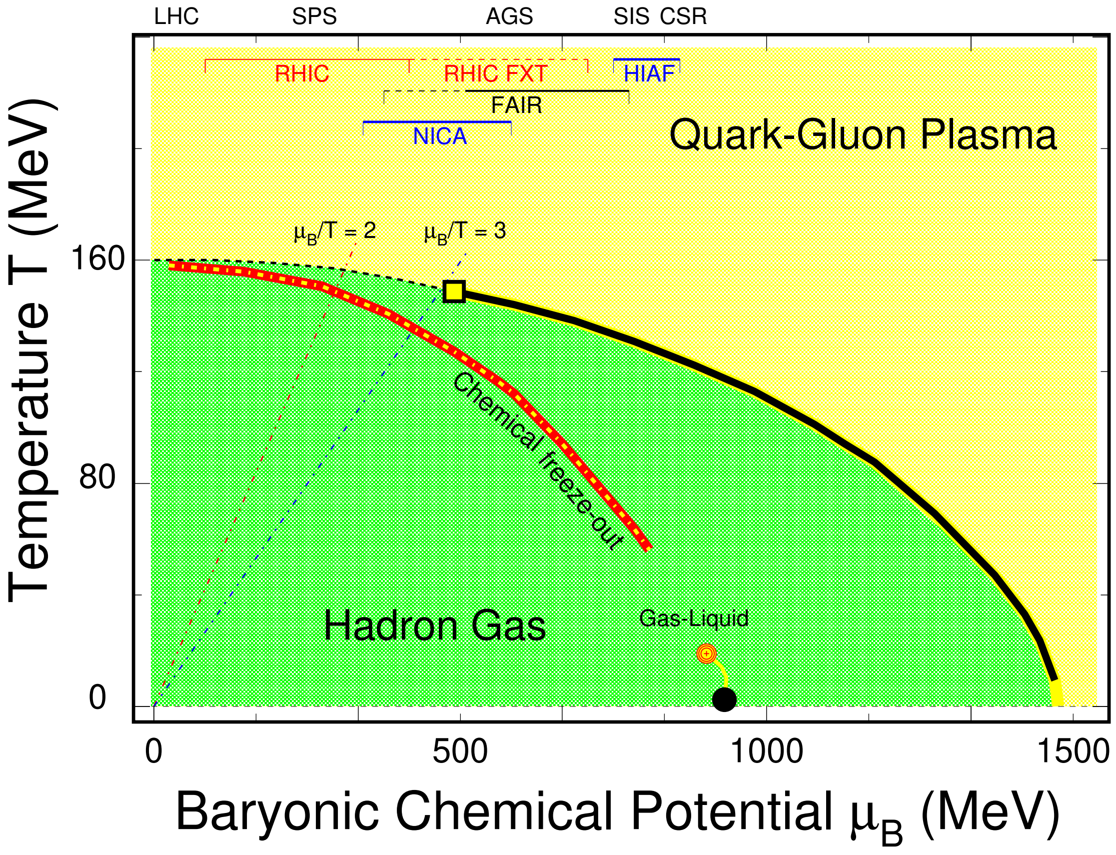
Outline

1. Introduction
2. BES Program
3. Analysis Details
4. Latest Results
5. Summary and Outlook

Introduction: QCD Phase Diagram

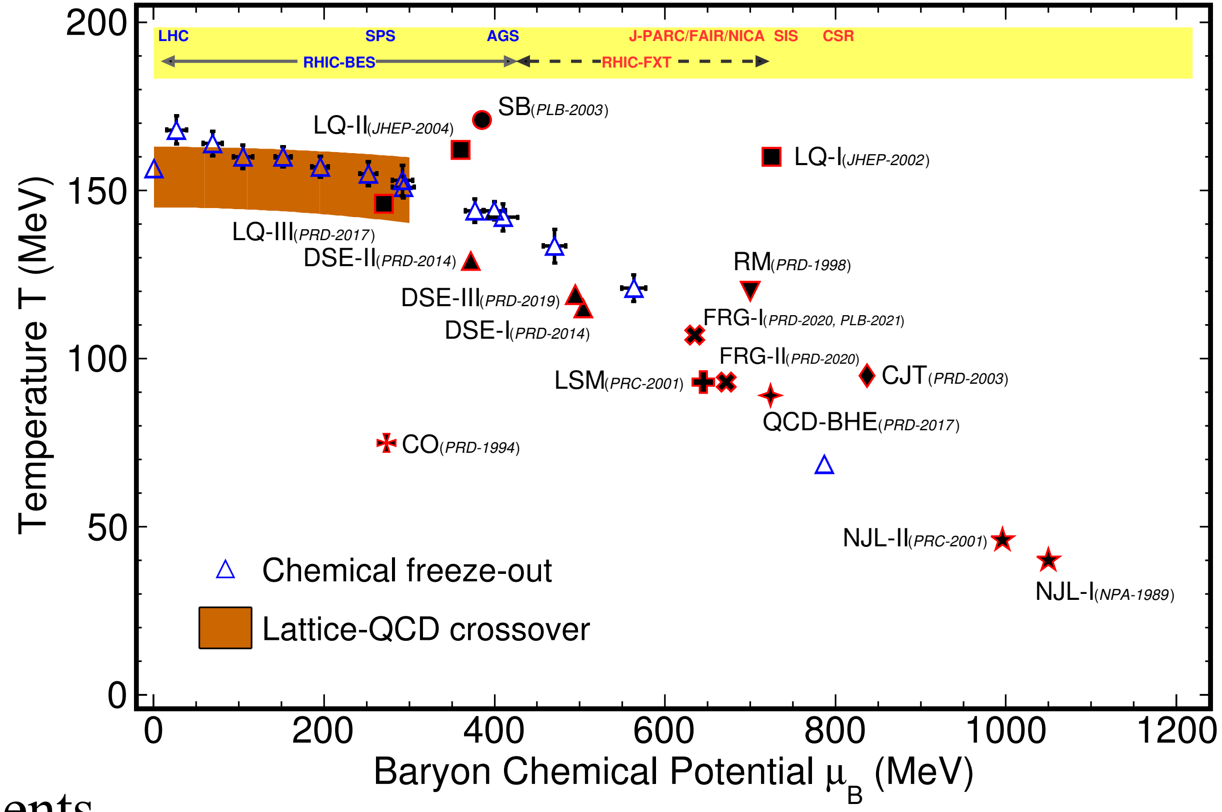
- Hadronic phase
- Quark-Gluon Plasma (QGP) phase
- QCD phase transition
  - Crossover at small μ_B ($\mu_B/T < 2$)
    - Expected by Lattice QCD
    - $T_c = 156.5 \pm 1.5$ MeV at $\mu_B = 0$
    - Compatible to experimental observations
  - First-order phase transition at higher μ_B
    - Predicted by QCD-based models
  - Critical point (CP)
    - Conjectured to terminate first-order phase boundary



B. Mohanty, N. Xu, arXiv:2101.09210
Y. Aoki *et al.*, Nature 443, 675-678 (2006)
HotQCD, PLB 795, 15-21 (2019)

Introduction: Theoretical Exploration of CP

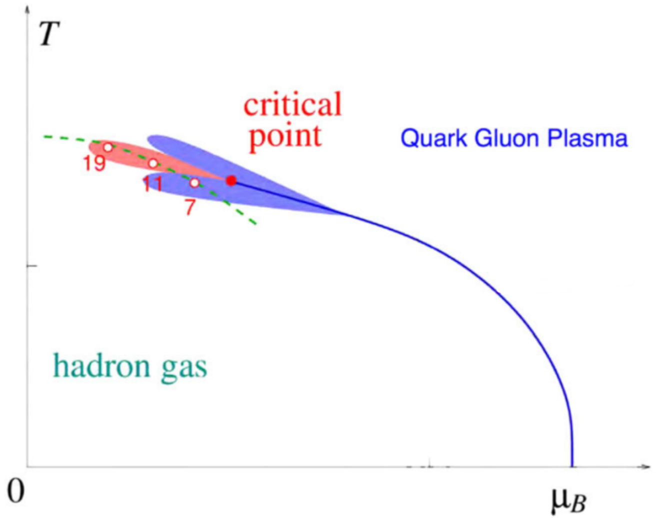
- Location of crossover
  - Prediction from Lattice QCD at small μ_B
- Location of critical point
  - Sign problem of Lattice QCD at finite μ_B
  - Various predictions from models applying estimation/approximation
  - Wide region:
    T = 40–180 MeV, μ_B = 200–1100 MeV
- Crucial to search for and locate CP in experiments



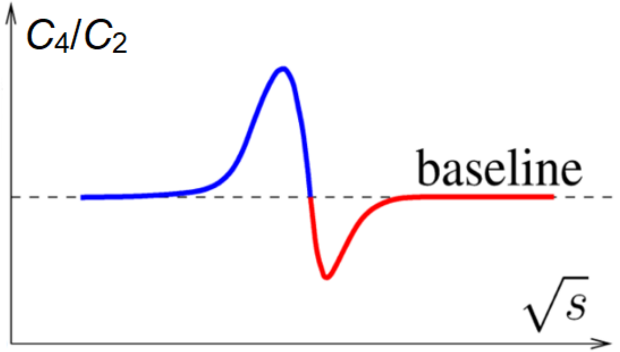
A. Pandav *et al.*, PPNP 125, 103960 (2022)

Introduction: Observables and Expected Signal

- Correlation length ξ and rth susceptibility $\chi_{r,q}$ ($q = B, Q, S$)
  - Expected to diverge at CP
  - Reduced by effect of finite size/time
  - Significantly influence higher-order fluctuations



- Observables: $C_{r,q}$ (rth-order cumulant of event-by-event q)
  - $C_2 \sim \xi^2$, $C_3 \sim \xi^{4.5}$, $C_4 \sim \xi^7$, $C_5 \sim \xi^{9.5}$, $C_6 \sim \xi^{12}$
  - $C_{r,q} = VT^3\chi_{r,q}$
  - $C_{r,q}/C_{s,q} = \chi_{r,q}/\chi_{s,q}$
  - Direct comparison with lattice QCD, HRG, QCD-based model calculations

