WQC symposium on quantum simulation of lattice gauge theory (QSLGT)

Experimental Scan of the QCD Phase Diagram

— (Net-)Proton Number Fluctuations in Relativistic Heavy-Ion Collisions

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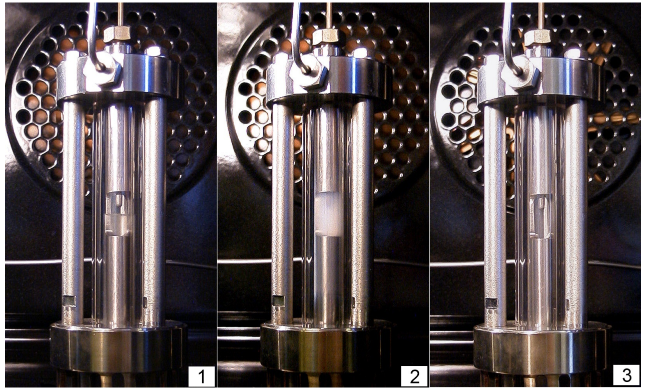
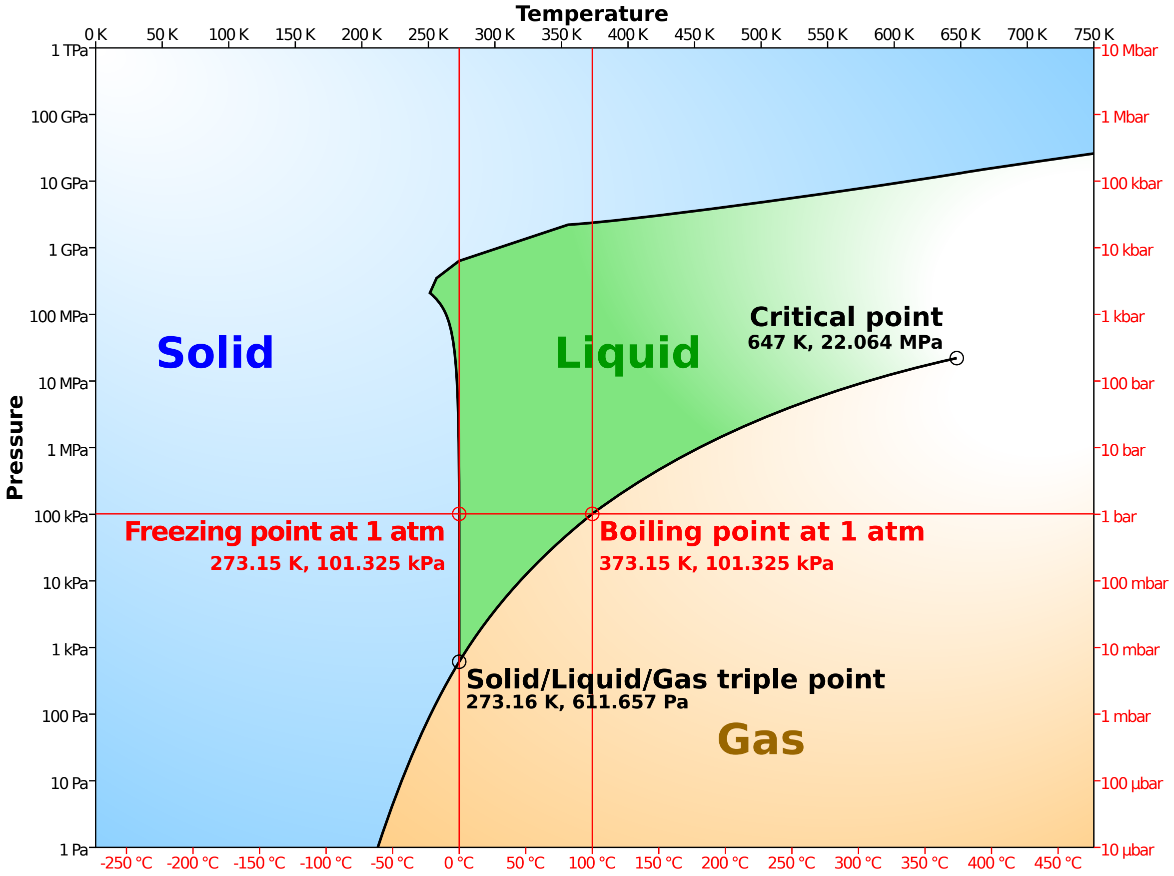
Outline

- 1. Introduction
- 2. Selected Results
  - (Net-)Proton Fluctuations (7.7–27 GeV)
  - Proton Fluctuations (3.2–3.9 GeV)
- 3. Summary and Outlook

Introduction: Phase Diagram of Water

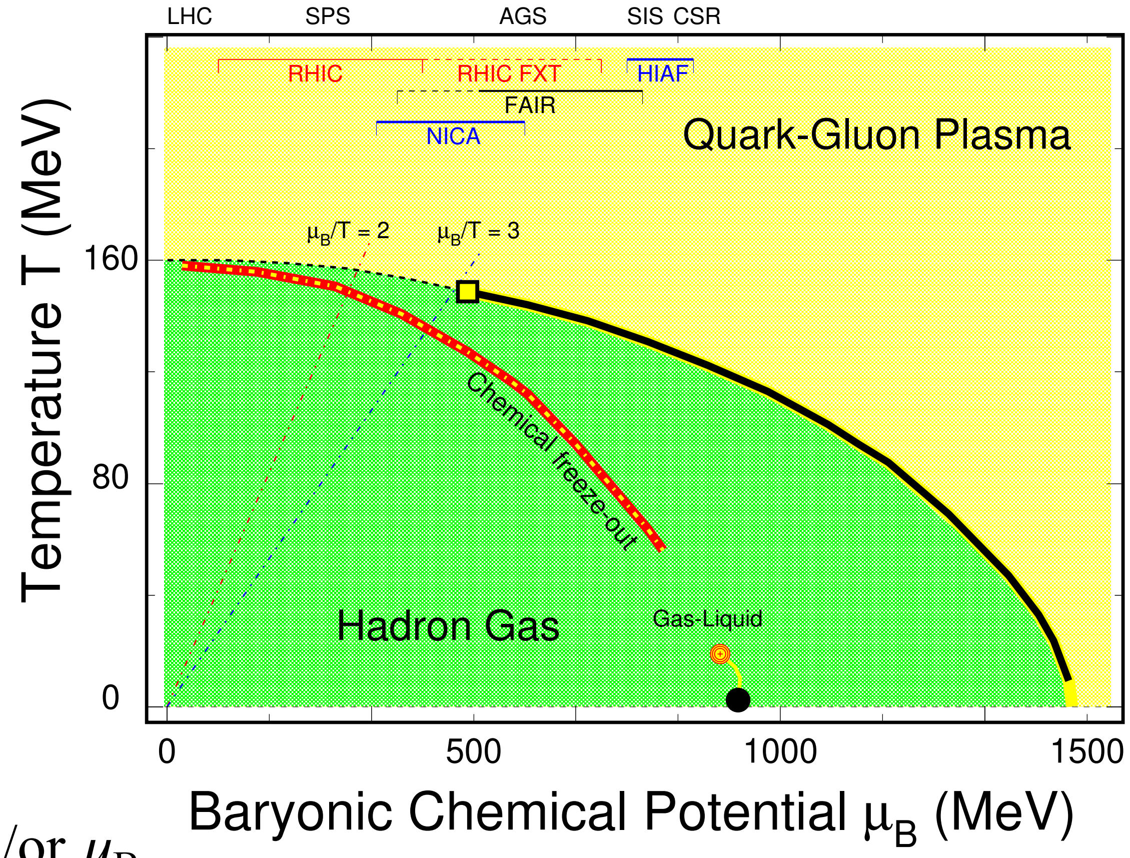
- Governed by electromagnetic interaction
  - Dependence on temperature (T) and pressure
- Phase boundaries between solid, liquid, gas
  - First-order phase transitions
- Critical point: endpoint of liquid-gas boundary
  - Second-order phase transition
  - Long-range correlation, density fluctuation
  - Critical opalescence





Introduction: QCD Phase Diagram

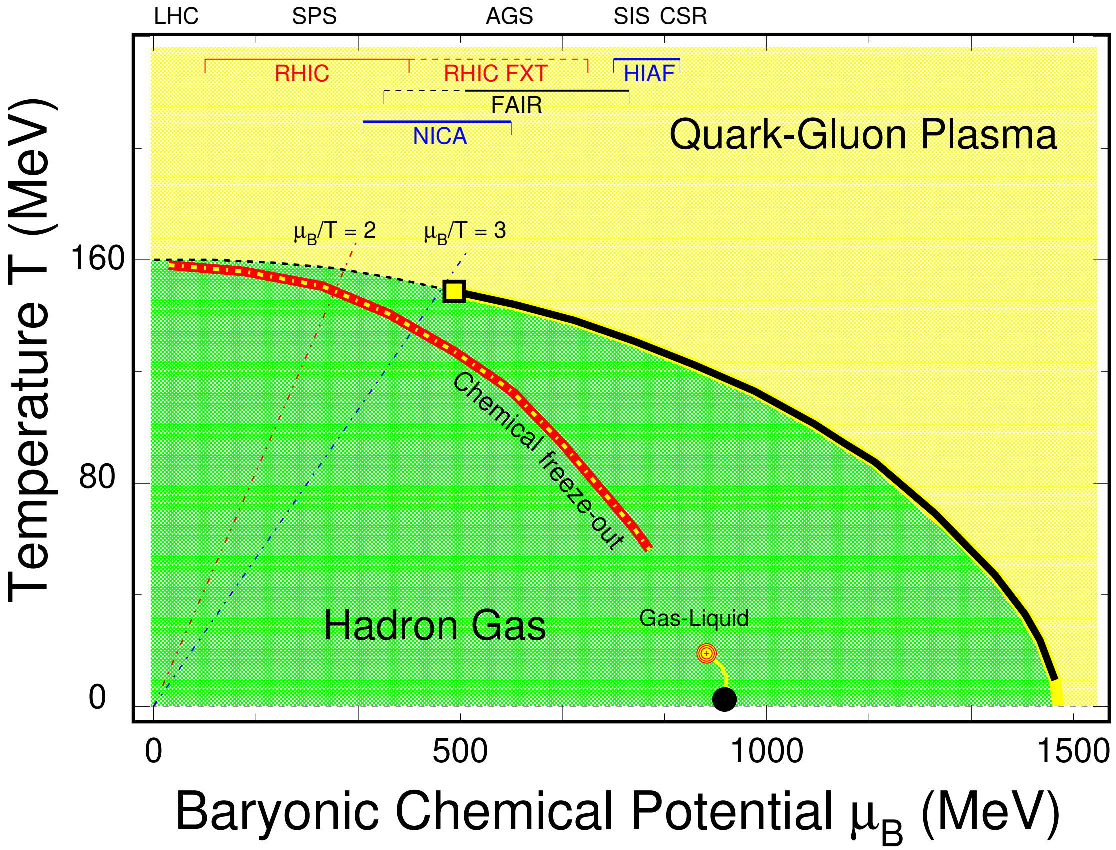
- Governed by strong interaction
- Baryonic chemical potential μ_B
  - Energy required to add a baryon to system
  - Reflects net-baryon density
- Hadronic phase at low T and μ_B
  - Degrees of freedom: hadrons
  - Color confinement
  - Quarks confined within hadrons
- Quark-Gluon Plasma (QGP) phase at high T and/or μ_B
  - Perfect liquid
  - Degrees of freedom: quarks and gluons
  - Color deconfinement



B. Mohanty, N. Xu, arXiv:2101.09210

Introduction: QCD Phase Diagram

- QCD phase transition: hadron ⇔ QGP
- Crossover at small μ_B ($\mu_B/T < 2$)
  - No distinct phase boundary
  - Expected by Lattice QCD
  - $T = 156.5 \pm 1.5$ MeV (10^{12} K) 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 boundary

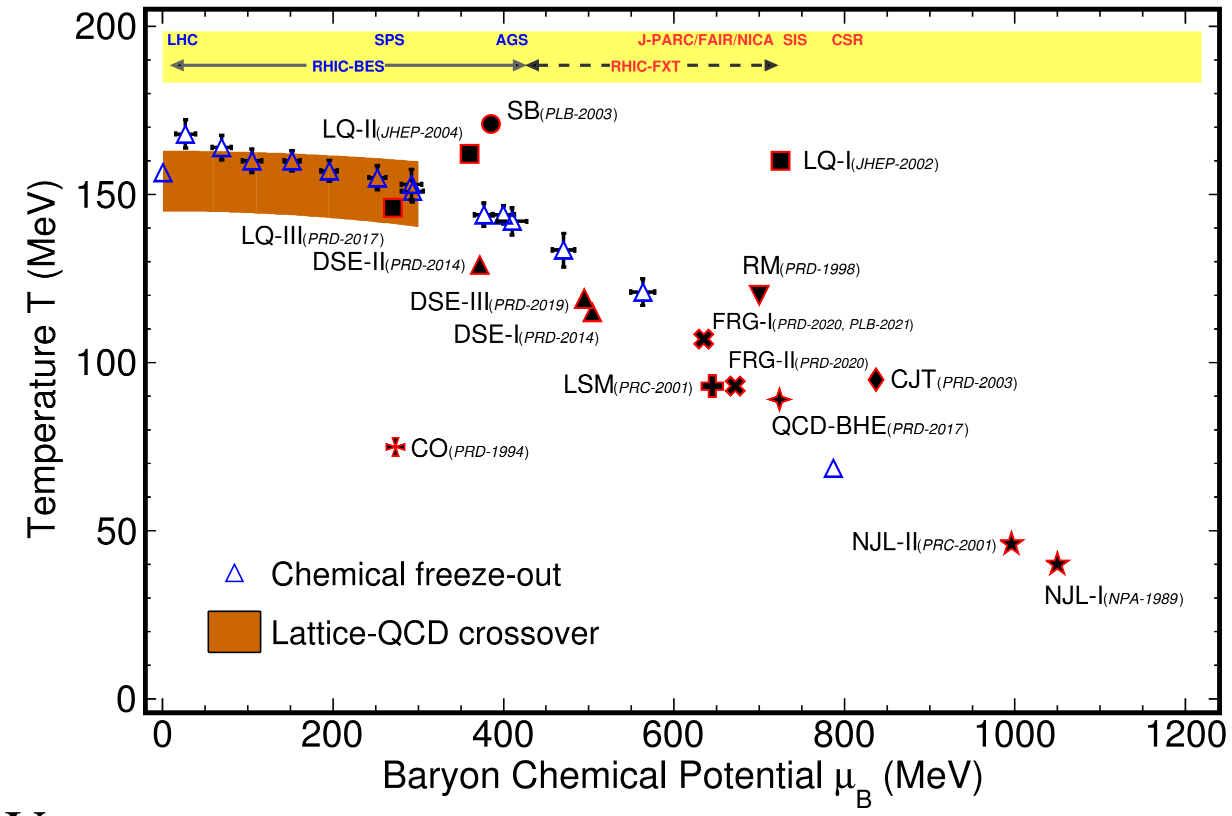


B. Mohanty, N. Xu, arXiv:2101.09210
Y. Aoki *et al.*, Nature 443, 675-678 (2006)
HotQCD, PLB 795, 15-21 (2019)

- No direct observation yet: crossover, 1st-order transition or CP
- Critical physics goal: search for and locate CP, understand QCD phase structure

