Workshop on physics performance studies at NICA (NICA 2024)

November 25–27, 2024

Experimental Methods and Results of Fluctuation Measurements at RHIC

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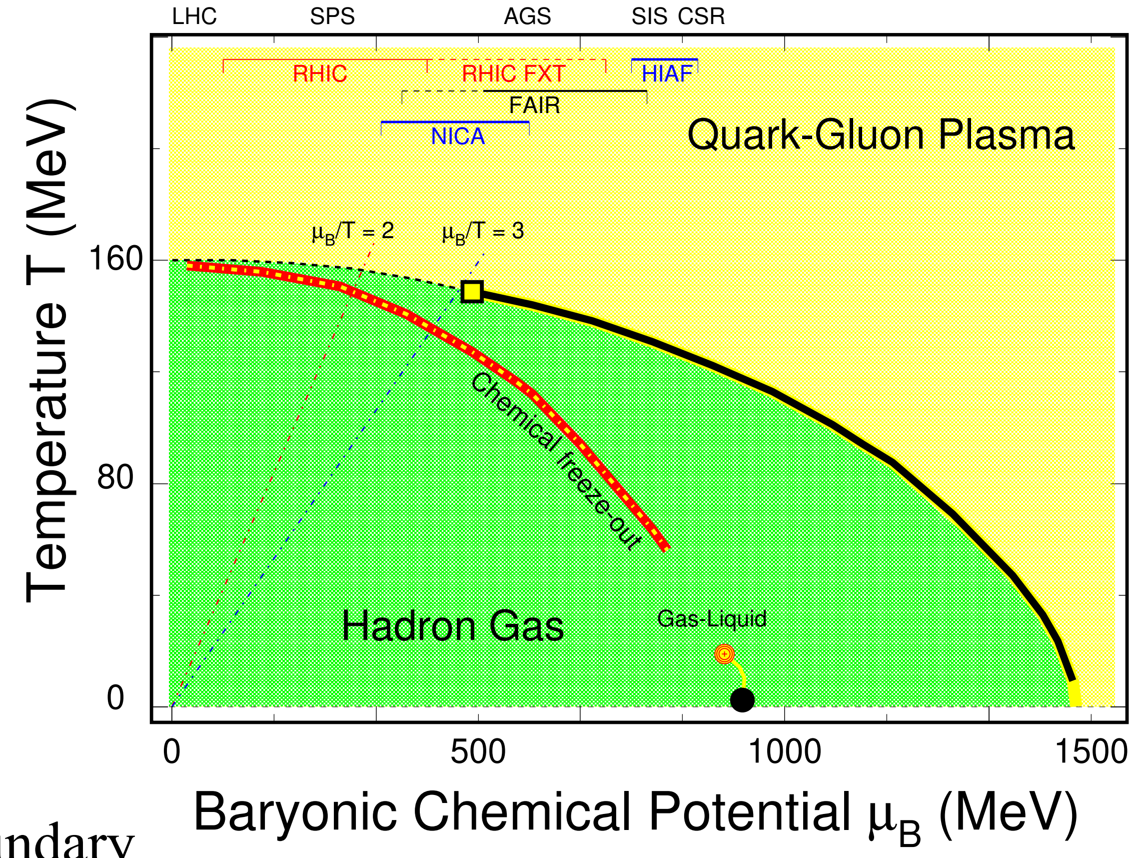
Outline

- 1. Introduction
- 2. BES-I Measurements
- 3. BES-II Net-Proton Fluctuations
  - Analysis Details
  - Latest Results
- 4. Summary and Outlook

Introduction: QCD Phase Diagram

- QCD phase transition
  - Hadronic phase ⇔ QGP phase
- Crossover at small μ_B ($\mu_B/T < 2$)
  - Expected by Lattice QCD
  - $T_c = 156.5 \pm 1.5$ MeV at $\mu_B = 0$
- 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)

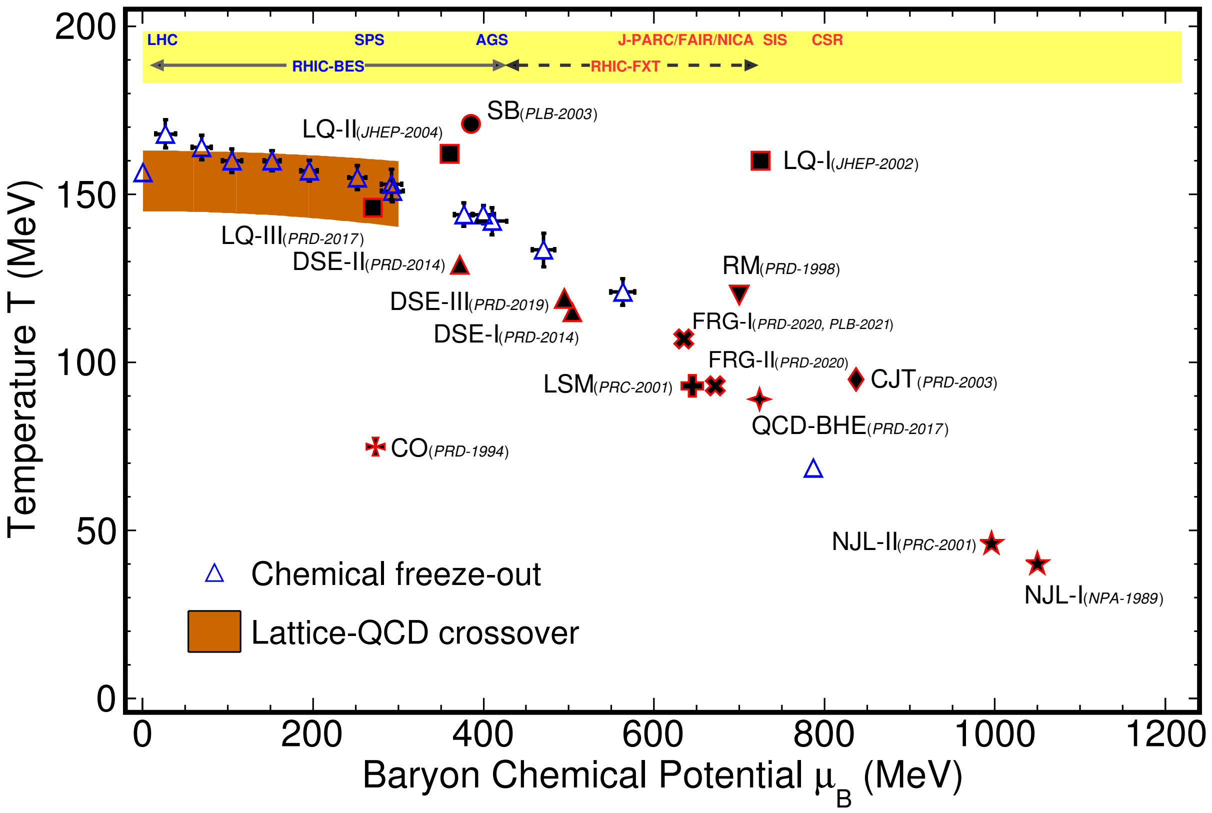
- Critical physics goal: search for and locate CP, understand QCD phase structure

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 with approximation/assumption/estimation
  - Wide region:

    $T = 40\text{–}180$ MeV,

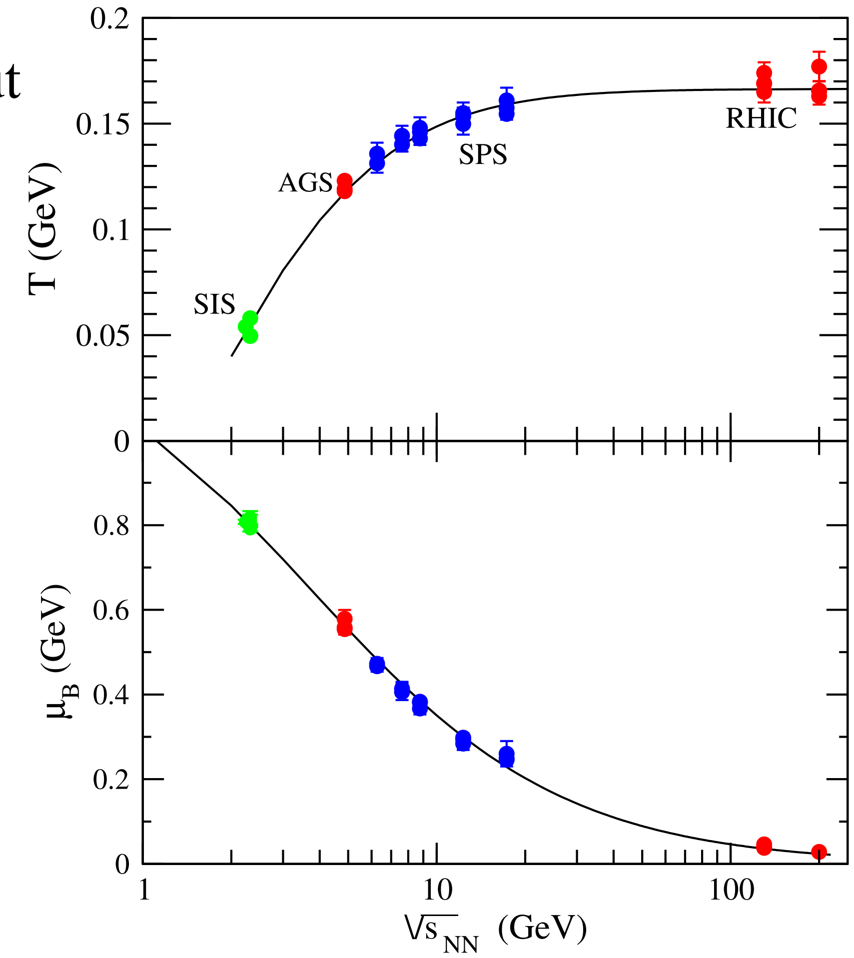
    $\mu_B = 200\text{–}1100$ MeV
- Crucial to search for and locate CP in experiments



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

Introduction: Experimental Scan of Phase Diagram

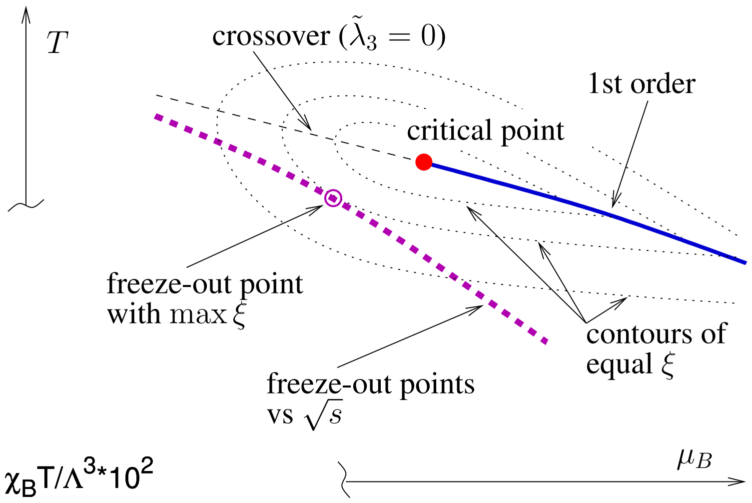
- Scan QCD phase diagram by varying $\sqrt{s_{\mathrm{NN}}}$
  - Lower energy ⇒ lower T, higher μ_{B} at chemical freeze-out
- LHC: $\sqrt{s_{\mathrm{NN}}}$ at TeV-level, $\mu_{\mathrm{B}} \sim 0$
- RHIC-STAR
  - Collider: $\sqrt{s_{\mathrm{NN}}}$ = 200–7.7 GeV, μ_{B} = 25–420 MeV
  - FXT: $\sqrt{s_{\mathrm{NN}}}$ = 13.7–3 GeV, μ_{B} up to ~750 MeV
- NICA-MPD: $\sqrt{s_{\mathrm{NN}}}$ = 11–4 GeV, μ_{B} up to ~620 MeV
- FAIR-CBM, HIAF-CEE: μ_{B} up to ~800 MeV



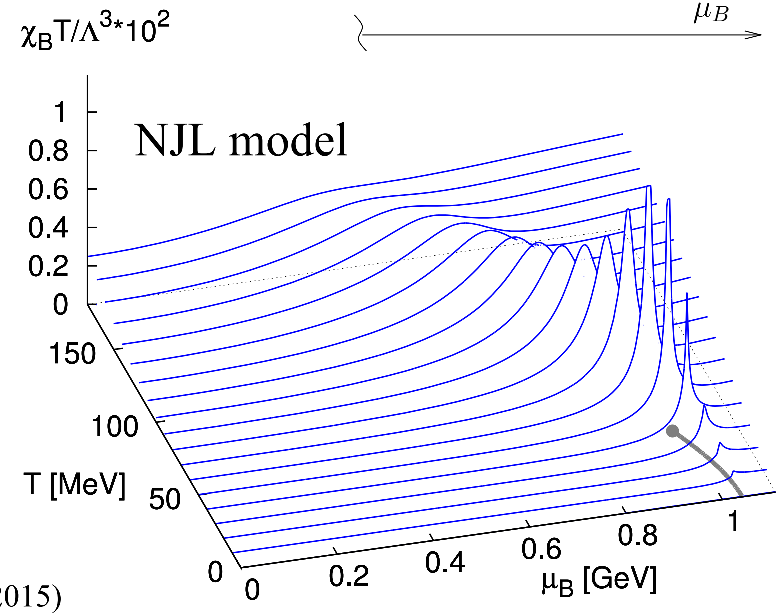
J. Cleymans *et al.*, PRC 73, 034905 (2006)

Introduction: Observables

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



- $C_{r,q}$: rth-order cumulant of event-by-event q
  - $C_r \sim \xi^{5r/2-3}$
  - $C_{r,q} = VT^3\chi_{r,q}$
  - $C_{r,q}/C_{s,q} = \chi_{r,q}/\chi_{s,q}$, trivial volume dependence cancelled
  - Direct comparison with theoretical and model calculations

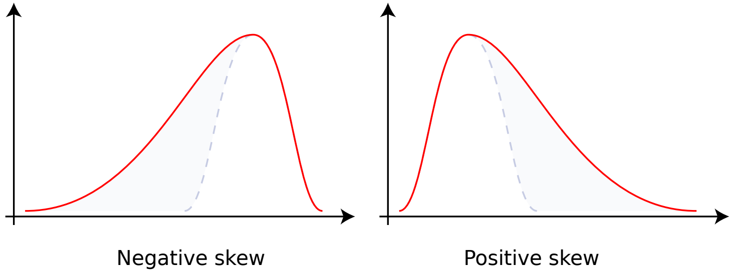


- $\kappa_{r,q}$: rth-order factorial cumulant
  - Quantification of r-particle correlation
  - Usually normalized to $\kappa_{r,q}/\kappa_{1,q}$

M. Stephanov, PRL 102, 032301 (2009)
M. Asakawa, PRL 103, 262301 (2009)
H.-T. Ding et al., Int.J.Mod.Phys.E 24(10), 1530007 (2015)

Introduction: (Factorial) Cumulants

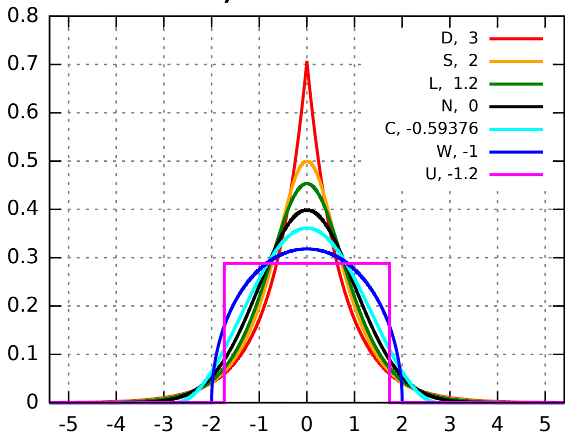
- N: event-by-event net-proton/net-charged-hadron/net-charged-kaon number (proxy for B, Q, S)
- $\mu_r = \langle (N - \langle N \rangle)^r \rangle$: rth-order central moment
- Cumulants:
  - $C_1 = \mu \quad = \langle N \rangle$
  - $C_2 = \sigma^2 \quad = \mu_2$
  - $C_3 = S\sigma^3 = \mu_3$
  - $C_4 = \kappa\sigma^4 = \mu_4 - 3\mu_2^2$
  - $C_5 \quad = \mu_5 - 10\mu_3\mu_2$
  - $C_6 \quad = \mu_6 - 15\mu_4\mu_2 - 10\mu_3^2 + 30\mu_2^3$
- 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 $S = \mu_3/\sigma^3 \Leftrightarrow$ asymmetry

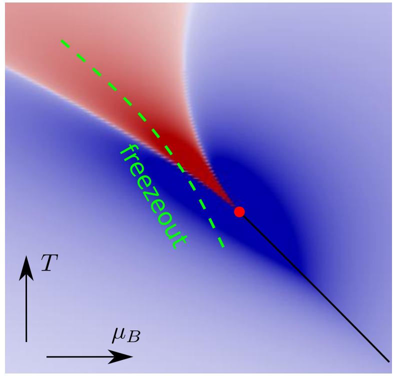
Gaussian: $C_r = 0\ (r > 2)$
Poisson: $C_r = C_1,\ \kappa_r = 0\ (r > 1)$
Skellam (Poisson − Poisson):
$C_{\mathrm{odd}}/C_{\mathrm{odd}} = C_{\mathrm{even}}/C_{\mathrm{even}} = 1$

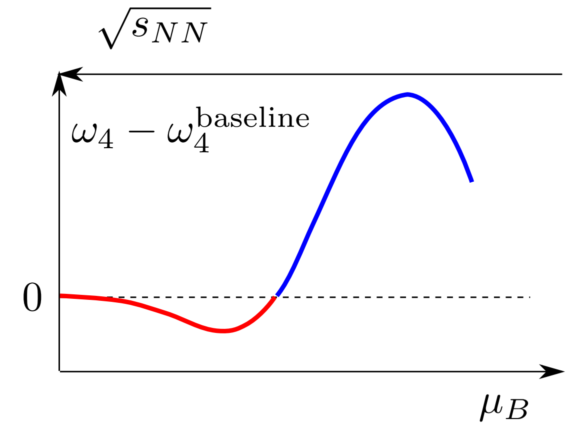
kurtosis $\kappa = \mu_4/\sigma^4 - 3 \Leftrightarrow$ peakedness



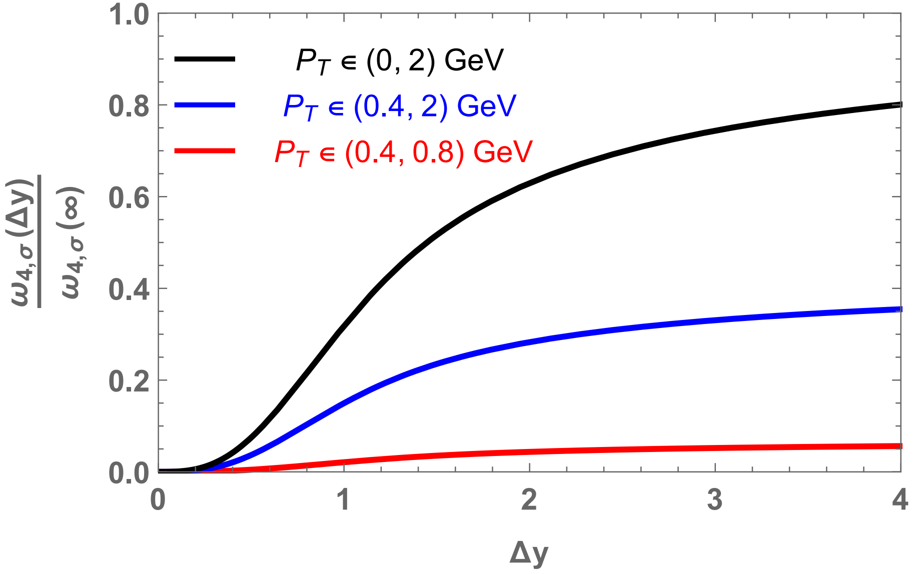
Introduction: Expected Signals

- Critical signal: non-monotonic energy dependence of C_4/C_2
  - ω_4: scaled C_4
  - Baseline: determined by models without CP