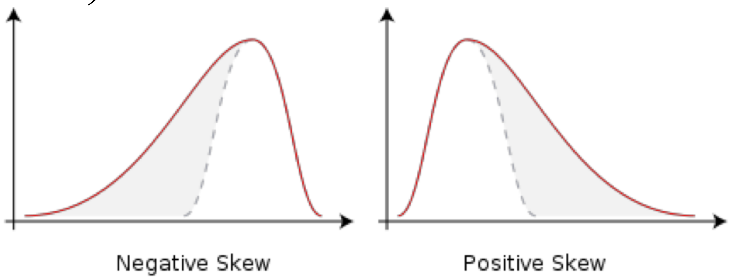


- Expected signal of critical region: non-monotonic energy dependence of C_4/C_2 around baseline
  - Assumption: thermodynamic equilibrium

M. A. Stephanov, PRL 102, 032301 (2009)
M. A. Stephanov, PRL 107, 052301 (2011)

Introduction: (Factorial) Cumulants

- N: event-by-event net-proton number (proxy for net-baryon number B)
- $\mu_r = \langle (N - \langle N \rangle)^r \rangle$: rth-order central moment
- Cumulants
  - $C_1 = \mu \quad = \langle N \rangle$
  - $C_2 = \sigma^2 \quad = \mu_2$
  - $C_3 = S\sigma^3 = \mu_3$
  - $C_4 = \kappa\sigma^4 = \mu_4 - 3\mu_2^2$
  - $C_5 \quad = \mu_5 - 10\mu_3\mu_2$
  - $C_6 \quad = \mu_6 - 15\mu_4\mu_2 - 10\mu_3^2 + 30\mu_2^3$
- Factorial cumulants
  - $\kappa_1 = C_1$
  - $\kappa_2 = C_2 - C_1$
  - $\kappa_3 = C_3 - 3C_2 + 2C_1$
  - $\kappa_4 = C_4 - 6C_3 + 11C_2 - 6C_1$
  - $\kappa_5 = C_5 - 10C_4 + 35C_3 - 50C_2 + 24C_1$
  - $\kappa_6 = C_6 - 15C_5 + 85C_4 - 225C_3 + 274C_2 - 120C_1$



skewness $S = \mu_3/\sigma^3 \rightarrow$ asymmetry

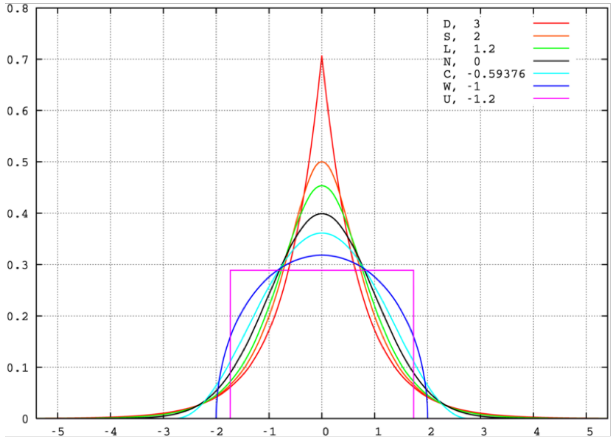
Gaussian: $C_r = 0$ $(r > 2)$

Poisson: $C_r = C_1$, $\kappa_r = 0$ $(r > 1)$

Skellam (Poisson – Poisson):

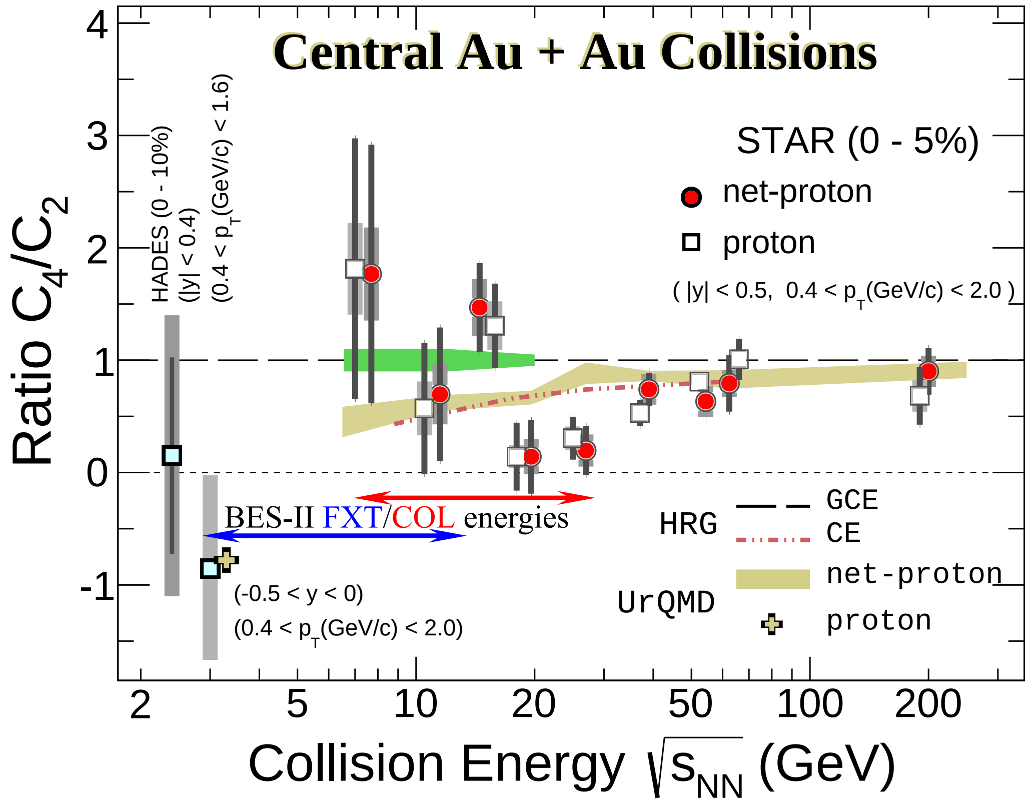
$$C_{\text{odd}}/C_{\text{odd}} = C_{\text{even}}/C_{\text{even}} = 1$$

kurtosis $\kappa = \mu_4/\sigma^4 - 3 \rightarrow$ peakedness



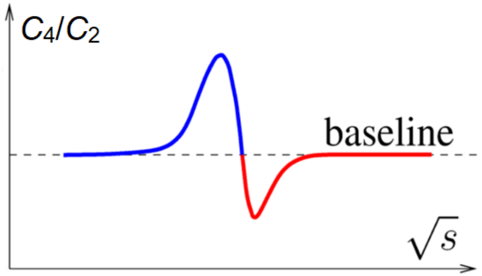
Experimental Search for CP from BES-I

$\sqrt{s_{NN}}$ (GeV)	Used Events (10^6)	μ_B (MeV)
200	238	25
62.4	47	75
54.4	550	85
39	86	112
27	30	156
19.6	15	206
14.5	20	262
11.5	6.6	316
7.7	3	420
3 (FXT)	140	750

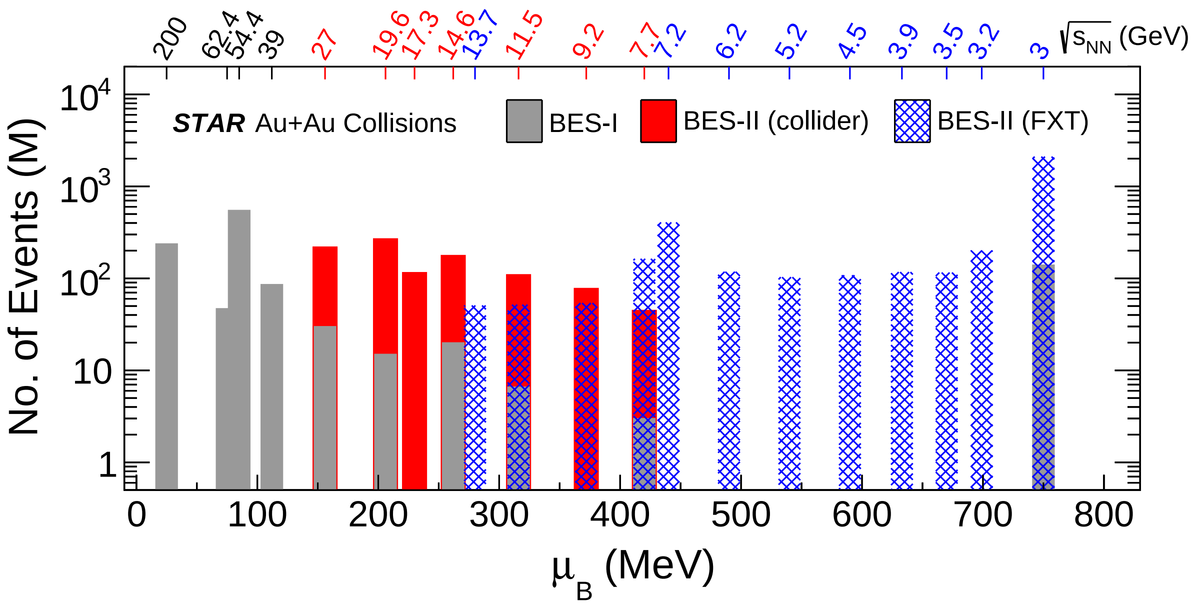


- Non-monotonic energy dependence of C_4/C_2 (3.1σ)
  - Deviation from non-CP models showing monotonic trend
- C_4/C_2 from 3 GeV shows agreement with UrQMD
- Crucial to have precision measurement in BES-II

STAR: PRL 127, 262301, PRC 104, 24902,
PRL 128, 202302, PRC 107, 24908
HADES: PRC 102, 024914 (2020)