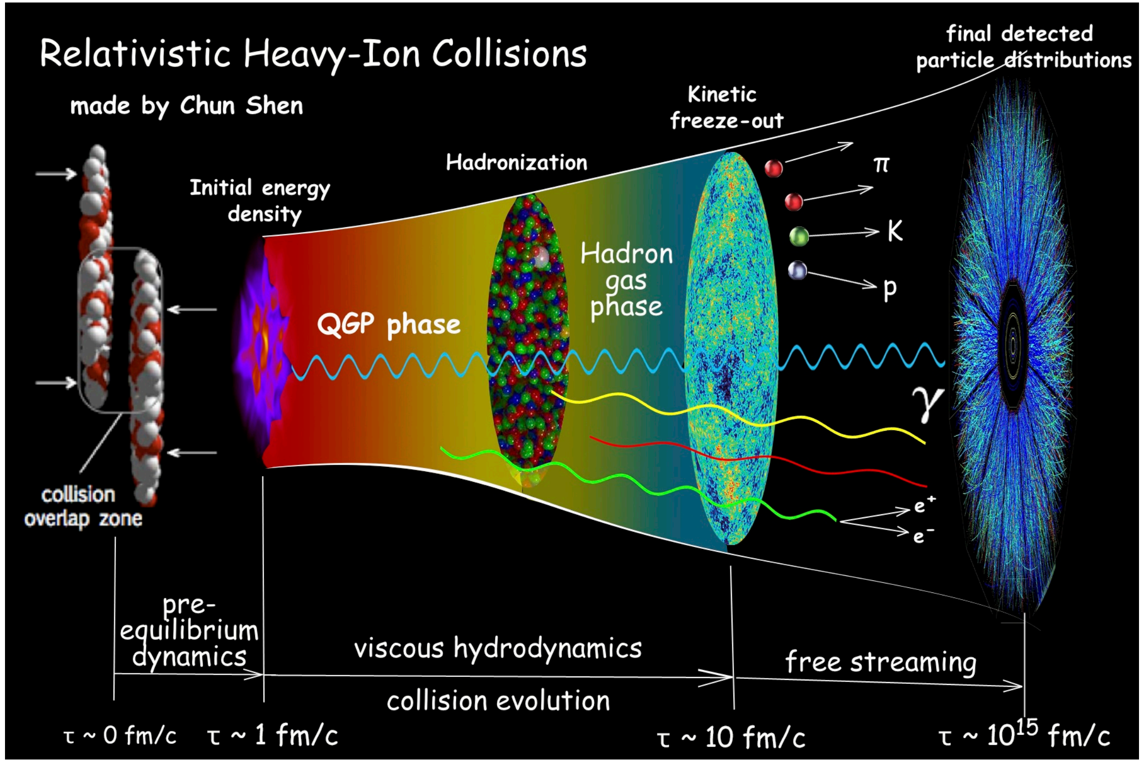
Introduction: Theoretical Exploration of CP

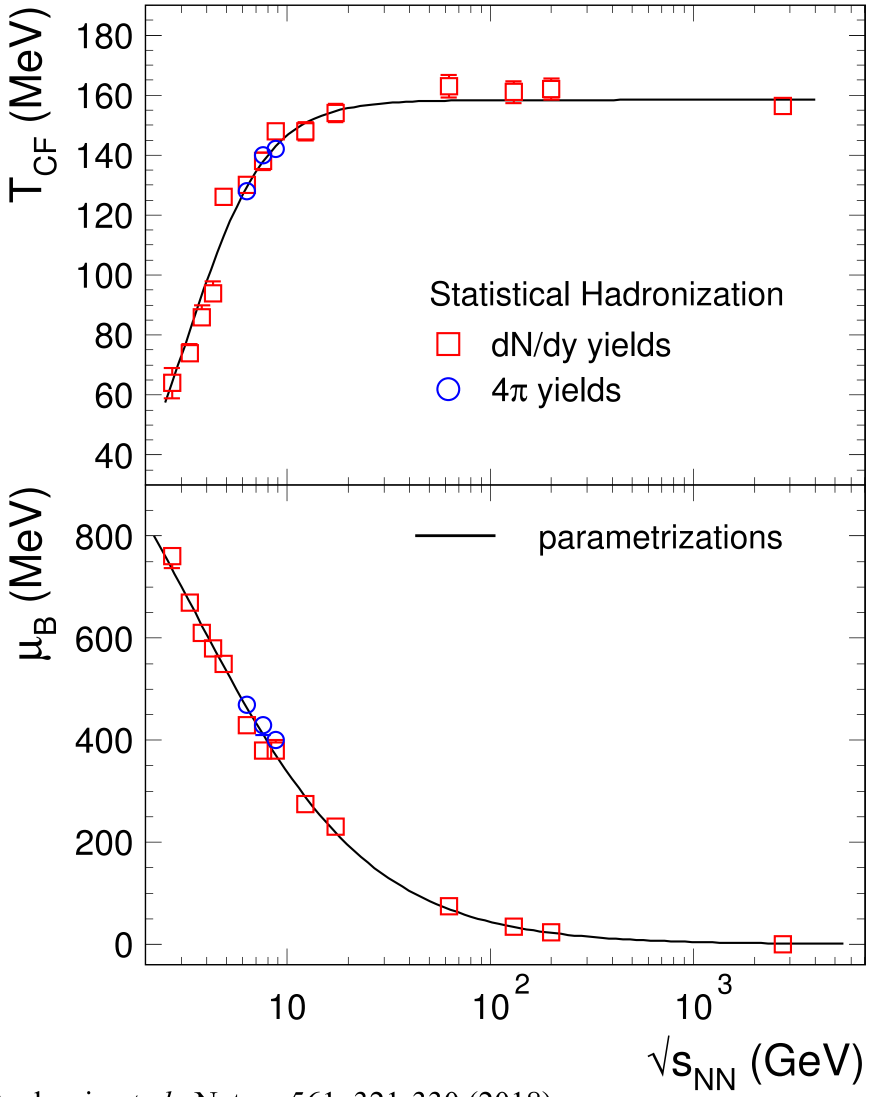
- Location of chemical freeze-out
  - Precisely extracted from experimental data
- Location of crossover
  - Prediction from Lattice QCD at small μ_B
- Location of CP
  - Sign problem of Lattice QCD at finite μ_B
  - Various predictions from models with approximation/assumption/estimation
  - Last several decades:
    $T = 40\text{–}180$ MeV, $\mu_B = 200\text{–}1100$ MeV
  - Latest:
    $T = 90\text{–}120$ MeV, $\mu_B = 500\text{–}700$ MeV



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

Introduction: Relativistic Heavy-Ion Collisions



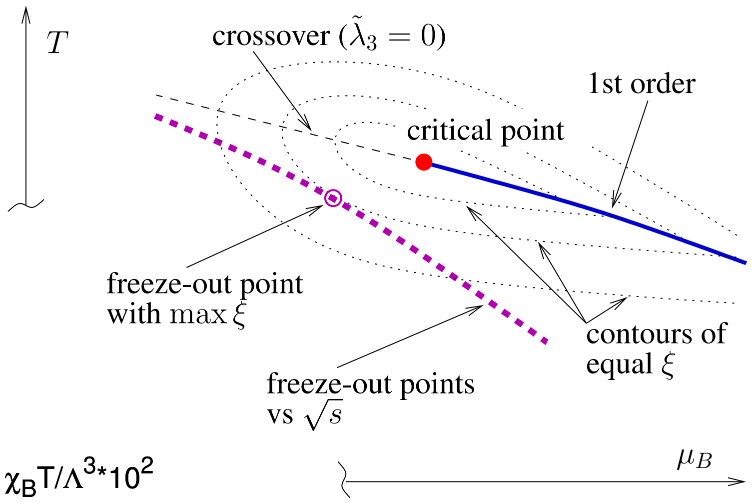


A. Andronic *et al.*, Nature 561, 321-330 (2018)

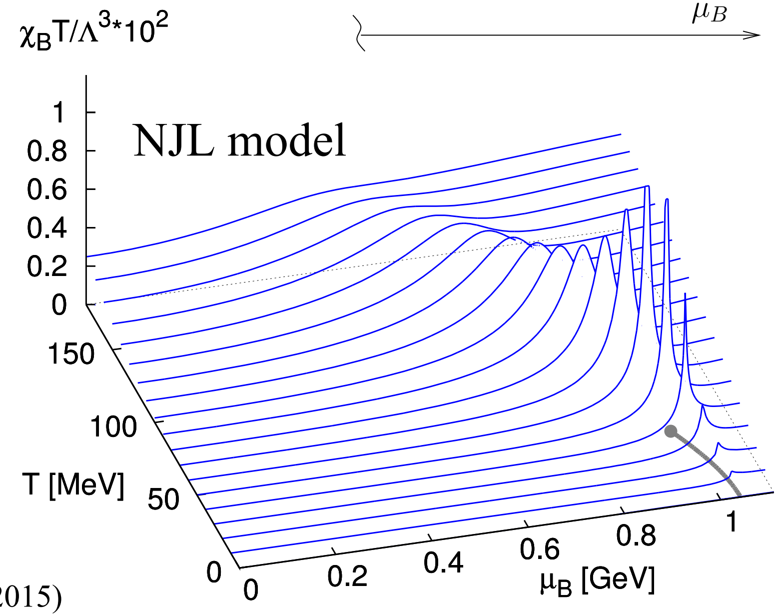
- QGP created through phase transition at extreme conditions
- Scan QCD phase diagram by varying collision energy $\sqrt{s_{\mathrm{NN}}}$
  - Low energy ⇒ low T, high μ_{B} at chemical freeze-out

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
  - $C_r \sim \xi^{5r/2-3}$: higher-orders are more sensitive
  - $C_{r,q} = VT^3\chi_{r,q}$
  - $C_{r,q}/C_{s,q} = \chi_{r,q}/\chi_{s,q}$: trivial volume dependence canceled
  - Direct comparison with theoretical and model calculations

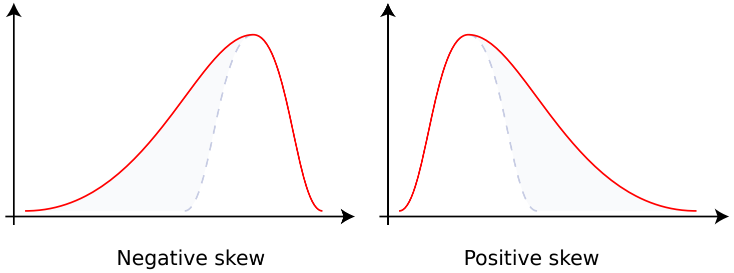


- $\kappa_{r,q}$: rth-order factorial cumulant
  - Quantification of r-particle correlation
  - Usually normalized to $\kappa_{r,q}/\kappa_{1,q}$

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

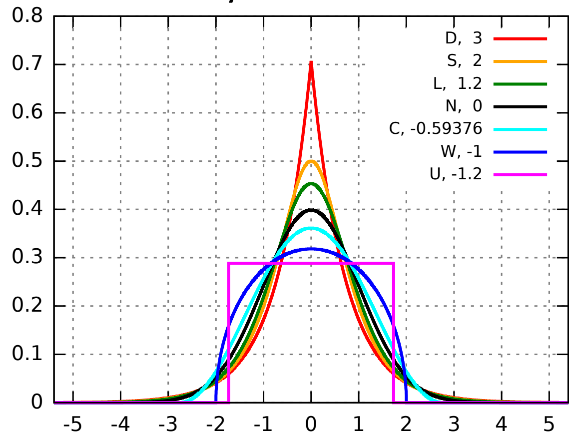
- N: event-by-event net-proton/net-charged-hadron/net-charged-kaon number (proxy for B, Q, S)
- $\mu_r = \langle (N - \langle N \rangle)^r \rangle$: rth-order central moment
- Cumulants:
  - $C_1 = \mu = \langle N \rangle$
  - $C_2 = \sigma^2 = \mu_2$
  - $C_3 = S\sigma^3 = \mu_3$
  - $C_4 = \kappa\sigma^4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

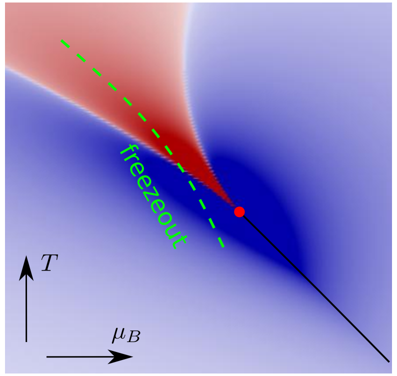
Gaussian: $C_r = 0$ $(r > 2)$
Poisson: $C_r = C_1$, $\kappa_r = 0$ $(r > 1)$
Skellam (Poisson − Poisson):
$$C_{\text{odd}}/C_{\text{odd}} = C_{\text{even}}/C_{\text{even}} = 1$$

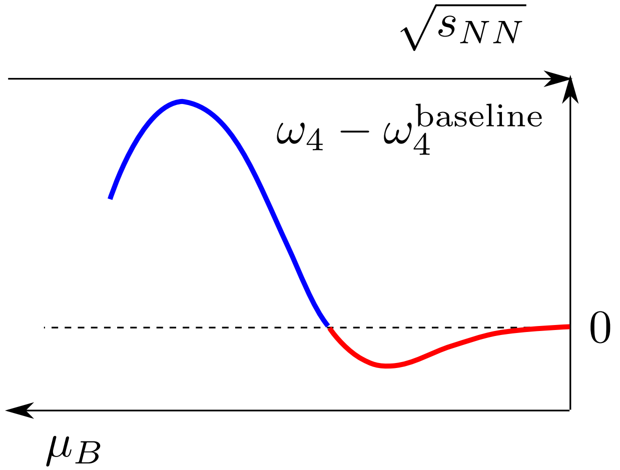
kurtosis $\kappa = \mu_4/\sigma^4 - 3 \Leftrightarrow$ peakedness



