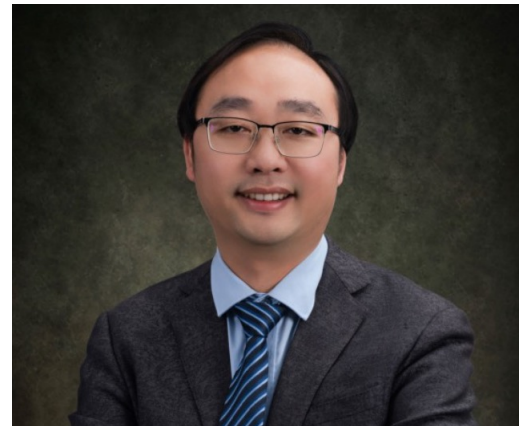


Experimental Review On QCD Critical Point Search



Xiaofeng Luo
Central China Normal University



<https://iopp.cnu.edu.cn/en/info/1097/3408.htm>

The 22nd International Conference on
Strangeness in Quark Matter
22-27 March, 2026, Los Angeles, CA



Outline

1) Introduction

2) Recent Results from RHIC BES and Comparison with Other Results

3) Centrality Determination at FXT

4) Summary and Outlook

Monday: A. Pandav (STAR), A. Marcinek (NA49/SHINE), J. Orlinski (HADES)

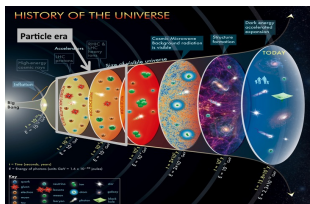
Tuesday: G. Pihan, J. Jahan

Wednesday: J. Noronha-Hostler

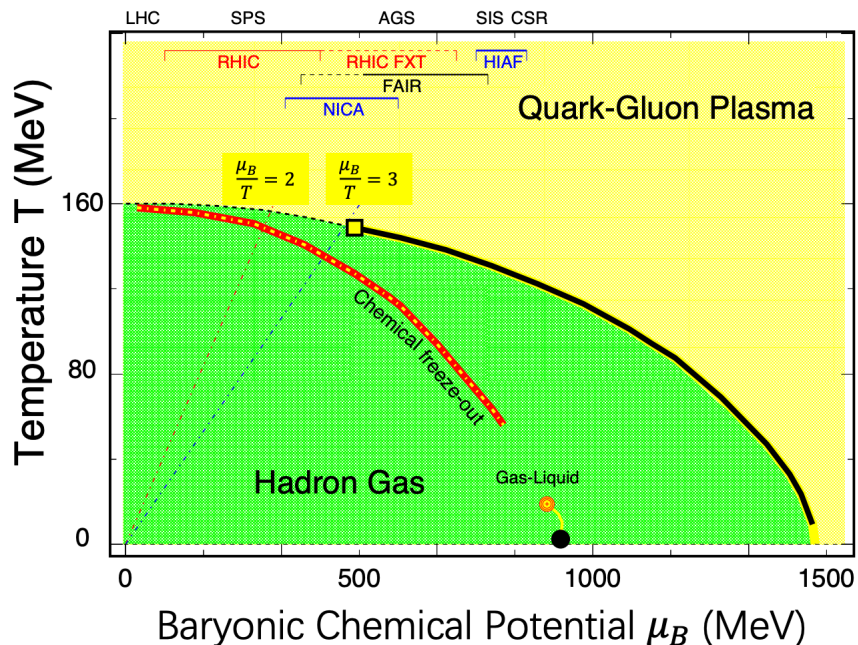
Thursday: XF. Luo, M. Pradeep

QCD Phase Diagram

Rich structure at High Baryon Density

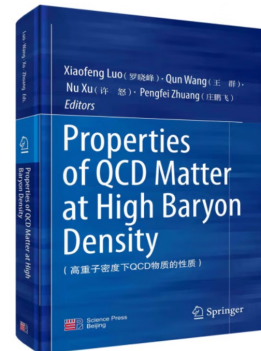
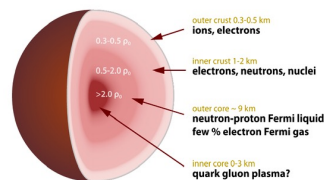


Evolution of the Universe



Lattice QCD : at $\mu_B = 0$, smooth crossover. $T_c \sim 156$ MeV
 Large μ_B : 1st order phase transition and QCD critical point ?

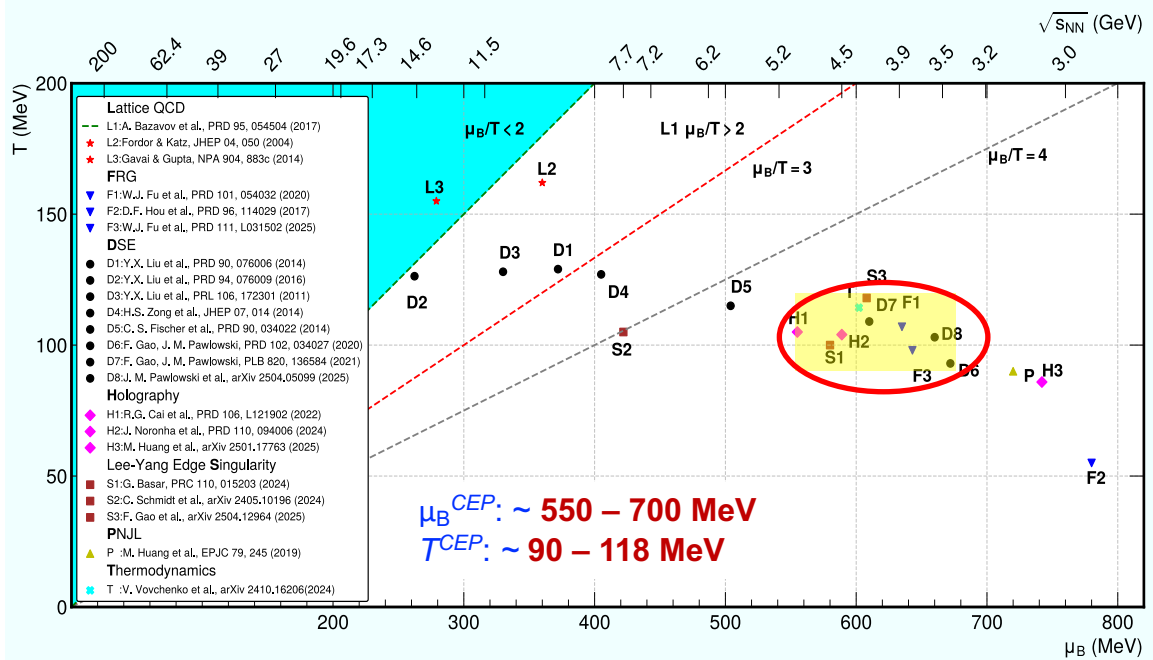
- Y. Aoki et al., Nature 443, 675 (2006) ;
- A. Bazavov et al (HotQCD), PRD 85, 054503 (2012).
- K. Fukushima and C. Sasaki, PNP, 72, 99 (2013).
- A. Bzdak et al., Phys. Rep. 853, 1 (2020).



Key Physics : QCD phase structure and EoS of QCD matter at high baryon density. (critical point and 1st order phase boundaries)

<https://doi.org/10.1007/978-981-19-4441-3>

Theoretical Estimations (2004-2025)