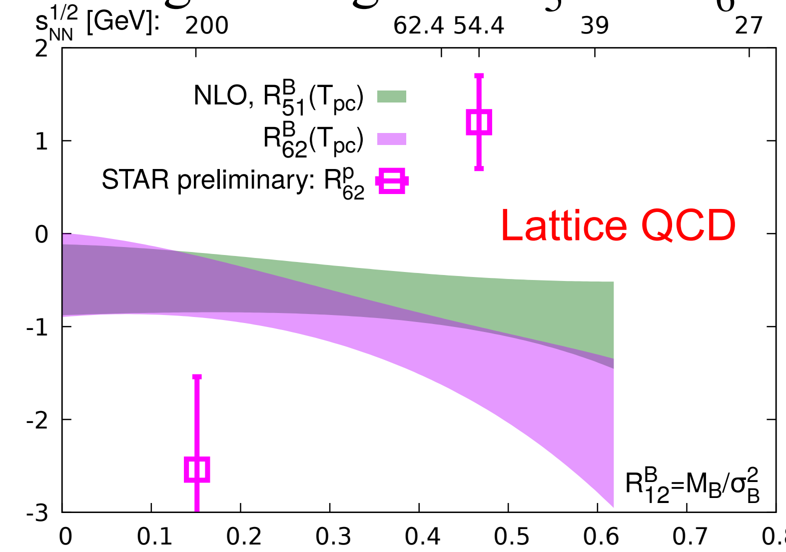




- Larger acceptance ⇒ larger signal
  - More correlations included

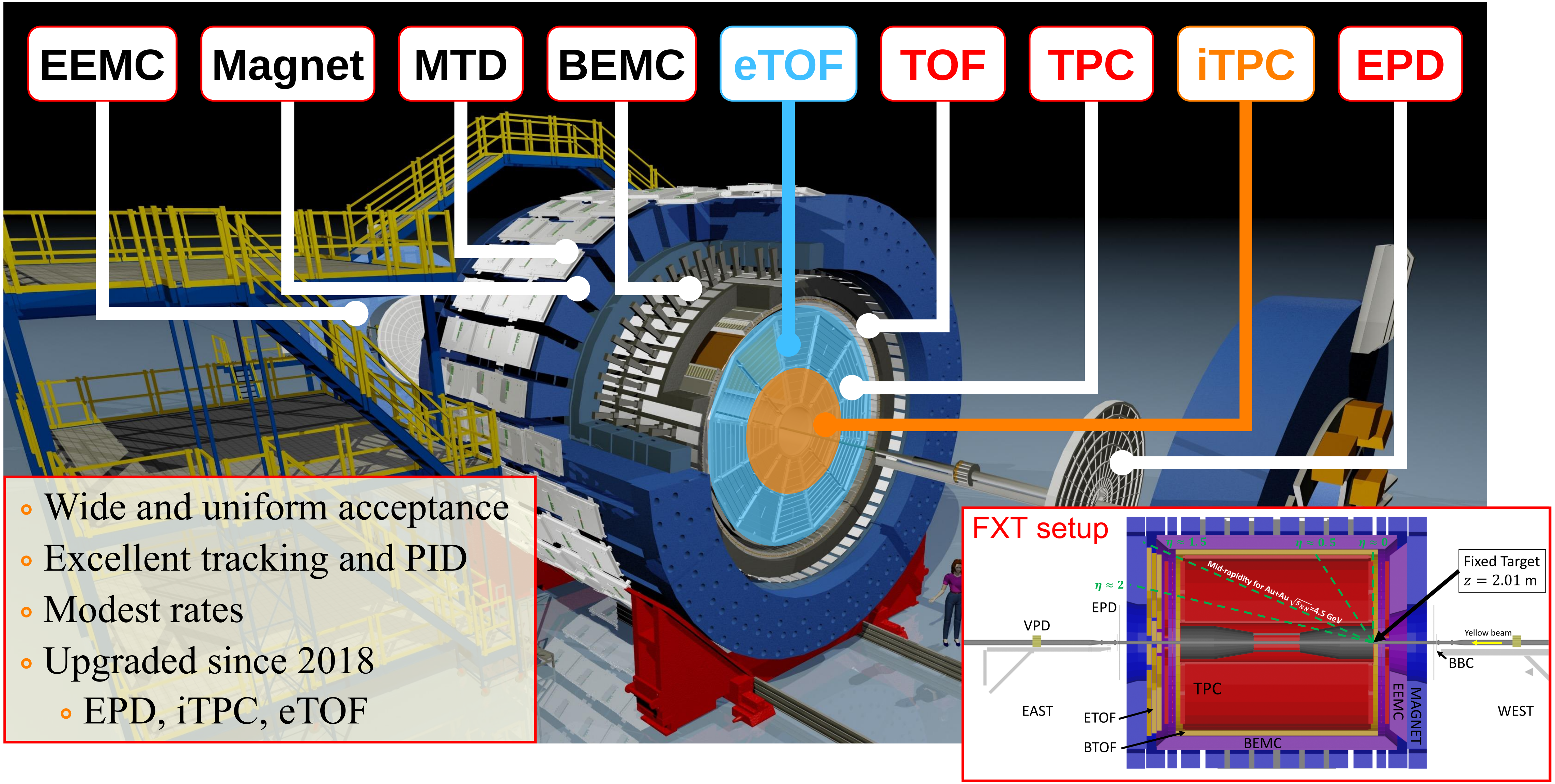


- Crossover signal: negative C_5 and C_6



B. Ling, M. Stephanov, PRC 93, 034915 (2016)
A. Bazavov et al., PRD 101, 074502 (2020)
M. Stephanov, Acta Phys. Polon. B 55, 5-A4 (2024)

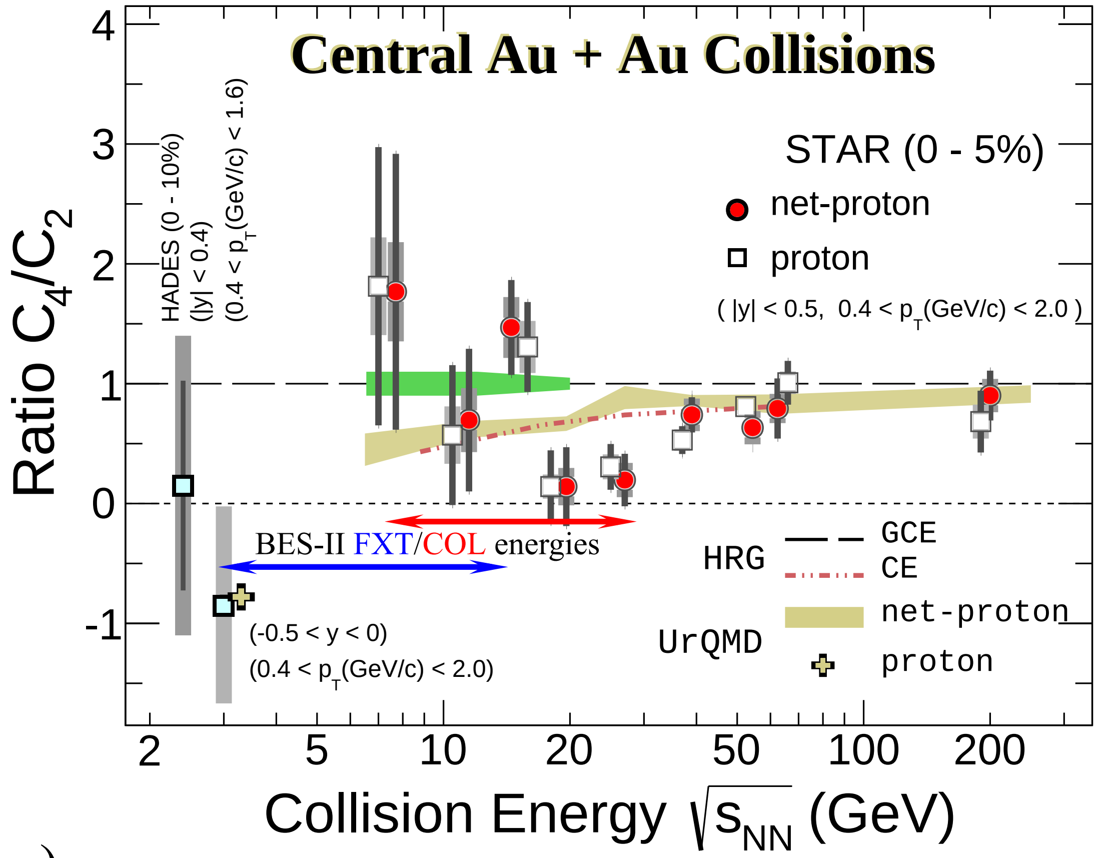
Introduction: STAR Detector System



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

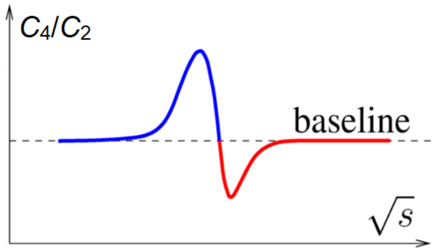
BES-I: Net-Proton Number Fluctuations

$\sqrt{s_{NN}}$ (GeV)	Year	Events (10^6)	μ_B (MeV)
200	2010	238	25
62.4	2010	47	75
54.4	2017	550	85
39	2010	86	112
27	2011	30	156
19.6	2011	15	206
14.5	2014	20	262
11.5	2010	6.6	316
7.7	2010	3	420
3 (FXT)	2018	140	750



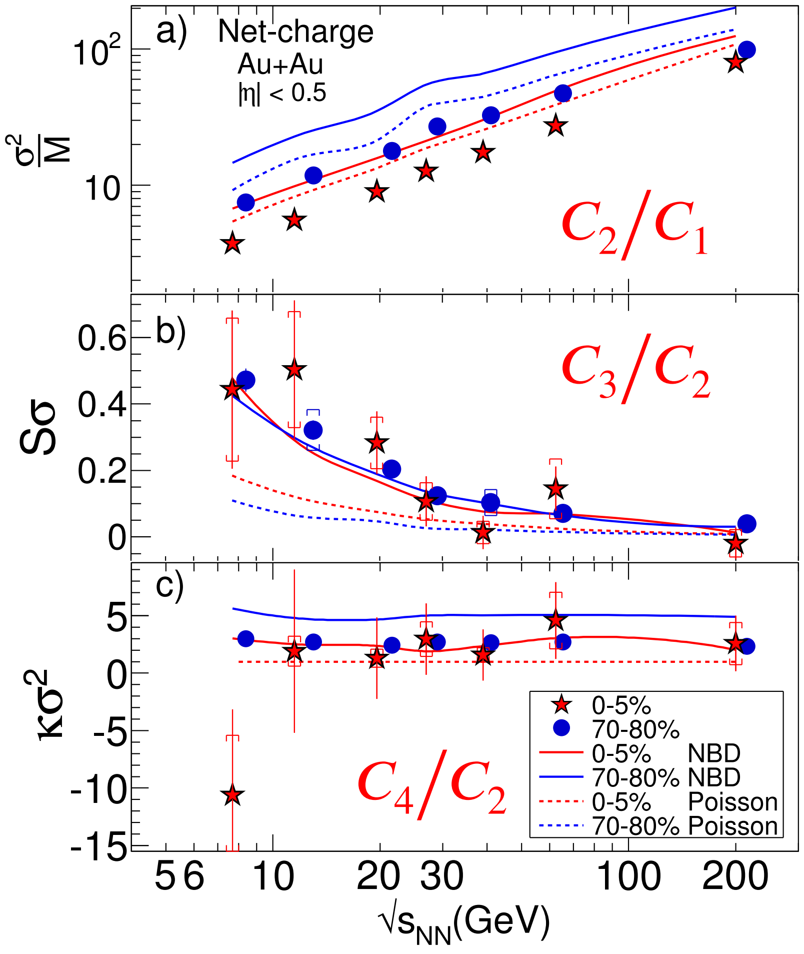
- Non-monotonic energy dependence of C_4/C_2 (3.1σ)
  - Deviation from non-CP models showing monotonic trend
- C_4/C_2 from 3 GeV shows agreement with UrQMD
  - Predominantly hadronic matter

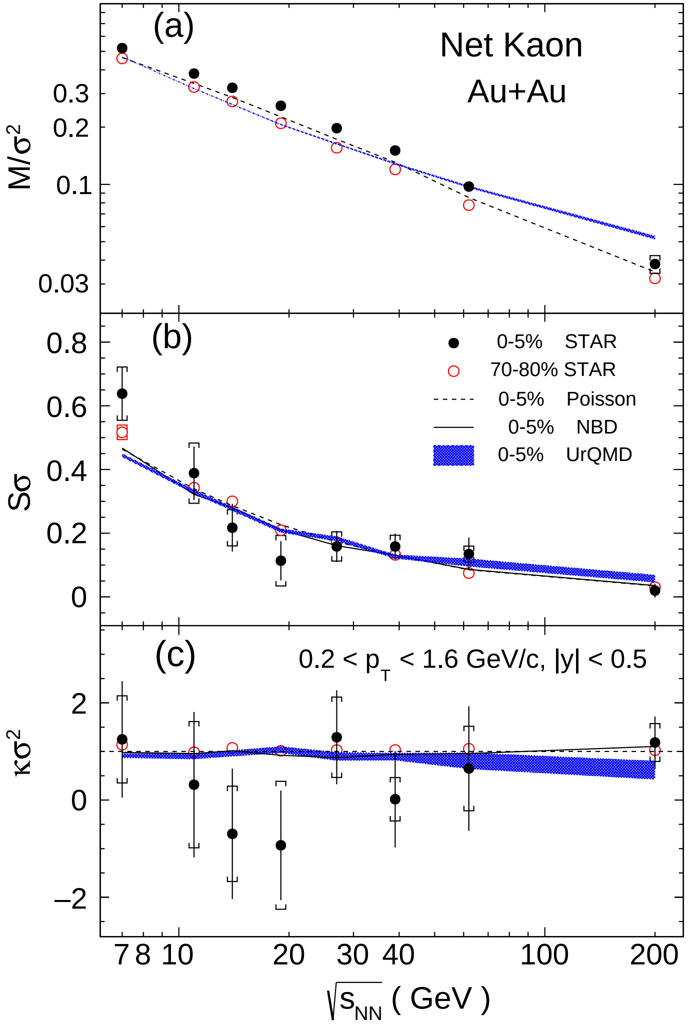
M. Stephanov, PRL 107, 052301 (2011)
STAR: PRL 127, 262301, PRC 104, 024902, PRL 128, 202302, PRC 107, 024908
HADES: PRC 102, 024914 (2020)



BES-I: Net-Charge and Net-Kaon Fluctuations

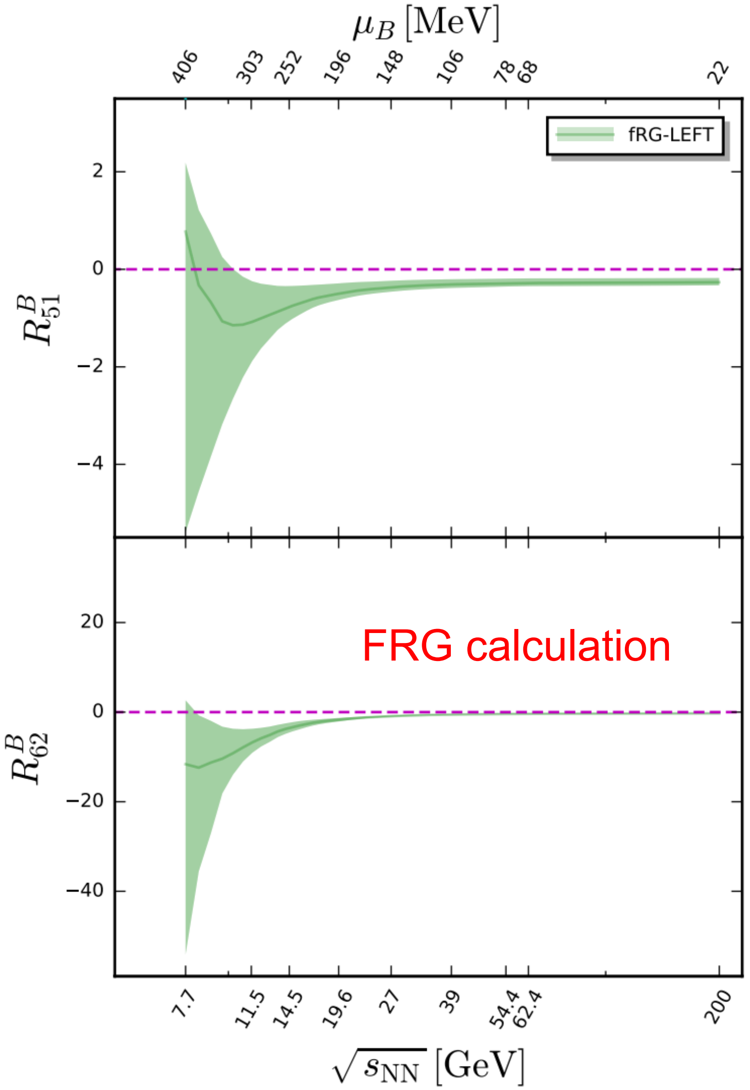
- No clear centrality dependence in C_3/C_2 or C_4/C_2
- Monotonic energy dependence of the three cumulant ratios
- Large uncertainties based on the BES-I statistics

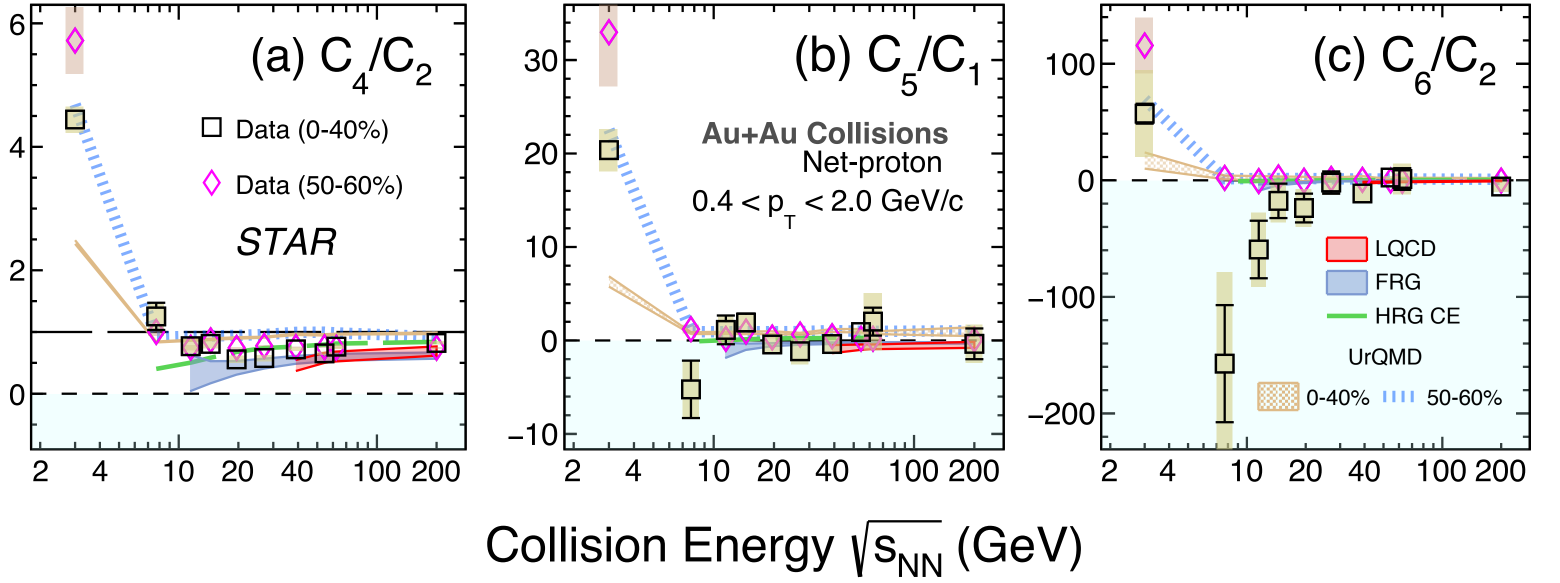




STAR, PRL 113, 092301 (2014)
STAR, PLB 785, 551-560 (2018)