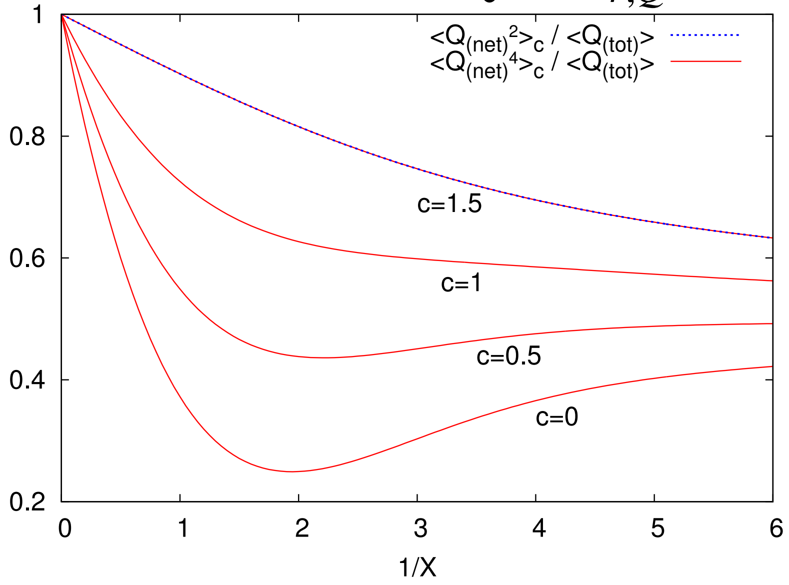
Introduction: Expected Signals

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



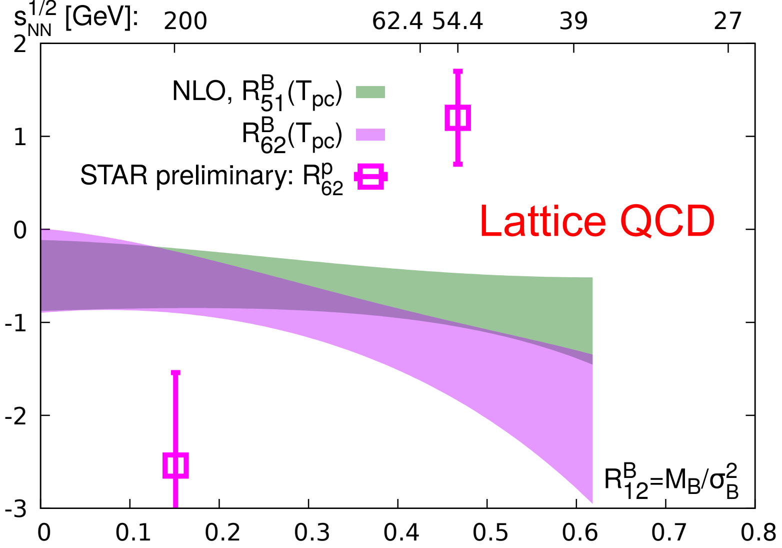


- Possible structures in acceptance dependence
  - $1/X$: acceptance; $\langle Q^r \rangle_c = C_{r,Q}$

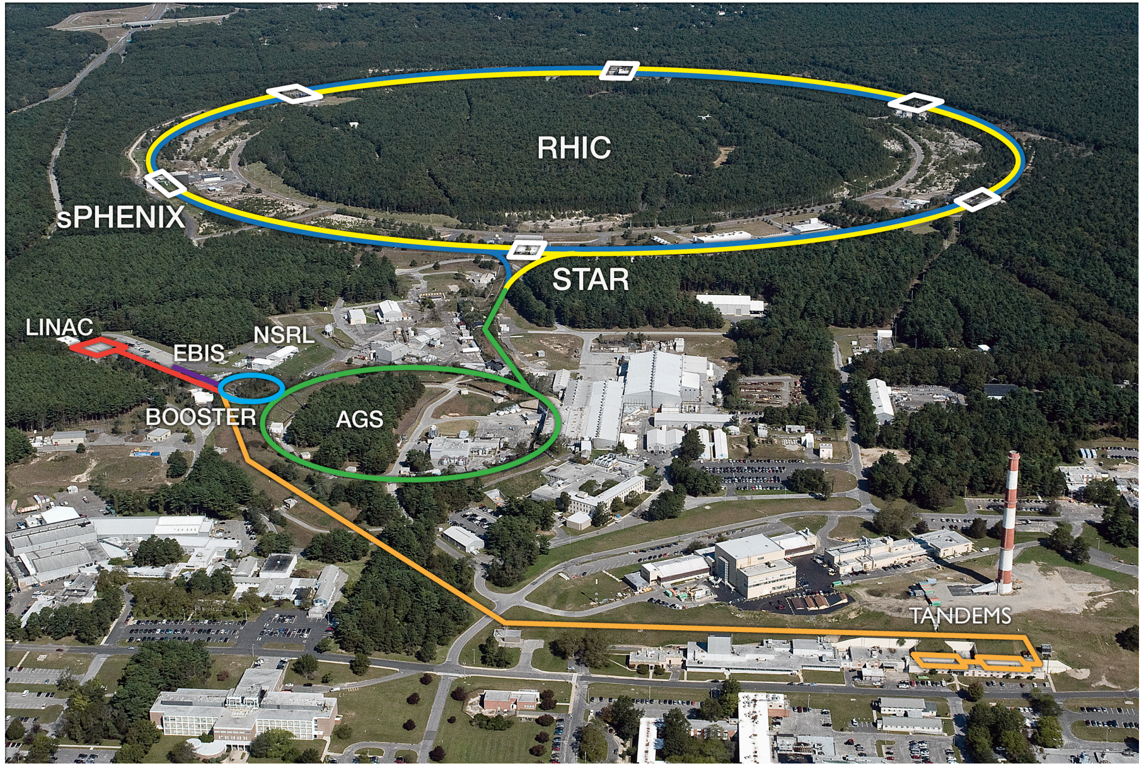


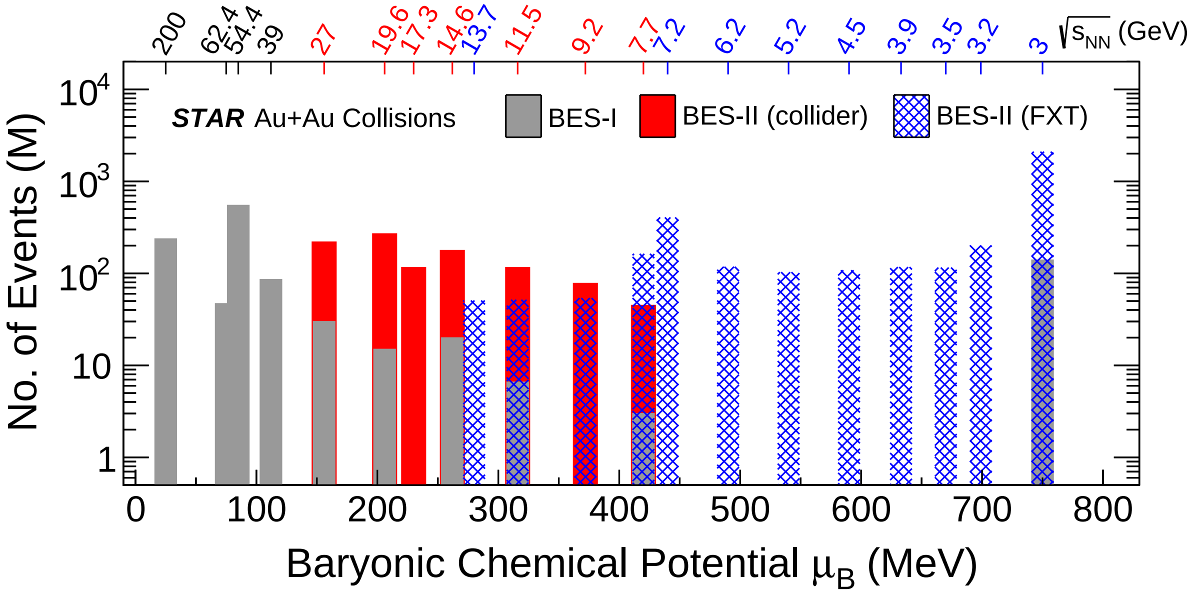
M. Kitazawa, M. Asakawa, H. Ono, PLB 728, 386-392 (2014)
A. Bazavov *et al.*, PRD 101, 074502 (2020)
M. Stephanov, Acta Phys. Polon. B 55, 5-A4 (2024)

- Crossover signal: negative C_5 and C_6



Introduction: RHIC BES Program

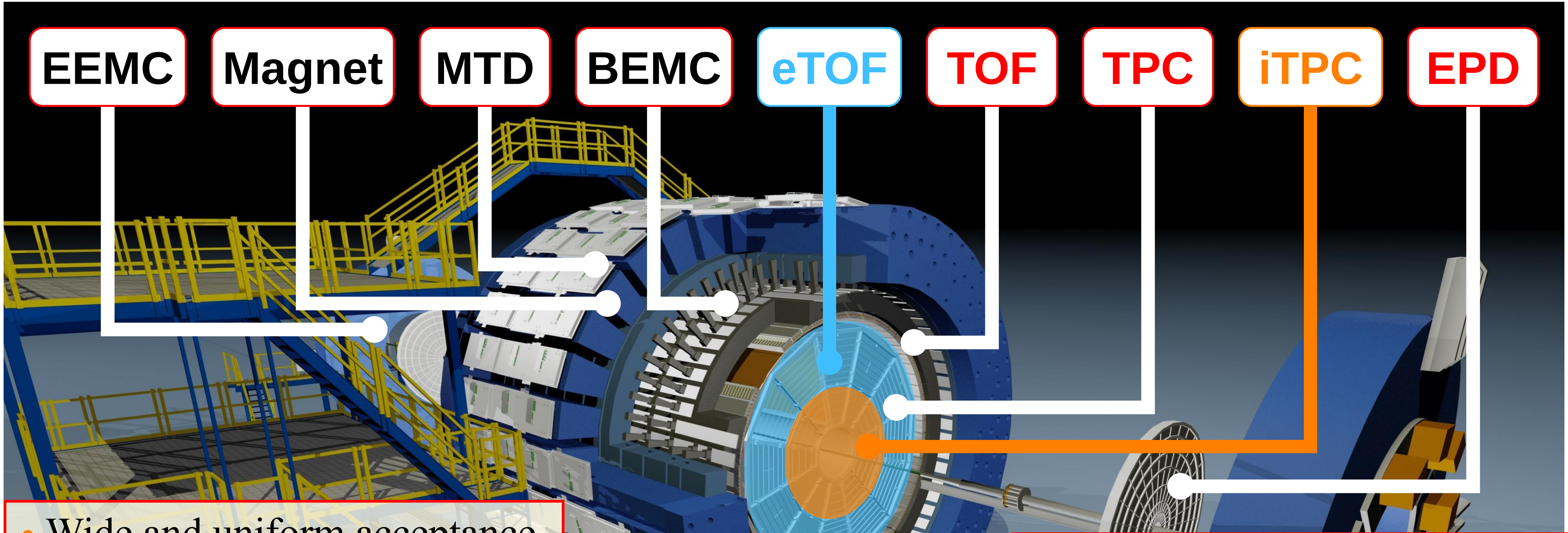




- Relativistic Heavy Ion Collider (BNL, USA)
  - Primarily collides Au+Au

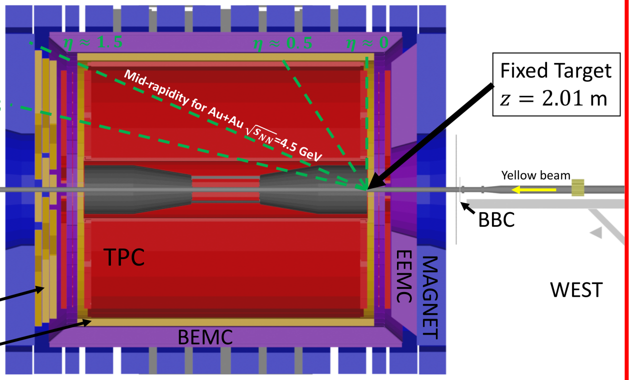
- Beam Energy Scan program
  - BES-I (2010–2017): $\sqrt{s_{NN}} = 7.7$–200 GeV
  - BES-II (2018–2021):
    - Collider mode: $\sqrt{s_{NN}} = 7.7$–27 GeV
    - Fixed-target mode: $\sqrt{s_{NN}} = 3$–13.7 GeV
  - $750 \gtrsim \mu_B$ (MeV) $\gtrsim 25$
    - High precision, widest μ_B coverage to date

Introduction: STAR Detector System

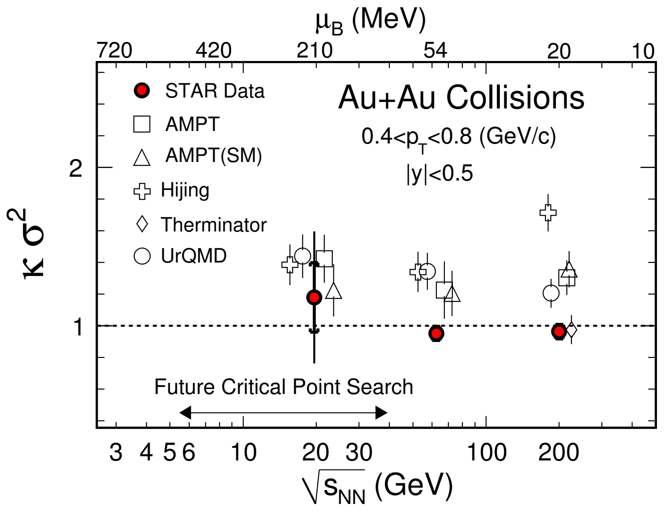


- Wide and uniform acceptance
- Excellent tracking and PID
- Modest rates
- Upgraded since 2018
  - EPD, iTPC, eTOF

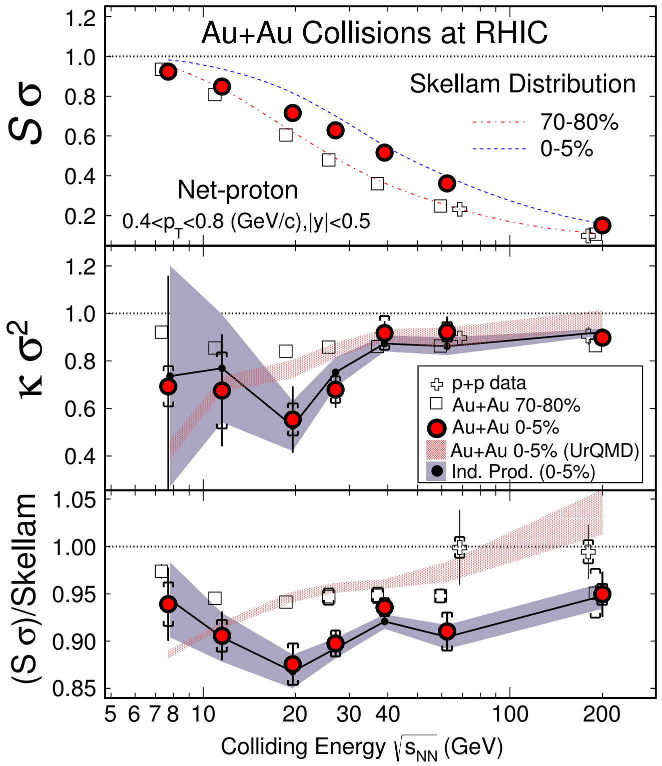
FXT setup



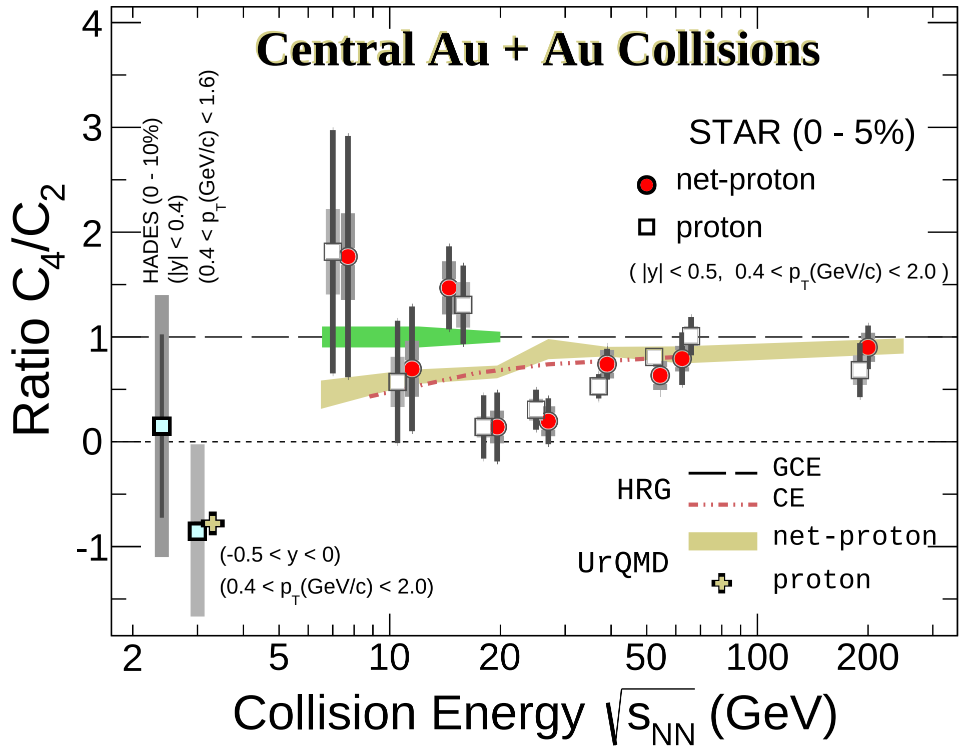
Introduction: Previous Measurements at RHIC