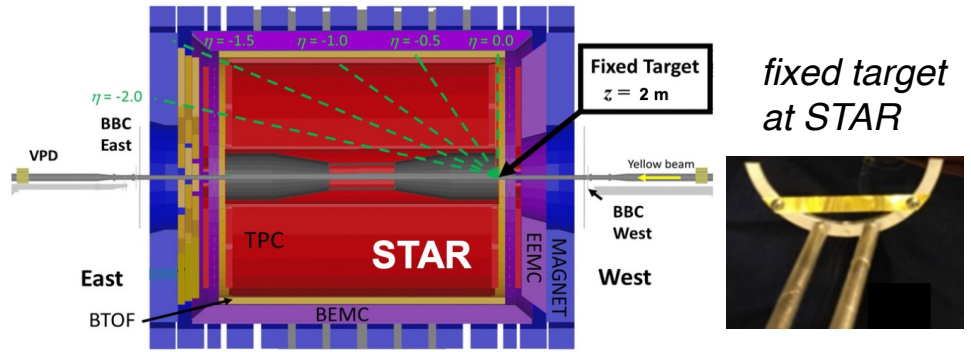
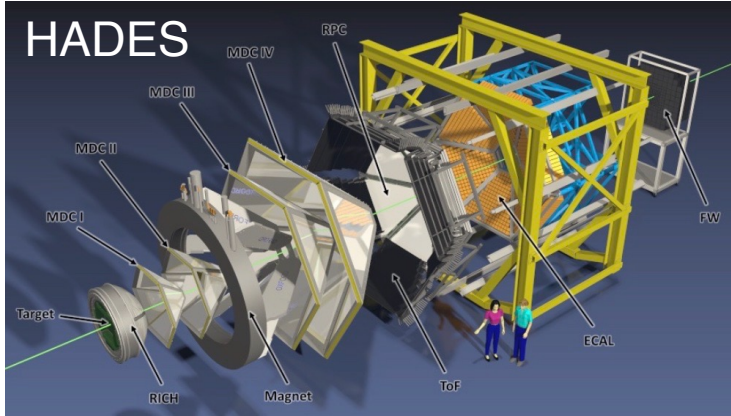
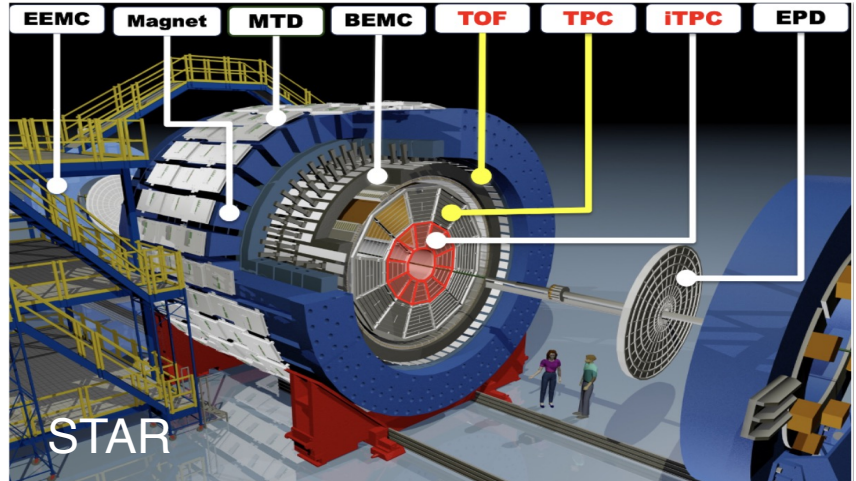
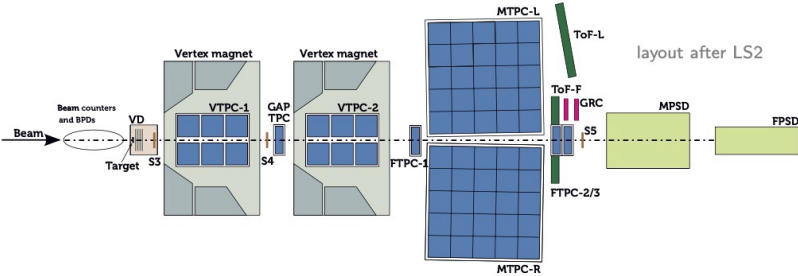


“...experimental measurements are essential to determine whether a QCD critical point exists.” *2023 US Long Range Plan for Nuclear Science*

Y. Zhang, Z. Wang, X. Luo, N. Xu, arXiv : 2602.08356
 Christian S. Fischer, Jan M. Pawłowski, arXiv : 2603.11135

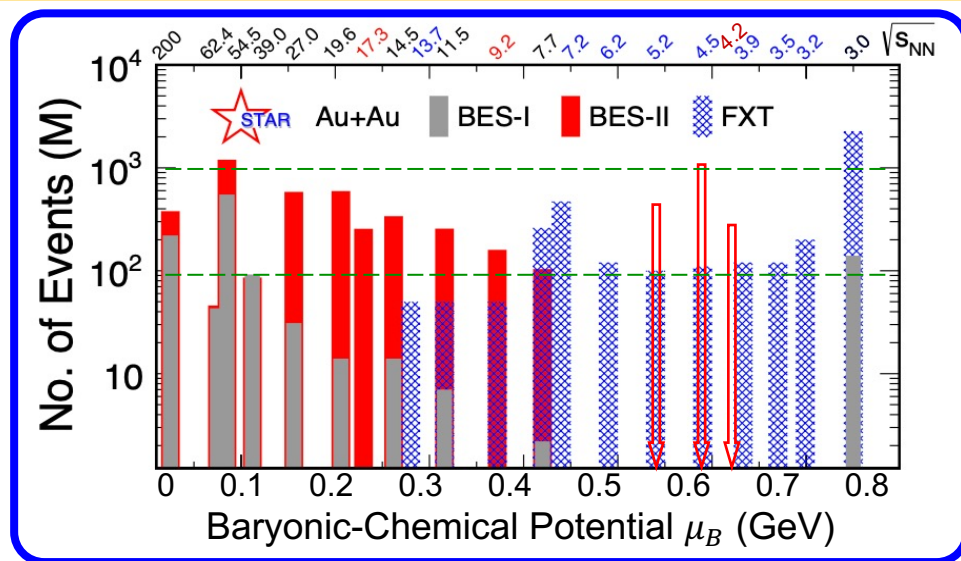
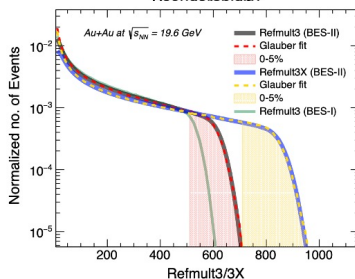
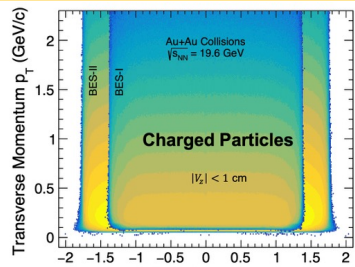
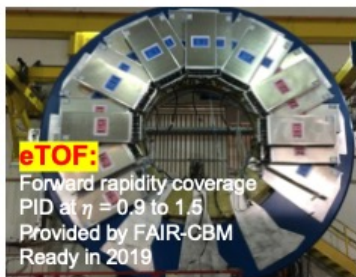
Search for QCD Critical Point in Heavy-ion Collisions Experiments

NA61/SHINE



RHIC Beam Energy Scan Program (2010 – 2026)

Detector Upgrades BES-II



(1) Enlarge rapidity acceptance; (2) Improve particle identification; (3) Better centrality/event plane resolution

1) BES-I (2010 – 2014): 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, 200 GeV;

2) BES-II (2018 – 2026): Collider mode (7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27 GeV),
FXT mode: (3.0, 3.2, 3.5, 3.9, 4.2, 4.5, 5.2, 6.2, ..., 13.7 GeV)

3) μ_B coverage : $25 < \mu_B < 750$ MeV

X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017)

Jinhui Chen, et al., Nucl. Sci. Tech. 35, 214 (2024)

Observables : Fluctuations of Conserved Quantities

➤ **At critical point with an infinite system**

- correlation length should diverge
- susceptibilities should diverge

$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial (\mu_q)^n}, q = B, Q, S$$

Conserved Charges q : Net Baryon Number (B), Net Charge (Q), Net Strangeness (S)

➤ **Experimental Observables: Cumulants of Conserved Quantities Dis.**

- 1) Sensitive to correlation length (ξ)
- 2) Directly related to the susceptibility ratios

$$\langle\langle (\delta N)^3 \rangle\rangle_c \approx \xi^{4.5}, \quad \langle\langle (\delta N)^4 \rangle\rangle_c \approx \xi^7$$

Notation: Cumulants: $C_{1,2,\dots}$
Factorial Cumulants: $\kappa_{1,2,\dots}$

$$\begin{aligned} \kappa_1 &= C_1 = \langle N \rangle, \\ \kappa_2 &= -C_1 + C_2, \\ \kappa_3 &= 2C_1 - 3C_2 + C_3, \\ \kappa_4 &= -6C_1 + 11C_2 - 6C_3 + C_4, \end{aligned}$$

Measured multiplicity N , $\langle \delta N \rangle = N - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3 / C_2^{3/2}$

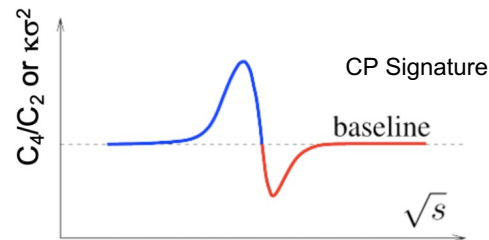
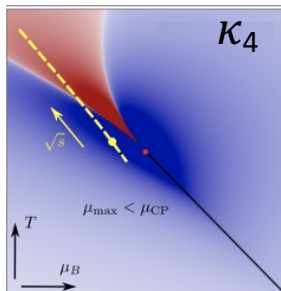
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 = C_4 / C_2^2$