BES-I: Net-Proton Hyper-Order Fluctuations



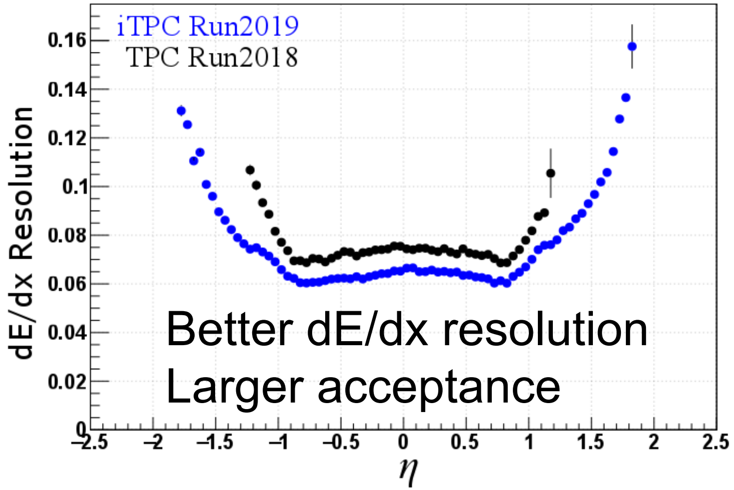


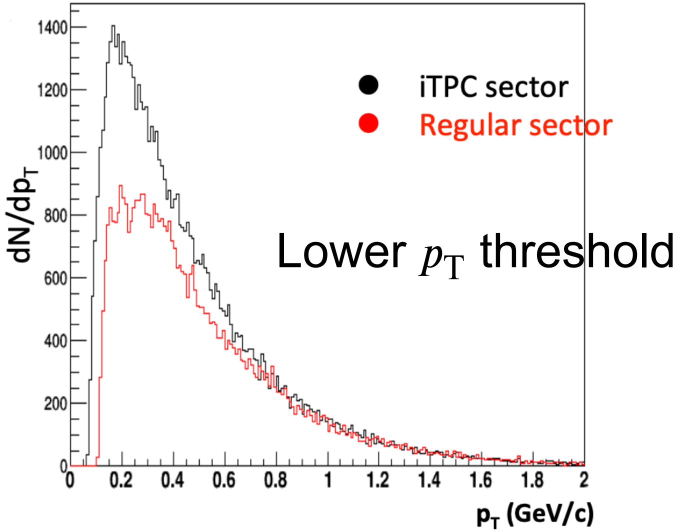
- BES-I $\sqrt{s_{NN}}$ = 7.7–200 GeV (μ_B = 420–25 MeV)
  - C_6/C_2 (0–40%): increasingly negative as energy decreases
  - Trend consistent with LQCD and FRG calculations
- Fixed-target $\sqrt{s_{NN}}$ = 3 GeV (μ_B = 750 MeV)
  - C_5/C_1 and C_6/C_2: positive signs reproduced by UrQMD

FRG: W.-j. Fu *et al.*, PRD 104, 094047 (2021)
STAR: PRL 127, 262301 (2021), PRL 128, 202303 (2022)

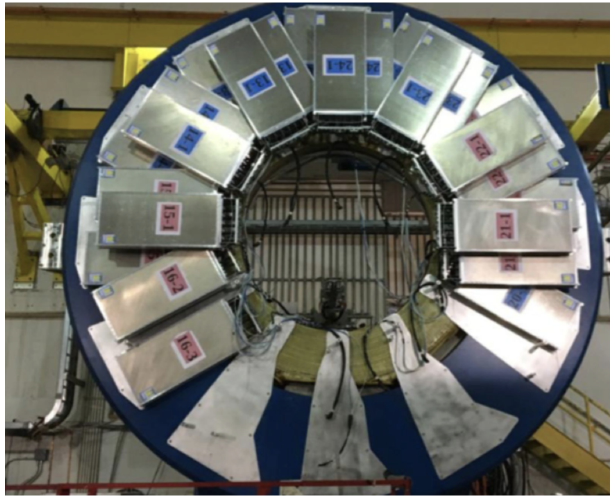
BES-II: STAR Major Upgrades

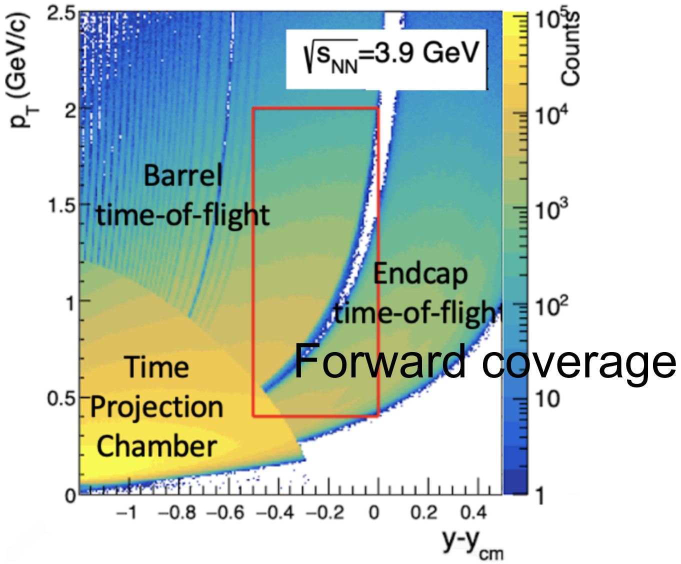
Inner TPC (2019+)



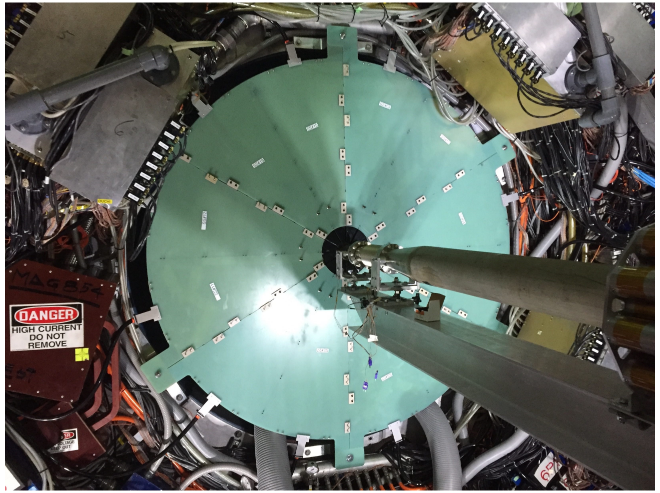


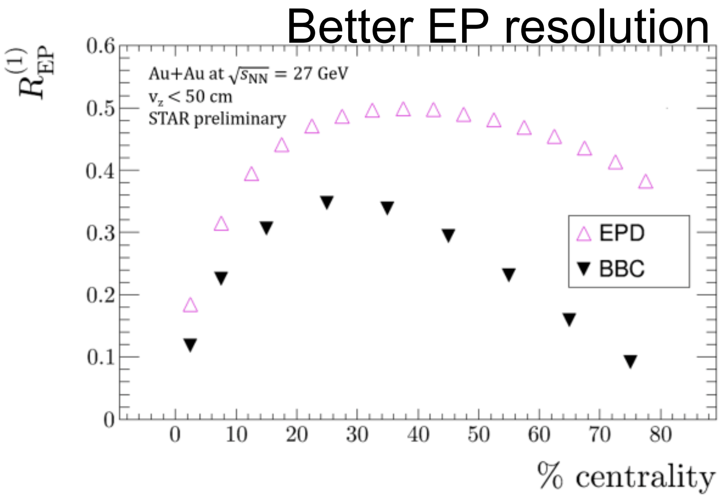
End-cap TOF (2019+)





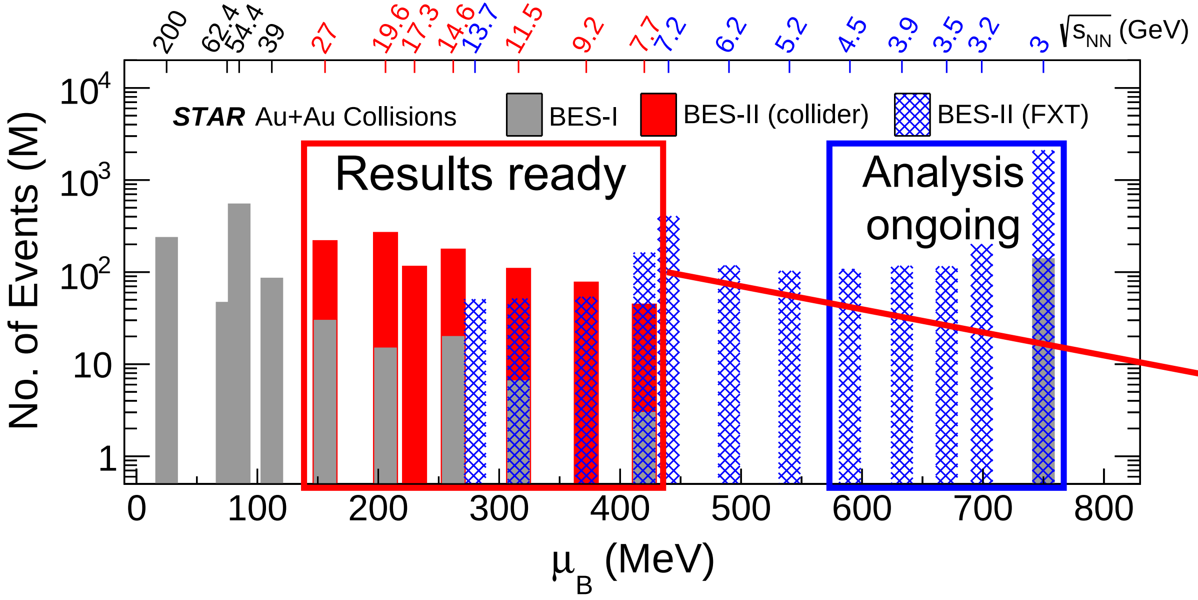
Event Plane Detector (2018+)





Y. Yang (STAR), NPA 1005, 121758 (2021)

BES-II: Data Sets



$\sqrt{s_{NN}}$ (GeV)	Used Events (10^6)		μ_B (MeV)
	BES-I	BES-II	
27	30	220	156
19.6	15	270	206
17.3	/	116	230
14.6	20	178	262
11.5	6.6	110	316
9.2	/	78	372
7.7	3	45	420

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

- Larger statistics: × 7–18
- New energies: 9.2 and 17.3 GeV

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

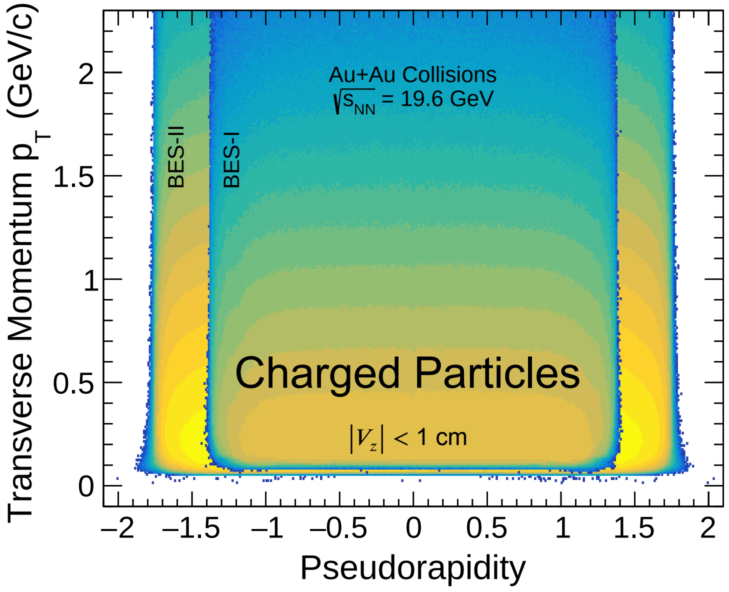
A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

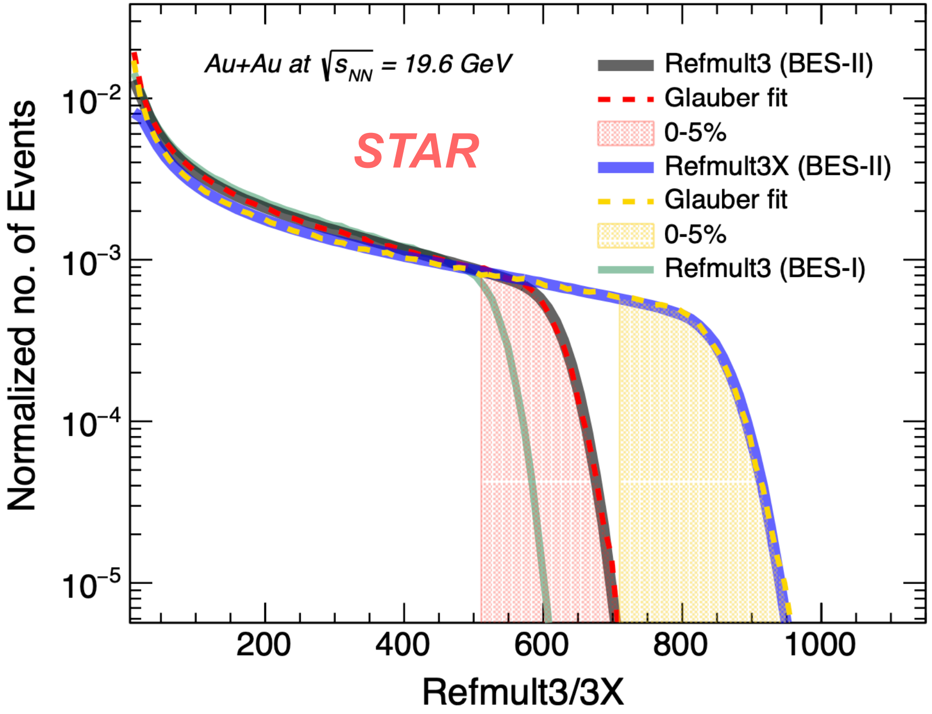
Net-Proton: Centrality Determination

Two multiplicity definitions with different acceptances

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

- Measured charged-particle multiplicities for centrality
- (Anti)protons excluded to avoid self-correlation



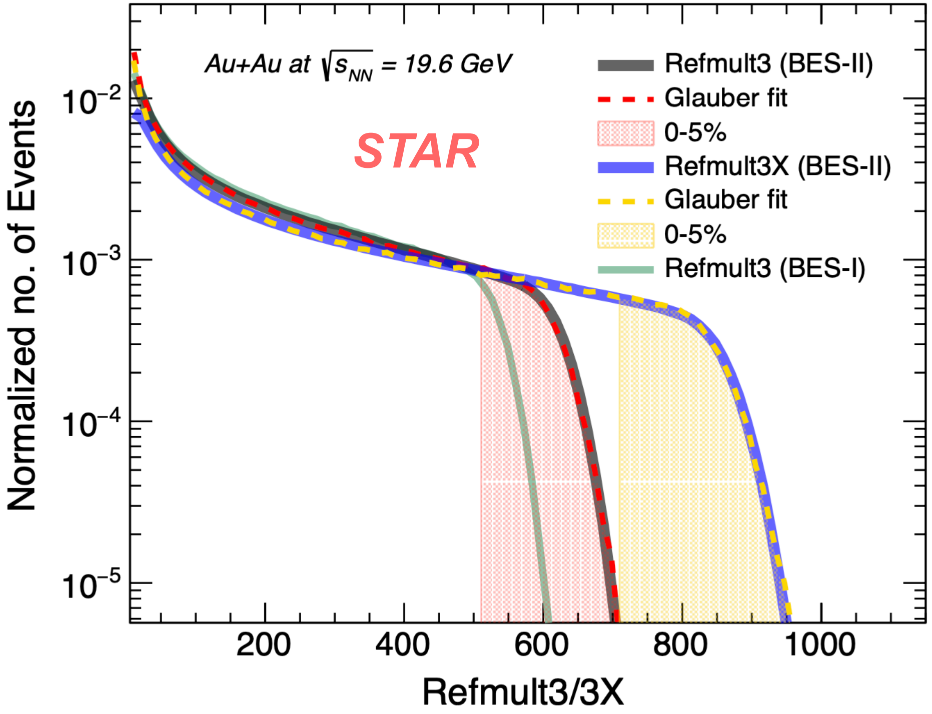


A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024
Y. Huang (STAR), RHIC/AGS 2024

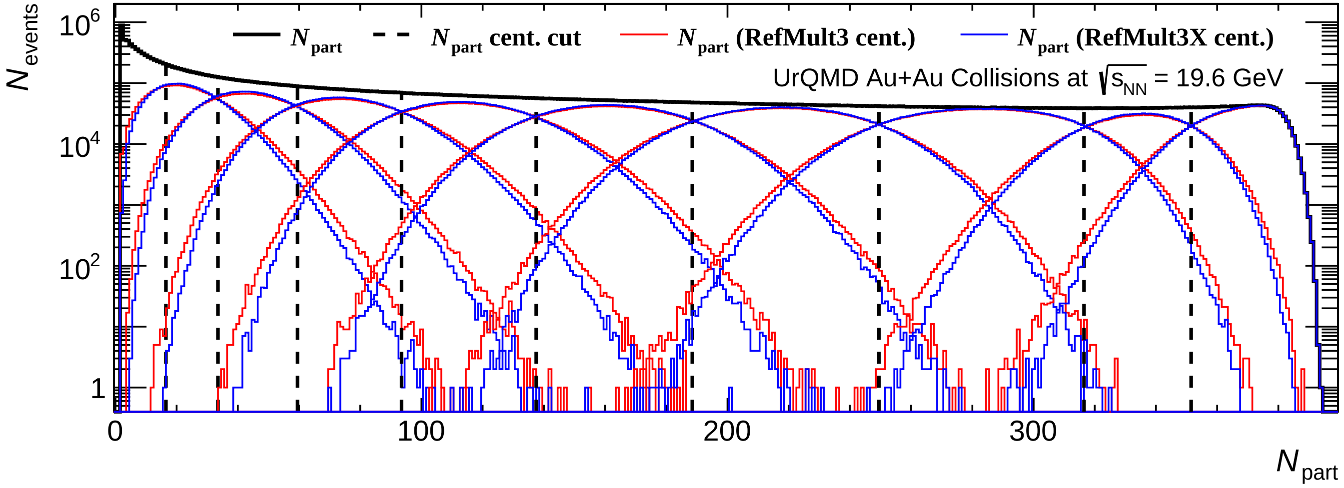
Net-Proton: Centrality Determination

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 > RefMult3 (BES-II) > RefMult3 (BES-I)



⇐ In UrQMD, RefMult3X cent. has
- Thinner N_{part} distribution
- More common events with N_{part} cent.

A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

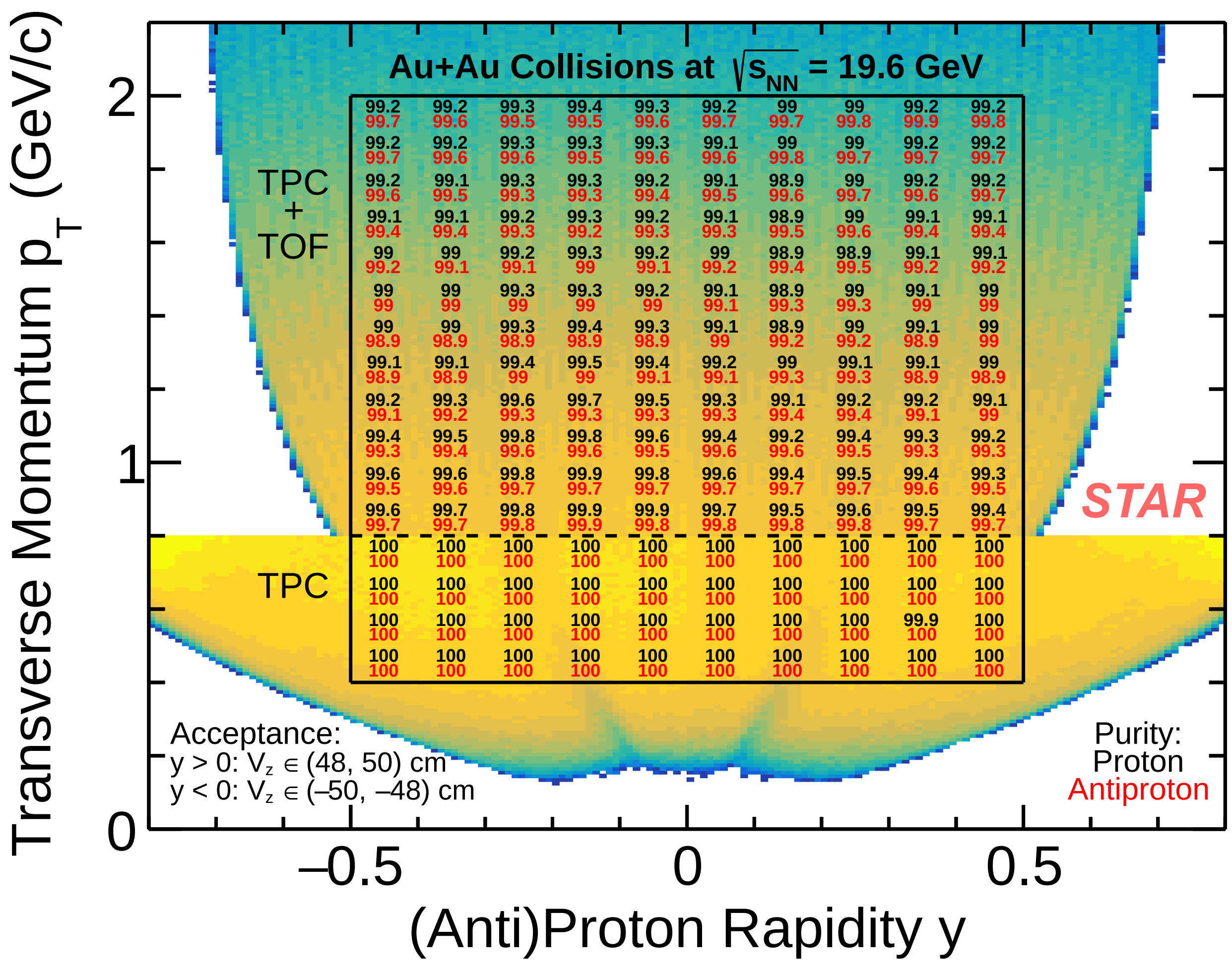
Net-Proton: Particle Identification

- (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	$\lvert y\rvert < 0.5$	
Detector	TPC	TPC+TOF
TPC dE/dx	$\lvert n\sigma_{proton}\rvert < 2$	
TOF m^2 (GeV^2/c^4)	/	0.6–1.2