- PRL 105, 022302 (2010)
- Before BES-I
- First attempt



- PRL 112 032302 (2014)
- BES-I (7.7–200 GeV)
- Only low p_T (without TOF)



- PRL 126, 092301 (2021); 128, 202303 (2022)
- Final results from BES-I and 3 GeV (2018)
- Non-monotonic energy dependence (3.1σ)
- Consistency with UrQMD at 3 GeV
  - Likely returns to non-CP baseline

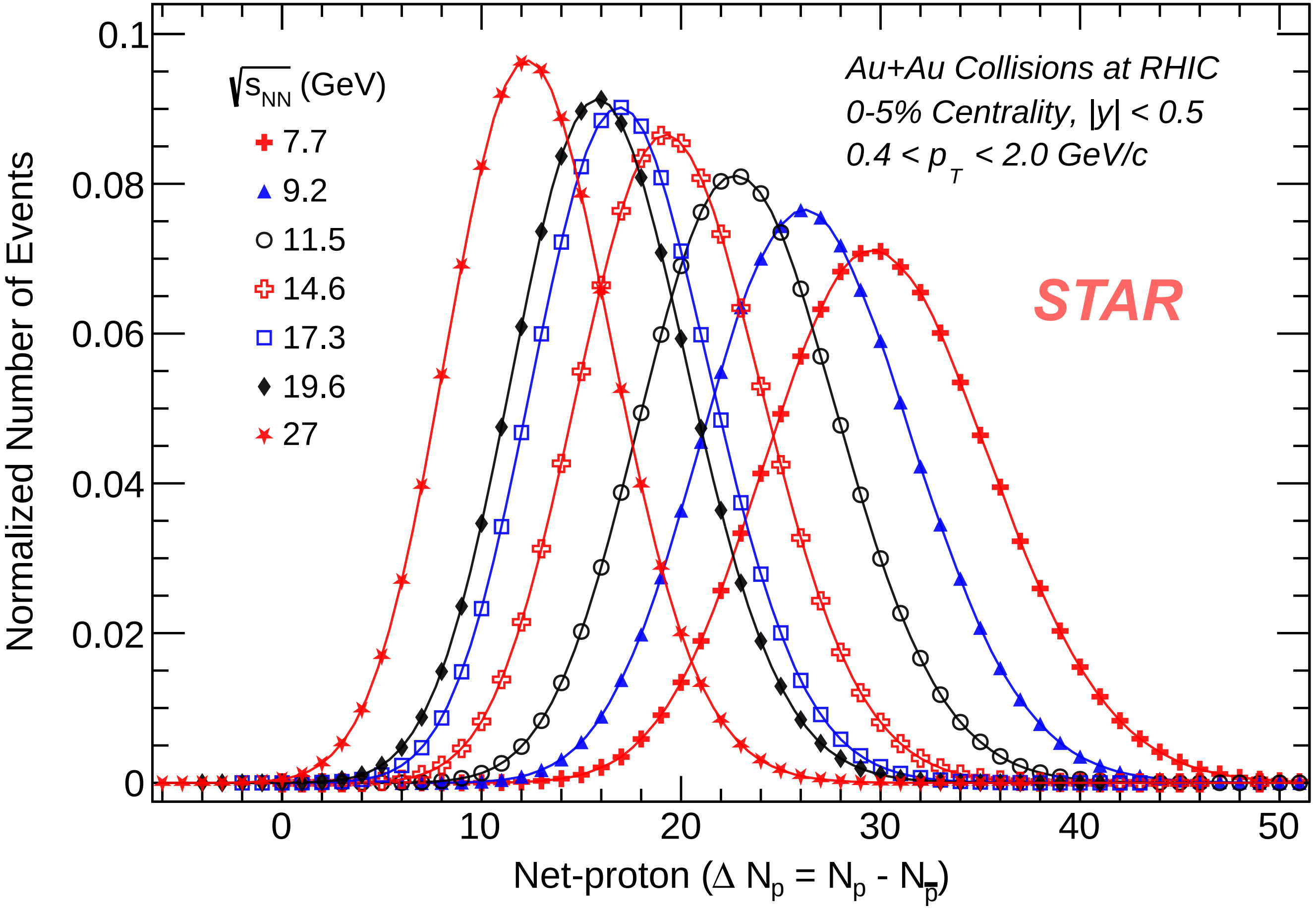
Collision Centrality and Energy Dependence of (Net-)Proton Number Fluctuations from 7.7–27 GeV (BES-II Collider Mode)

Event-by-Event Net-Proton Number Distributions

- Collision centrality determined by charged-particle multiplicities excluding (anti)protons
  - RefMult3: $|\eta| < 1.0$
  - RefMult3X: $|\eta| < 1.6$

- Analysis window
  - $0.4 < p_T$ (GeV/c) < 2.0
  - $|y| < 0.5$

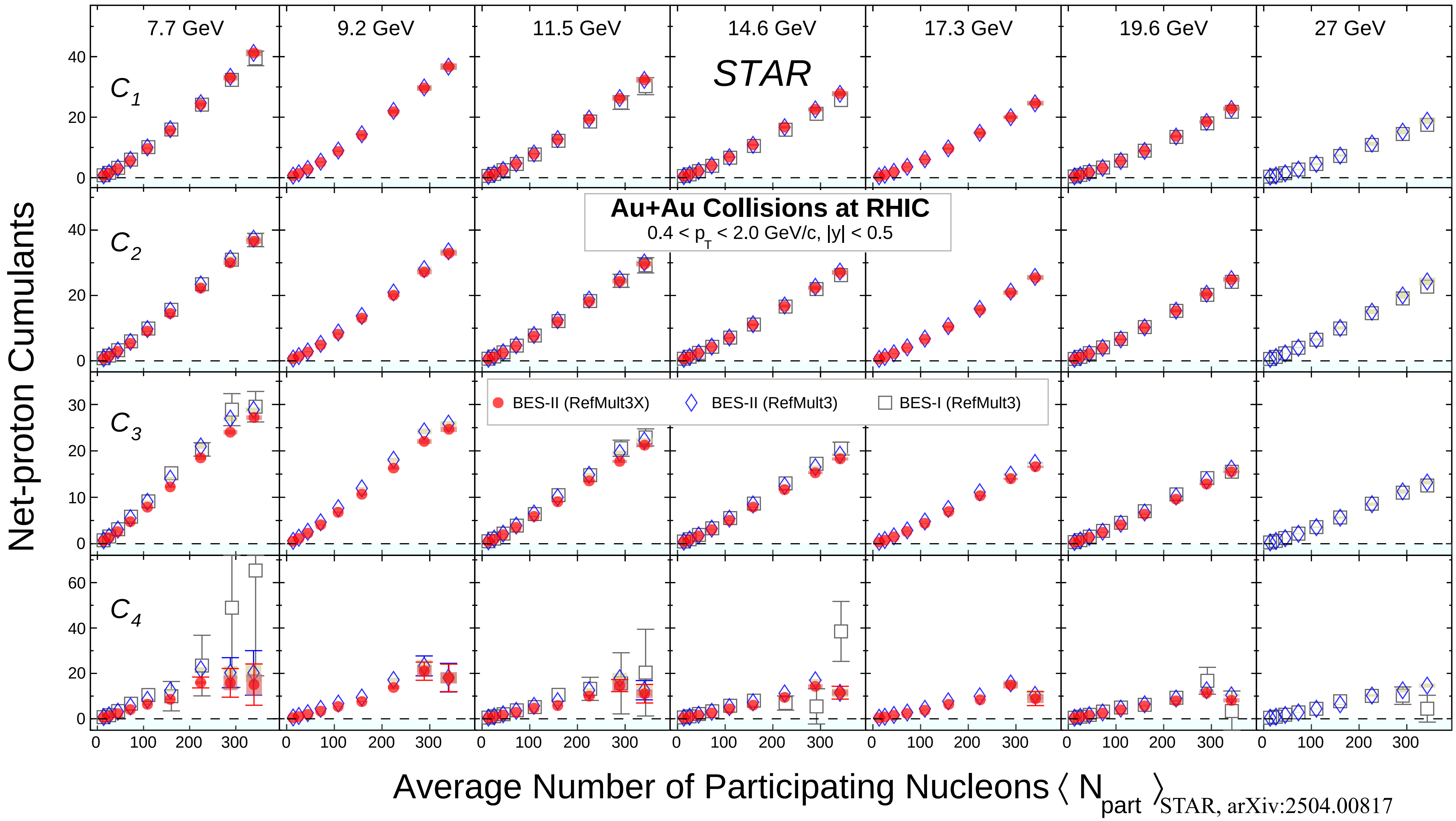
- Raw net-proton number distributions
  - Uncorrected for detector efficiency



- Mean and width increase with decreasing collision energy

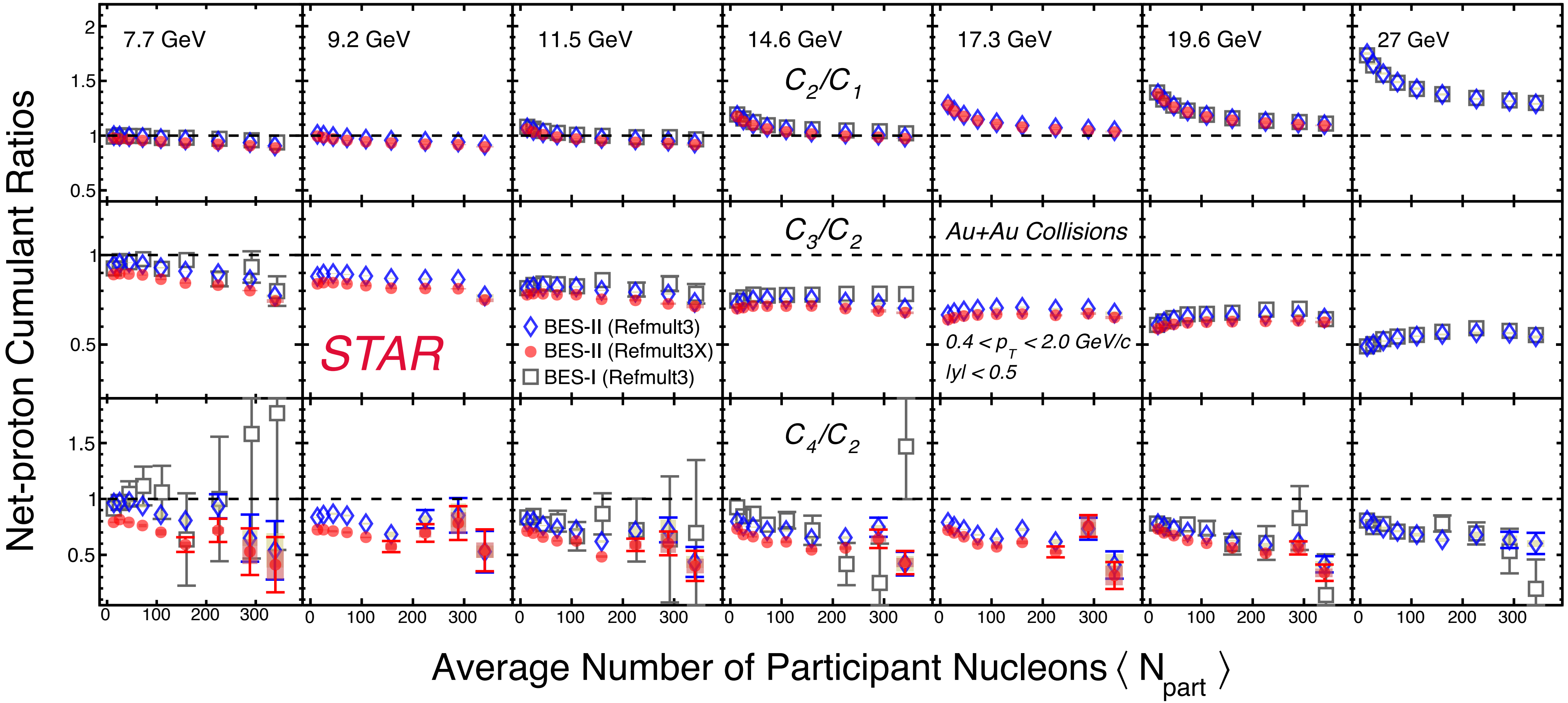
STAR, arXiv:2504.00817

Cumulants vs. Collision Centrality and Energy



STAR, arXiv:2504.00817

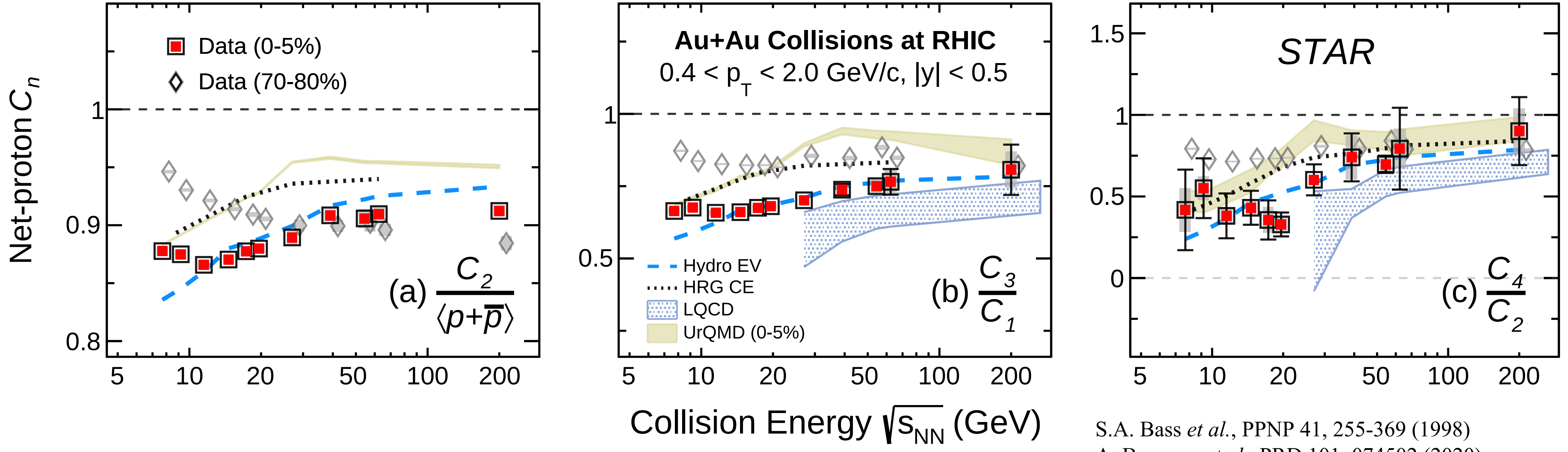
Cumulant Ratios vs. Collision Centrality and Energy