Moments, cumulants and susceptibilities:

2nd order: $\sigma^2 / M \equiv C_2 / C_1 = \chi_2 / \chi_1$

3rd order: $S \sigma \equiv C_3 / C_2 = \chi_3 / \chi_2$

4th order: $\kappa \sigma^2 \equiv C_4 / C_2 = \chi_4 / \chi_2$



M. A. Stephanov, PRL 102 (2009) 032301

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); 107, 052301 (2011). M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009). Cheng et al, PRD (2009) 074505. F. Karsch and K. Redlich, PLB 695, 136 (2011). B. Friman et al., EPJC 71 (2011) 1694. S. Gupta, et al., Science, 332, 1525(2012). A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13)

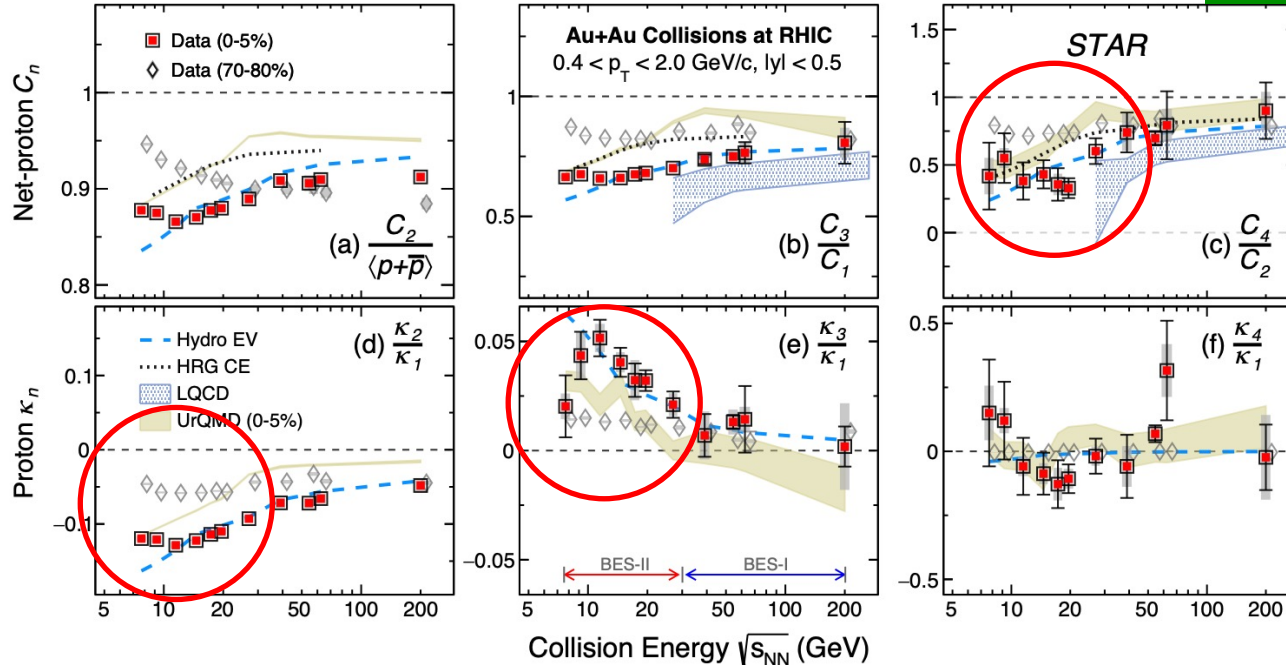
Outline

- 1) Introduction
- 2) Recent Results from RHIC BES and Comparison with Other Results**
- 3) Centrality Determination at FXT
- 4) Summary and Outlook

Energy Dependence (collider)

Au+Au Collisions at RHIC

STAR: PRL135, 142305(2025)



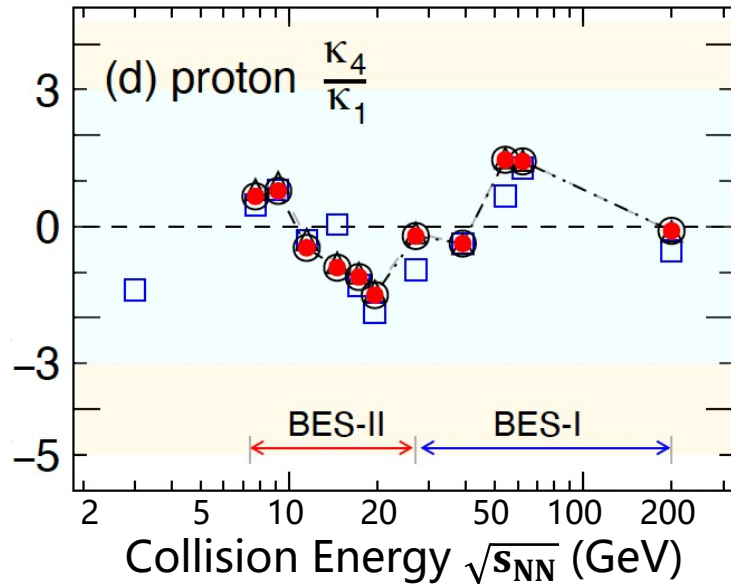
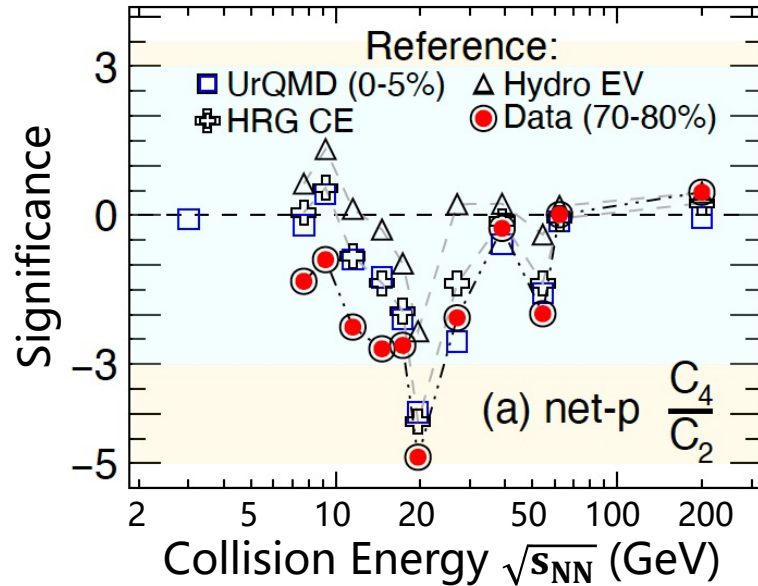
- 1) **UrQMD**: (hadronic transport calculations and the results are analyzed in the same way as data.) S. Bass *et al.*, Prog. Part. Nucl. Phys., **41**, 255 (1998);
- 2) **HRG CE**: P.B. Munzinger *et al.* Nucl. Phys. **A1008**, 122141(2021);
- 3) **Hydro**: HRG CE + EV, V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).
- 4) **LQCD**: (done for net-baryon) A. Bazavov *et al.*, Phys. Rev. D101, 074502 (2020). arXiv : 2407.09335

- 1) The energy dependence is reproduced by most calculations at high energy;
- 2) Deviations appear below $\sqrt{s_{NN}} < 35$ GeV