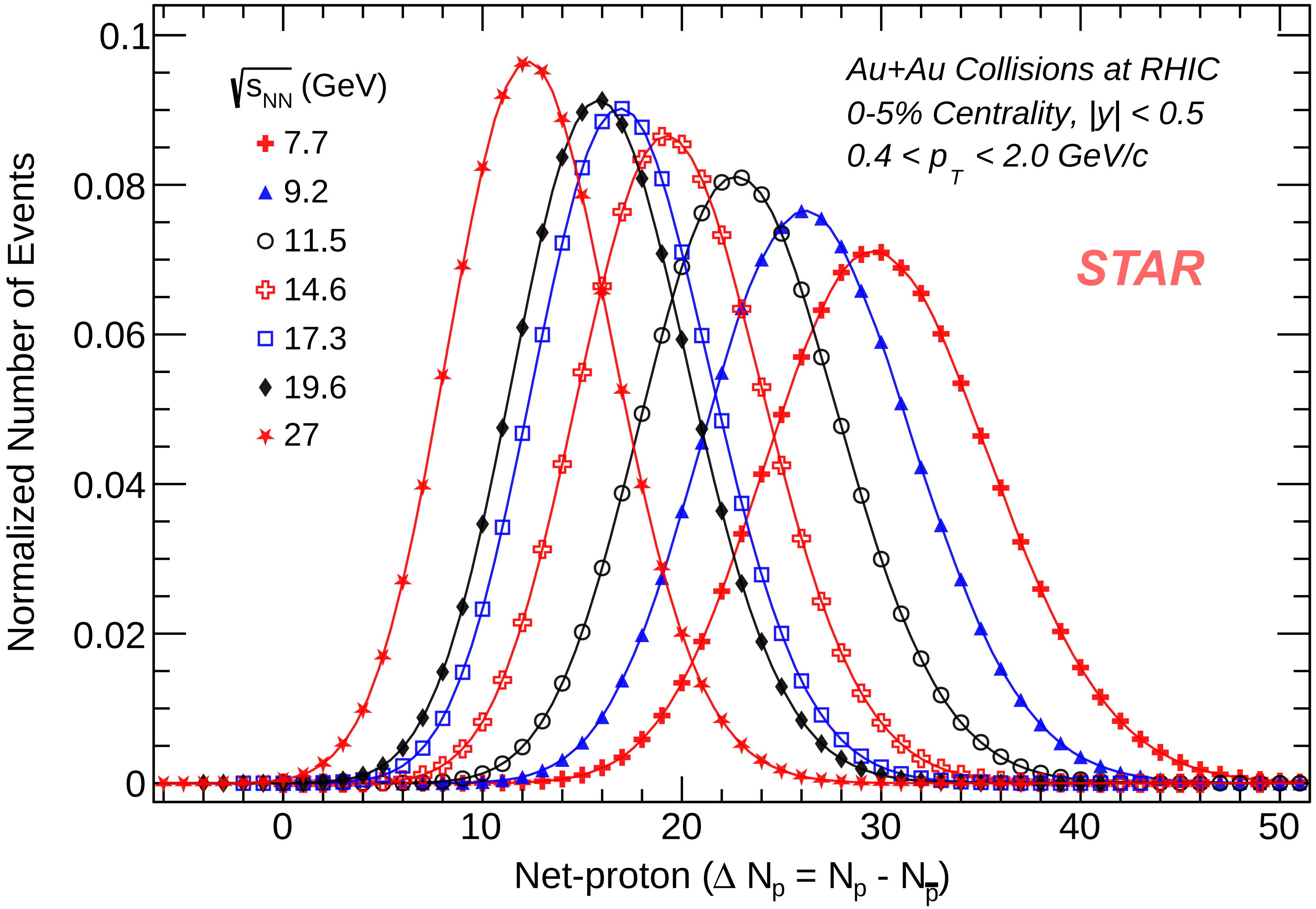
- Uniform (anti)proton acceptance in $|y| < 0.5$ within $|V_z| < 50$ cm
- Bin-by-bin proton/antiproton purity > 99%



A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

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



A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

Efficiency Correction

- Assumed binomial response of efficiency: $B_{\varepsilon,X}(x) = \frac{X!}{x!(X-x)!}\varepsilon^x(1-\varepsilon)^{X-x}$
  - ε: efficiency (binomial probability); X, x: true and measured particle numbers

- Efficiency correction on track-by-track basis
  - $C_1^{\text{corr}} = \langle q_{(1,1)} \rangle_c$
  - $C_2^{\text{corr}} = \left\langle q_{(1,1)}^2 \right\rangle_c + \langle q_{(2,1)} \rangle_c - \langle q_{(2,2)} \rangle_c$
  - $C_3^{\text{corr}} = \left\langle q_{(1,1)}^3 \right\rangle_c + 3\langle q_{(1,1)} q_{(2,1)} \rangle_c - 3\langle q_{(1,1)} q_{(2,2)} \rangle_c + \langle q_{(3,1)} \rangle_c - 3\langle q_{(3,2)} \rangle_c + 2\langle q_{(3,3)} \rangle_c$
  - $C_4^{\text{corr}} = \ldots$
  - $q_{(r,s)} = \sum_{i=1}^{x} \frac{a_i^r}{\varepsilon_i^s}$, where a_i and ε_i represents charge and efficiency of the ith track

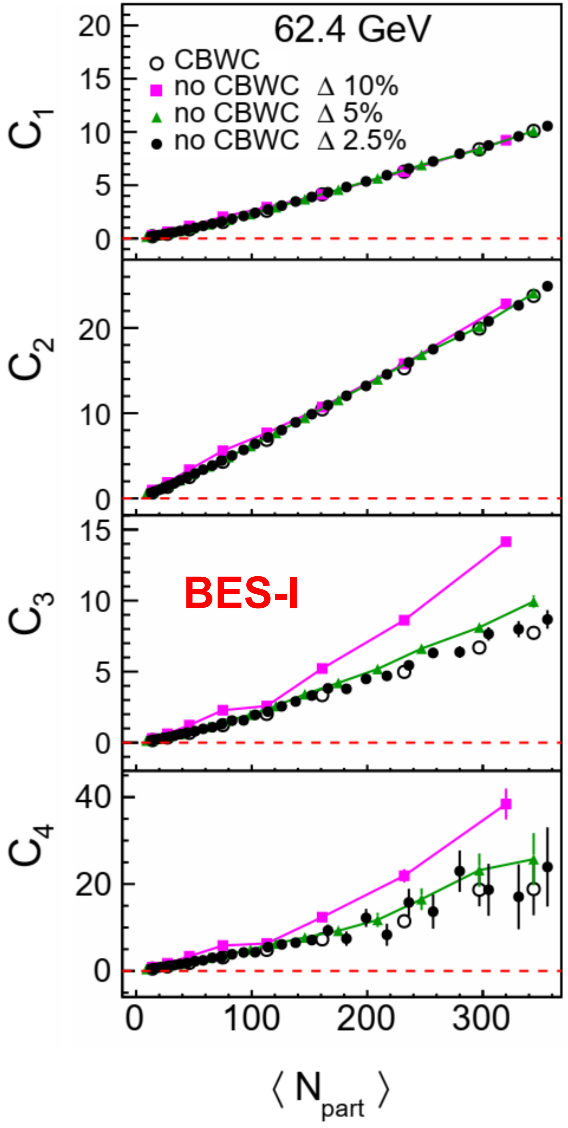
- Differential dependence of efficiency on event and track variables considered
  - Event primary vertex position, centrality, track p_T and rapidity

- Higher efficiency with iTPC than BES-I, particularly at low p_T

T. Nonaka, M. Kitazawa, S. Esumi, PRC 95, 064912
X. Luo, T. Nonaka, PRC 99, 044917 (2019)
S. He, X. Luo, CPC 42, 104001 (2018)
F. Si, Y. Zhang, X. Luo, CPC 45, 124001 (2021)

Centrality Bin Width Correction (CBWC)

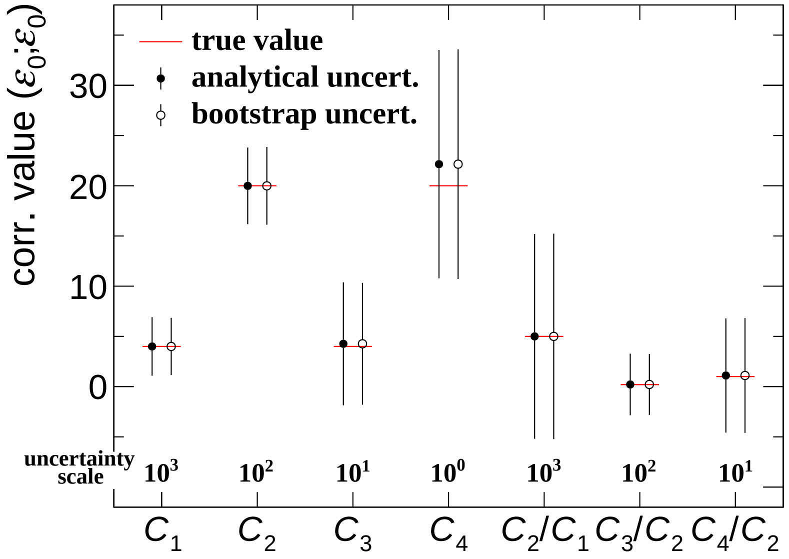
- Positive correlation between initial volume and final multiplicity
- Volume varies within a centrality class defined by multiplicity
  - Stronger volume fluctuation within a broader centrality class
- Cumulants are calculated in each signal multiplicity bin as the finest centrality class
- Averages are taken within a broad centrality class
  - $C_r = \frac{\sum_i n_i C_{r,i}}{\sum_i n_i} = \sum_i w_i C_{r,i}$
  - n_i: number of events in ith multiplicity bin
  - $w_i = n_i / \sum_i n_i$



X. Luo, J. Xu, B. Mohanty, N. Xu, JPG 40, 105104 (2013)
STAR PRC 104, 024902

Statistical Uncertainty Estimation

- Analytical formulae: derived by covariances with various terms of correlations
  - $\mathrm{Error}\left(\hat{C}_r^{\mathrm{corr}}\right) = \sqrt{\mathrm{Var}\left(\hat{C}_r^{\mathrm{corr}}\right)} = \mathrm{Cov}\left(\hat{C}_r^{\mathrm{corr}}, \hat{C}_r^{\mathrm{corr}}\right)$
  - $\mathrm{Cov}\left(\hat{C}_r^{\mathrm{corr}}, \hat{C}_s^{\mathrm{corr}}\right) \propto \frac{1}{n}\frac{C_{r+s}}{\varepsilon^{r+s}}$
  - $\mathrm{Var}\left(\frac{\hat{C}_r}{\hat{C}_s}\right) = \frac{\mathrm{Var}\left(\hat{C}_r\right)}{C_s^2} + \frac{C_r^2\,\mathrm{Var}\left(\hat{C}_s\right)}{C_s^4} - \frac{2C_r\,\mathrm{Cov}\left(\hat{C}_r, \hat{C}_s\right)}{C_s^3}$
- Bootstrap method: computation-intensive approach
  - By randomly resampling real data B times
  - $\mathrm{Var}(\Phi) = \frac{1}{B-1}\sum_{b=1}^{B}\left(\Phi_b - \frac{1}{B}\sum_{b\prime=1}^{B}\Phi_{b\prime}\right)^2$
  - Statistical fluctuations including intrinsic correlations reflected



X. Luo, PRC 91, 034907 (2015)
F. Si, Y. Zhang, PRC 105, 024907 (2022)

- Statistical uncertainties estimated through analytical and bootstrap methods are comparable

Systematic Uncertainty Estimation

- Cuts are varied to study systematic variations in results
  - Track quality cuts
  - PID cuts
  - Efficiency varied by a factor of 2% (5% without iTPC in BES-I)

- Barlow check applied to suppress statistical contributions
  - For each varied cut, $Y_{\text{diff}} = Y_{\text{var}} - Y_{\text{def}}$, $\sigma^2_{\text{stat,diff}} = \left|\sigma^2_{\text{stat,var}} - \sigma^2_{\text{stat,def}}\right|$
  - Barlow check requires $Y^2_{\text{diff}} > \sigma^2_{\text{stat,diff}}$
  - Systematic contribution $\sigma_{\text{sys}} = \sqrt{Y^2_{\text{diff}} - \sigma^2_{\text{stat,diff}}}$

R. Barlow, arXiv:hep-ex/0207026

Improvements in BES-II

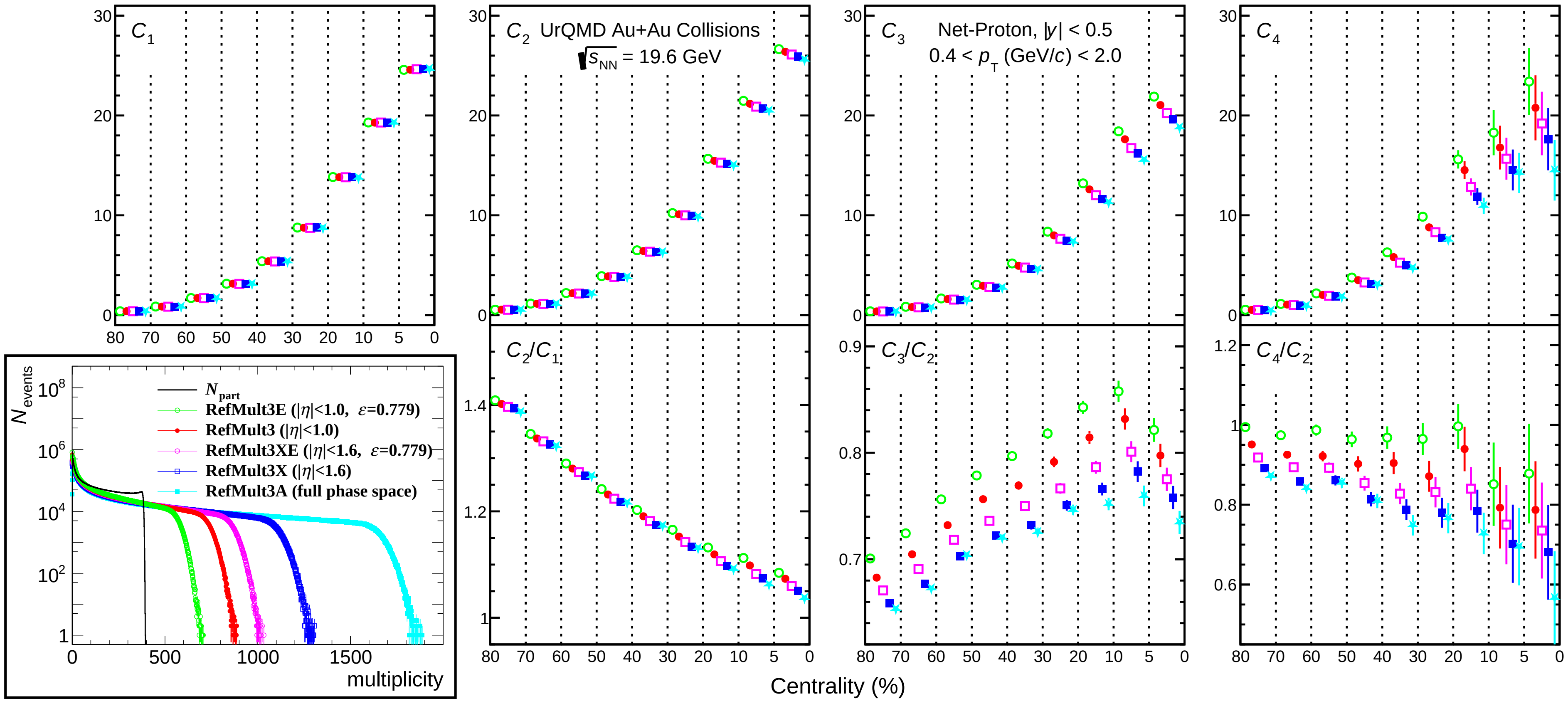
- More collision energies: 9.2 GeV and 17.3 GeV
  - Finer scan of μ_{B} in the phase diagram
- Better statistics
  - Event statistics enlarged by a factor of 7–18
  - $\sim$10% higher tracking efficiency from iTPC
- Better systematics
  - Tracking and PID performance improved by iTPC
  - Efficiency uncertainty suppressed from 5% down to 2%
- Better centrality resolution
  - Low-p_{T} tracking enhanced
  - Acceptance expanded

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

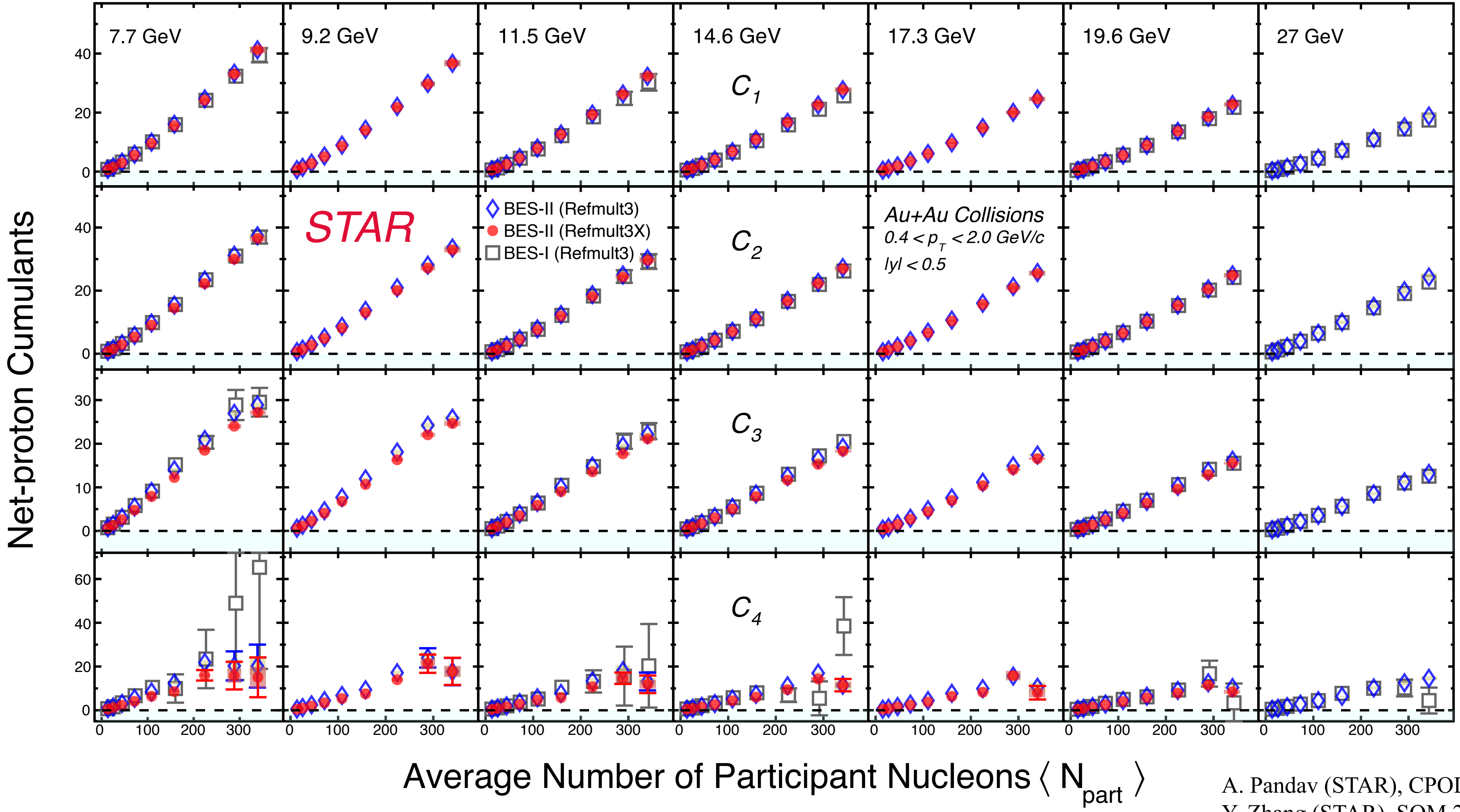
A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

