The 3rd International Workshop on Physics at High Baryon Density

Search for the QCD Critical Point in High Energy Nuclear Collisions

Yu Zhang

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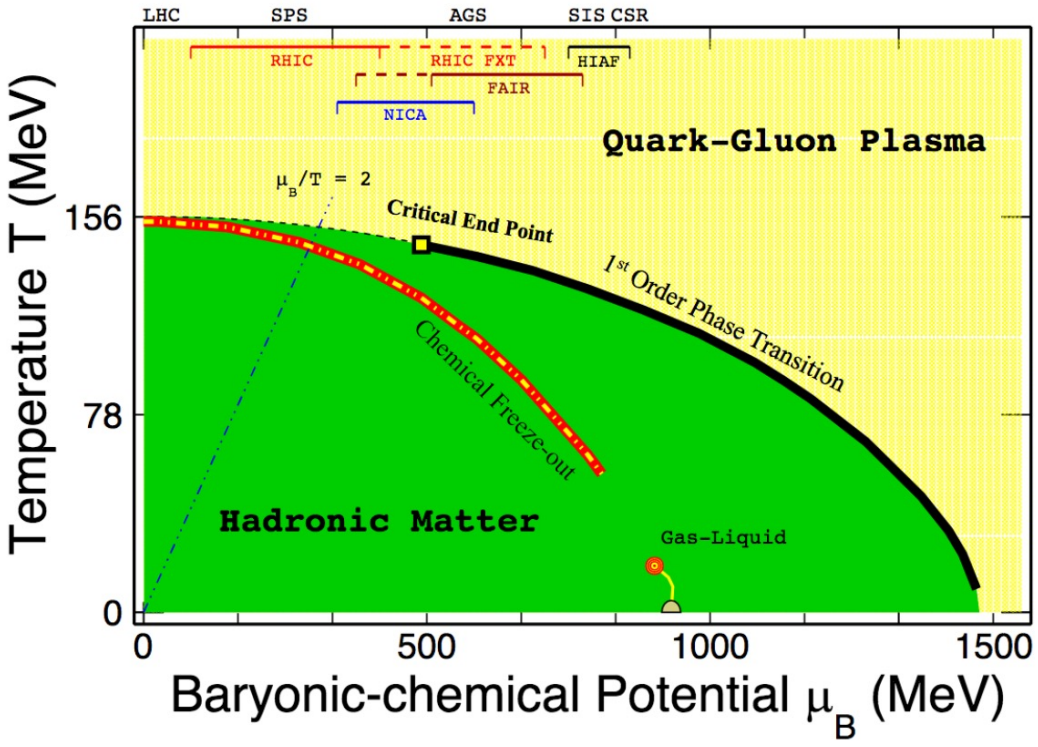
2026-11-11



Outline

1. Introduction
2. Results (BES-II & FXT)
   - Net-proton Fluctuation
   - Baryon-strangeness Correlation
   - Particle Ratio Fluctuation
3. Summary