Significances at the 4TH Orders

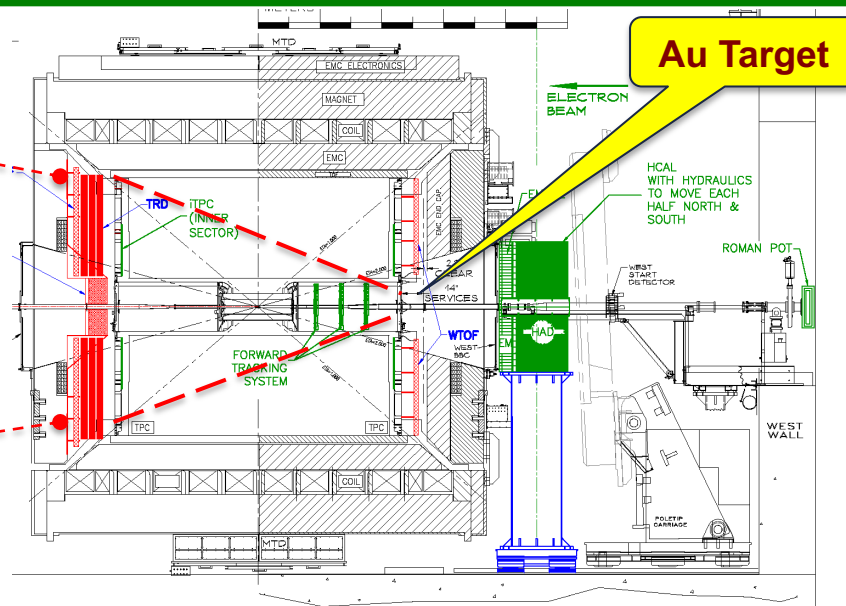
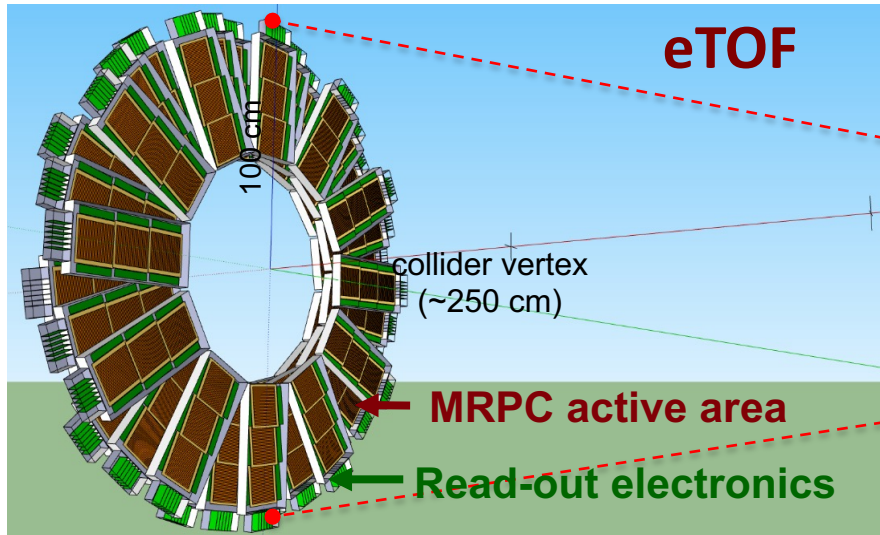
STAR: PRL135, 142305(2025)

0-5% Au+Au Collisions at RHIC



Significant deviations from non-critical references are observed!

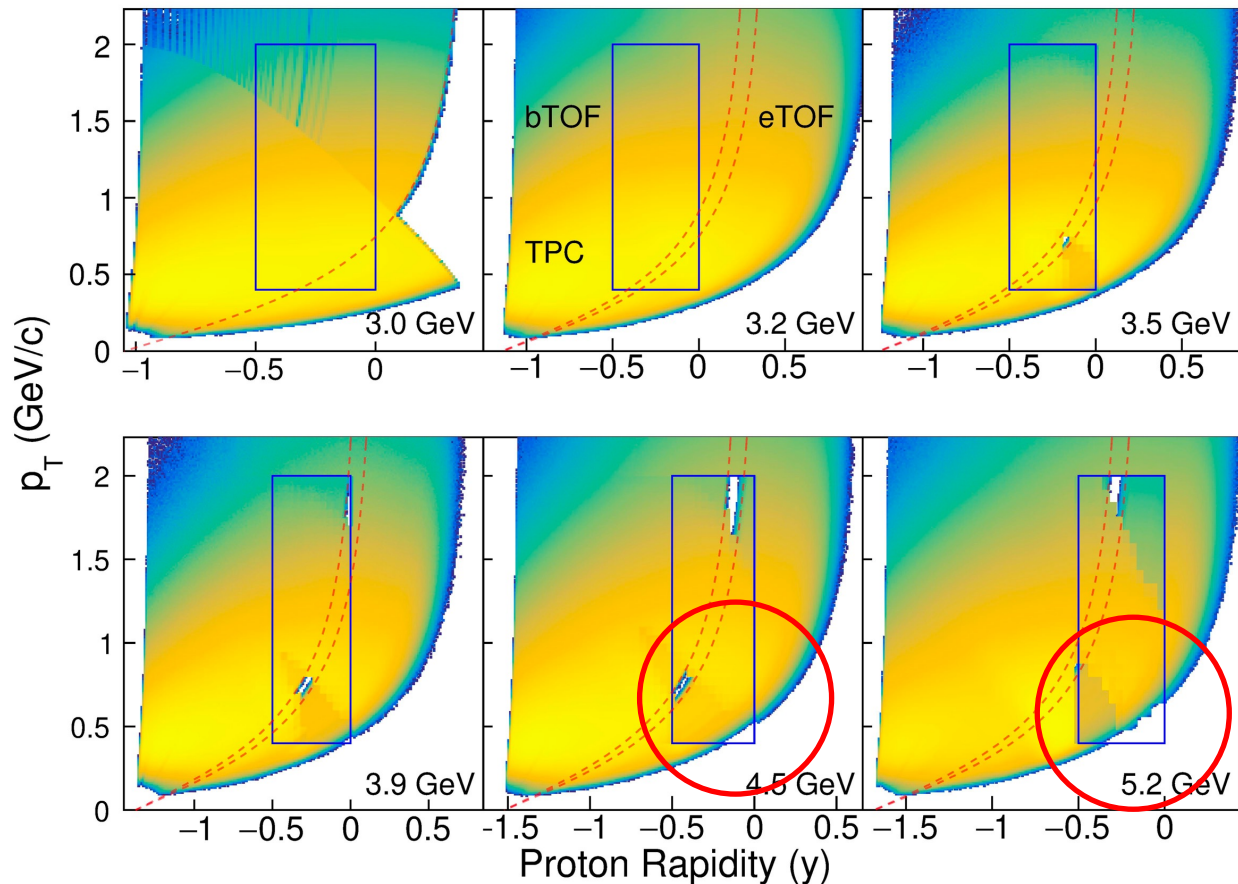
STAR Fixed Target Setup



CBM participates in RHIC BES-II in 2019 – 2021:

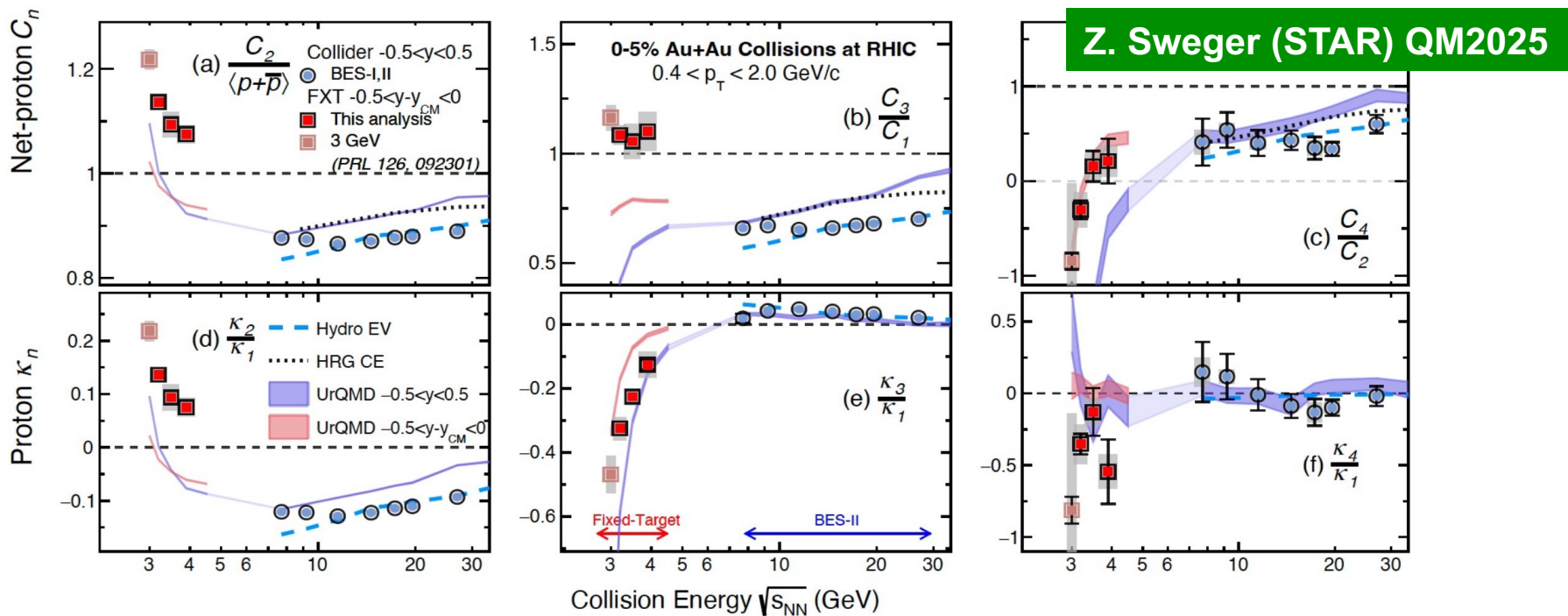
- Complementary to CBM program: $\sqrt{s_{NN}} = 3 - 7.2 \text{ GeV}$ ($760 \geq \mu_B \geq 420 \text{ MeV}$)
- Strange-hadron, hyper-nuclei and fluctuation at the high baryon density region