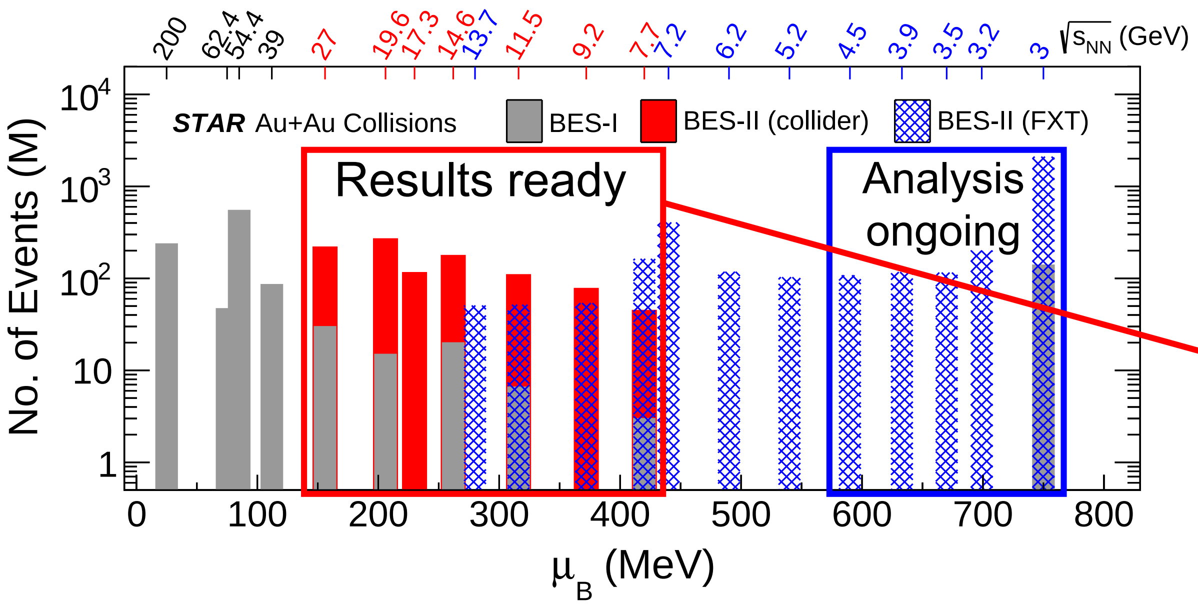
STAR BES-II Program



- Beam Energy Scan (BES) Program
  - BES-I (including 3 GeV FXT)
  - BES-II (collider mode)
  - BES-II (fixed-target mode)

- $3 \leq \sqrt{s_{NN}}$ (GeV) $\leq 200 \rightarrow 750 \geq \mu_B$ (MeV) ≥ 25: high precision, widest μ_B coverage to date

STAR BES-II Program



Events used for net-proton analyses in BES-I and BES-II (collider mode)

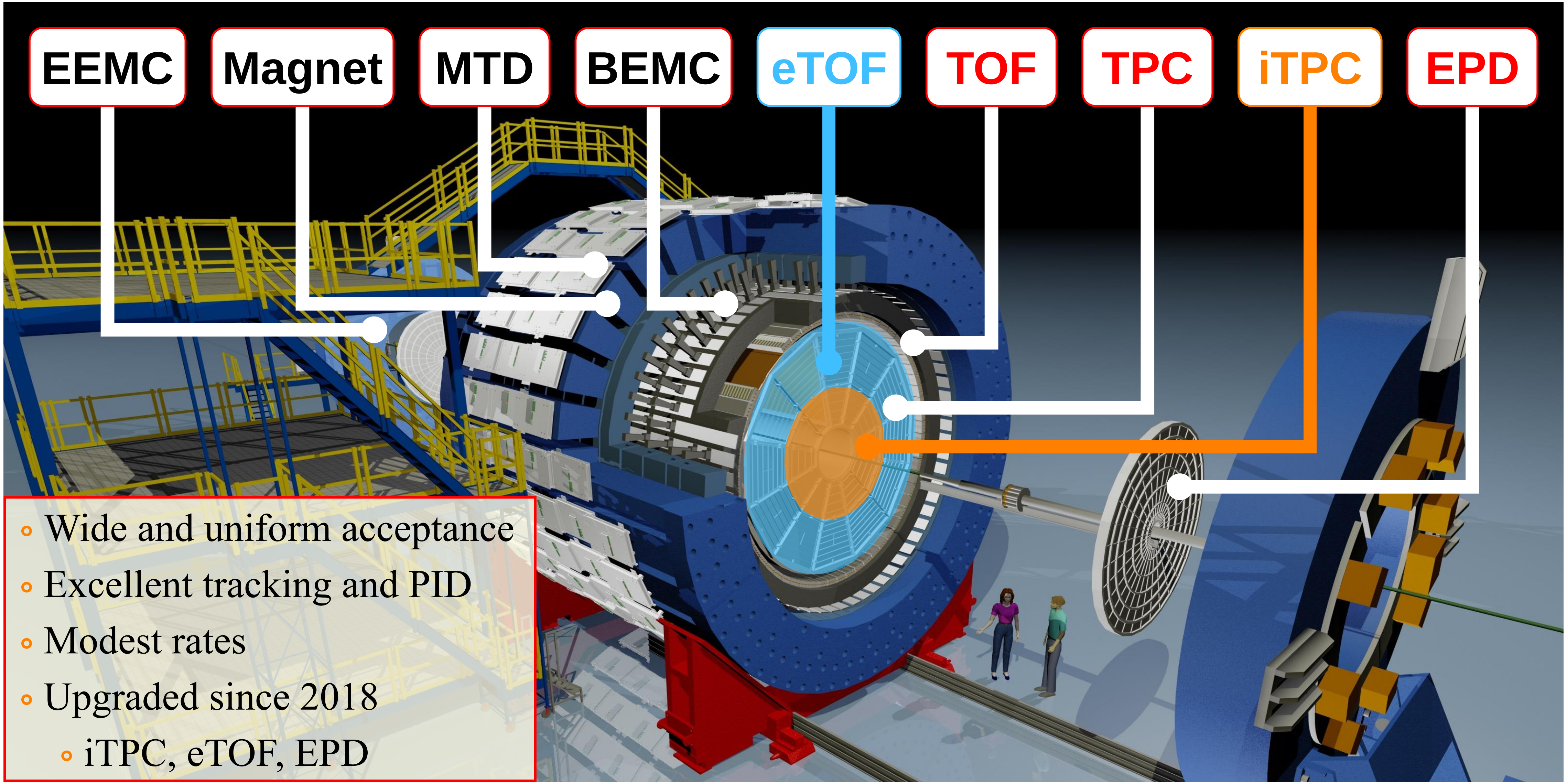
$\sqrt{s_{NN}}$ (GeV)	Used Events (10^6)	
	BES-I	BES-II
27	30	220
19.6	15	270
17.3	/	116
14.6	20	178
11.5	6.6	110
9.2	/	78
7.7	3	45

- Beam Energy Scan (BES) Program
  - BES-I (including 3 GeV FXT)
  - BES-II (collider mode)
  - BES-II (fixed-target mode)

- Larger statistics: $\times \sim 10\text{–}18$
- New energies: 9.2 and 17.3 GeV

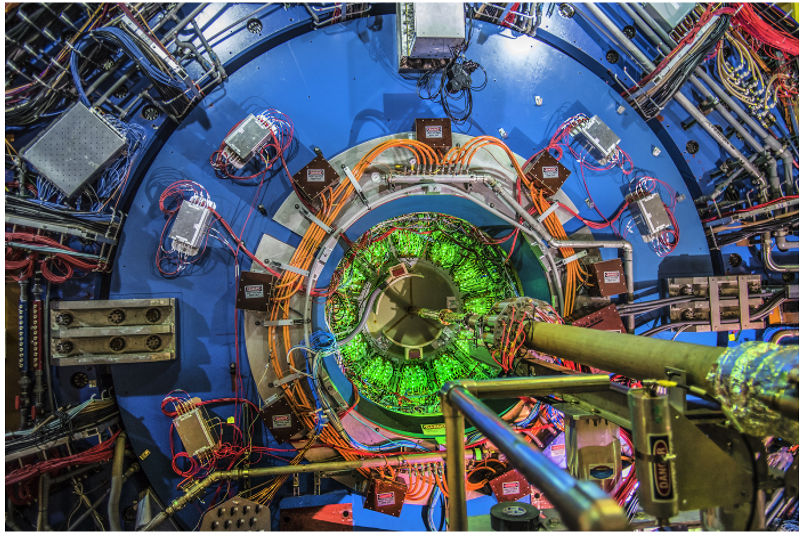
- $3 \leq \sqrt{s_{NN}}$ (GeV) $\leq 200 \rightarrow 750 \geq \mu_B$ (MeV) ≥ 25: high precision, widest μ_B coverage to date

STAR Detector System

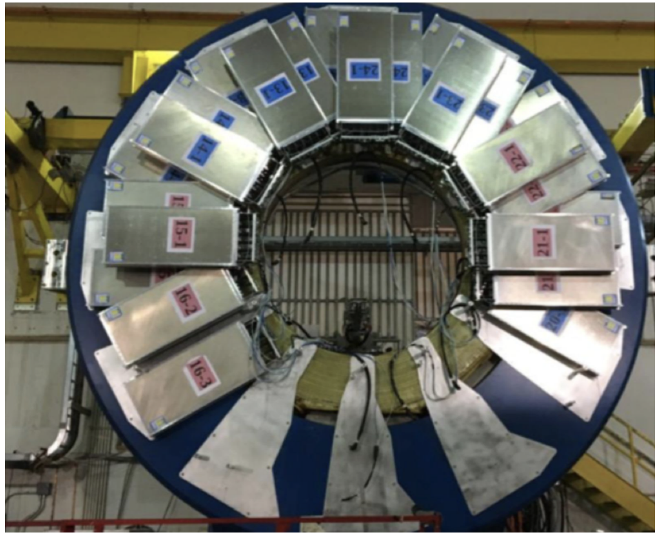


- Wide and uniform acceptance
- Excellent tracking and PID
- Modest rates
- Upgraded since 2018
  - iTPC, eTOF, EPD