1. Precision measurement of 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

STAR, arXiv:2504.00817

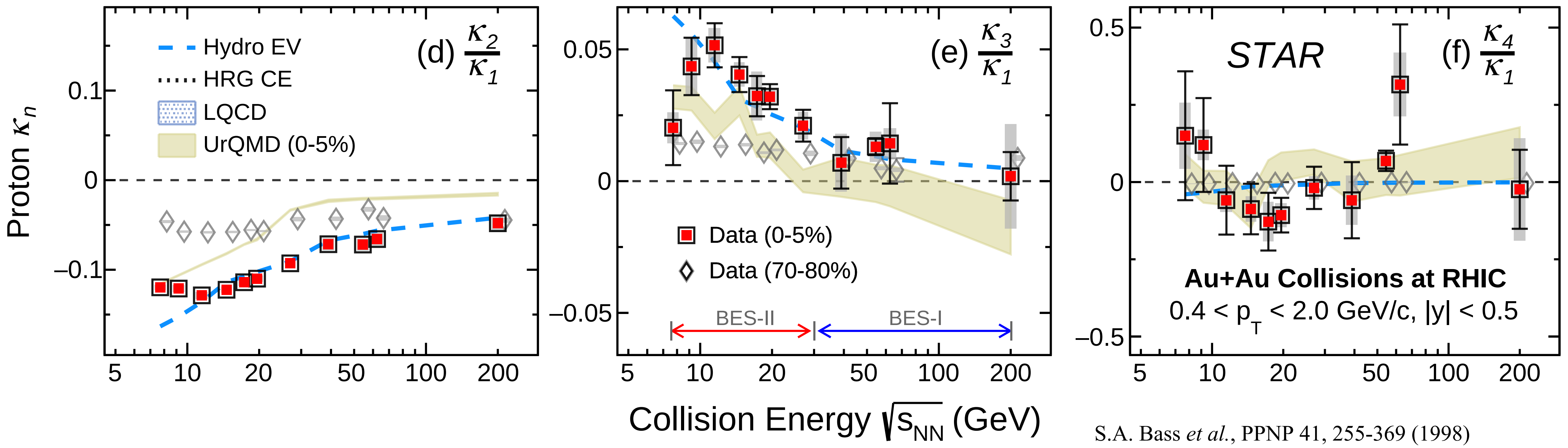
Energy Dependence of Cumulant Ratios



S.A. Bass *et al.*, PPNP 41, 255-369 (1998)
A. Bazavov *et al.*, PRD 101, 074502 (2020)
P. Braun-Munzinger *et al.*, NPA 1008, 122141 (2021)
V. Vovchenko *et al.*, PRC 105, 014904 (2022)
STAR, arXiv:2504.00817

1. High precision in both 0–5% and 70–80%
2. All cumulant ratios below Poisson baseline at unity
3. Peripheral data are closer to unity than central data
4. In central collisions,
   - Decreasing trend as energy decreases, except hint of rising $C_2/\langle p+\bar{p}\rangle$ at low energies
   - C_4/C_2 shows deviation at $\sqrt{s_{NN}} \sim 20$ GeV w.r.t non-CP models (with baryon conservation)

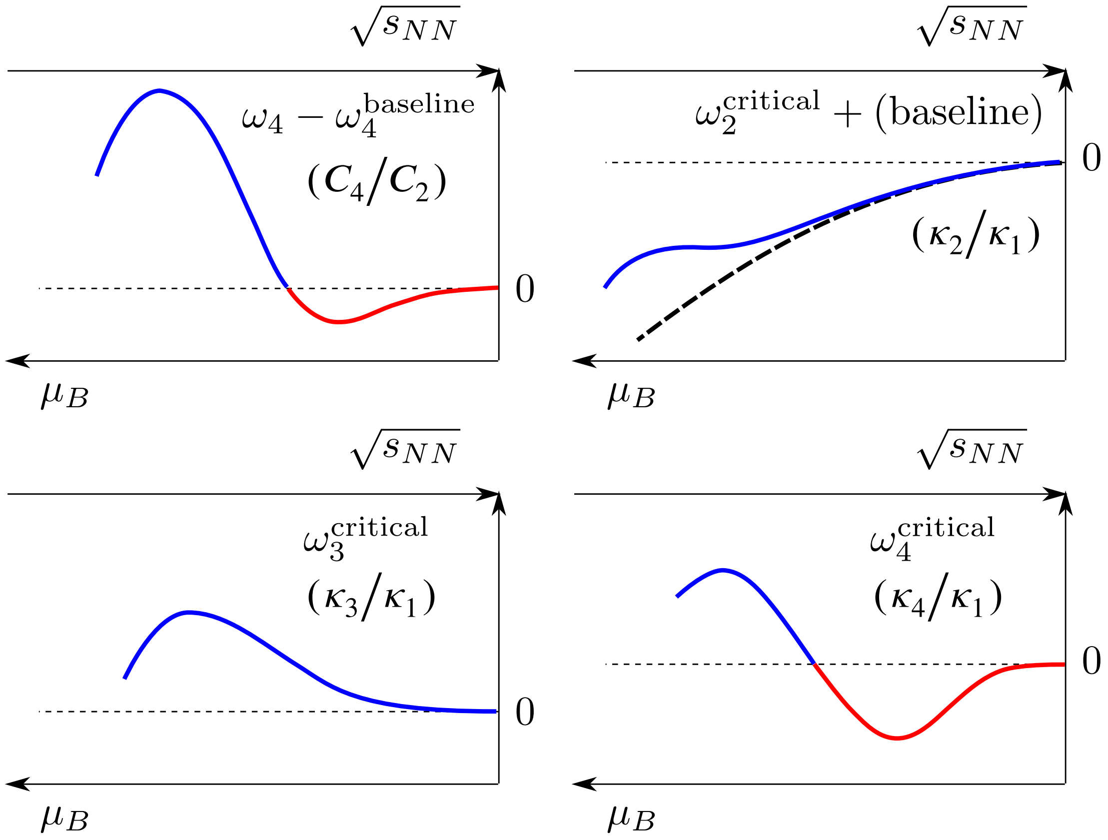
Energy Dependence of Factorial Cumulant Ratios



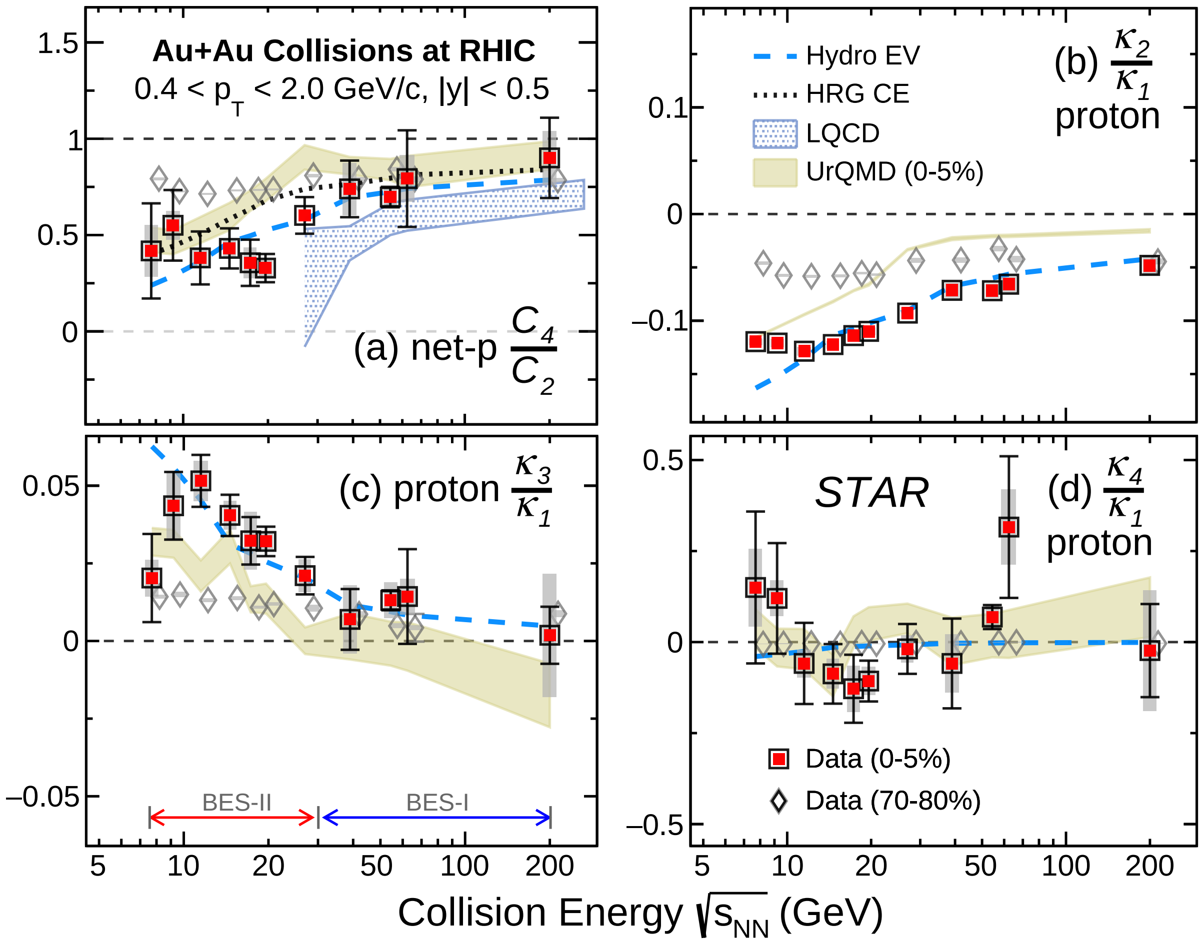
S.A. Bass *et al.*, PPNP 41, 255-369 (1998)
P. Braun-Munzinger *et al.*, NPA 1008, 122141 (2021)
V. Vovchenko *et al.*, PRC 105, 014904 (2022)
STAR, arXiv:2504.00817

1. High precision in both 0–5% and 70–80%
2. Negative κ_2; positive κ_3; κ_4/κ_1 consistent with Poisson baseline at zero within uncertainties
3. Peripheral data are closer to zero than central data
4. In central collisions,
   - κ_2/κ_1 and κ_3/κ_1 show hint of non-monotonic energy dependence, with maximum deviation from zero at $\sqrt{s_{NN}} \sim 11.5$ GeV

Comparison to Theoretical Expectation of CP



M. Stephanov, Acta Phys.Polon.B 55, 5-A4 (2024)
M. Stephanov, EPJ Web Conf. 314, 00042 (2024)



STAR, arXiv:2504.00817

- Qualitative consistency observed

(a) C_4/C_2: decreases and reaches a dip at ~19.6 GeV

(b) κ_2/κ_1: its decrease likely interrupted below ~11.5 GeV

(c) κ_3/κ_1: peak at ~11.5 GeV

(d) κ_4/κ_1: dip at ~19.6 GeV, enhancement at lower energy

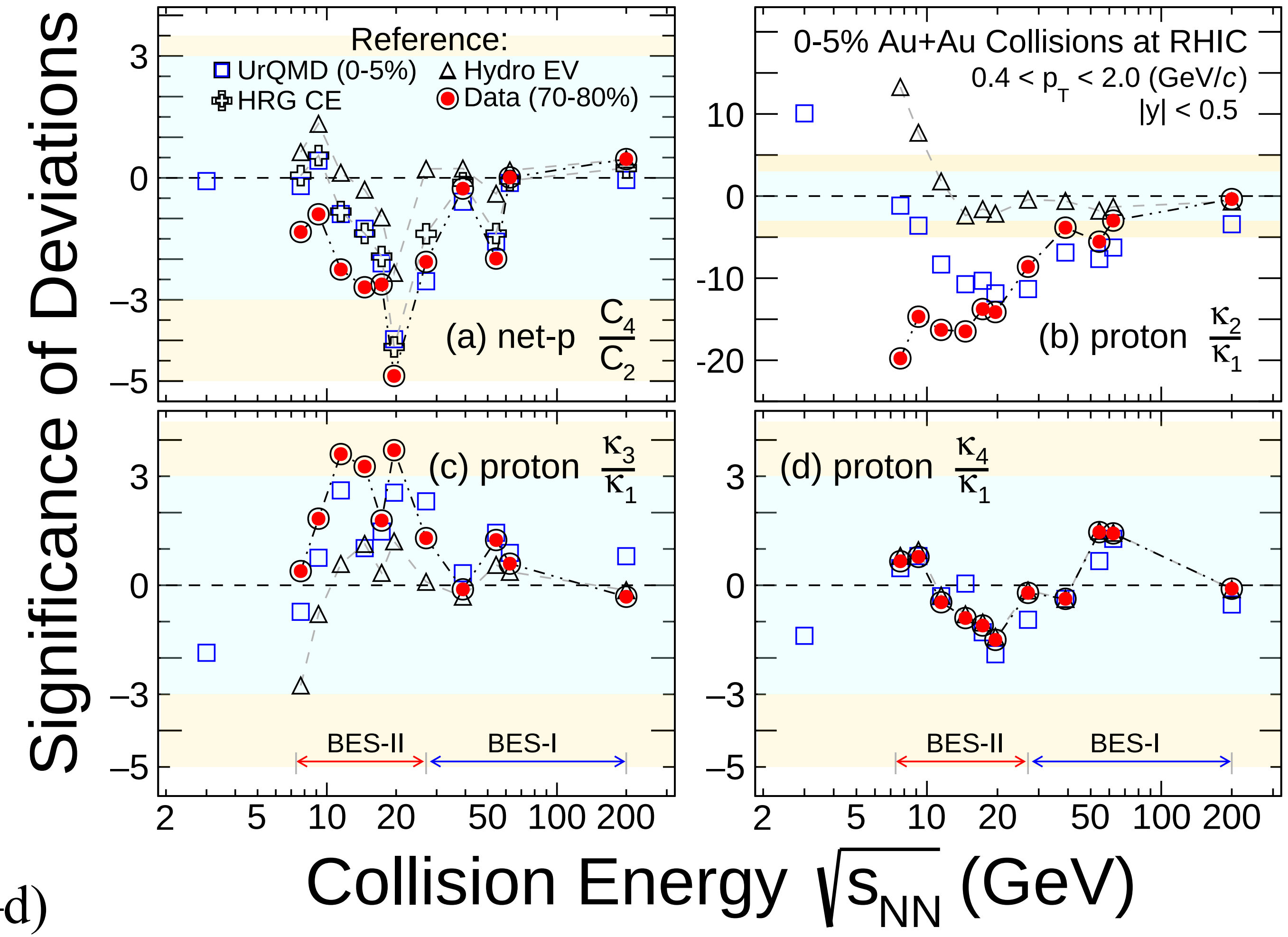
Deviations between Data and Non-CP References

1. References
   - 3 non-CP models
   - 70–80% data

2. Significance = $\dfrac{\text{0–5\% data} - \text{reference}}{\sqrt{\sigma^2_{\text{0–5\% data}} + \sigma^2_{\text{reference}}}}$