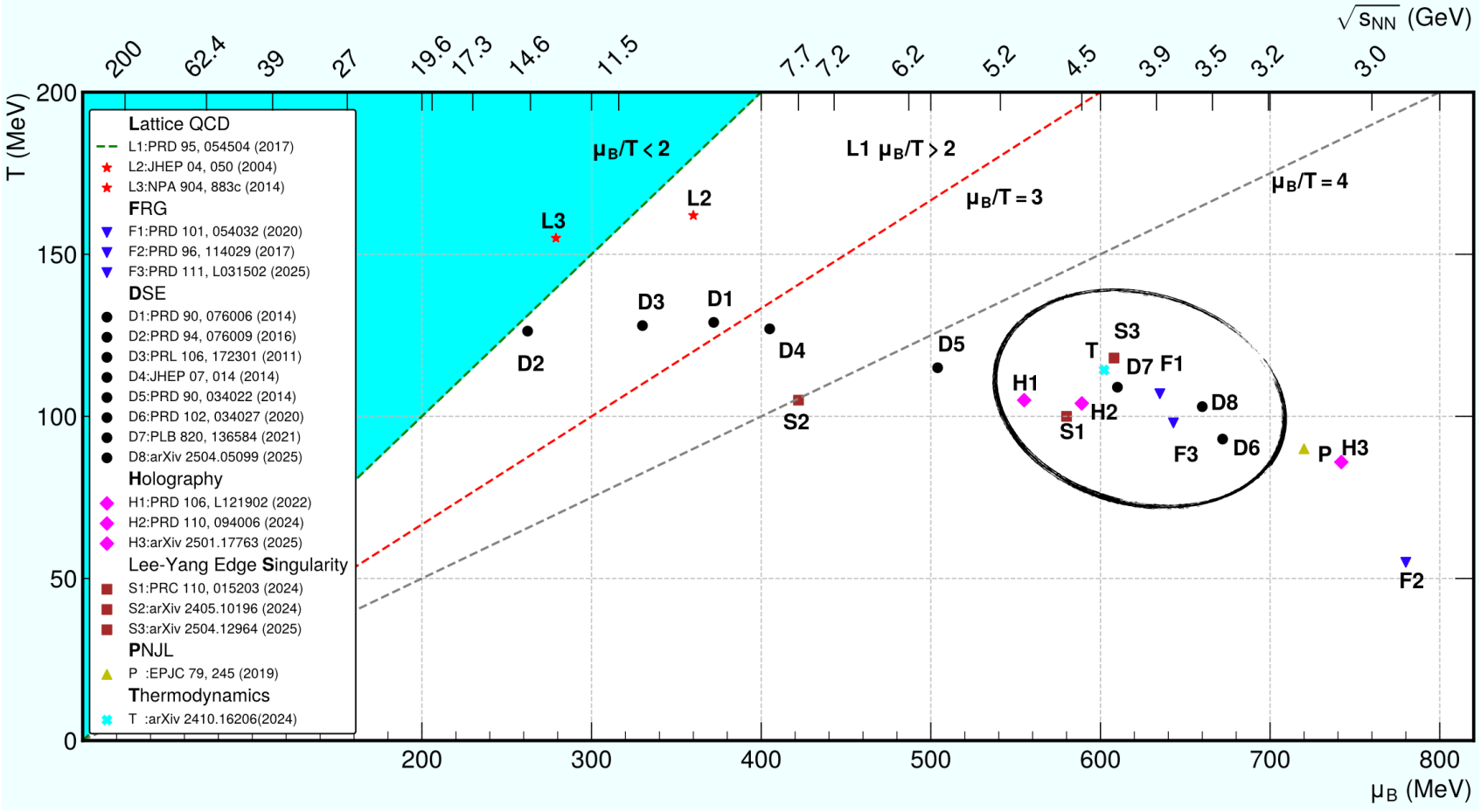
QCD Phase Diagram



1. Smooth crossover at $\mu_B = 0$ MeV by Lattice QCD
2. 1st-order phase transition at large μ_B by various models
3. QCD critical point ?

Y. Aoki et al, Nature 443, 675(2006)
A. Bzdak et al, Physics Reports 853,1-87(2020)
X. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017)
X. Luo, Q. Wang, N. Xu, P. F. Zhuang. Properties of QCD Matter at High Baryon Density. Springer, 2022, doi:10.1007/978-981-19-4441-3

QCD Phase Diagram



- Recent progress from theory converge around high baryon density region, which is coverd by STAR fixed-target experiment !

Observable: Cumulants of Conserved Quantities

At around critical point, correlation length should diverge

Moments of Net-B, Net-Q, Net-S are

1. sensitive to correlation length

$$C_3 = \langle (\delta N)^3 \rangle \sim \xi^{4.5}$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle \sim \xi^{7}$$

2. directly related to susceptibility ratios

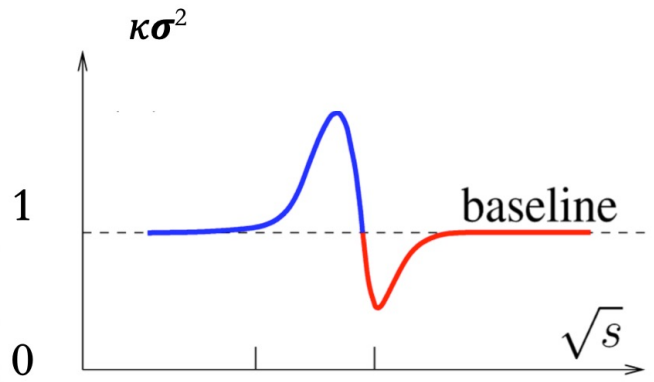
$$\frac{\chi_4^q}{\chi_2^q} = \kappa\sigma^2 = \frac{C_4^q}{C_2^q}, \quad \frac{\chi_3^q}{\chi_2^q} = S\sigma = \frac{C_3^q}{C_2^q}$$
$$\chi_n^q = \frac{1}{VT^3} \cdot C_n^q = \frac{\partial^n (p/T^4)}{\partial (\mu^q)^n}, \quad q = B, Q, S$$