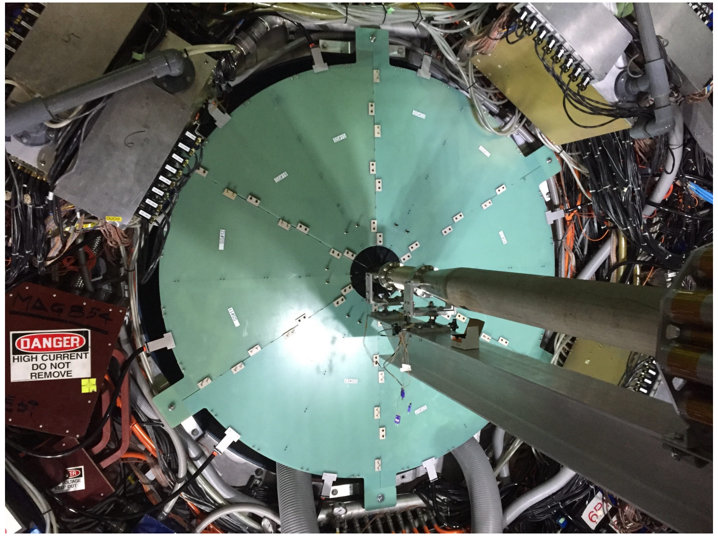
STAR Major Upgrades for BES-II



- Inner TPC (since 2019)
  - Improves dE/dx
  - Extends η coverage from 1.0 to 1.6
  - Lowers p_T cut-in from 125 to 60 MeV/c



- End-cap TOF (since 2019)
  - Forward rapidity coverage
  - PID at $1.05 < \eta < 1.50$
  - Borrowed from FAIR-CBM



- Event Plane Detector (since 2018)
  - $2.14 < |\eta| < 5.09$
  - Improves trigger
  - Better centrality & event plane

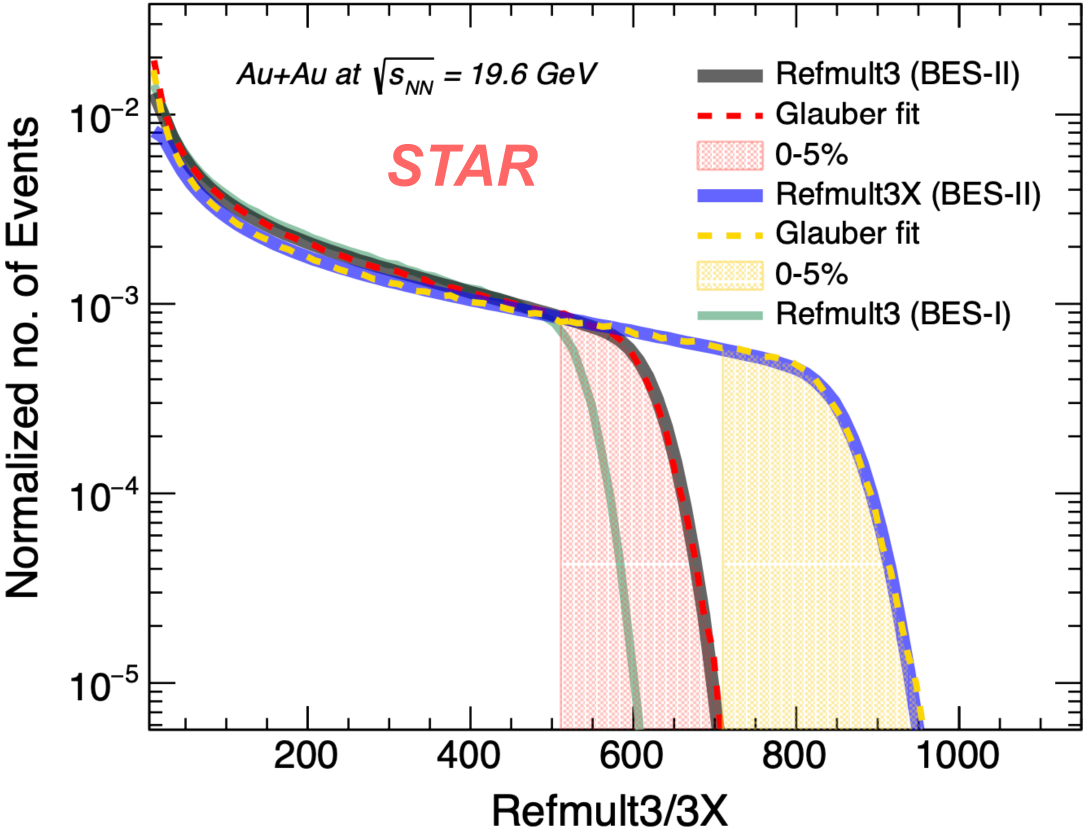
1. Enlarge rapidity acceptance: $|\eta| < 1.0 \rightarrow |\eta| < 1.6$
2. Improve particle identification: $p_T > 125$ MeV/c $\rightarrow p_T > 60$ MeV/c
3. Enhance centrality/event plane resolution, suppress auto corrections
4. Enable the fixed-target program: $\mu_B \leq 420$ MeV $\rightarrow \mu_B \leq 750$ MeV

Centrality Determination

- Measured multiplicities of charged particles used for centrality determination
- (Anti)protons excluded to avoid self-correlation

Two multiplicity definitions with different acceptances

RefMult3		RefMult3X
BES-I	BES-II	BES-II
w/o iTPC	w/ iTPC	w/ iTPC
$\|\eta\| < 1.0$	$\|\eta\| < 1.0$	$\|\eta\| < 1.6$



- Larger multiplicity → better centrality resolution
  - RefMult3X (BES-II) > RefMult3 (BES-II) > RefMult3 (BES-I)

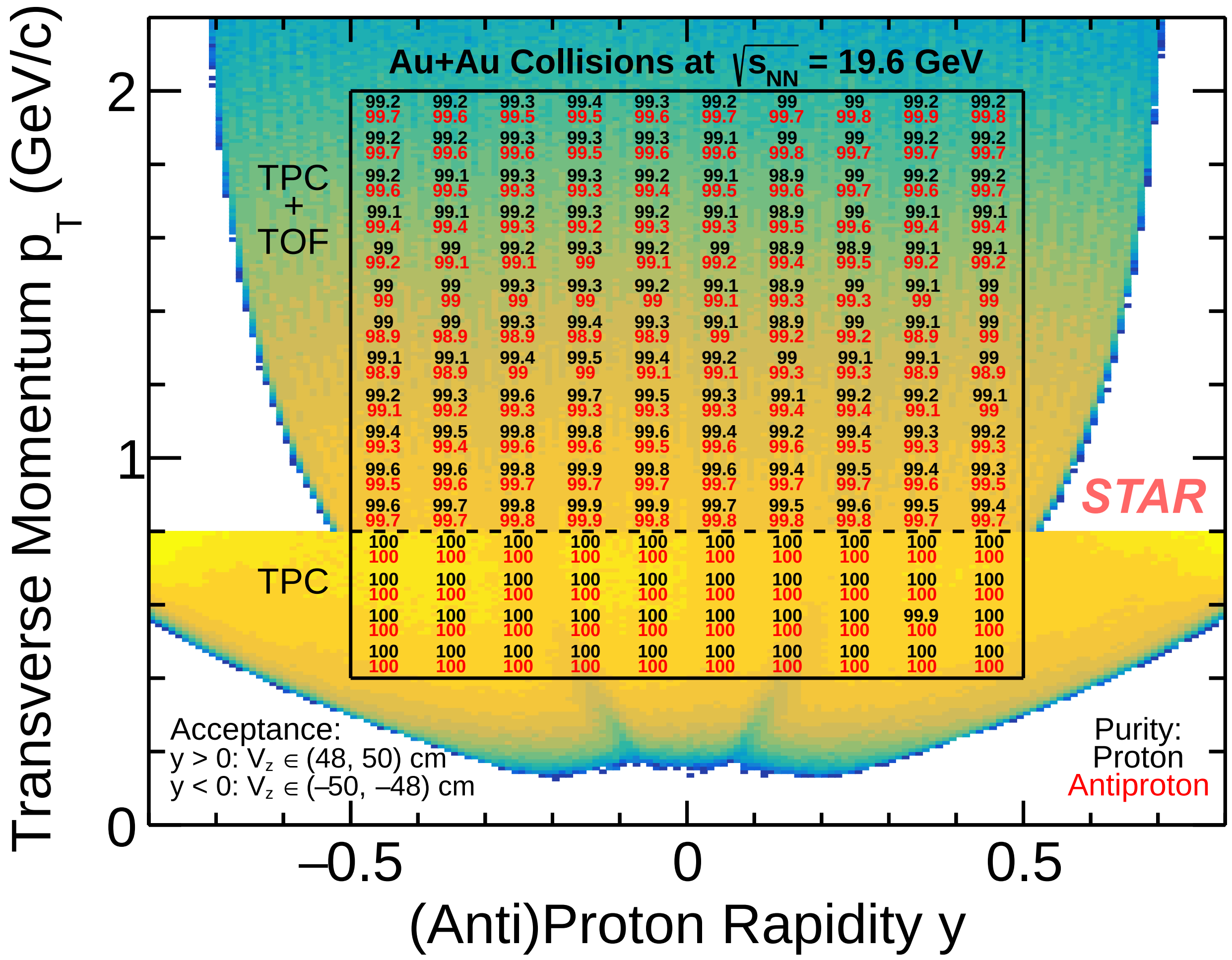
Best centrality resolution taking advantage of iTPC

Particle Identification

- (Anti)proton acceptance in this analysis: $0.4 < p_T$ (GeV/c) < 2.0, $|y| < 0.5$