Centrality Resolution Effect in UrQMD (19.6 GeV)



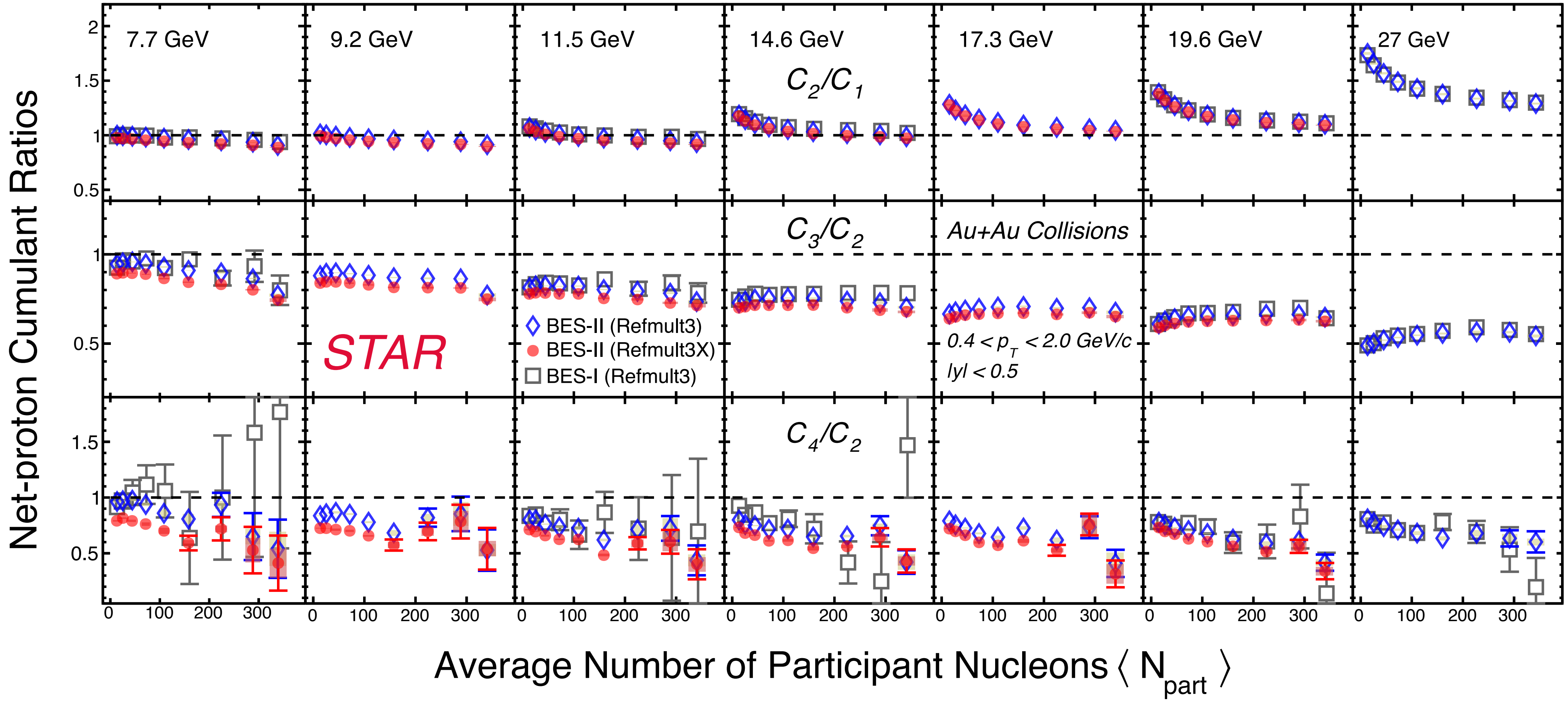
1. Better centrality resolution ⇒ lower cumulants/ratios (especially in mid-central events)
   Results from RefMult3A < RefMult3X < RefMult3XE < RefMult3 < RefMult3E
2. A saturation of centrality resolution effect observed comparing results from RefMult3A and RefMult3X
   Measurement using RefMult3X is supported
3. For 0–5% C_4/C_2, weak effect of centrality resolution

Cumulants vs. Centrality and Collision Energy



A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

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)

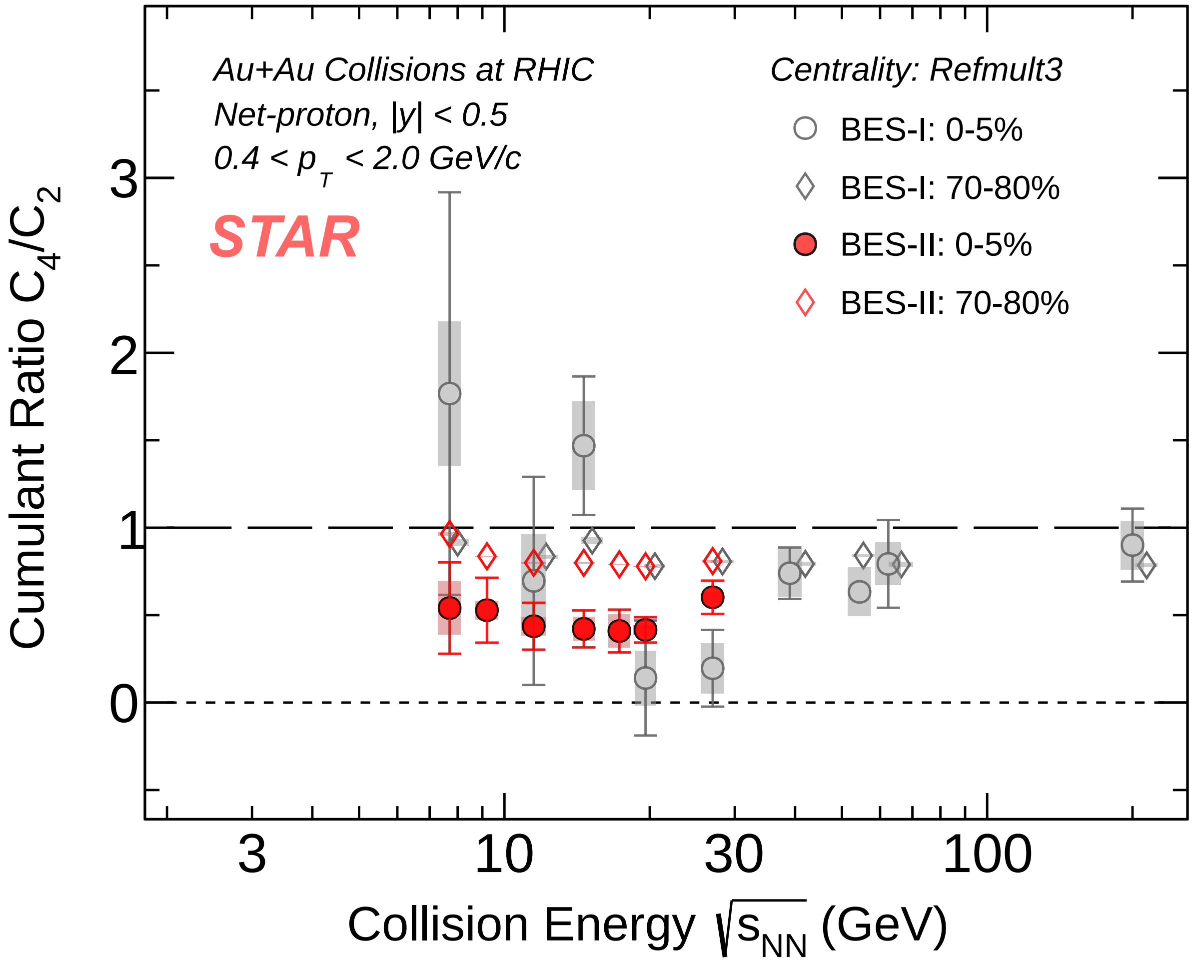
   Results from RefMult3X (BES-II) < RefMult3 (BES-II) < RefMult3 (BES-I)
3. For 0–5% C_4/C_2, weak effect of centrality resolution

A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

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

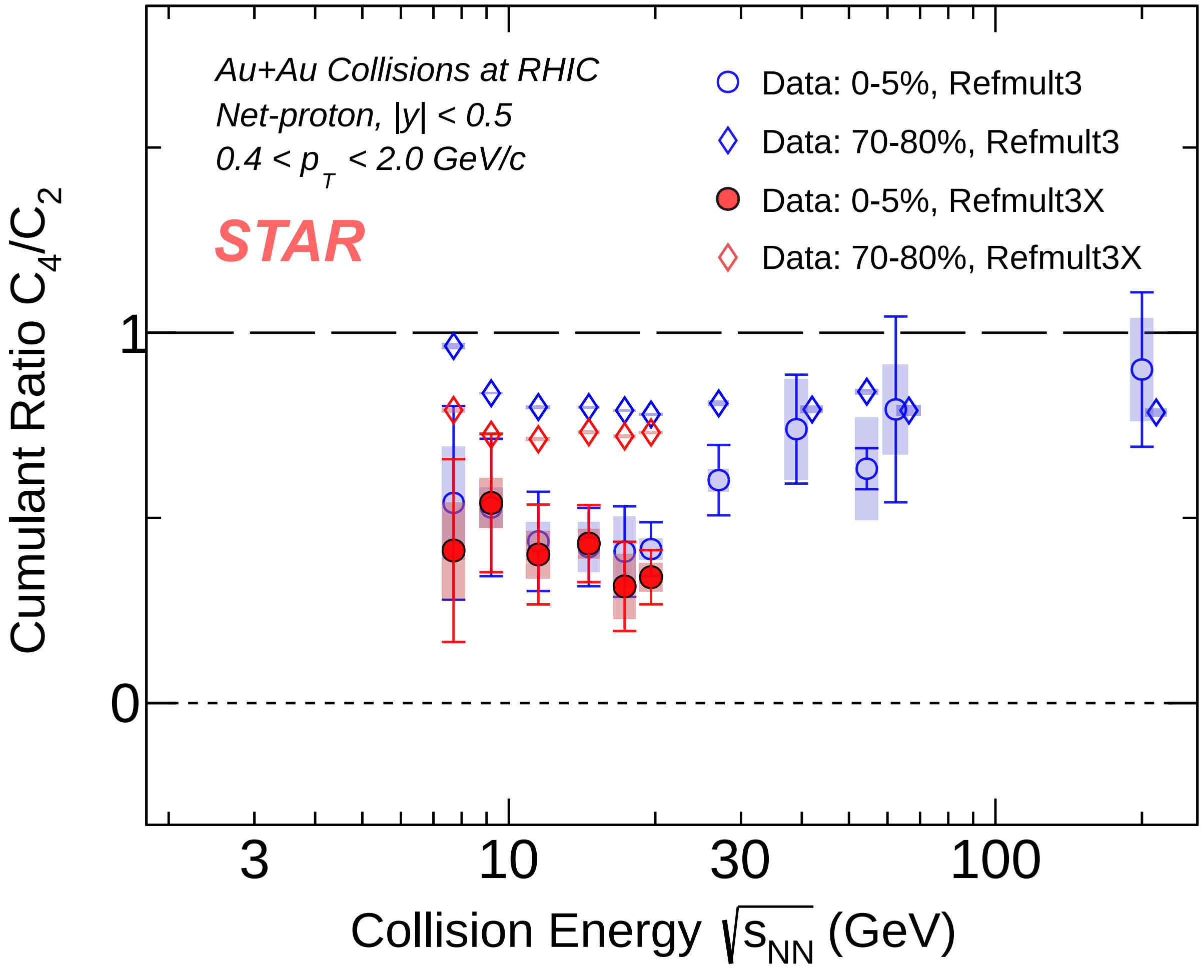


- BES-II results consistent with BES-I mostly within $\sim 1\sigma$

A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

Effect of Centrality Resolution on C_4/C_2

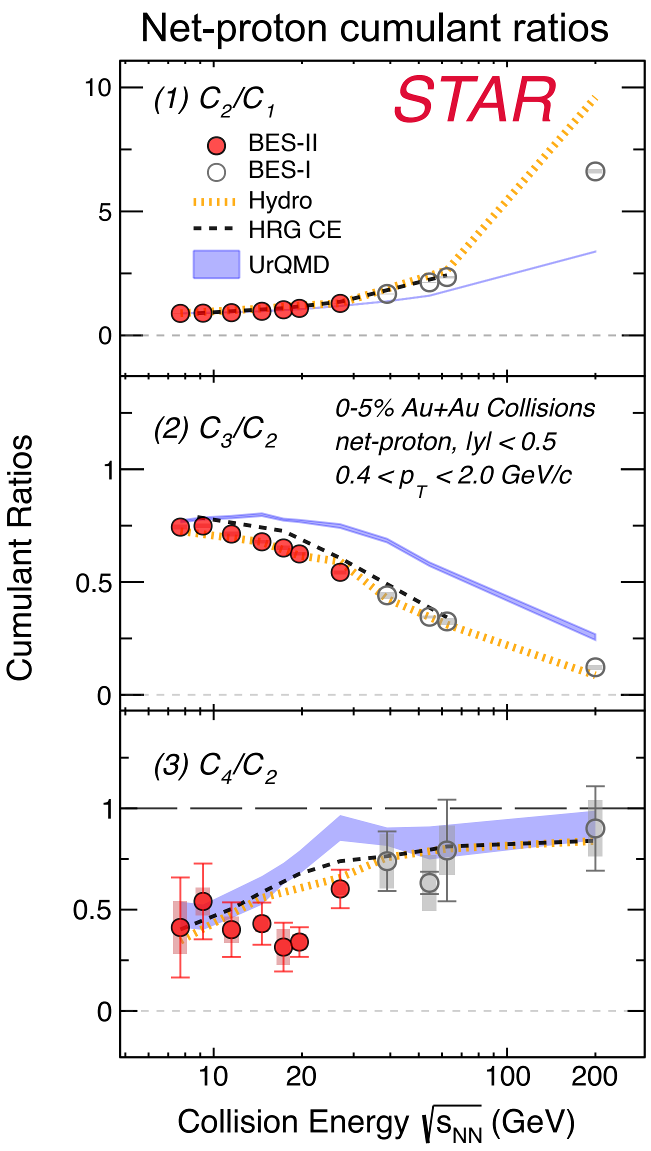
- For C_4/C_2 at 70–80% centrality, clear deviation between RefMult3/3X
  - Smaller difference at higher energy
- For C_4/C_2 at 0–5% centrality, results from RefMult3 and RefMult3X show good agreement with each other
  - Weak effect of centrality resolution



A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

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)



A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

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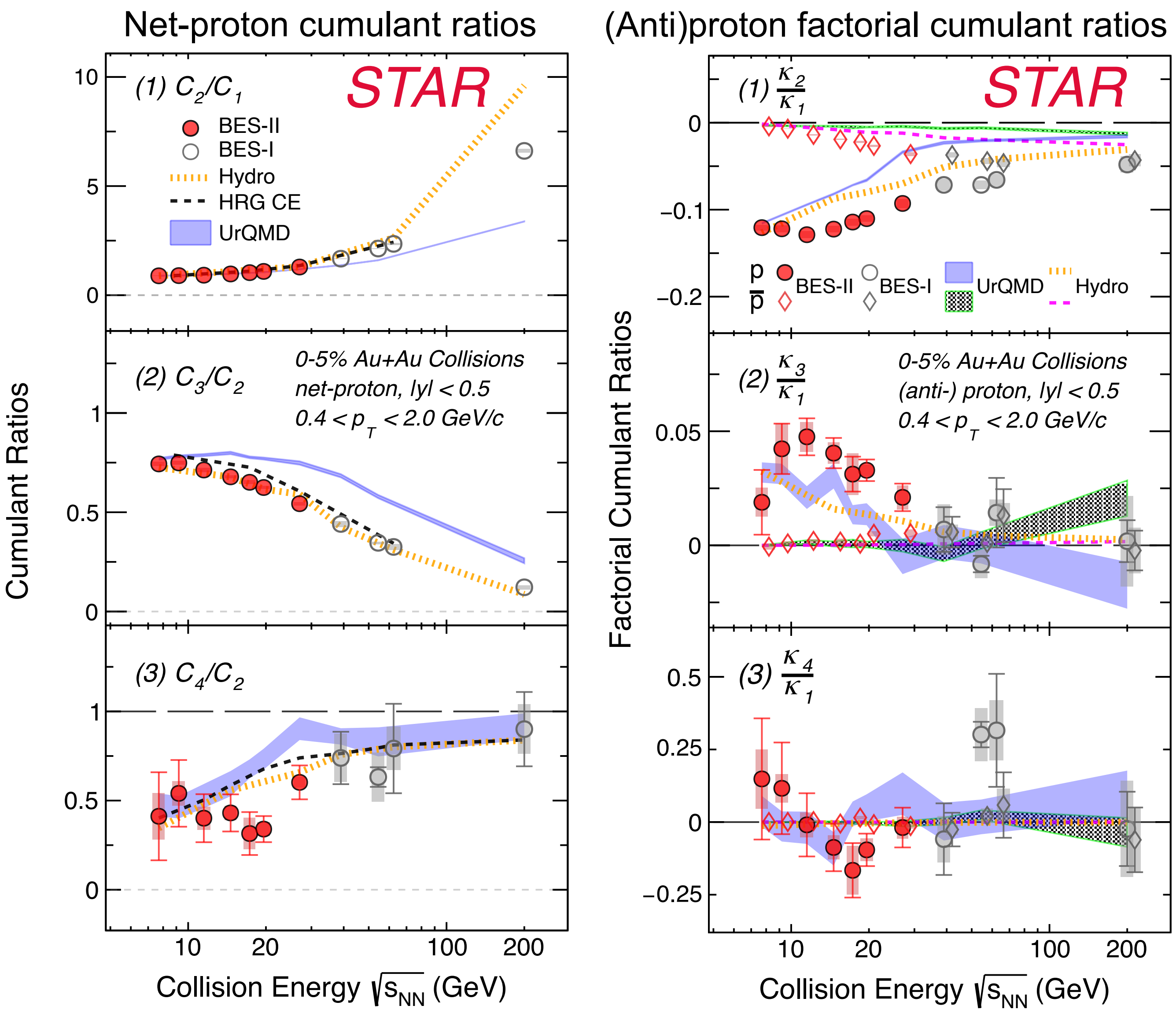
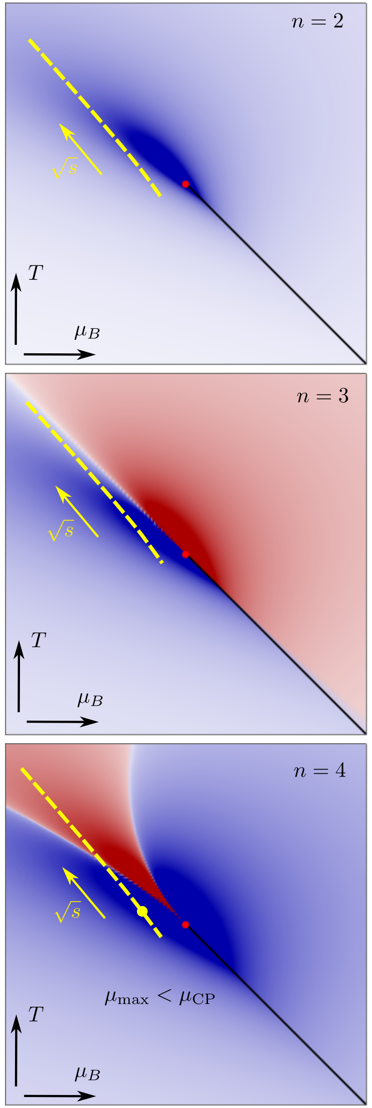
  P. B Munzinger *et al.*, NPA 1008, 122141 (2021)
  3. UrQMD: hadronic transport model
  S. A. Bass *et al.*, PPNP, 41, 255 (1998)
- Proton κ ratios deviate from Poisson baseline at 0
  Antiproton κ_3/κ_1 and κ_4/κ_1 closer to 0
- Clear deviations in net-proton C_4/C_2 and proton κ ratios from models