Proton PID and Acceptance in FXT



- 1) TPC, iTPC, bTOF, eTOF are used in the FXT program;
- 2) Lossing mid-y acceptance for energy higher than 4.5 GeV!
- 3) Analysis is focused on the mid-y region;

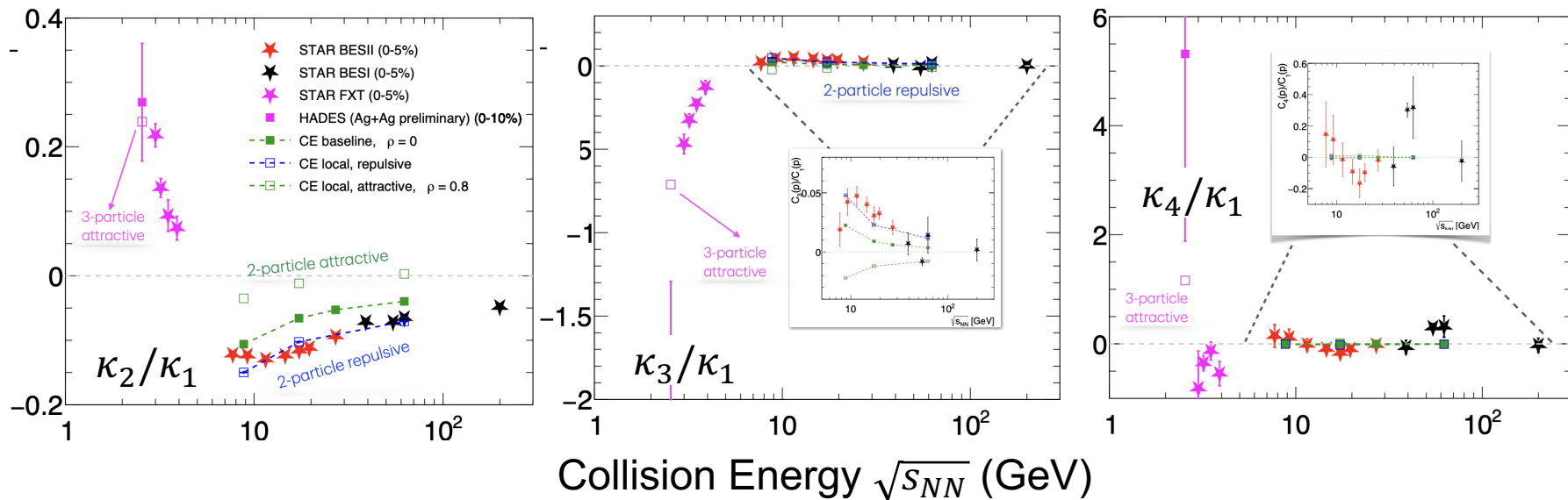
(Net-) Protons (C_4/C_2) from FXT Program



At 3.0 – 3.9 GeV central collisions (0-5%, $-0.5 < y < 0$):

- 1) Change of trends and increase above unity for 2nd and 3rd order cumulants;
- 2) Deviations from UrQMD model calculations is seen

ρ Factorial Cumulants: HADES vs. STAR



STAR, HADES, QM2025

STAR FXT: Au-Au, $\langle N_W \rangle \approx 320$:

$-0.5 < y < 0$

$0.4 < p_t < 2$ GeV/c

HADES: Ag-Ag, $\langle N_W \rangle \approx 170$

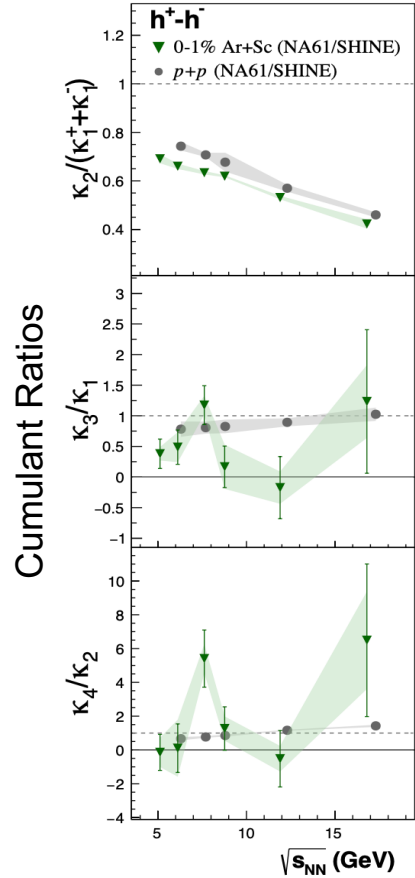
$-0.4 < y < 0.4$

$0.4 < p_t < 1.6$ GeV/c

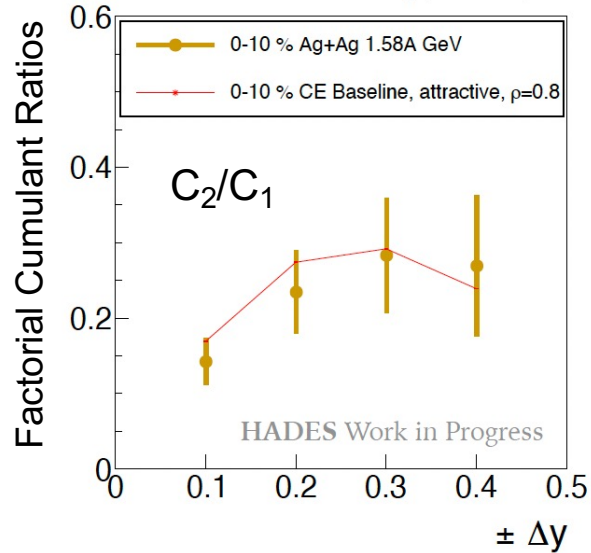
- Proton factorial cumulants of Ag+Ag 2.4 GeV from HADES follow the trend of STAR results.
- Changing from repulsive to attractive interactions

B. Friman, A. Rustamov, K. Redlich, arXiv : 2508.18879

Measurements at NA61/SHINE and HADES



QM2025/Monday (NA61/SHINE)
Antoni Marcinek



Tuesday: G. Pihan and V. Vovchenko in preparation

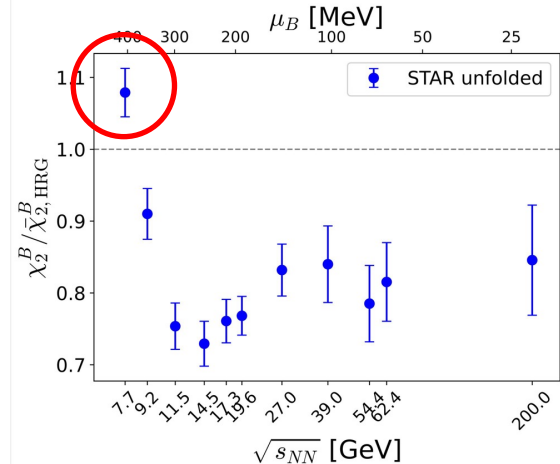
$$\frac{\chi_2^p(\text{data})}{\chi_2^B(\text{HRG})} \begin{cases} < 1 & \text{repulsive} \\ > 1 & \text{attractive} \end{cases}$$