PID selection criteria for protons and antiprotons

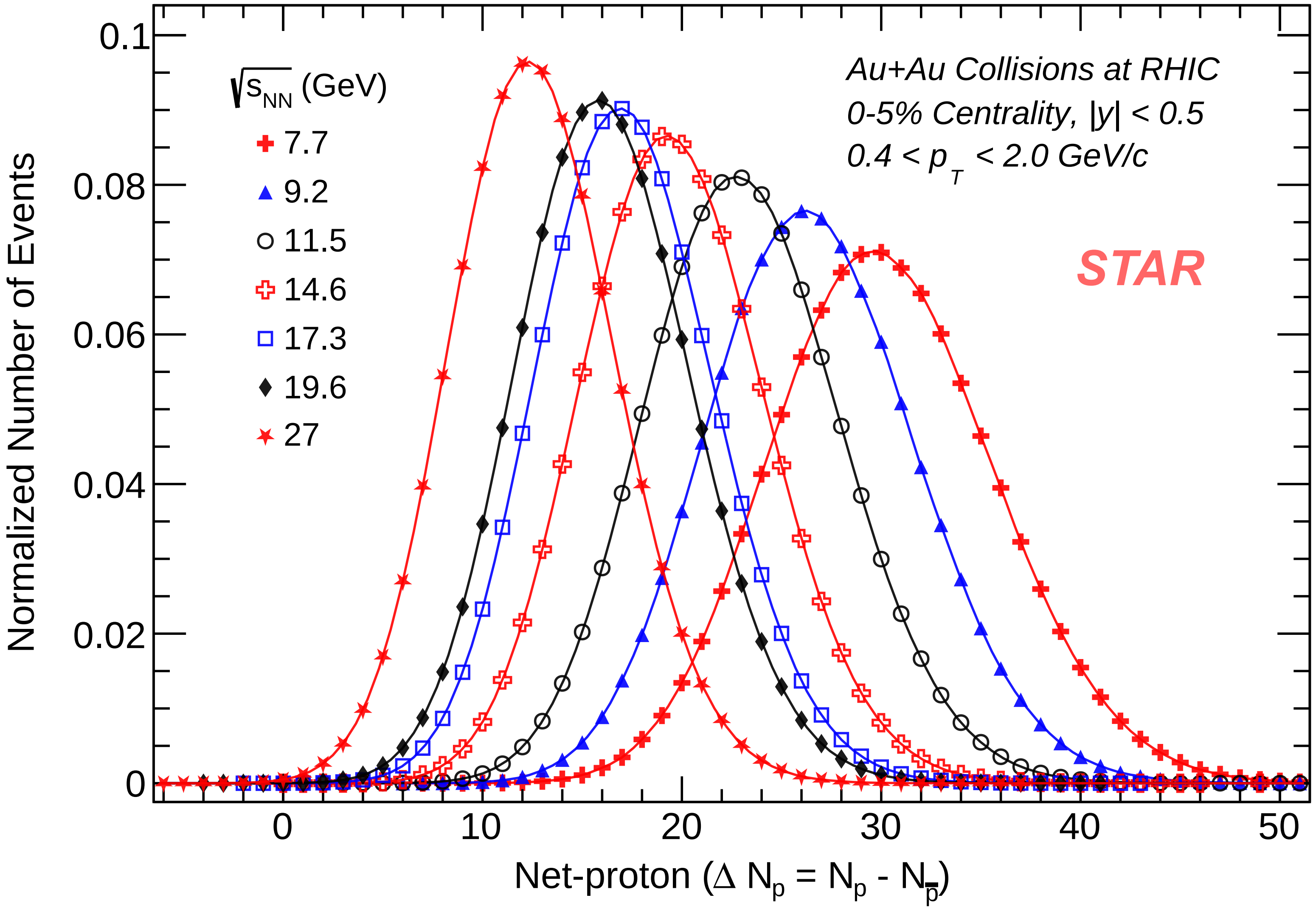
p_T (GeV/c)	0.4–0.8	0.8–2.0
Rapidity	$\|y\| < 0.5$	
Detector	TPC	TPC+TOF
TPC dE/dx	$\|n\sigma_{proton}\| < 2$	
TOF m^2 (GeV^2/c^4)	/	0.6–1.2



- Uniform (anti)proton acceptance in $|y| < 0.5$ within $|V_z| < 50$ cm
- Bin-by-bin proton/antiproton purity > 99%

Event-by-Event Net-proton Number Distributions

- Raw net-proton number distributions from BES-II
  - Uncorrected by detector efficiency
- Mean increases with decreasing collision energy
  - Effect of baryon stopping



Techniques and Improvements in BES-II Analysis

1. Efficiency correction (detector efficiency and PID cut efficiency)
   - Binomial assumption for the effect of efficiency
   - ~10% higher (anti)proton efficiency with iTPC compared to BES-I

X. Luo, T. Nonaka, PRC 99, 044917 (2019)
X. Luo, JPG 39 025008 (2012)
X. Luo *et al.*, JPG 40, 105104 (2013)
STAR, PRC 104 024902 (2021)
R. Barlow, arXiv:hep-ex/0207026

2. Statistical uncertainty estimation (delta theorem and bootstrap)
   - Smaller statistical error ($\propto \sigma^r/\sqrt{N}$ for C_r) due to more statistics than BES-I

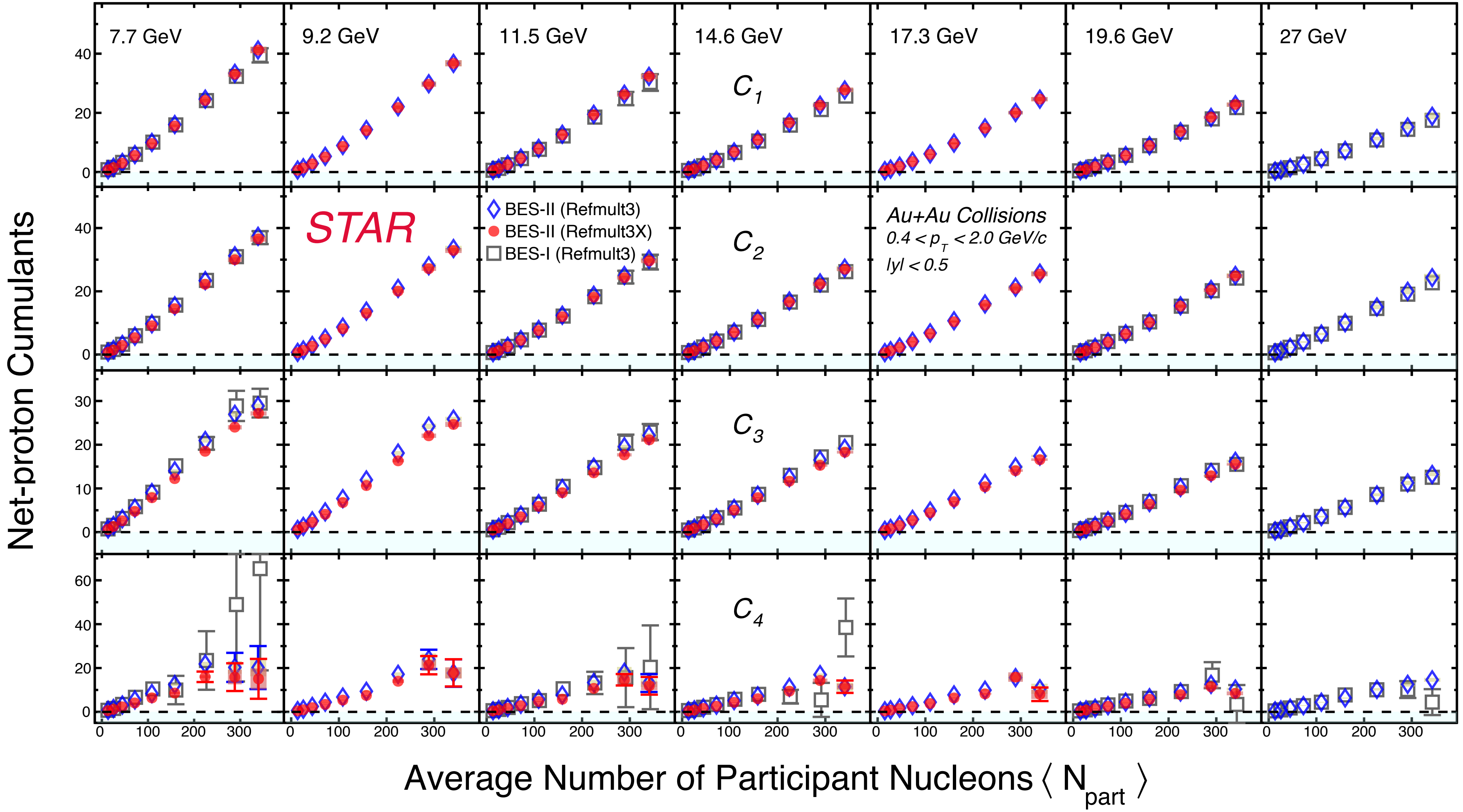
3. Systematic uncertainty calculation (Barlow check applied)
   - Smaller systematic error from efficiency: 2% with iTPC (5% in BES-I)

4. Centrality Bin Width Correction (CBWC)
   - Initial volume fluctuation suppressed
   - $C_r = \left(\sum_i n_i C_{r,i}\right)/\left(\sum_i n_i\right)$,
     where n_i is no. of events in ith multiplicity bin