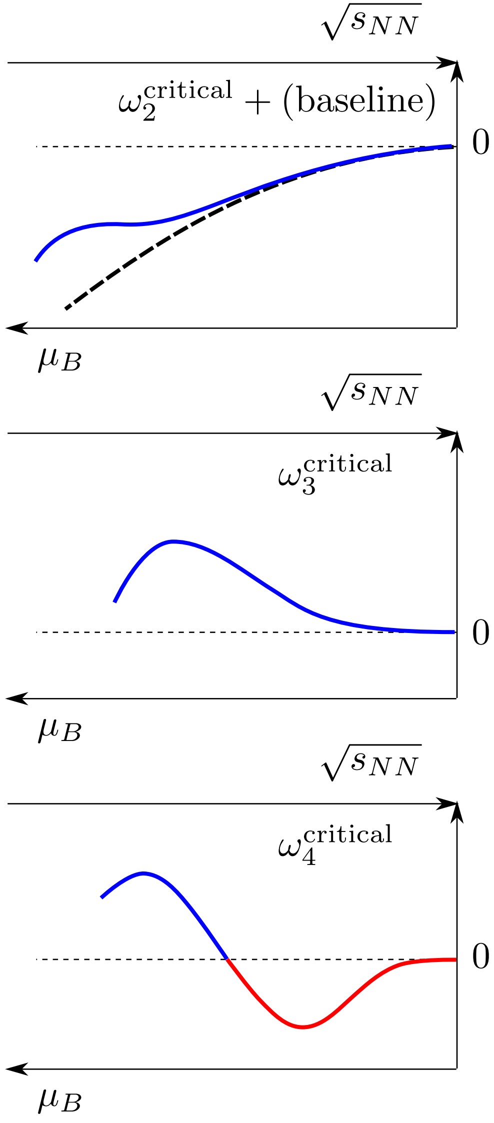
A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

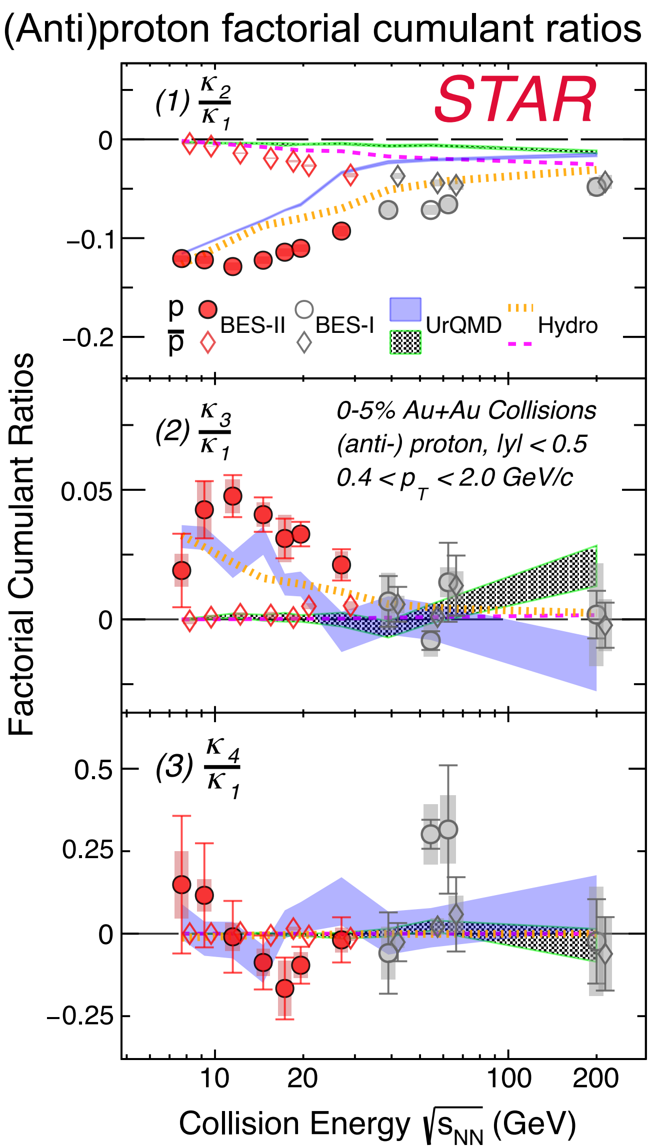


Comparison with Expected Critical Signature

- Left column
  - Positive/negative contrib. to cumulants around CP
- Middle column
  - $\omega_r = \kappa_r/\kappa_1$ of protons
- Qualitative consistency
- κ_2/κ_1: Decrease likely interrupted below 11.5 GeV
- κ_3/κ_1: peak at ~11.5 GeV
- κ_4/κ_1: dip at ~19 GeV, enhancement at lower energy

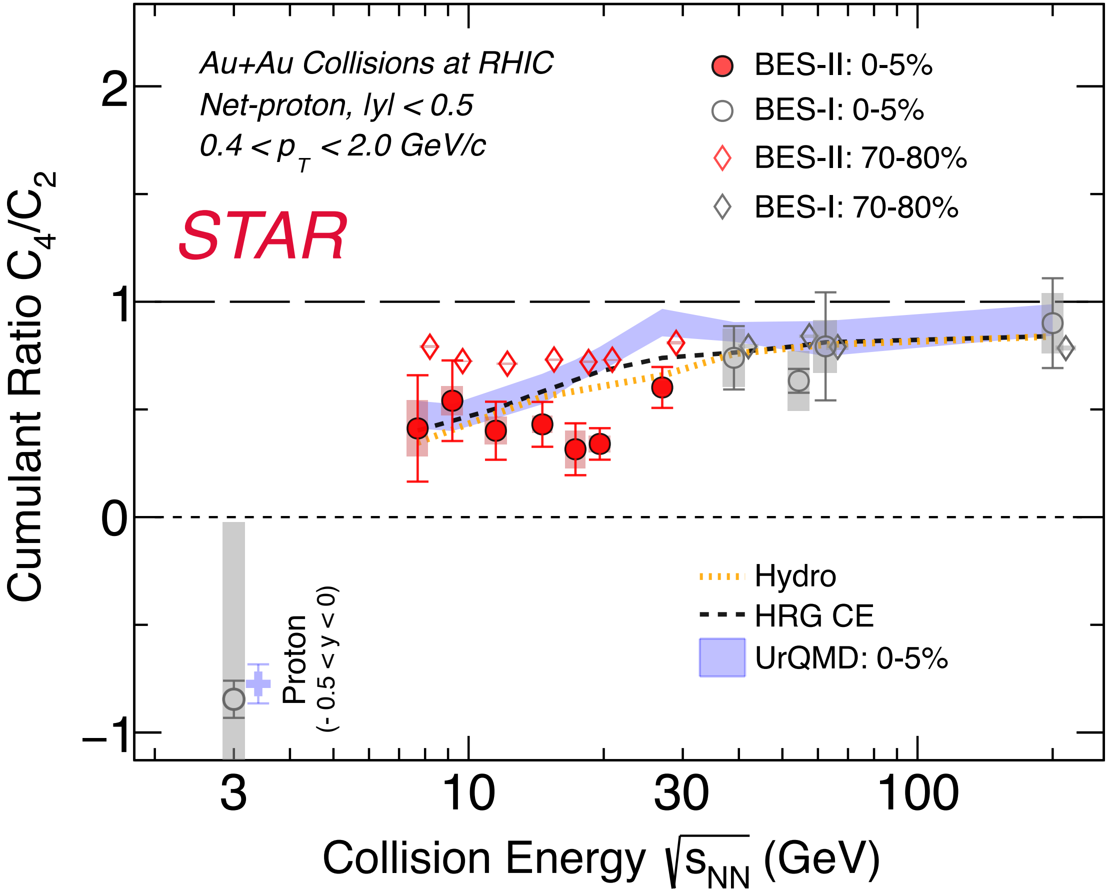






A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024
M. Stephanov, arXiv:2410.02861

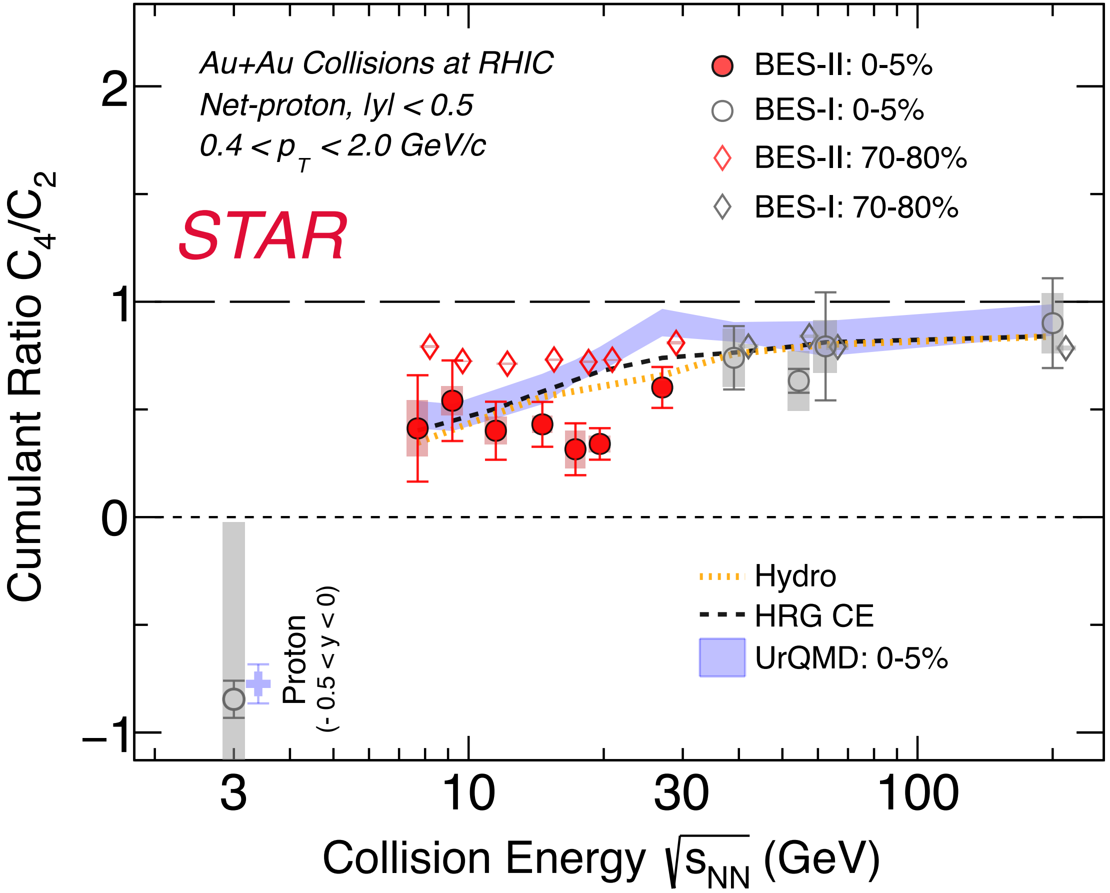
Collision Energy Dependence of C_4/C_2

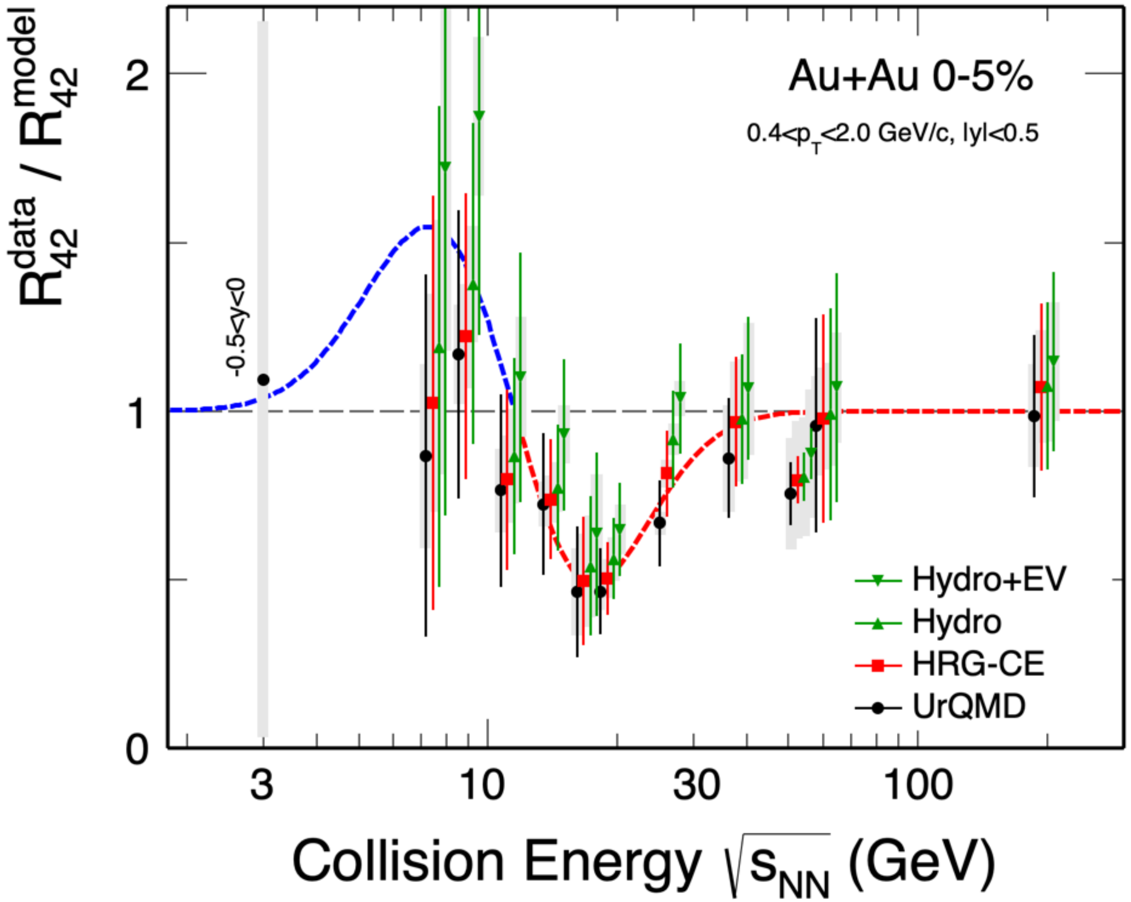


- C_4/C_2 (0–5%) shows a minimum at $\sqrt{s_{\mathrm{NN}}} \sim 20$ GeV w.r.t non-CP models and 70–80% data

A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

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

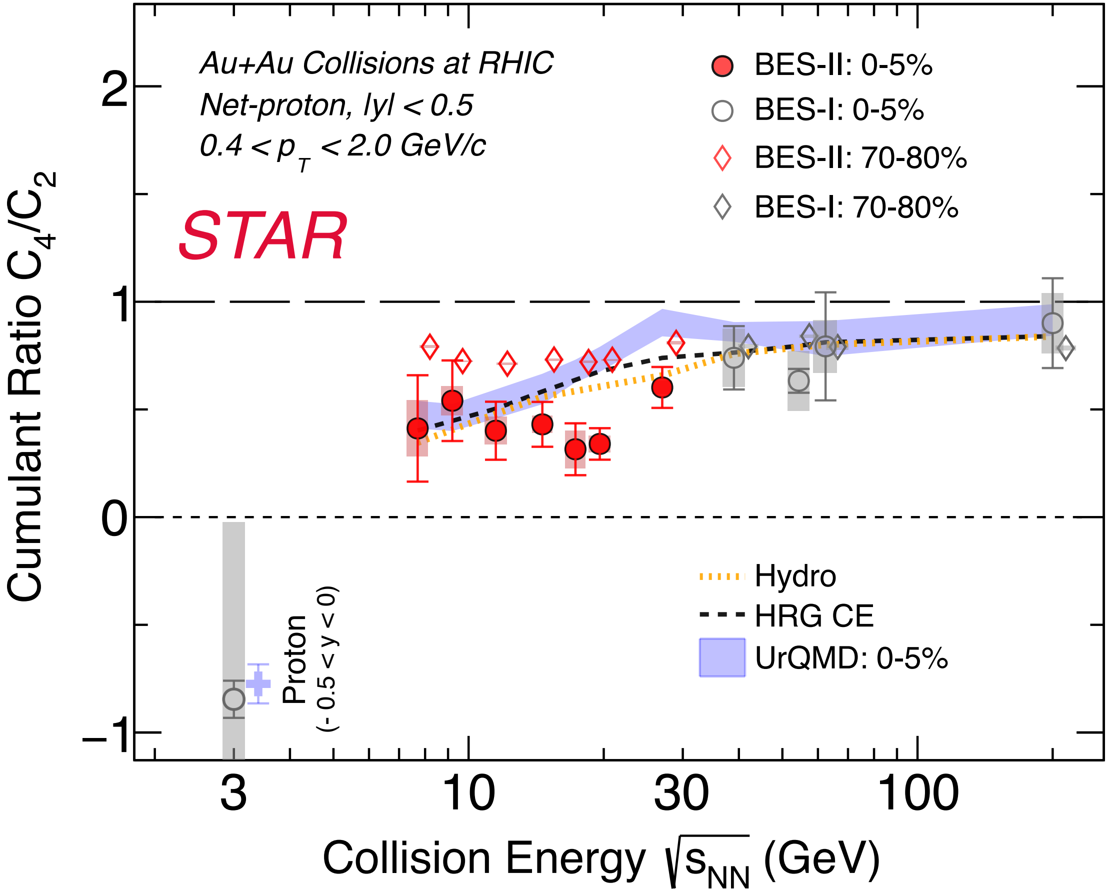


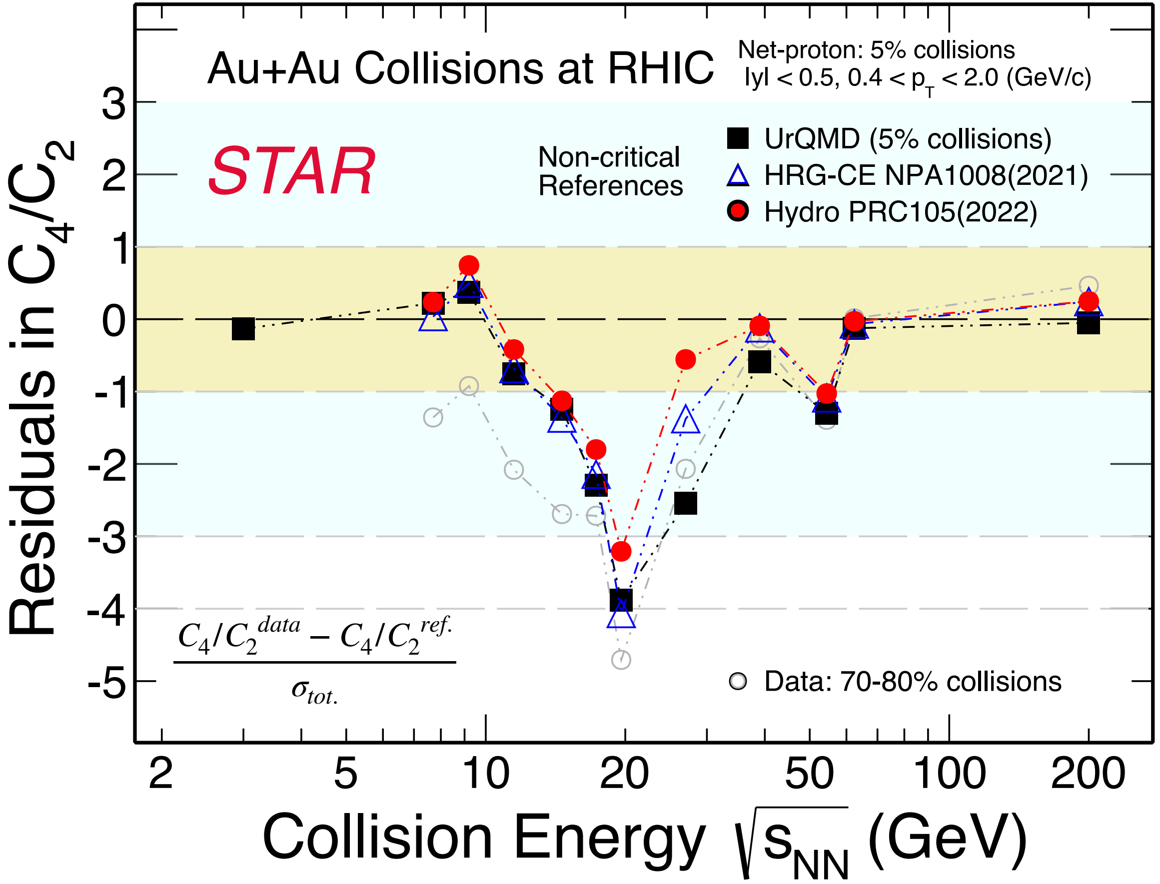


- C_4/C_2 (0–5%) shows a minimum at $\sqrt{s_{NN}} \sim 20$ GeV w.r.t non-CP models and 70–80% data
  - Maximum deviation around 20 GeV: 3.2–4.7σ (1.3–2σ at BES-I)
  - Overall deviation from 7.7 to 27 GeV: 1.9–5.4σ (1.4–2.2σ at BES-I)

A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024
X. Dong, DNP Fall 2024

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





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A. Pandav (STAR), CPOD 2024
Y. Zhang (STAR), SQM 2024