Monday: J. Orlinski

HADES, Ag+Ag 1.58 GeV

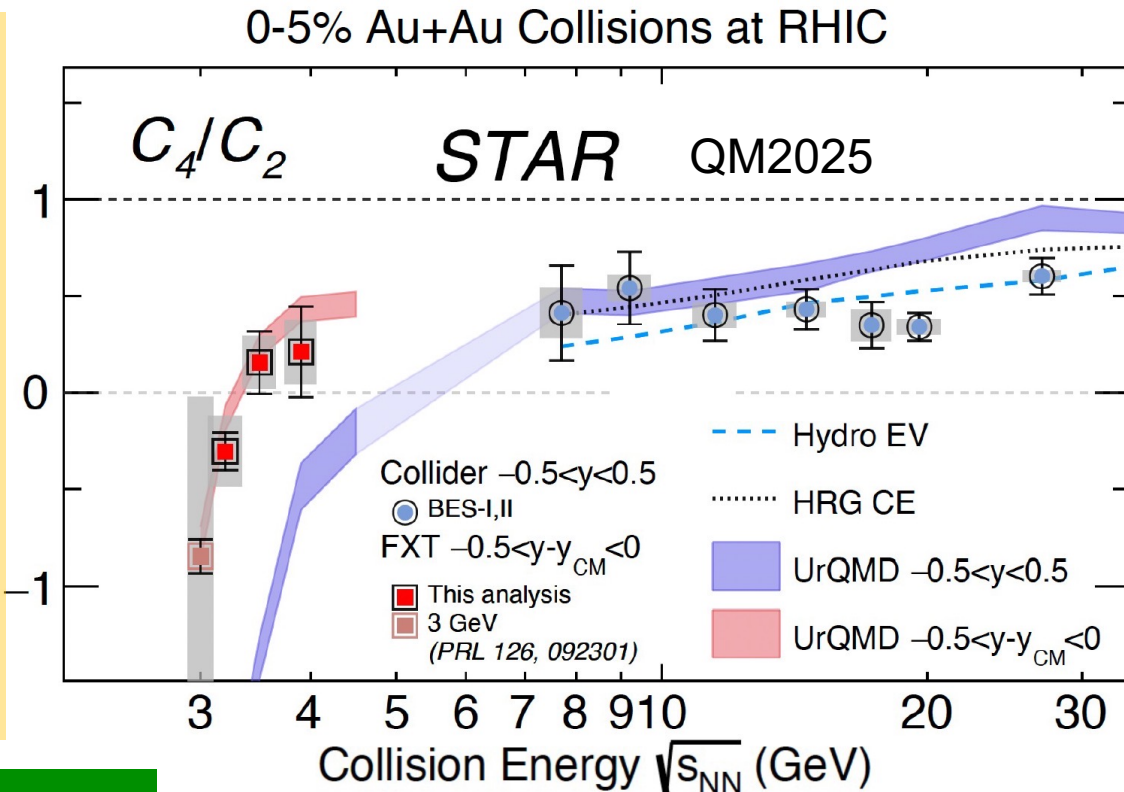
Attractive interactions is needed at the energy

B. Friman, A. Rustamov, K. Redlich, arXiv : 2508.18879



(Net-) Protons (C_4/C_2) from FXT Program

- 1) Collider mode: $|y| < 0.5$
FXT mode: $-0.5 < y < 0.0$
- 2) 3.0, 3.2, 3.5 and 3.9 GeV data were shown at QM2025
- 3) Data and UrQMD calculations are consistent for the FXT results. However, at the lowest energies, values of C_4/C_2 become negative: Centrality resolution issue



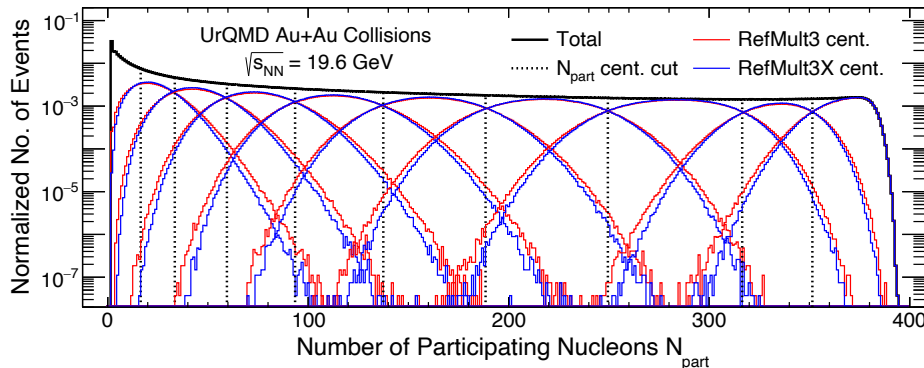
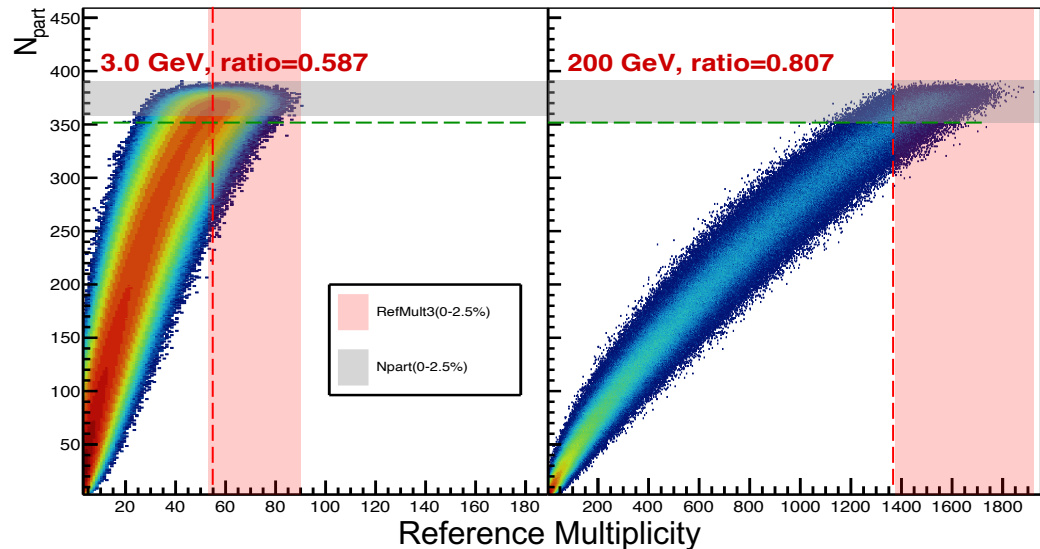
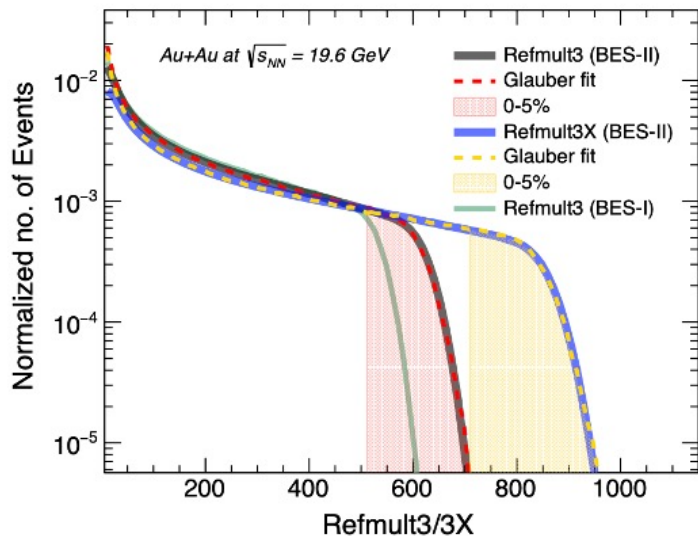
STAR 3GeV data:
Phys.Rev. C107, 024908 (2023)

Z. Sweger: (STAR) QM2025

Outline

- 1) Introduction
- 2) Recent Results from RHIC BES and Comparison with Other Results
- 3) Centrality Determination at FXT**
- 4) Summary and Outlook