3. For C_4/C_2 (Panel a)
   - All references show a maximum deviation (2–5σ) at 19.6 GeV
   - Data consistent with references at $\sqrt{s_{NN}}$ = 3 GeV and $\gtrsim$ 27 GeV

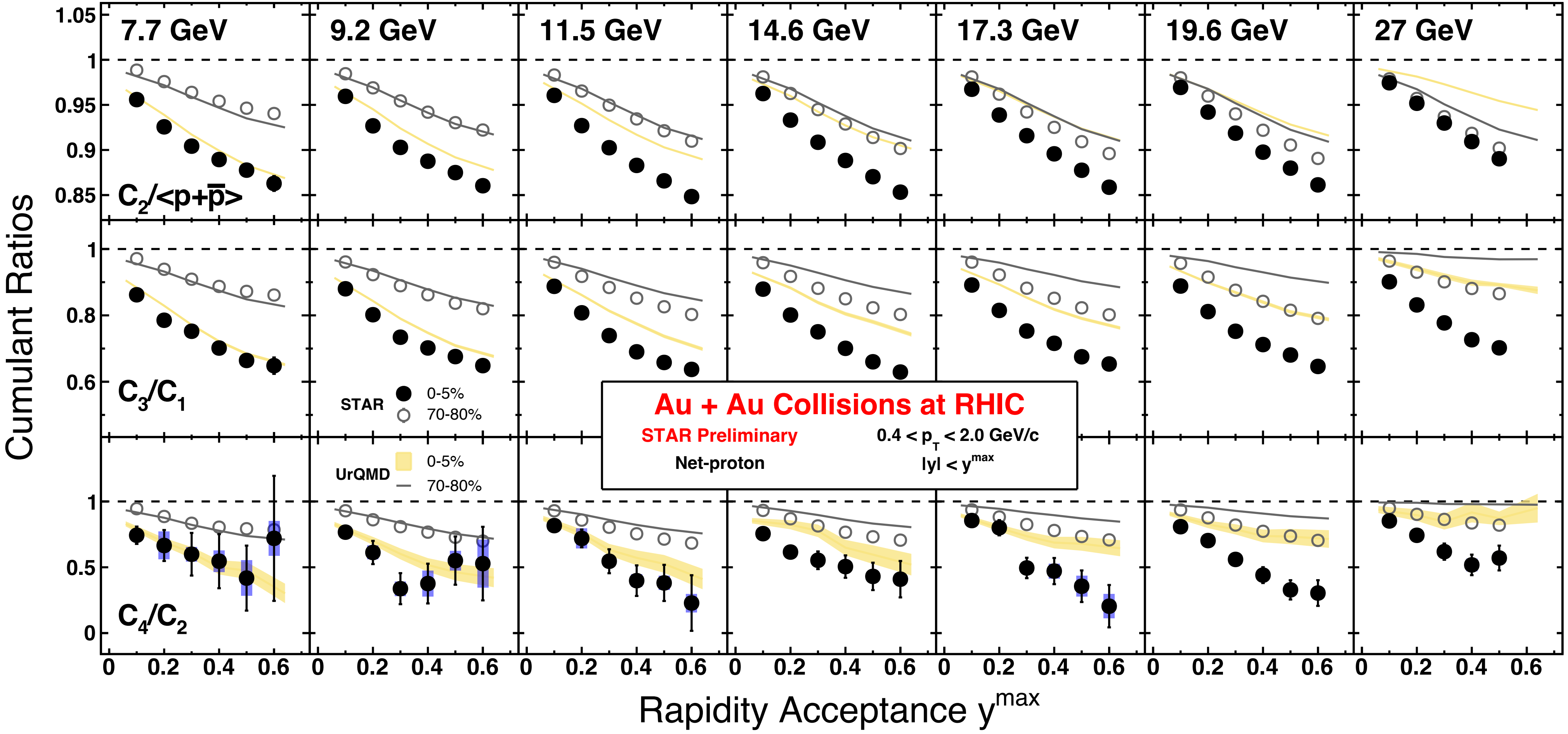
4. For factorial cumulant ratios (Panels b–d)
   - Decreasing deviation as the order increases, considering larger errors



STAR, arXiv:2504.00817

Acceptance Dependence of
(Net-)Proton Number Fluctuations from 7.7–27 GeV
(BES-II Collider Mode)

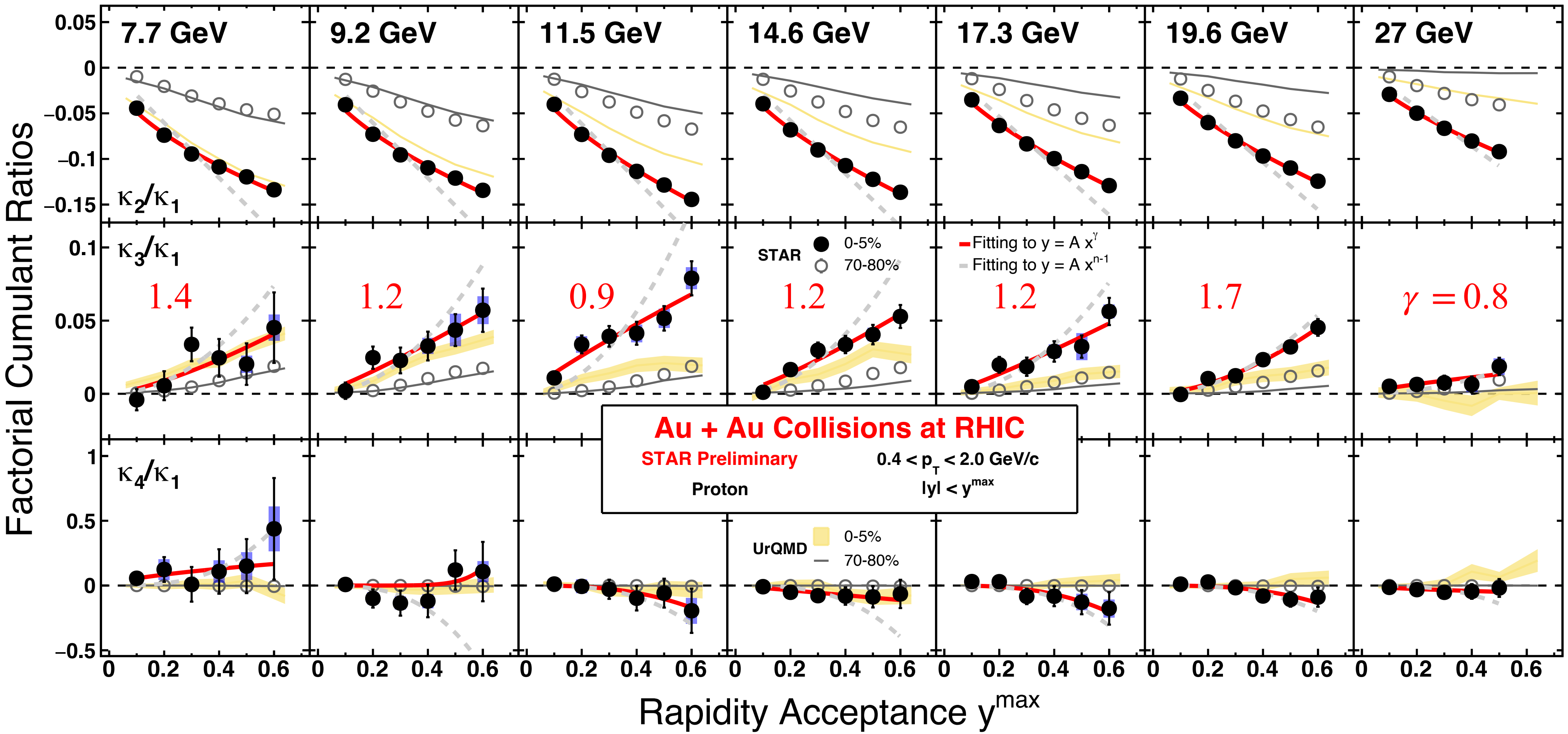
Rapidity Scan of Net-Proton Cumulant Ratios



1. Maximum rapidity extended to 0.6 taking advantage of iTPC
2. Decreasing trend as the rapidity window grows
3. UrQMD follows the trend, but deviate quantitatively at higher energies

Y. Huang (STAR), QM 2025

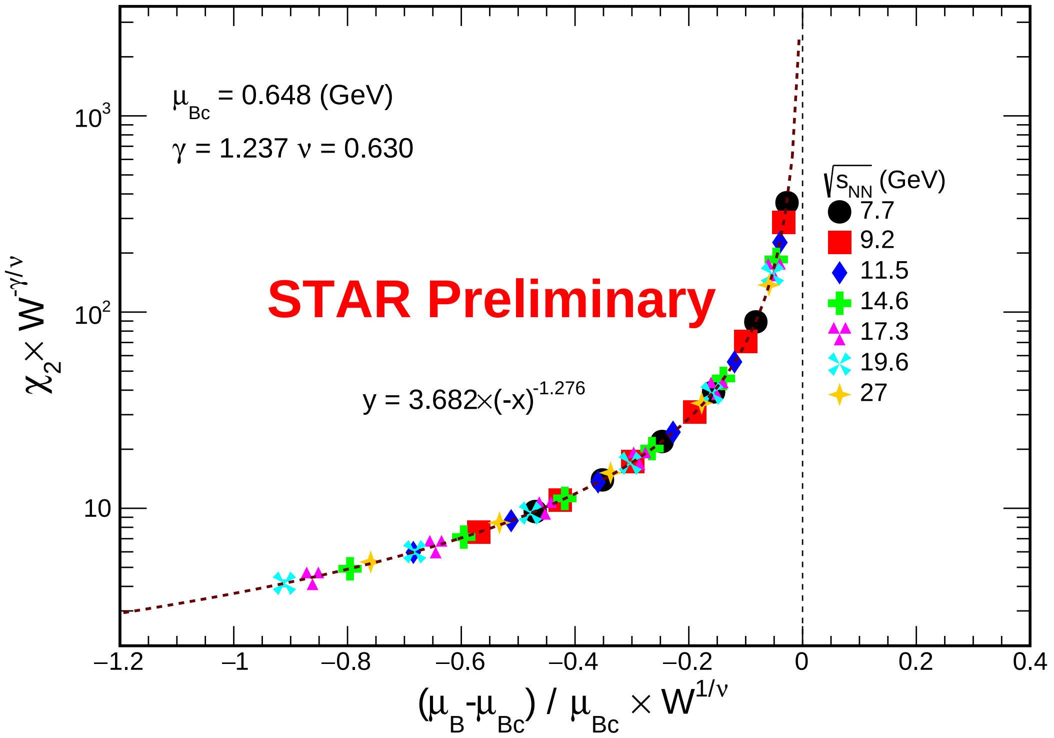
Rapidity Scan of Proton Factorial Cumulant Ratios

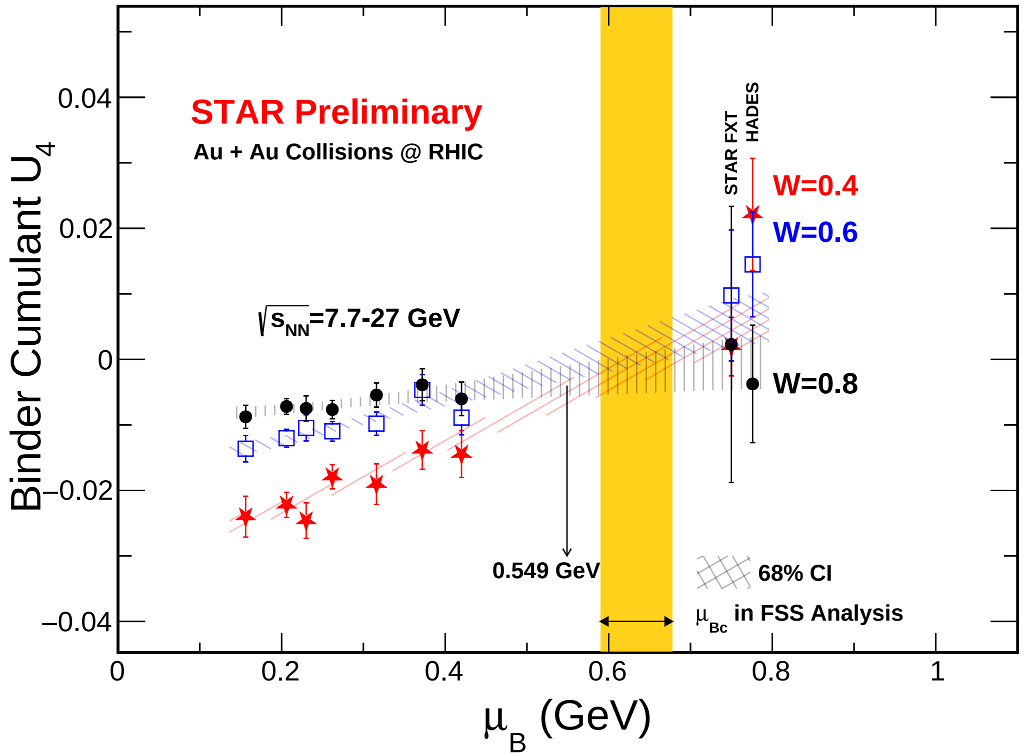


1. Test using parameterization of $\kappa_n/\kappa_1 = A(\Delta y)^{n-1}$ and $A(\Delta y)^\gamma$ ($\Delta y = 2y^{max}$)
2. κ_n/κ_1 follows a power function of Δy
3. The power index lower than expected $(n-1)$ in case of $\Delta y \ll \Delta y_{corr}$