Cumulants:

mean: M	$= \langle N \rangle$	$= C_1$
variance: σ^2	$= \langle (\delta N)^2 \rangle$	$= C_2$
skewness: S	$= \langle (\delta N)^3 \rangle / \sigma^3$	$= C_3 / C_2^{\frac{3}{2}}$
kurtosis: κ	$= \langle (\delta N)^4 \rangle / \sigma^4 - 3$	$= C_4 / C_2^2$

Factorial cumulants:

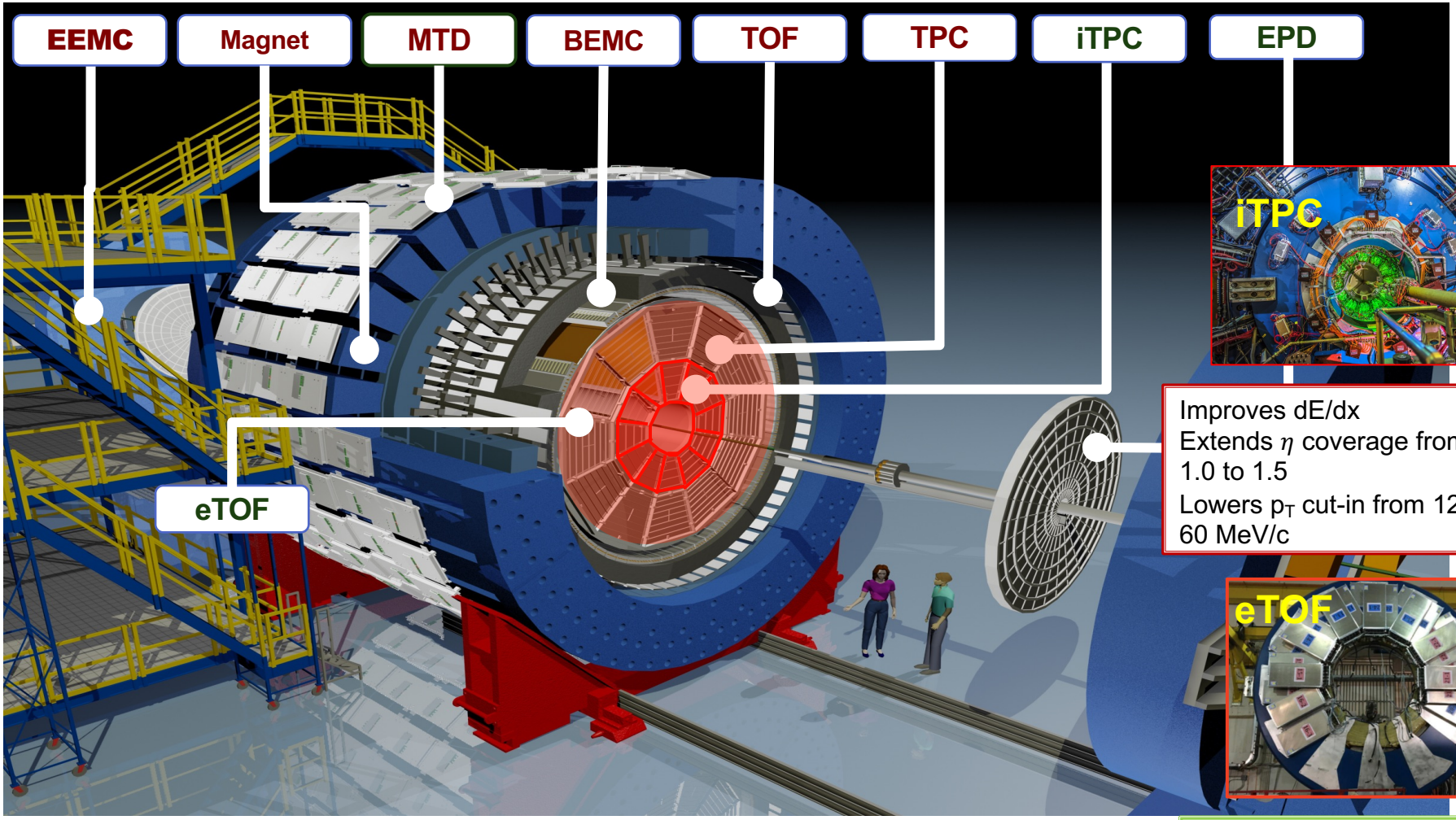
$$\kappa_1 = C_1$$
$$\kappa_2 = C_2 - C_1$$
$$\kappa_3 = C_3 - 3C_2 + 2C_1$$
$$\kappa_4 = C_4 - 6C_3 + 11C_2 - 6C_1$$