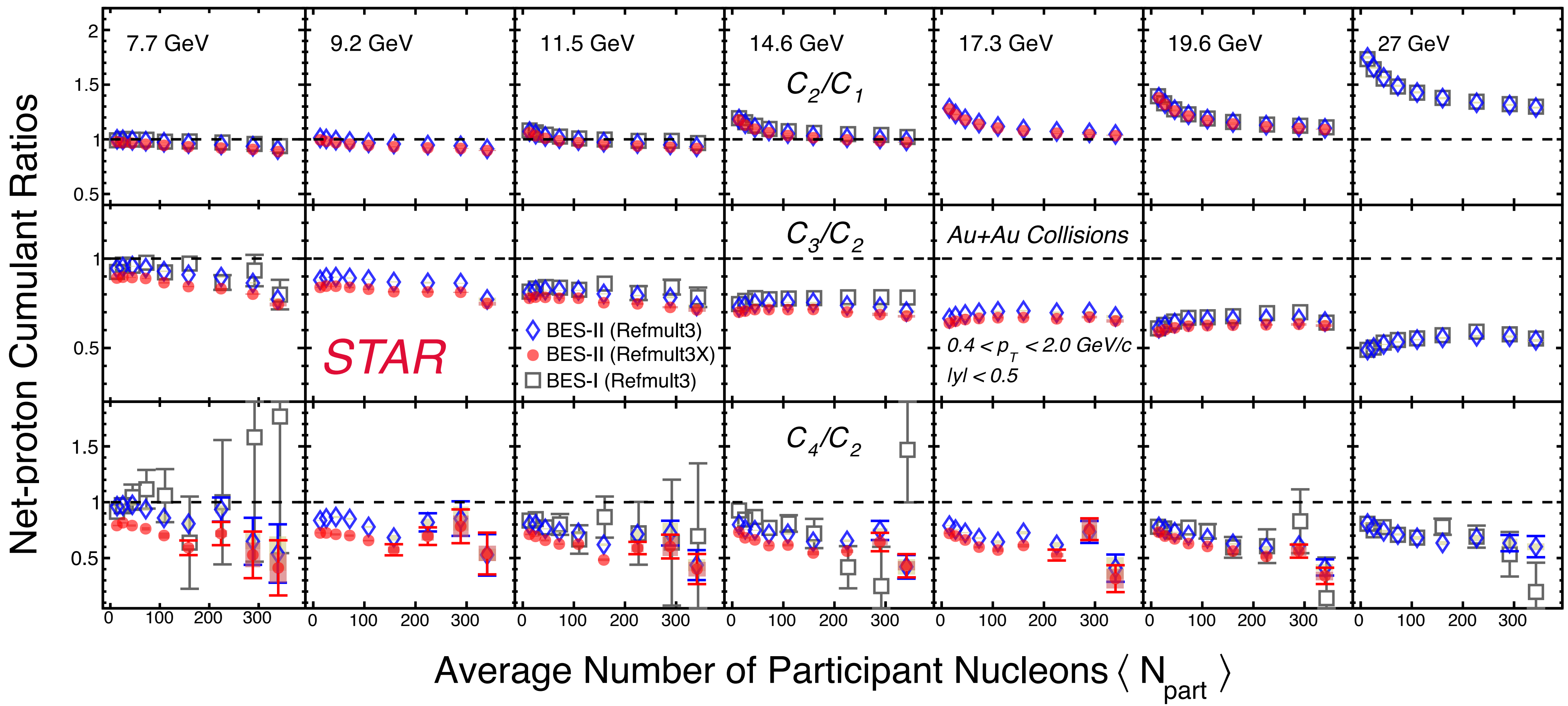
Reduction factor in uncertainties of 0–5% C_4/C_2 in BES-II compared to BES-I

	7.7 GeV	19.6 GeV
Stat.	4.7	4.5
Sys.	3.2	4

Cumulants vs. Centrality and Collision Energy



Cumulant Ratios vs. Centrality and Collision Energy

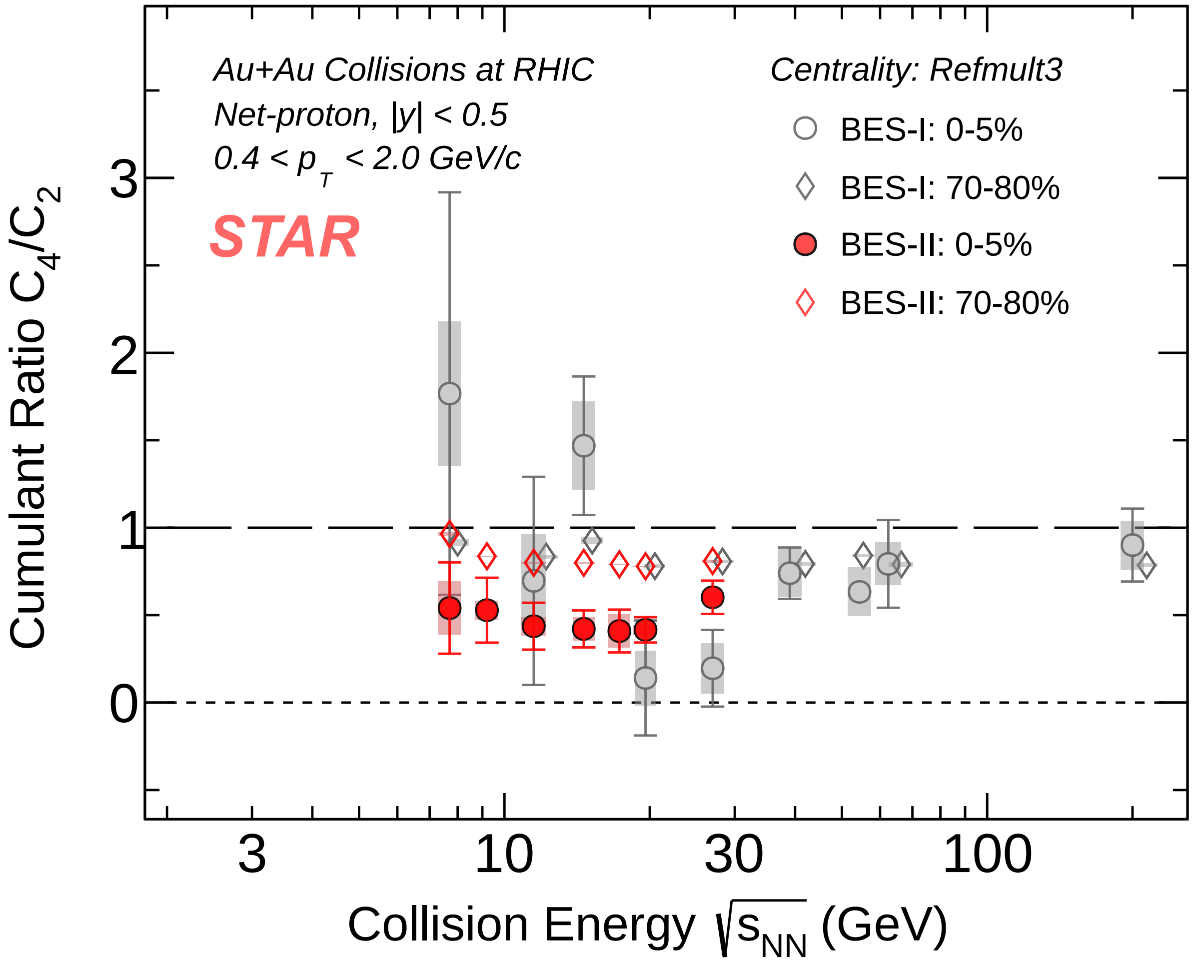


1. Precision measurement: smooth centrality dependence across collision energies
2. Better centrality resolution leads to lower cumulants/ratios (especially in mid-central events)
   Results from RefMult3X (BES-II) < RefMult3 (BES-II) < RefMult3 (BES-I)
3. For 0–5% C_4/C_2, weak effect of centrality resolution

Comparison of C_4/C_2 with BES-I

Deviation between BES-II and BES-I results

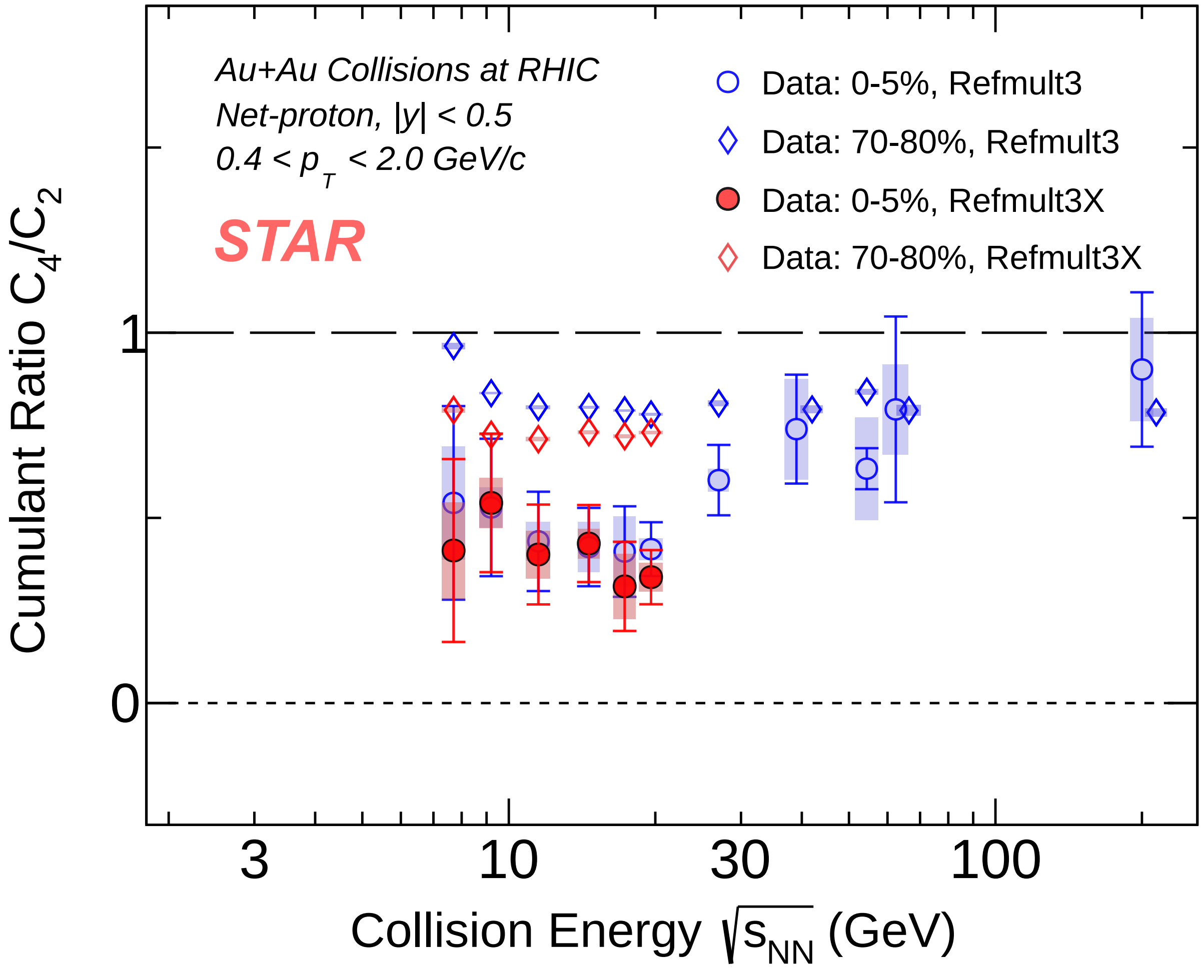
$\sqrt{s_{NN}}$ (GeV)	0–5%	70–80%
7.7	1.0σ	0.9σ
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.0σ
27	1.4σ	0.2σ