B. Ling, M.A. Stephanov, PRC 93, 034915, (2016)
Y. Huang (STAR), QM 2025

Finite-Size Scaling (FSS) Study



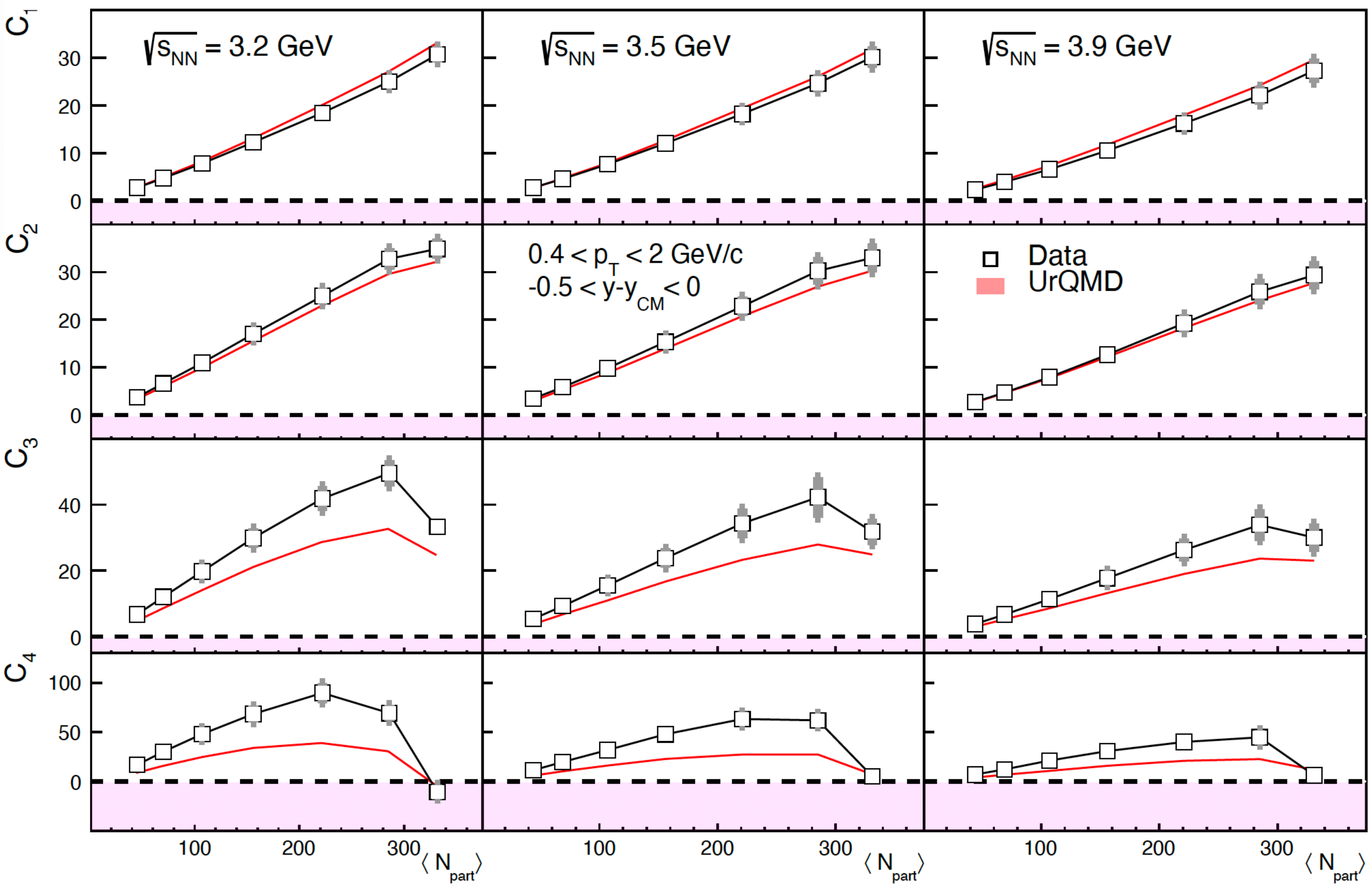


1. FSS study introduces $\mu_{\mathrm{B,c}} = 648^{+30/+2}_{-24/-58}$ MeV from this work
   - $\mu_{\mathrm{B,c}} = 625 \pm 60$ MeV based on BES-I results when FSS proposed
   - Susceptibility $\chi_2(W, \mu_{\mathrm{fo}}) = \dfrac{C_2(W, \mu_{\mathrm{fo}})}{T_{\mathrm{fo}}^3 W \, \mathrm{d}V_{\mathrm{fo}}/\mathrm{d}y}$ with rapidity window size W and freeze-out parameters $T, \mu, \mathrm{d}V/\mathrm{d}y$
   - Parameterization uses critical exponents γ, ν
2. Linear fits for binder cumulants $U_4 = -3\, C_4/C_2^2$ provide an overlapping μ_{B} region consistent with FSS

HADES, PRC 102, 024914 (2020)
STAR, PRC 107, 024908 (2023)
A.Sorensen, P.Sorensen, arXiv:2405.10278
Y. Huang (STAR), QM 2025

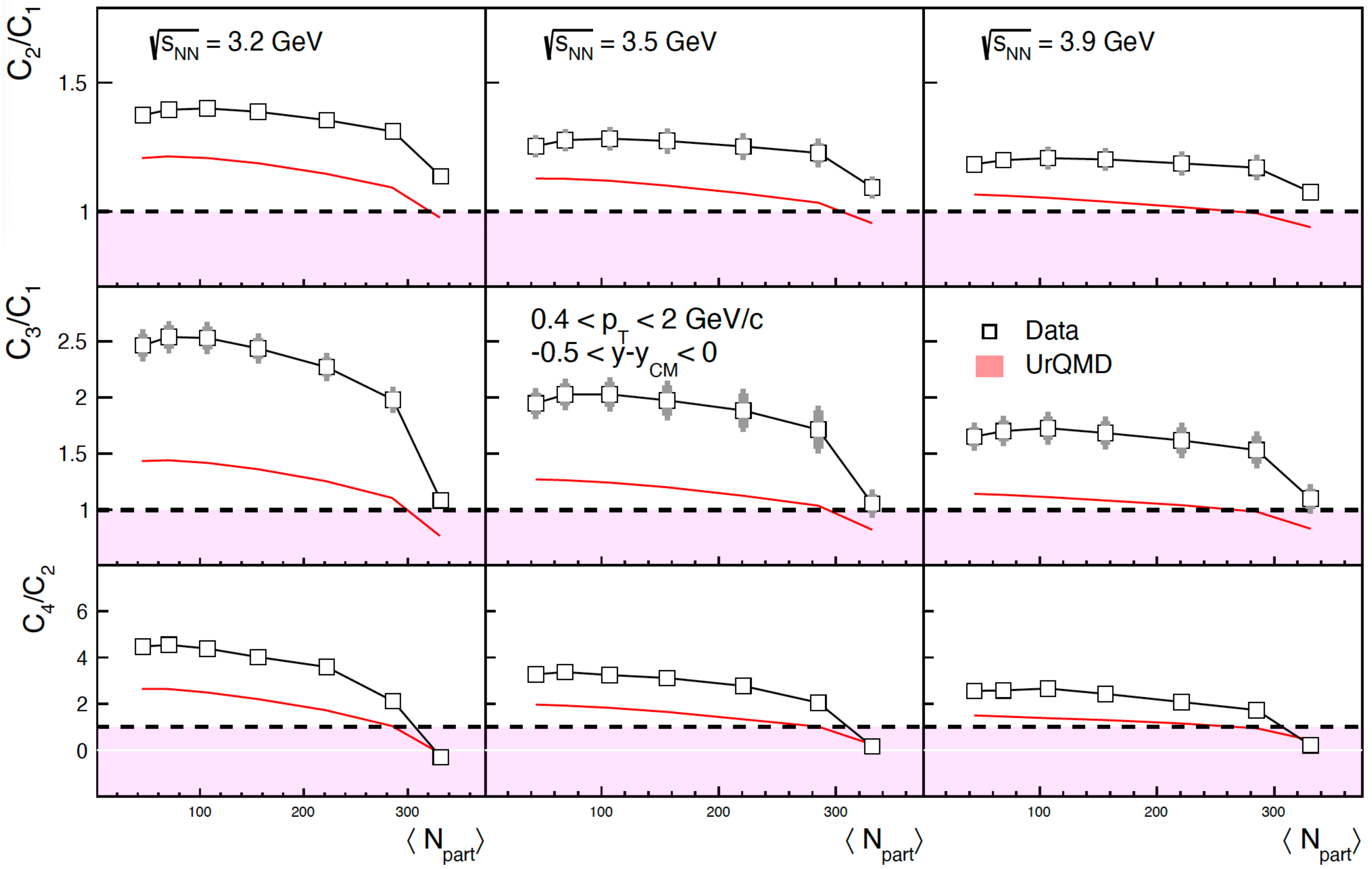
Collision Centrality and Energy Dependence of Proton Number Fluctuations from 3.2–3.9 GeV (BES-II FXT Mode)

Cumulants vs. Collision Centrality and Energy



Z. Sweger (STAR), QM 2025

Cumulant Ratios vs. Collision Centrality and Energy



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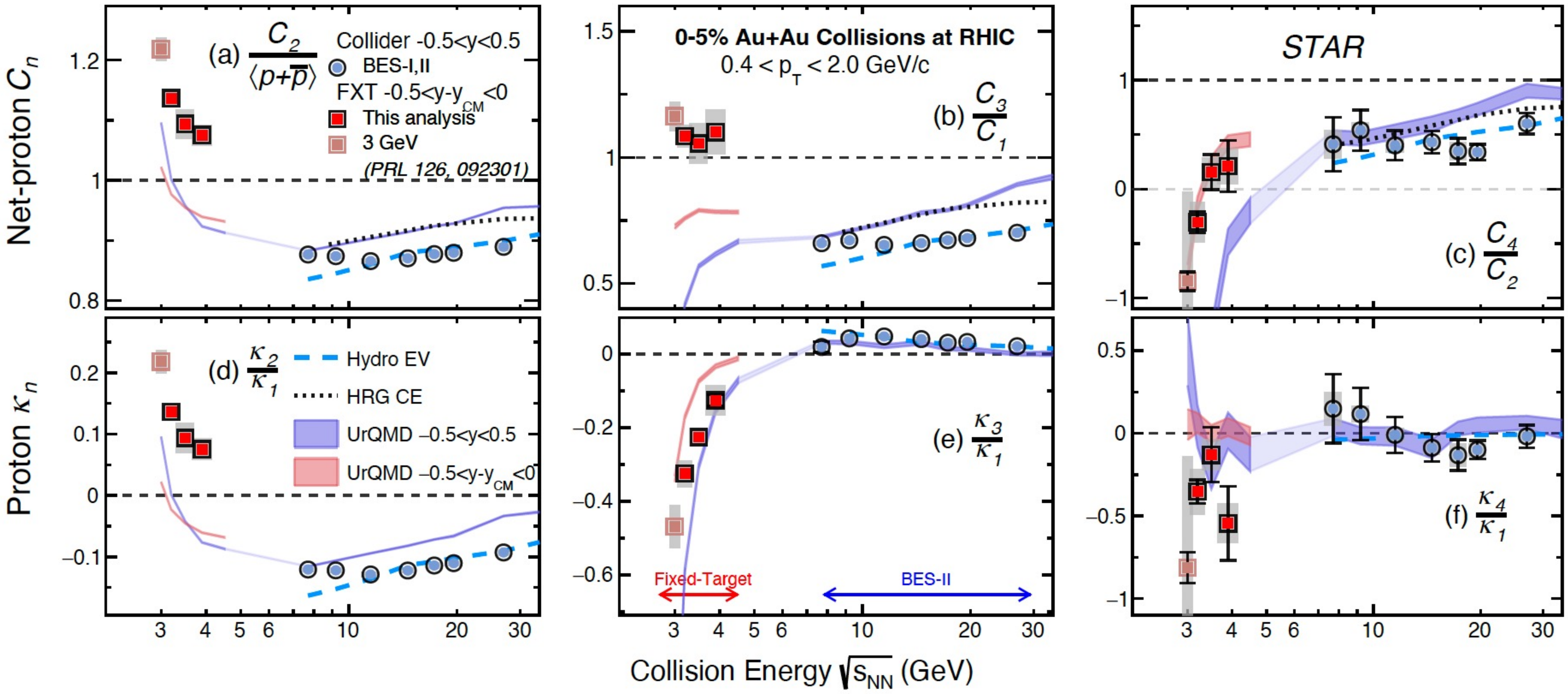
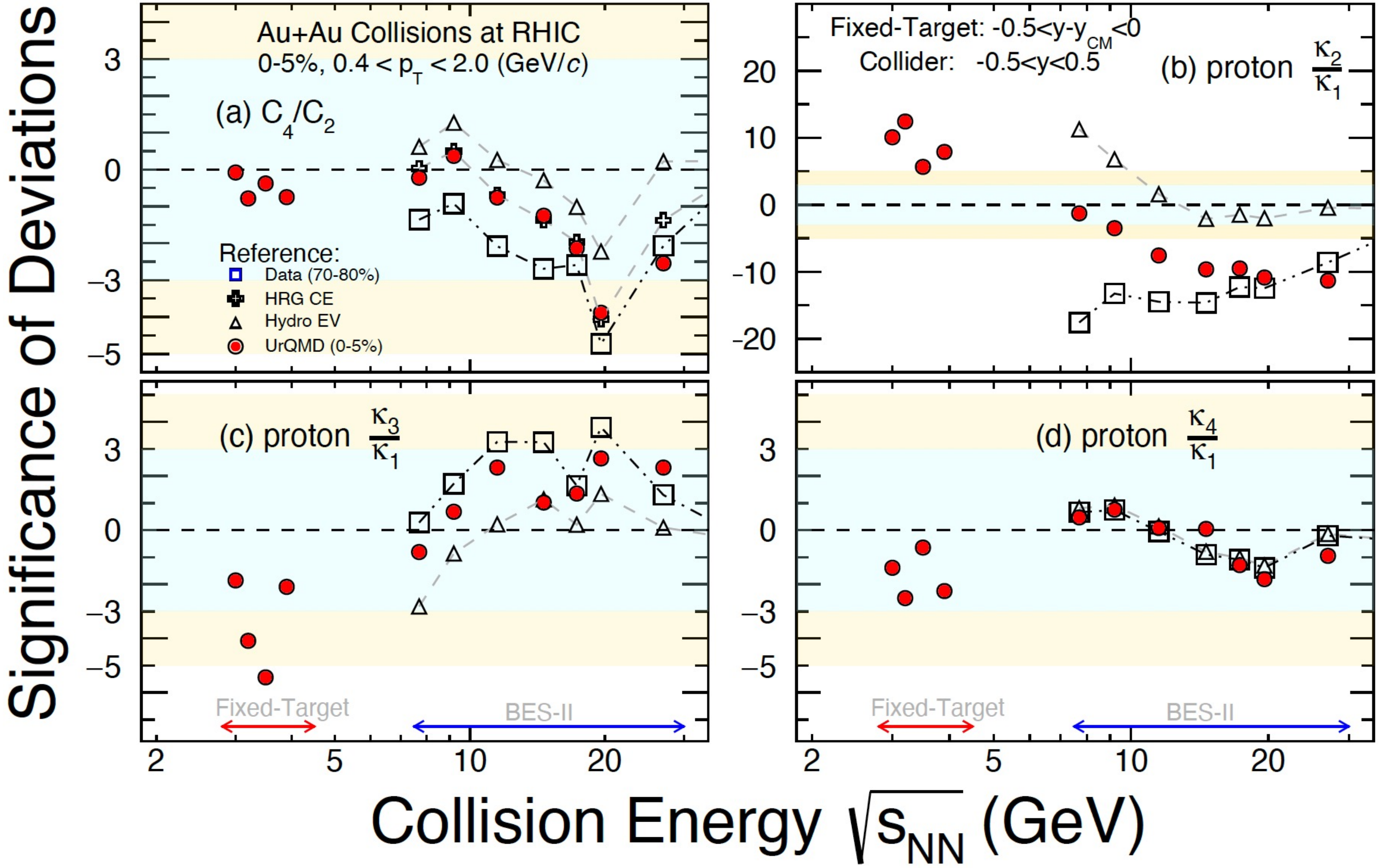
Energy Dependence of (Factorial) Cumulant Ratios



1. Decreasing C_2/C_1 and κ_2/κ_1, increasing C_4/C_2 and κ_3/κ_1 as energy increases
2. UrQMD calculations for half mid-rapidity (including acceptance gap) and full mid-rapidity reproduce trends of data
3. C_4/C_2 agrees well with UrQMD, while 2nd and 3rd orders show clear deviations