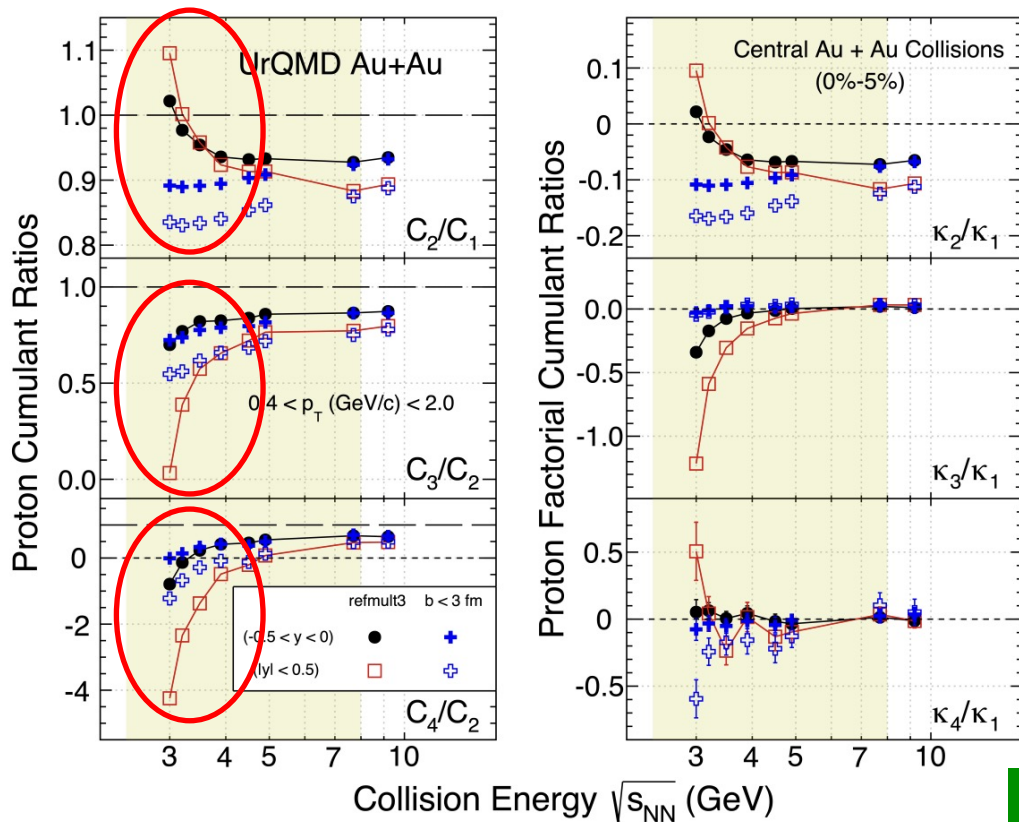
Collision Centrality Determination



UrQMD3.4 simulation:

- 1) The lower the collision energy, the smaller of the measure reference multiplicity;
- 2) The higher the RefMult, the better the centrality determination → **the smaller the initial volume fluctuation**

Initial Volume Fluctuations



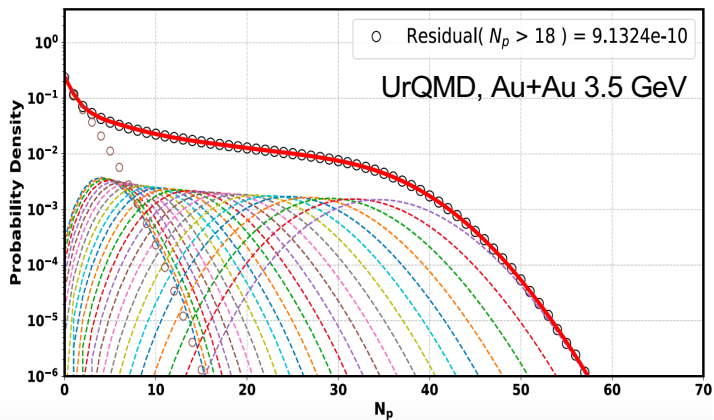
- 1) **Initial Volume Fluctuation:** The collision centrality is determined by charged particle multiplicities. Even in the same centrality bin, the collision volume varies event by event;
- 2) Simulations indicate that effects of the initial volume fluctuations becomes stronger at lower collision energies, which leads to the observed rapidly increase or decrease of κ_2/κ_1 and κ_3/κ_1 ;
- 3) At lower energies, as the centrality resolution becomes very poorer, initial volume fluctuations become more significant

X. Zhang, Y. Zhang, XFL, N. Xu, Chin. Phys. C 50, 011003 (2026)
 B. Friman, V. Koch, arXiv : 2511.11869

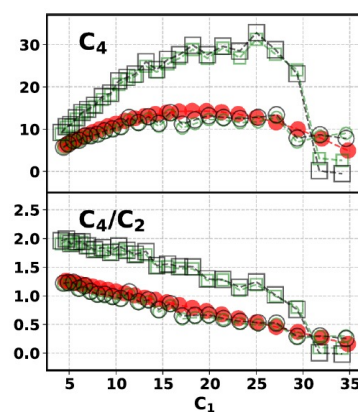
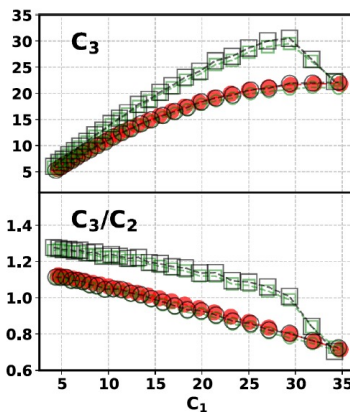
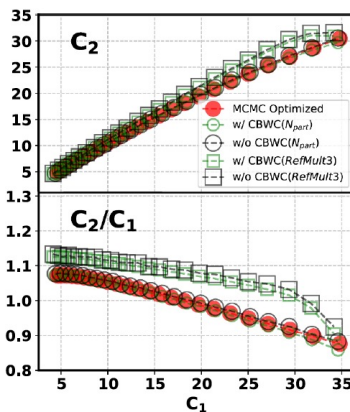
A New Approach

ZH. Wang, XF. Luo, Phys.Lett. B871, 139984(2025)

New



UrQMD, Au+Au 3.5 GeV



Edgeworth expansion :

$$\sigma p(\sigma x) = Z(x) \left\{ 1 + \sum_{s=1}^{\infty} \left[\sigma^s \sum_{\{k_m\}} H_{e_{s+2r}}(x) \prod_{m=1}^s \frac{1}{k_m!} \left(\frac{S_m + 2}{m + 2} \right)^{k_m} \right] \right\}$$

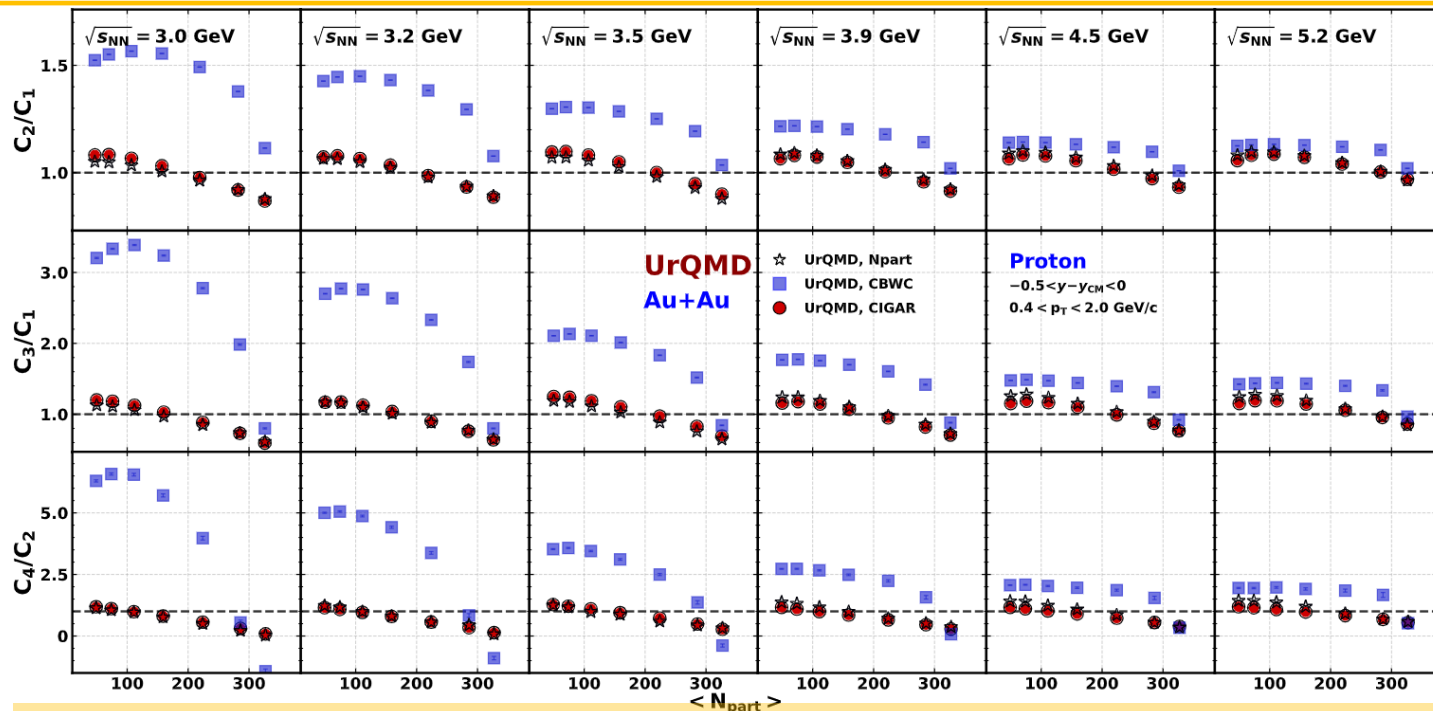
where Chebyshev-Hermite polynomials H_{e_n} is defined as:

$$H_{e_n}(x) = (-1)^n \exp(x^2/2) \frac{d^n}{dx^n} \exp(-x^2/2)$$

□ Ref. Multiplicity
● New approach

- 1) Using Edgeworth expansion to reconstruct the proton number distribution with cumulant as parameters;
- 2) The new approach is effective to suppress the initial volume fluctuations