- BES-II results consistent with BES-I mostly within $\sim 1\sigma$

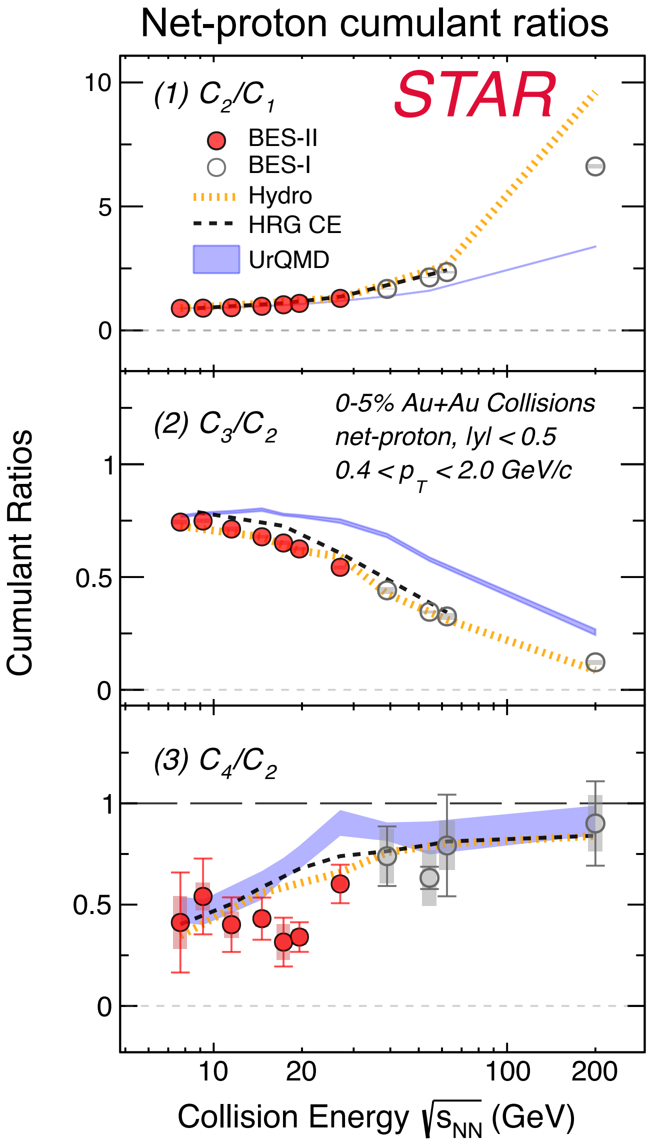
Effect of Centrality Resolution on C_4/C_2

- For C_4/C_2 at 70–80% centrality, clear deviation between RefMult3/3X
- For C_4/C_2 at 0–5% centrality, results from RefMult3 and RefMult3X show good agreement with each other
  - Weak effect of centrality resolution



Comparison of Energy Dependence with Models

- Smooth energy dependence observed in C_2/C_1 & C_3/C_2
  C_4/C_2 decreases with decreasing energy
- Non-CP models used for comparison
  1. Hydro: hydrodynamical model
  V. Vovchenko *et al.*, PRC 105, 014904 (2022)
  2. HRG CE: thermal model with canonical treatment of baryon charge
  P. B Munzinger *et al.*, NPA 1008, 122141 (2021)
  3. UrQMD: hadronic transport model
  S. A. Bass *et al.*, PPNP, 41, 255 (1998)



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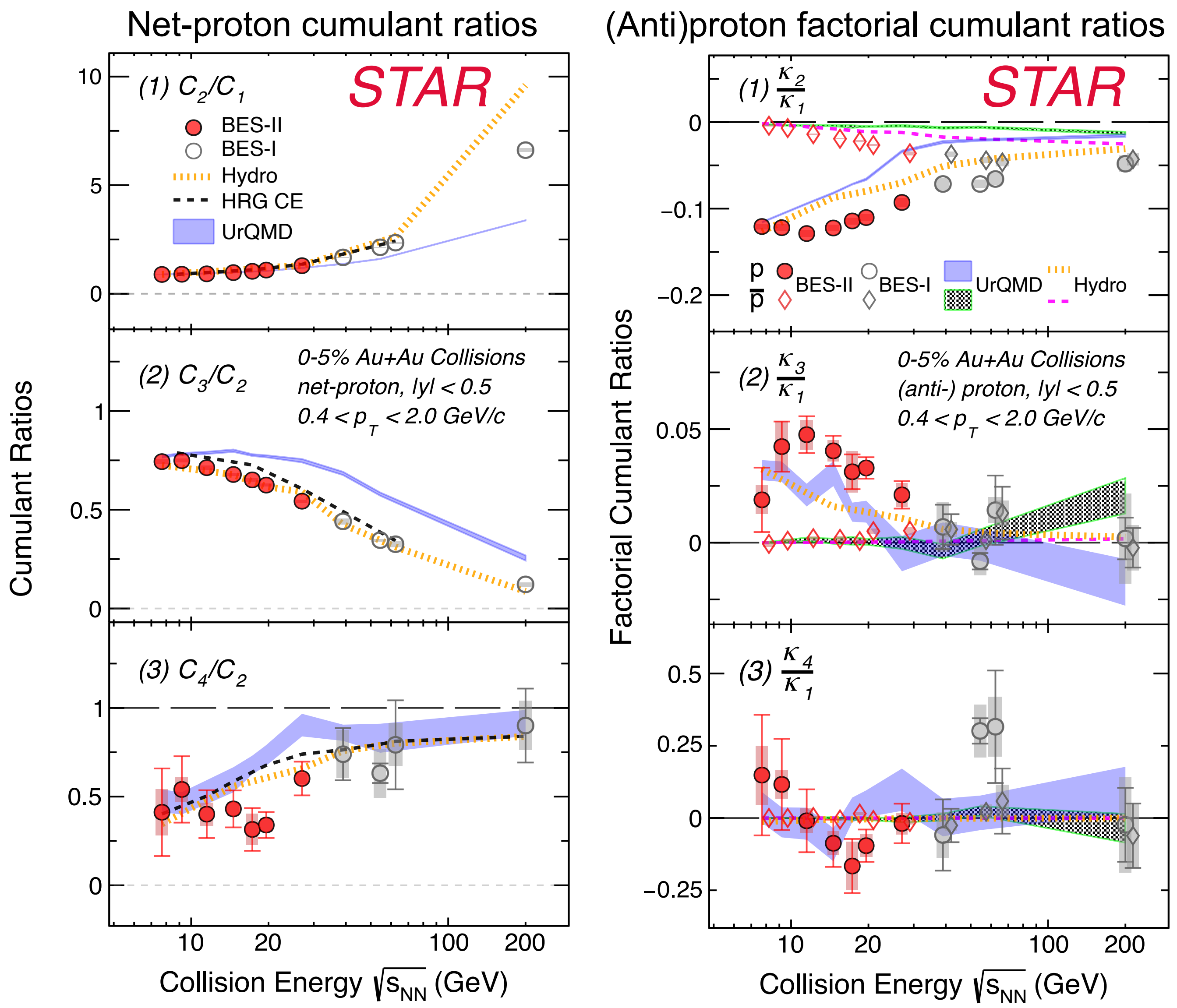
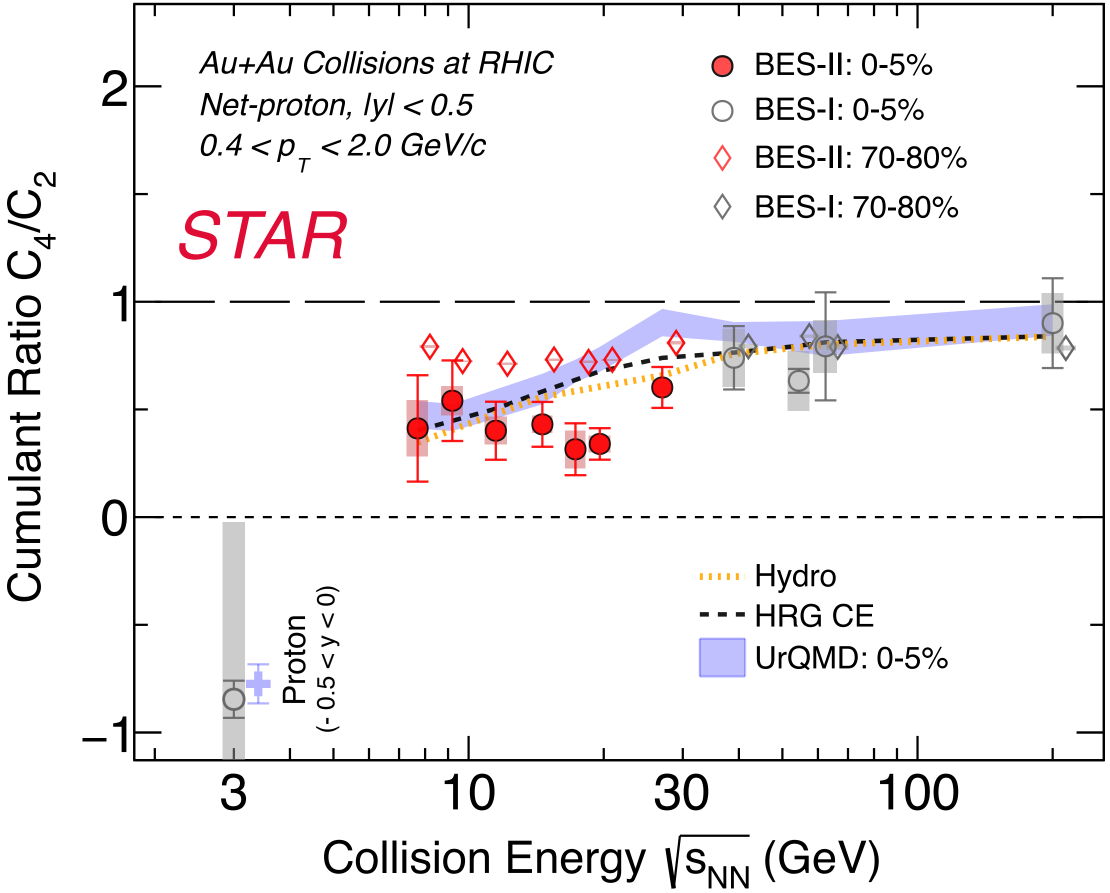
  3. UrQMD: hadronic transport model