Z. Sweger (STAR), QM 2025

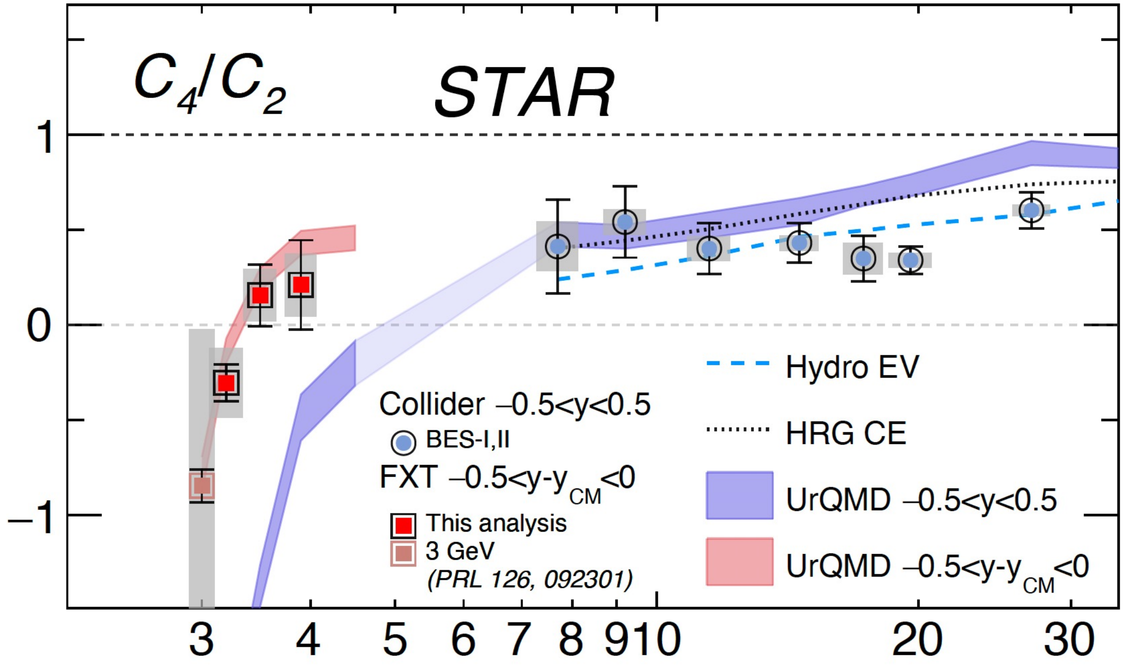
Significance of Deviations from References

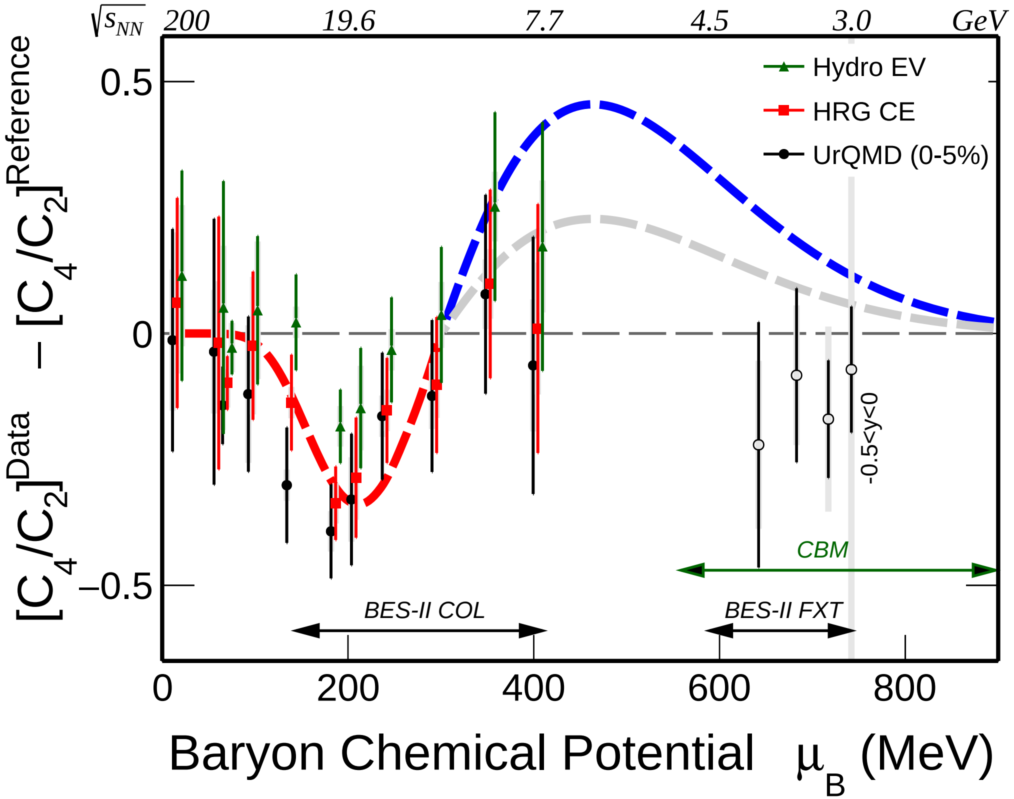


- Significant deviations of κ_2/κ_1 and κ_3/κ_1 from UrQMD
- C_4/C_2 deviates within 1σ, and κ_4/κ_1 deviates within 3σ

Z. Sweger (STAR), QM 2025

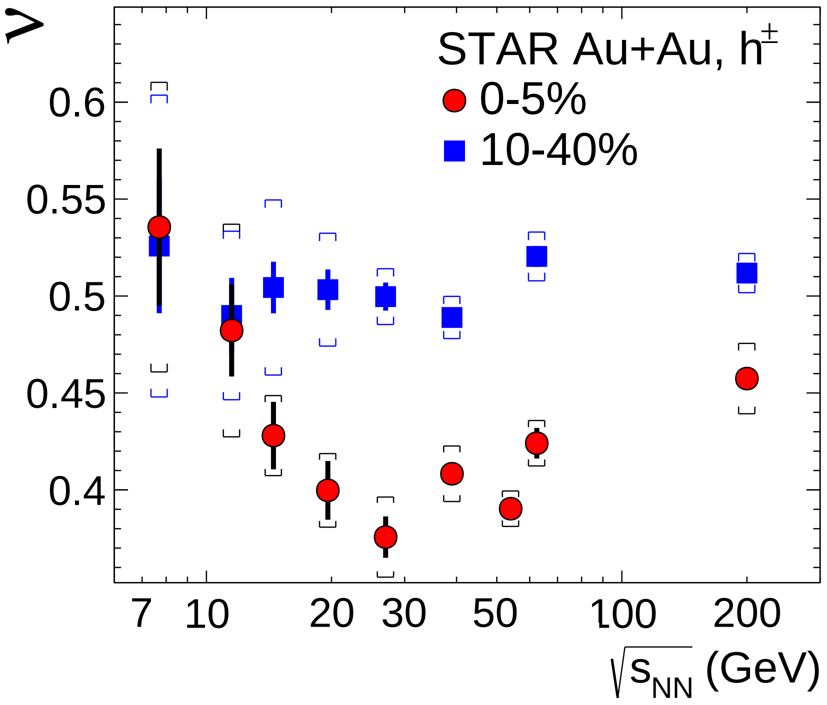
Summary

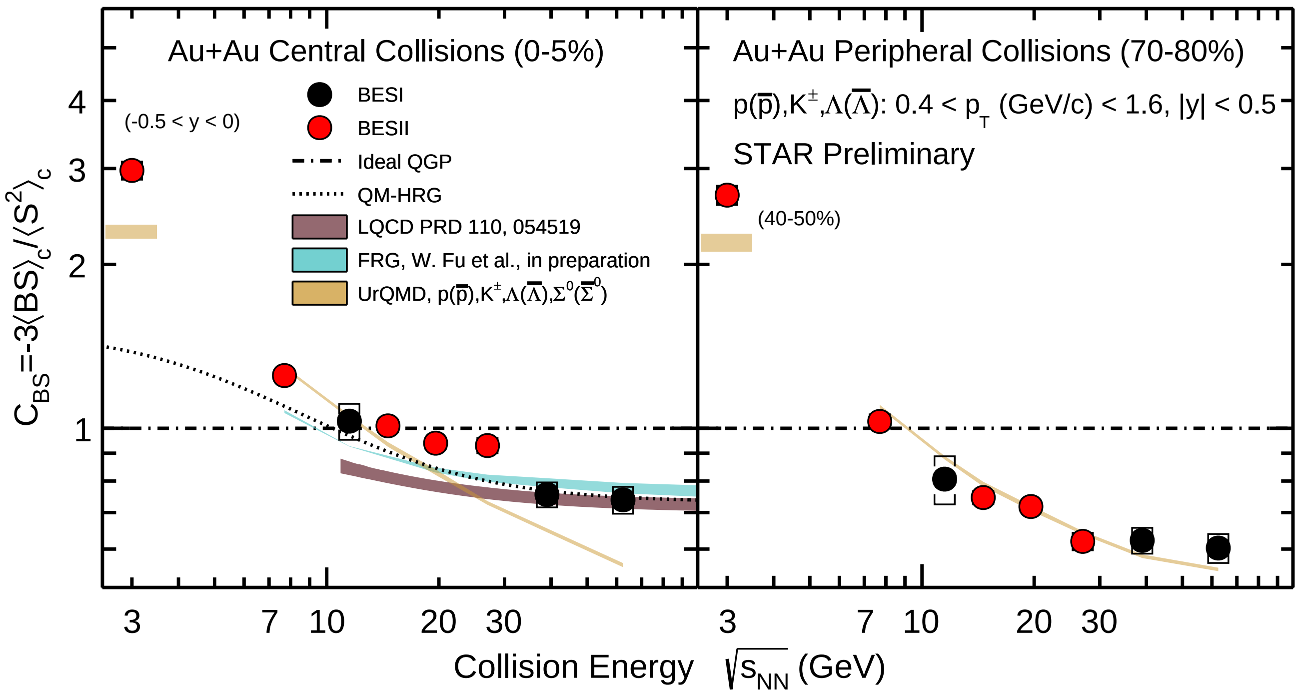




1. Precision measurement of (net-)proton number fluctuations in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2–3.9 GeV and 7.7–27 GeV from RHIC-STAR BES-II
2. Compared to non-CP refs., central C_4/C_2 shows a max. deviation at $\sqrt{s_{NN}} \sim 20$ GeV (2–5σ).
3. FSS and Binder cumulant studies introduce an interesting region of $\mu_B \sim 600$ MeV.

Outlook: Other Observables



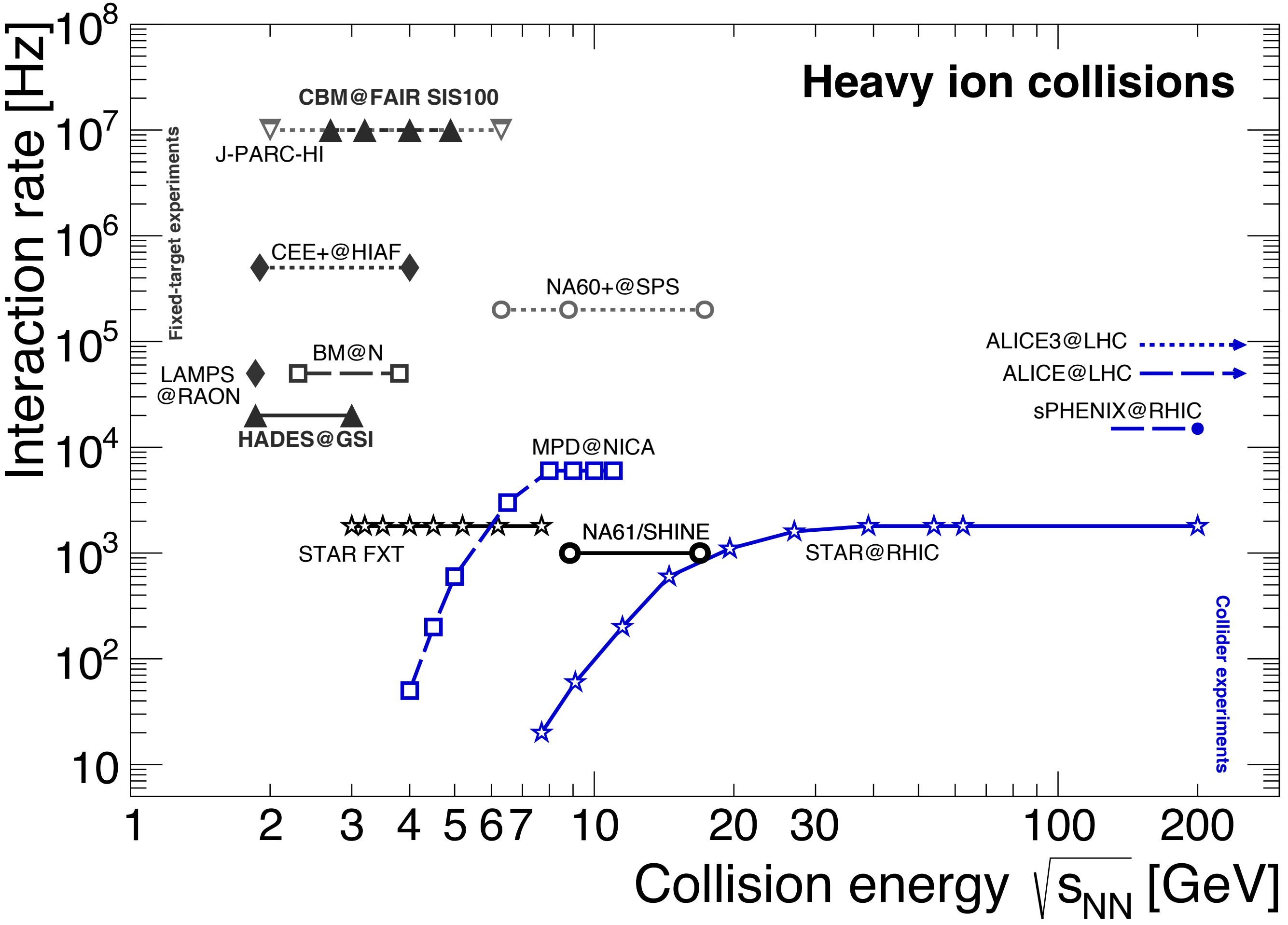


- Charged-hadron intermittency (ν): BES-I
- Baryon-strangeness correlation (C_{BS}): BES-I/II
- Non-monotonic behavior or deviation from references around $\sqrt{s_{NN}} = 20$ GeV
- Net-electric-charge and net-strangeness number fluctuations could also be studied

STAR, PLB 845, 138165 (2023)
H. Feng (STAR), QM 2025

Outlook: Future Facilities/Experiments

- Crucial for high baryon density
  - NICA-MPD in Russia:
    $\sqrt{s_{NN}} \sim 4\text{–}11$ GeV,
    $\mu_B \sim 620\text{–}330$ MeV
  - HIAF-CEE+ in China:
    $\sqrt{s_{NN}} \sim 2.1\text{–}4.5$ GeV,
    $\mu_B \sim 830\text{–}590$ MeV
  - FAIR-CBM in Germany:
    $\sqrt{s_{NN}} \sim 2.3\text{–}5.3$ GeV,
    $\mu_B \sim 800\text{–}530$ MeV
  - J-PARC-HI in Japan:
    $\sqrt{s_{NN}} \sim 2\text{–}6.2$ GeV,
    $\mu_B \sim 850\text{–}490$ MeV



C. Höhne (CBM), EPJ Web Conf. 296, 08004 (2024)

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