More Simulations



Ref. Multiplicity
 New approach

ZH. Wang, XF. Luo,
 Phys.Lett. **B871**,
 139984(2025)

- 1) At low energies, the RefMultiplicity method fails to suppress the volume fluctuation and the C_4/C_2 in central collisions become negative;
- 2) The new approach seems converging to the N_{part} -based centrality results, indicating the method can effectively suppress volume fluctuations.

Outline

- 1) Introduction
- 2) Recent Results from RHIC BES and Comparison with Other Results
- 3) Centrality Determination at FXT
- 4) Summary and Outlook**

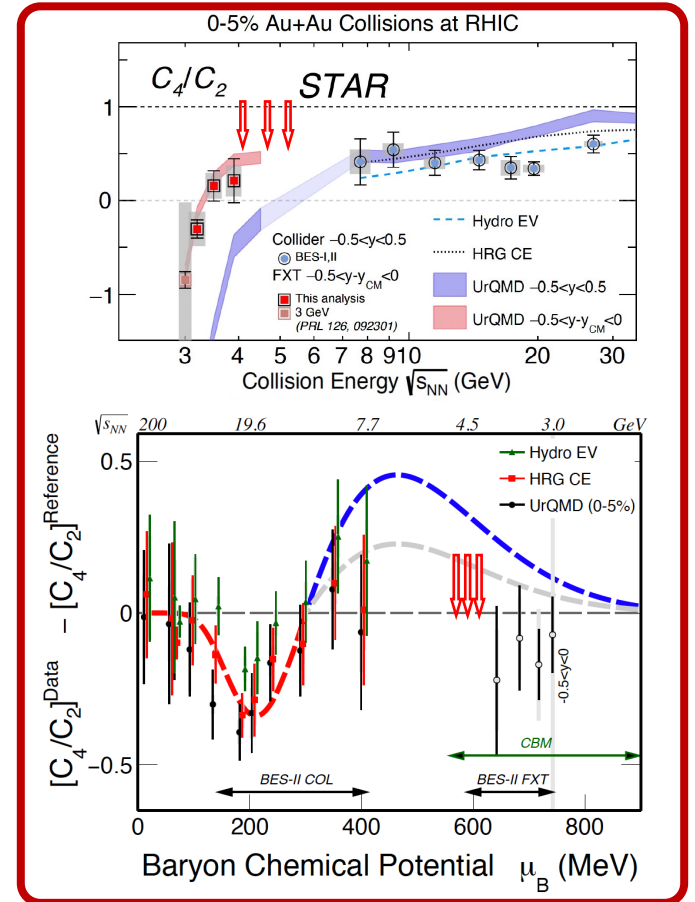
Summary and Outlook

- Precision measurement of (net-)proton fluctuations in Au+Au collisions from RHIC BES-II:

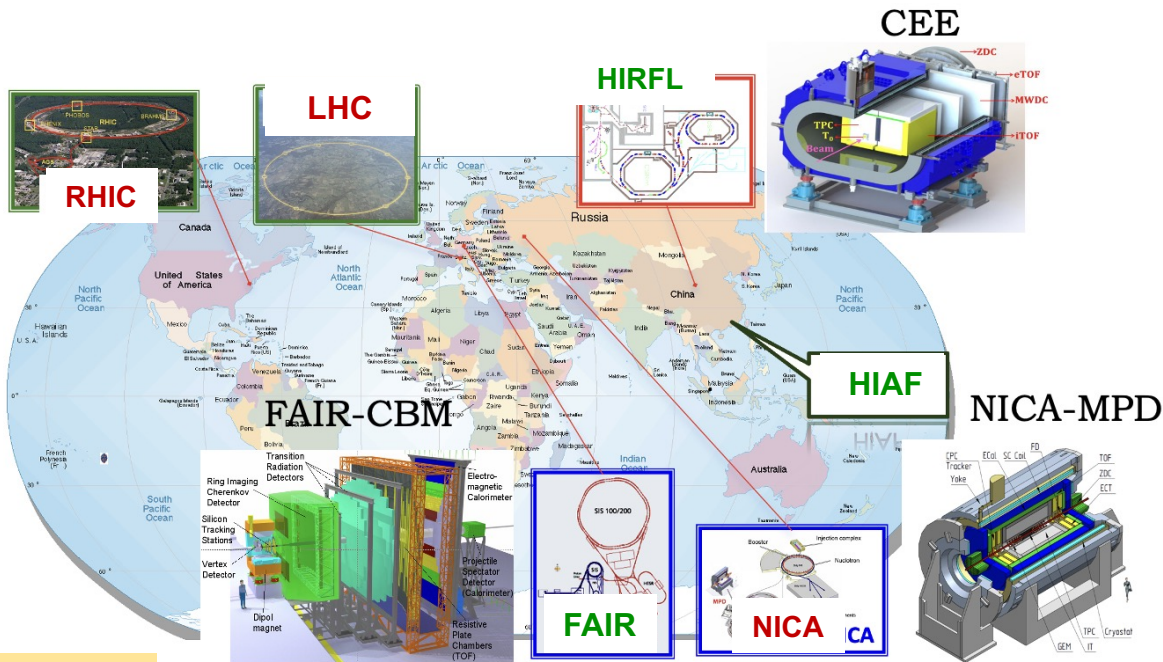
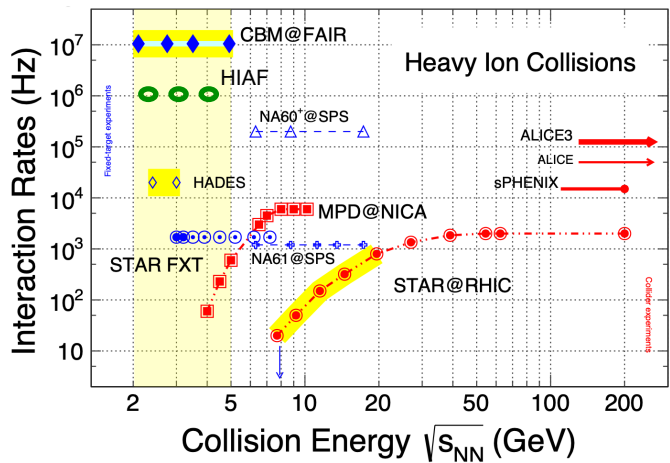
Collider energies: for net-proton C_4/C_2 in central collisions, deviations of 2-5 σ are observed w.r.t non-CP reference at 19.6 GeV

FXT energies: proton C_4/C_2 in central collisions are consistent with UrQMD calculations at 3.0 – 3.9 GeV while low orders changing trends and deviate from the transport model calculations

- STAR is working on a new analysis framework to determine the collision centrality, to suppress the initial volume fluctuation. Reanalyzing all data sets including 4.2, 4.5 and 5.2 GeV Au+Au collisions is under way;
- Modeling with dynamical effects including critical fluctuations and non-equilibrium effects are crucial to understand the experimental data



Summary and Outlook



Key Physics at High Baryon Density:

- (1) Critical point and phase boundary;
- (2) Y-N interactions;
- (3) Polarization

Many Thanks to:

Xin Dong, Shinichi Esumi, *Yige Huang*, Bedanga Mohanty, *Bappaditya Mondal*,
Ashish Pandav, *Fan Si*, *Zachary Sweger*, *Zhaohui Wang*, Nu Xu, *Yongcong Xu*,
Chenghao Zhu, *Xin Zhang*, *Yu Zhang*

STAR Collaboration and Theory Colleagues
RHIC Operation!

Thank you for your attention!