  S. A. Bass *et al.*, PPNP, 41, 255 (1998)
- Proton κ ratios deviate from Poisson baseline at 0

  Antiproton κ_3/κ_1 and κ_4/κ_1 closer to 0
- Clear deviations in net-proton C_4/C_2 and proton κ ratios from models

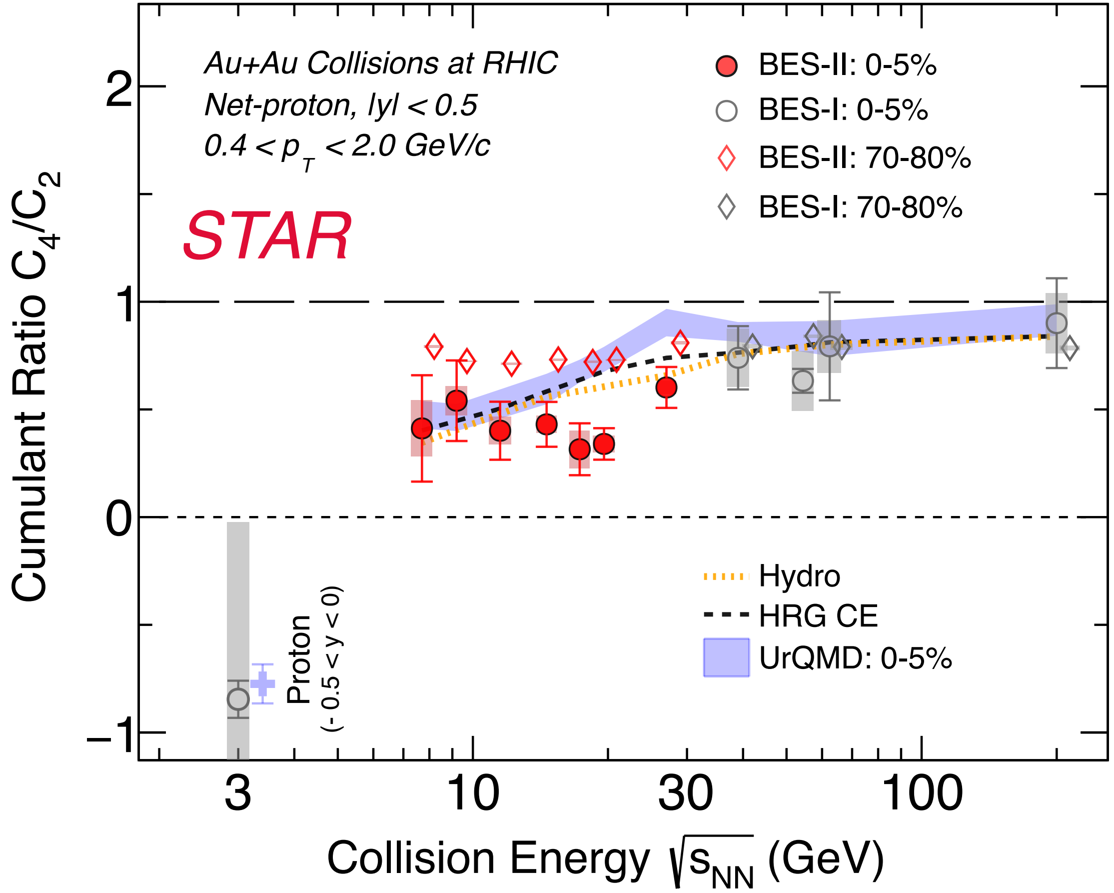


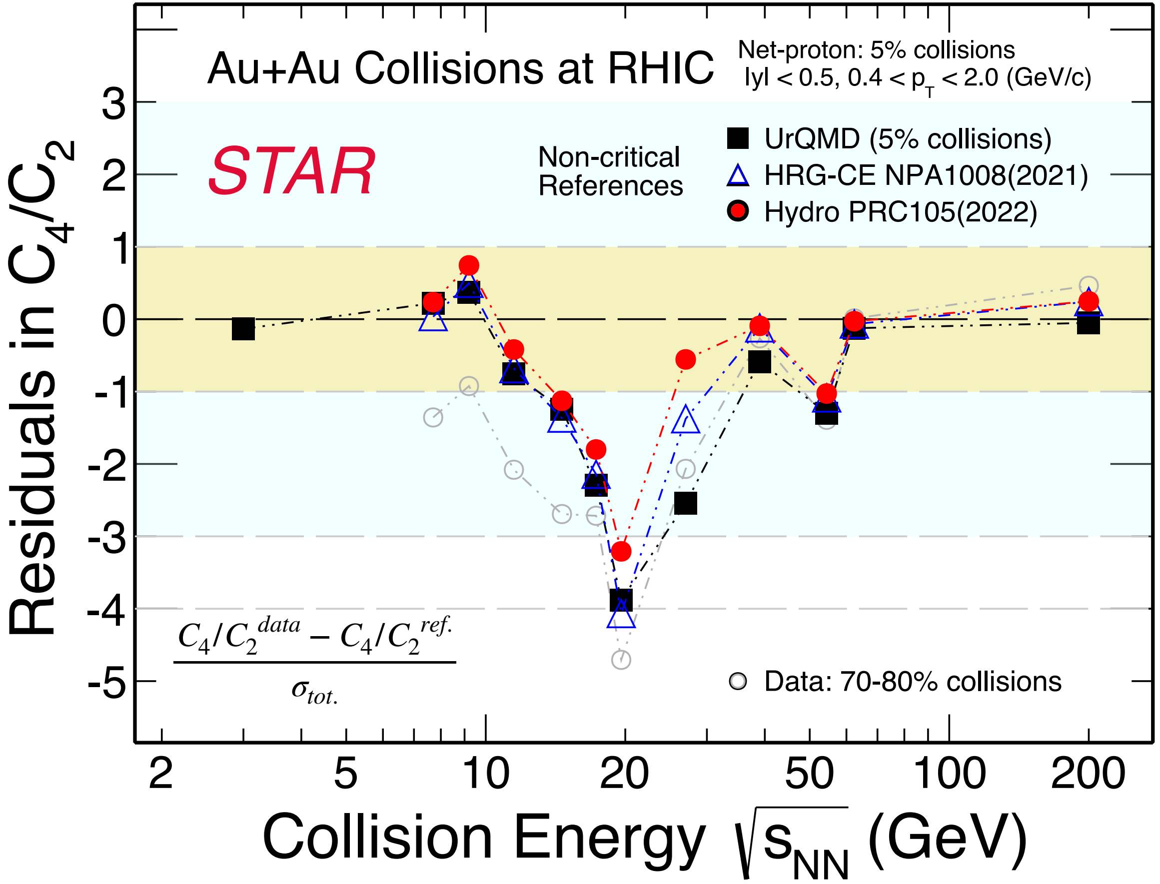
Collision Energy Dependence of C_4/C_2



- C_4/C_2 (0–5%) shows a minimum at $\sqrt{s_{\mathrm{NN}}} \sim 20$ GeV comparing to non-CP models and 70–80% data

Quantitative Deviations of C_4/C_2 from Non-CP Refs.





- C_4/C_2 (0–5%) shows a minimum at $\sqrt{s_{NN}} \sim 20$ GeV comparing to non-CP models and 70–80% data
  - Maximum deviation around 20 GeV: 3.2–4.7σ (1.3–2σ at BES-I)
  - Overall deviation from 7.7 to 27 GeV: 1.9–5.4σ (1.4–2.2σ at BES-I)

Summary and Outlook

- Summary

1. Precision measurement of net-proton number fluctuations vs. centrality and collision energy in Au+Au collisions from STAR BES-II reported. Compared to BES-I, we have
better statistical precision, better centrality resolution, better control on systematics.

2. Net-proton C_4/C_2 in 0–5% central collisions shows a maximum deviation from various non-CP references at $\sqrt{s_{\mathrm{NN}}} \sim 20$ GeV with a significance level of $3.2\text{–}4.7\sigma$.

- Outlook

1. Extend measurements to hyper-order fluctuations up to C_6 and κ_6.
2. Examine transverse momentum dependence and rapidity dependence of fluctuations.
3. Complete the measurements in Au+Au collisions at fixed-target (FXT) energies.

Thank you for your attention!