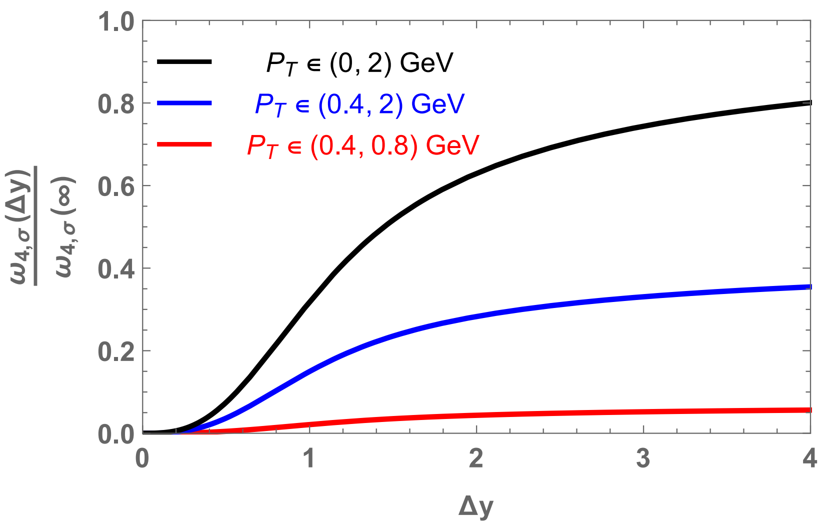
Summary

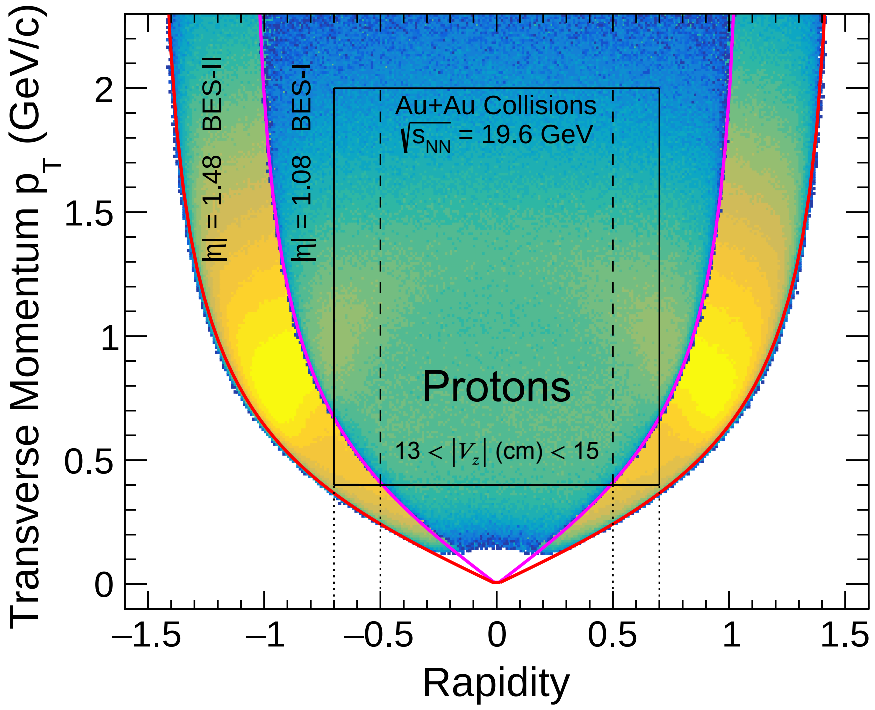
- Precision measurement of net-proton number fluctuations from STAR BES-II, including collision centrality and energy dependence at $\sqrt{s_{\mathrm{NN}}} = 7.7\text{–}27$ GeV

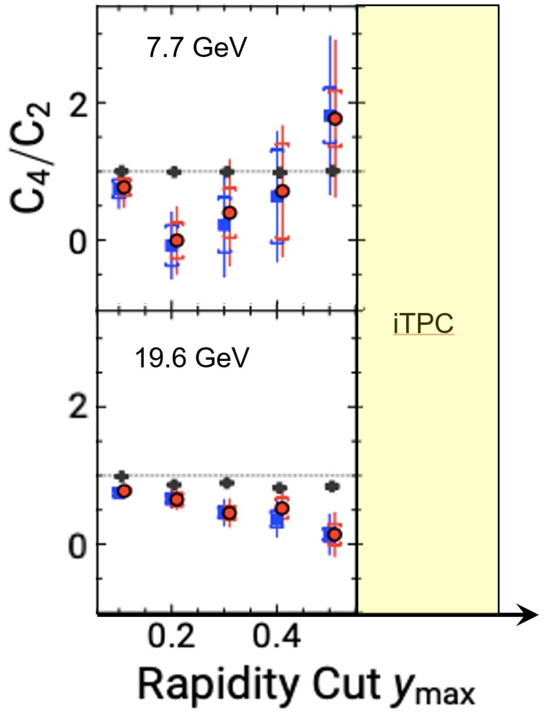
- Compared to BES-I,
  better statistical precision, better control on systematics, better centrality resolution.

- Compared to non-critical references (models and peripheral data),
  central C_4/C_2 shows a maximum deviation at $\sqrt{s_{\mathrm{NN}}} \sim 20$ GeV ($3.2\text{–}4.7\sigma$).

Outlook: Acceptance Scan

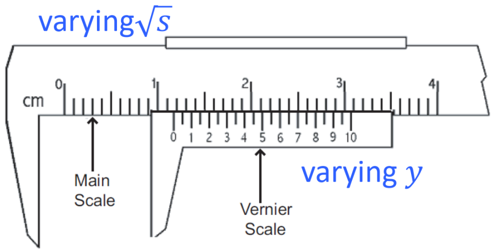


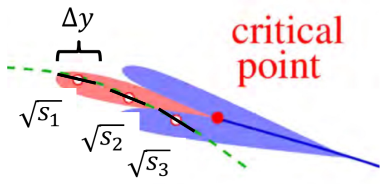




- Stronger fluctuations expected within wider acceptance

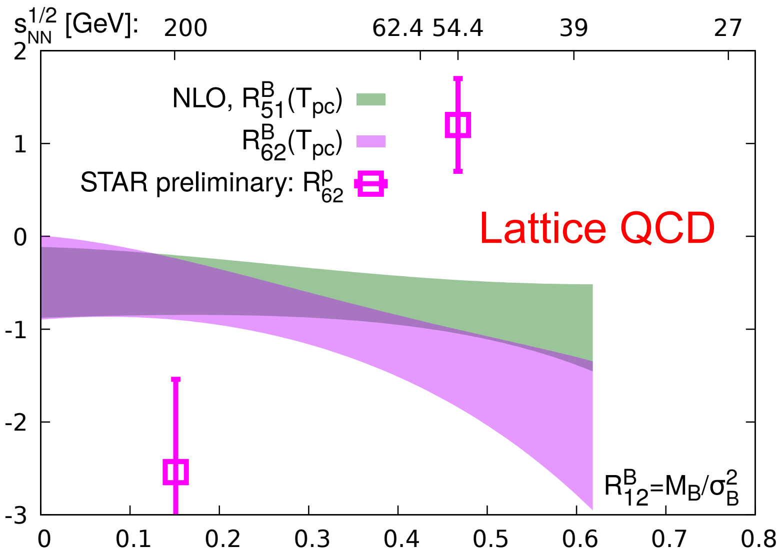
- Rapidity extension with iTPC: beyond $|y| < 0.5$
- Differential rapidity scan: $|y - y_c| < \Delta y/2$

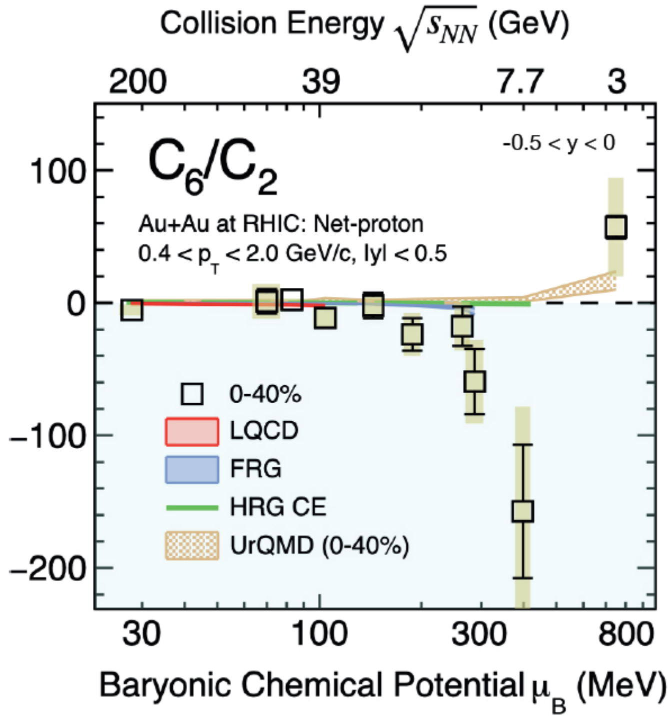


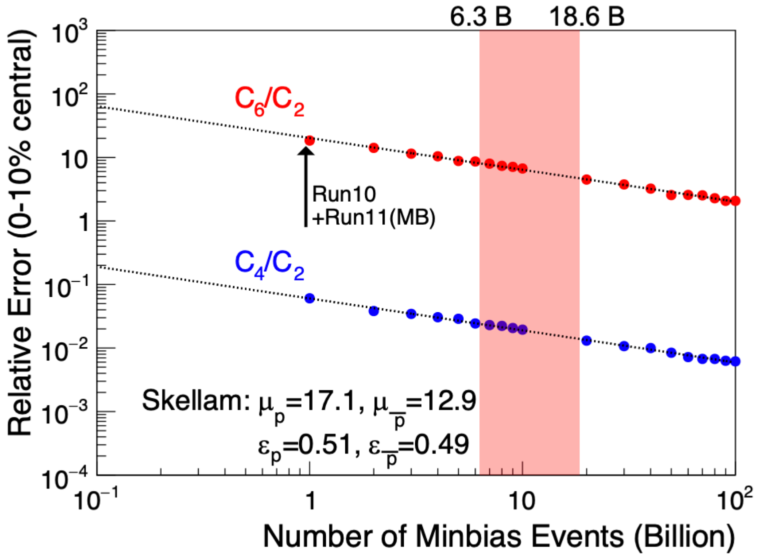


B. Ling, M. Stephanov, PRC 93, 034915 (2016)
Y. Huang, RHIC/AGS 2024
J. Brewer, S. Mukherjee, K. Rajagopal, PRC 98, 061901 (2018)

Outlook: Hyper-Order Fluctuations



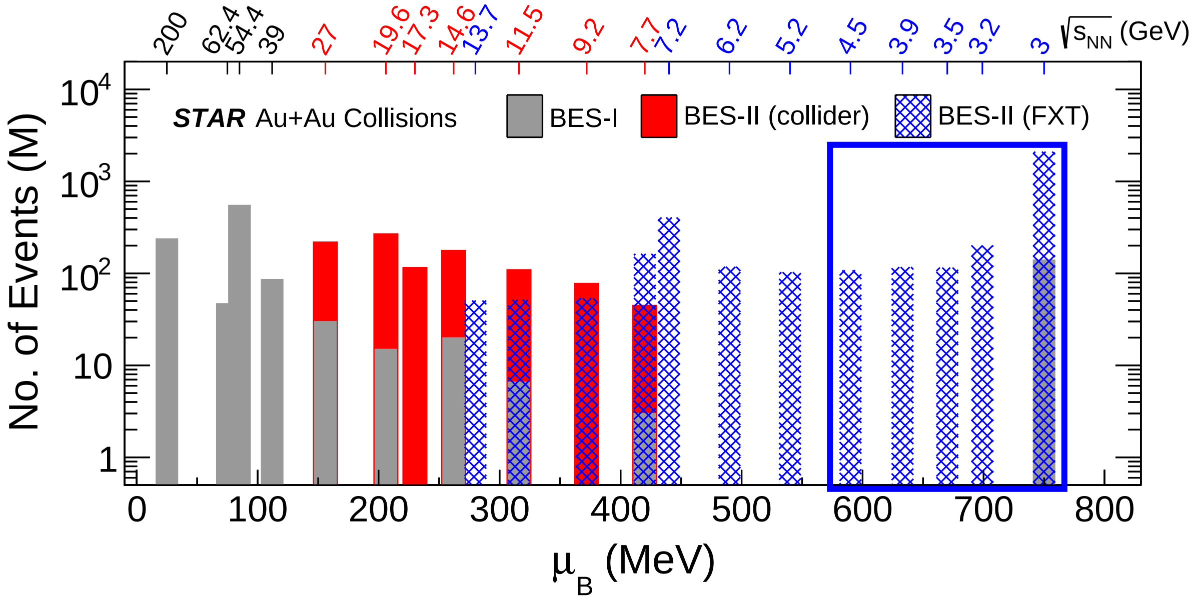


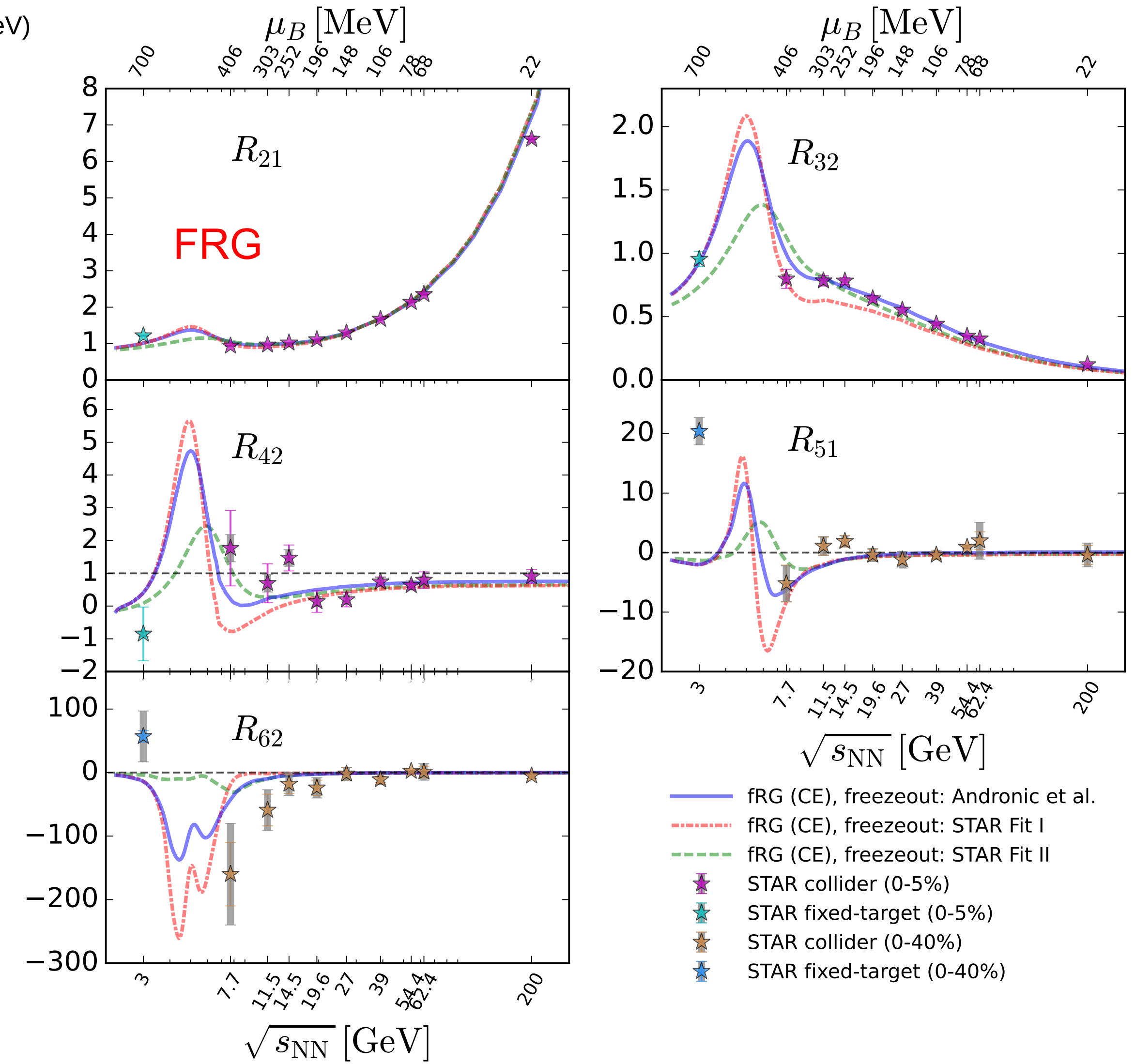


- Measurement of hyper-order fluctuations with better statistics
  - Sensitive to crossover signal
  - Vulnerable to backgrounds
  - Hungry for statistics
  - Could provide higher precision in BES-II

A. Bazavov *et al.*, PRD 101, 074502 (2020)
STAR, PRL 130, 082301 (2023)

Outlook: Extended Energy Range (FXT)

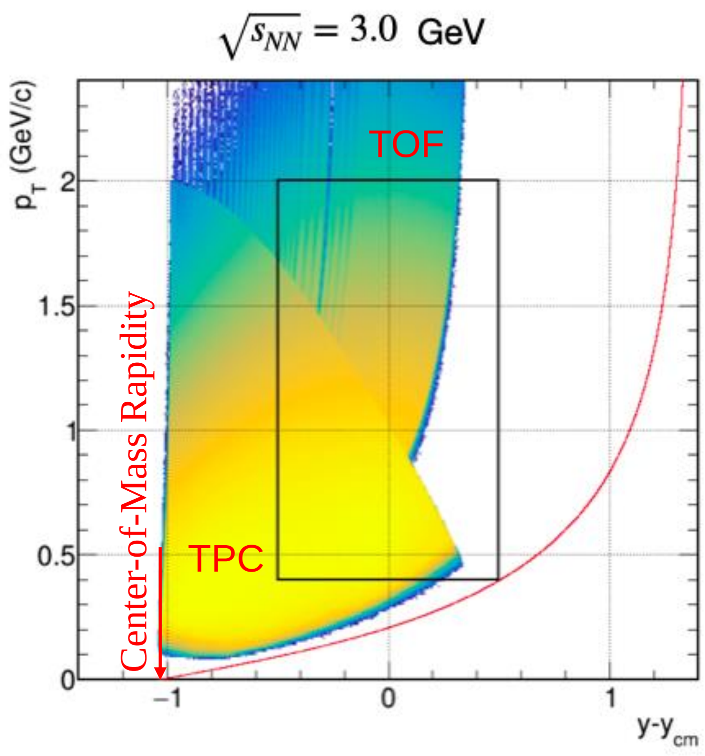


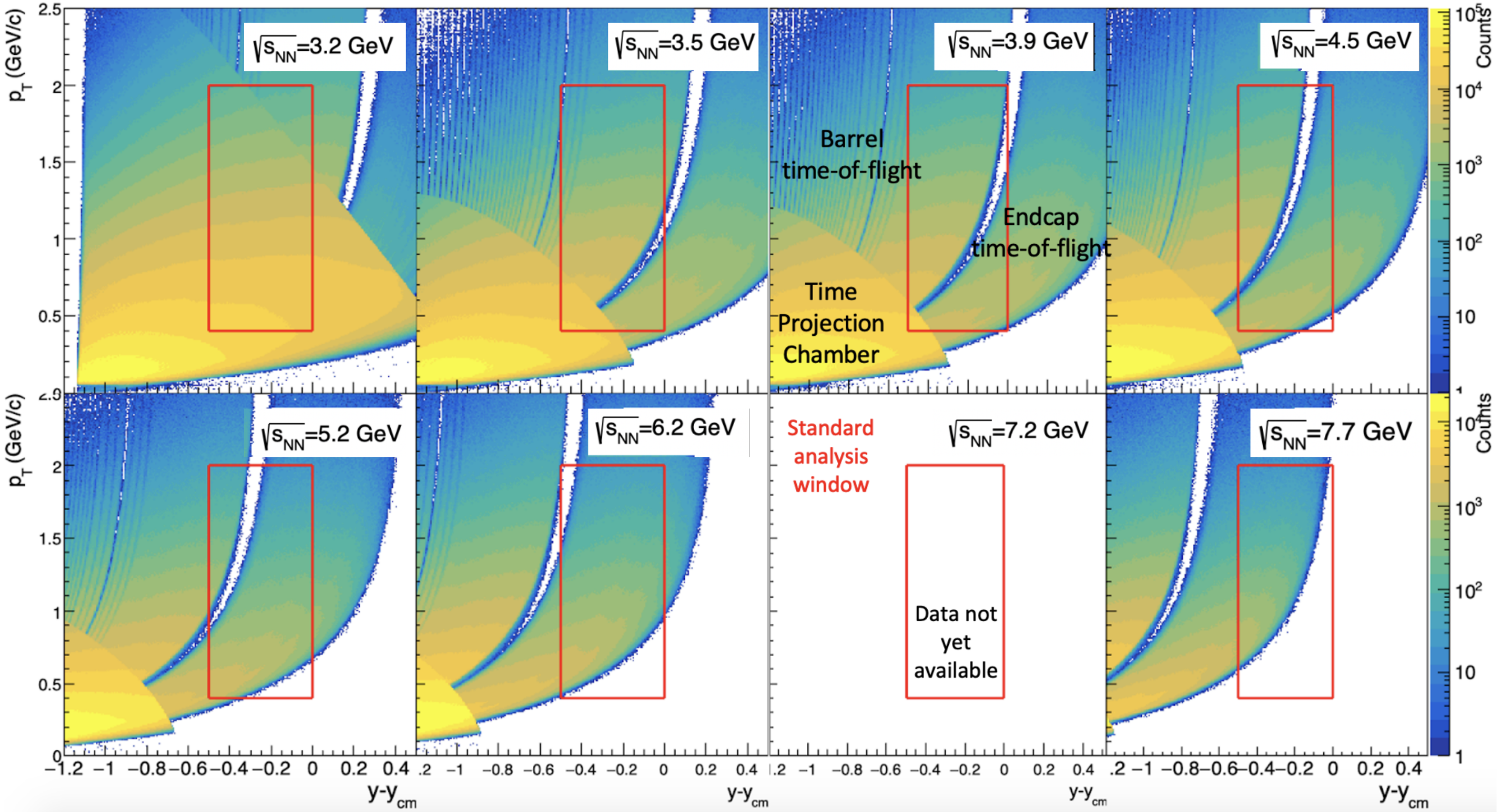


- Crucial to fill in energy gap at 3–7.7 GeV
  - μ_B extended from 420 MeV up to 750 MeV
- Several critical structures expected by FRG

W.-j. Fu, X. Luo, J. M. Pawlowski, F. Rennecke, S. Yin, arXiv:2308.15508

Challenge: Proton Acceptance in FXT Data Sets





Z. Sweger (STAR), QM 2023

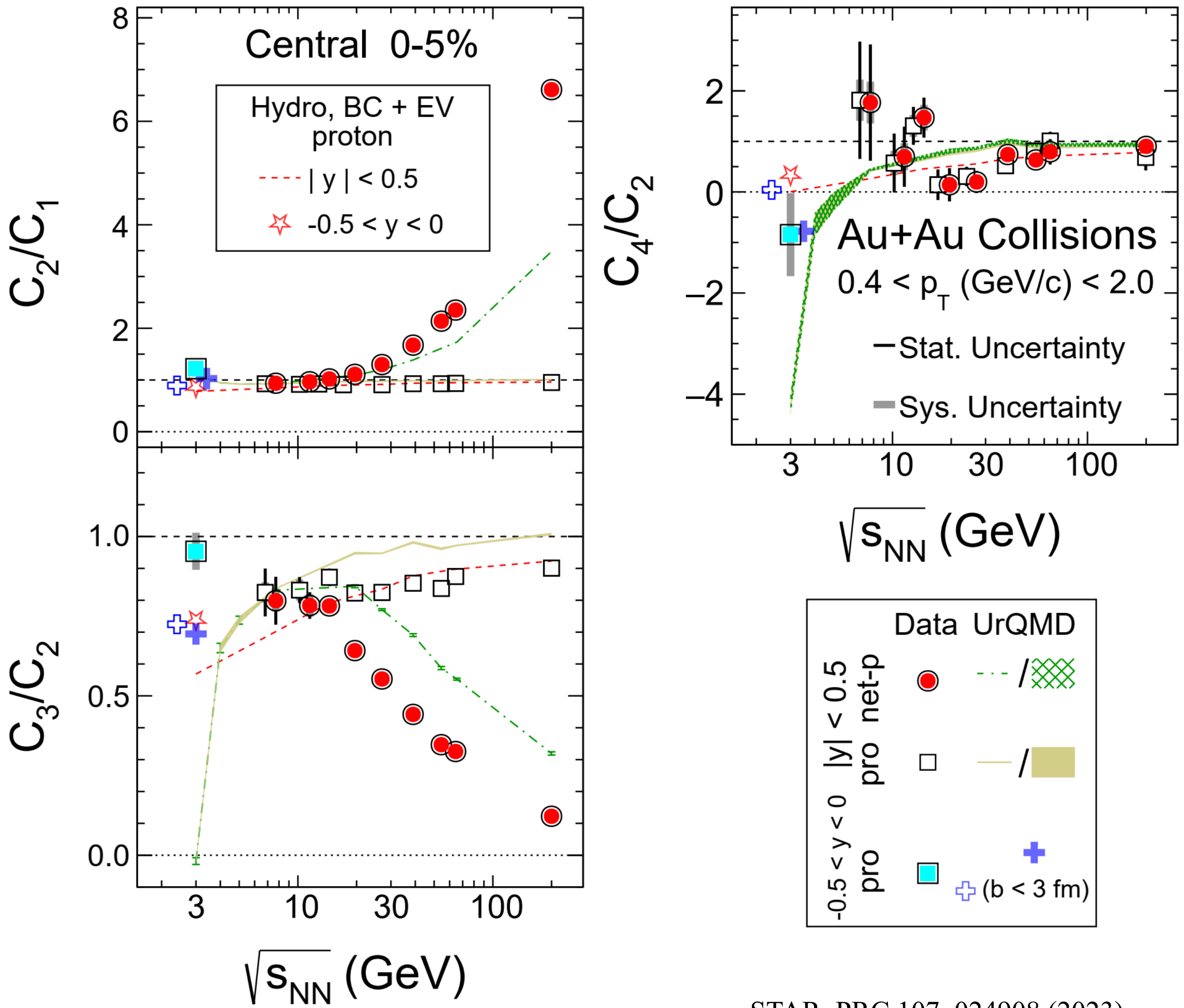
- Default analysis window: 0.4 GeV/$c < p_T < 2$ GeV/c, $-0.5 < y < 0$
  - Not fully covered by detectors for $\sqrt{s_{NN}} > 4.5$ GeV
  - Might be extended to $|y| < 0.5$ for $\sqrt{s_{NN}} = 3$ GeV (Run 21 with iTPC)
- TOF PID required at high momenta with low proton purity: a gap between bTOF and eTOF

Challenge: Half Rapidity Window in FXT analysis

- Models provide quite different results in half and symmetric mid-rapidity windows at $\sqrt{s_{NN}} = 3$ GeV
  - $-0.5 < y < 0$
  - $|y| < 0.5$
- Necessary to be studied in energy dependence in experiments

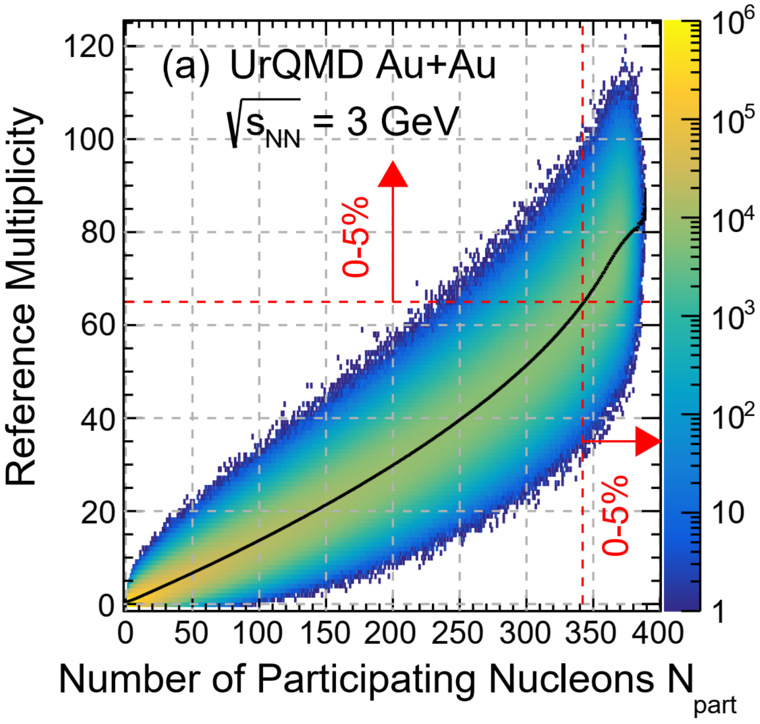
Proton number C_4/C_2 at $\sqrt{s_{NN}} = 3$ GeV

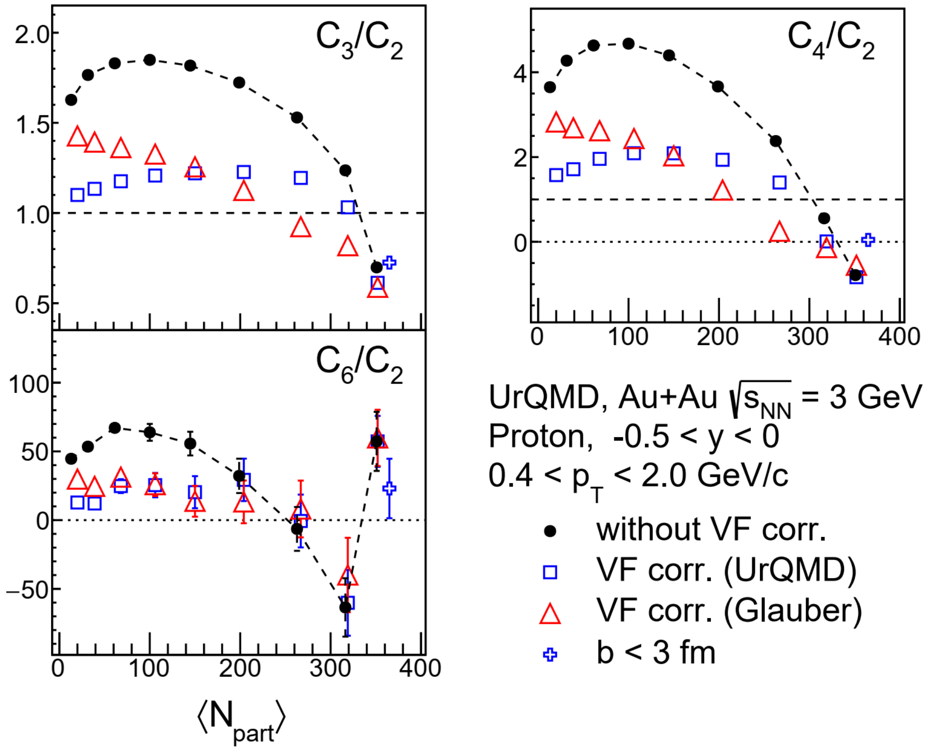
C_4/C_2	$-0.5 < y < 0$	$\|y\| < 0.5$
Data	~ -1	?
UrQMD	~ -1	~ -4
Hydro	~ 1	~ 0



STAR, PRC 107, 024908 (2023)

Challenge: Volume Fluctuation at Low Energy

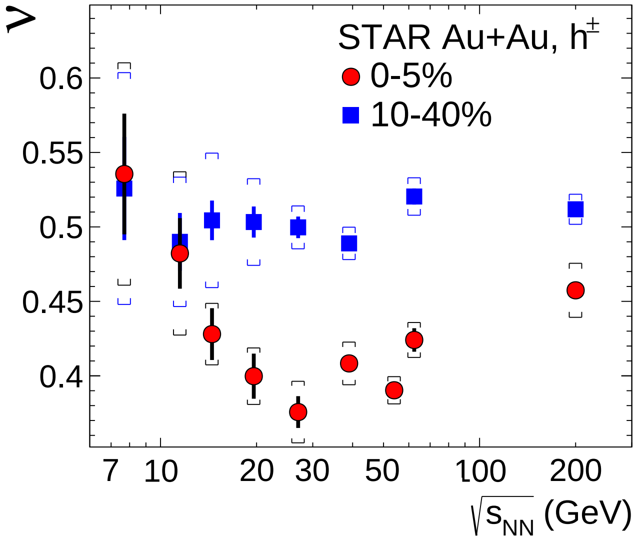


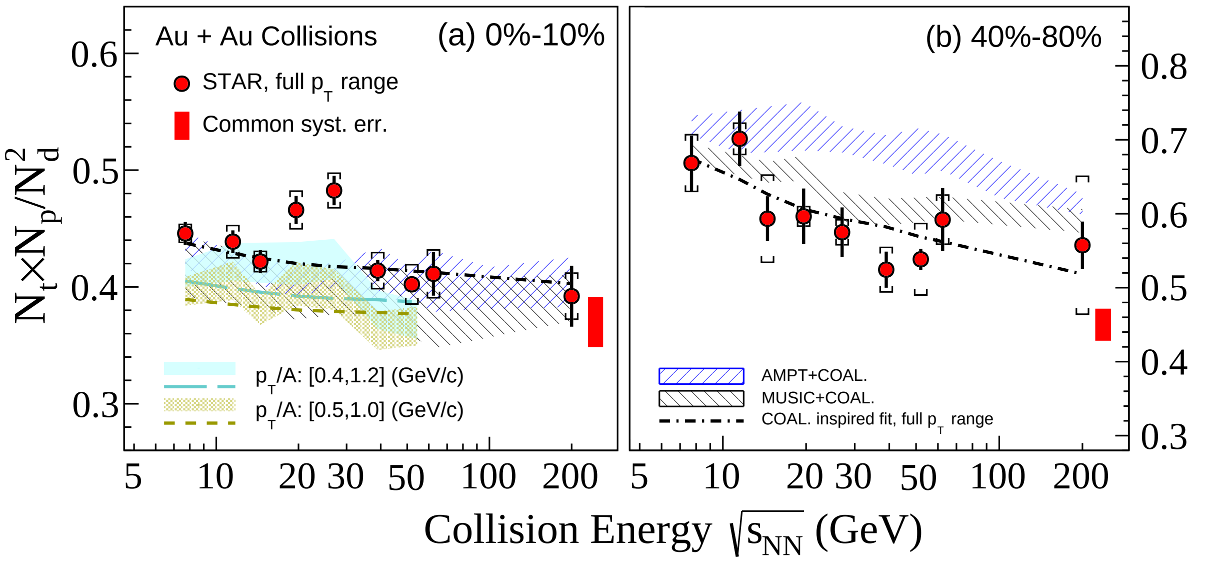


- Small charged-particle multiplicity at low collision energy
  - N_{part} varies a lot within a centrality class defined by multiplicity
  - Bad centrality resolution with large volume fluctuation
- Volume fluctuation correction (HADES, PRC 102, 024914) could help suppress such effect

STAR, PRC 107, 024908 (2023)

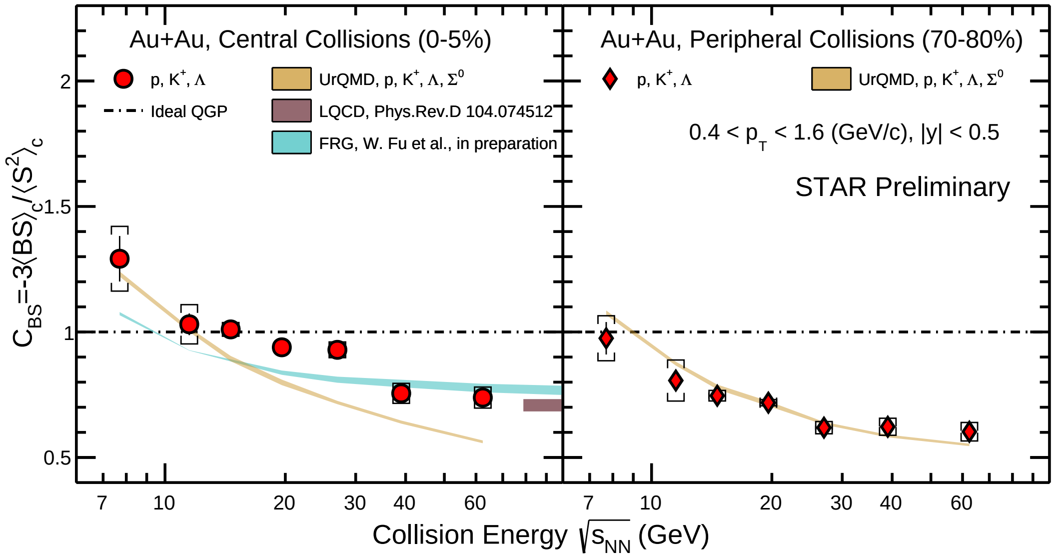
Outlook: Other Observables





- Charge-hadron intermittency (ν): BES-I
- Triton yield ratio ($N_t N_p / N_d^2$): BES-I
- Baryon-strangeness correlation (C_{BS})

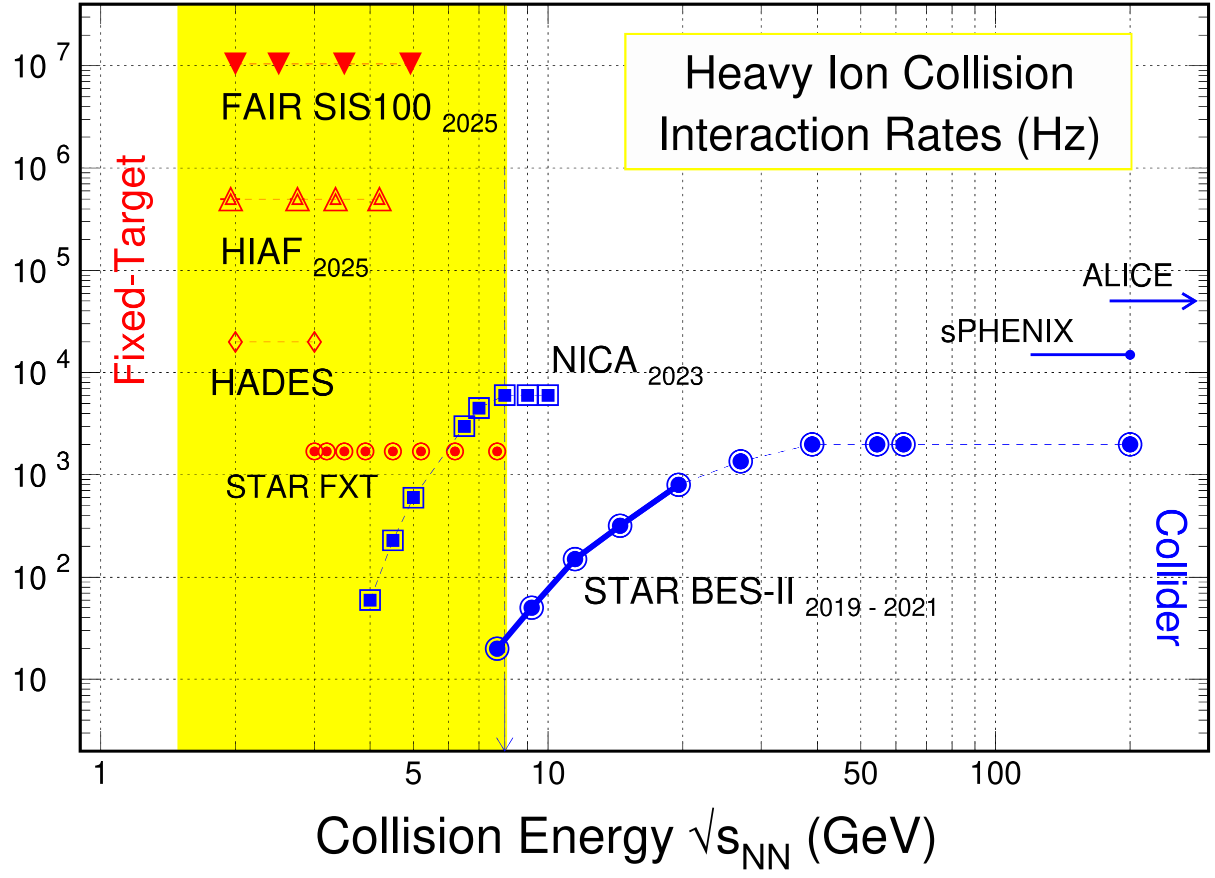
- Non-monotonic behavior or deviation from non-CP models around 20 GeV



STAR, PLB 845, 138165 (2023)
STAR, PRL 130, 202301 (2023)
H. Feng (STAR), CPOD 2024

Outlook: Future Facilities/Experiments

More experiments for the physics at high baryon density are anticipated.



B. Mohanty, N. Xu, arXiv:2101.09210

Acknowledgements

Alphabetically: Xin Dong, ShinIchi Esumi, Yige Huang, Xiaofeng Luo, Bedangadas Mohanty, Bappaditya Mondal, Toshihiro Nonaka, Ashish Pandav, Zachary Sweger, Nu Xu, Yongcong Xu, Xin Zhang, Yifei Zhang, Yu Zhang and STAR Collaboration

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