$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

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

STAR Detector System

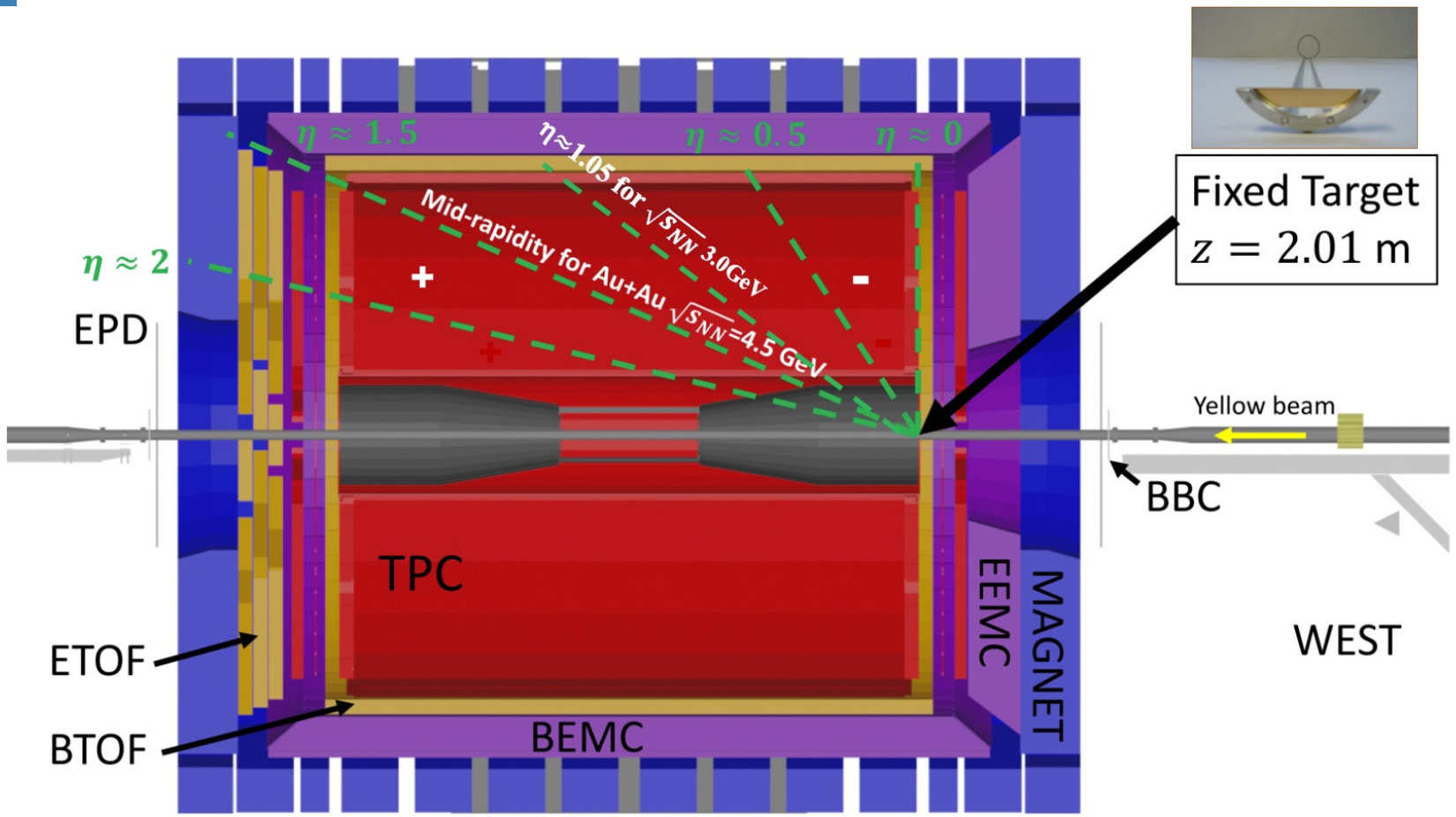


Improves dE/dx
Extends η coverage from 1.0 to 1.5
Lowers p_T cut-in from 125 to 60 MeV/c

- **Large** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

Forward rapidity coverage
PID at η = 0.9 to 1.5
Provided by FAIR-CBM

STAR Fixed-target setup



- Extending analysis to high baryon density region !

Au+Au collisions data from BES & FXT (2019-2021)

Au+Au Collisions at RHIC

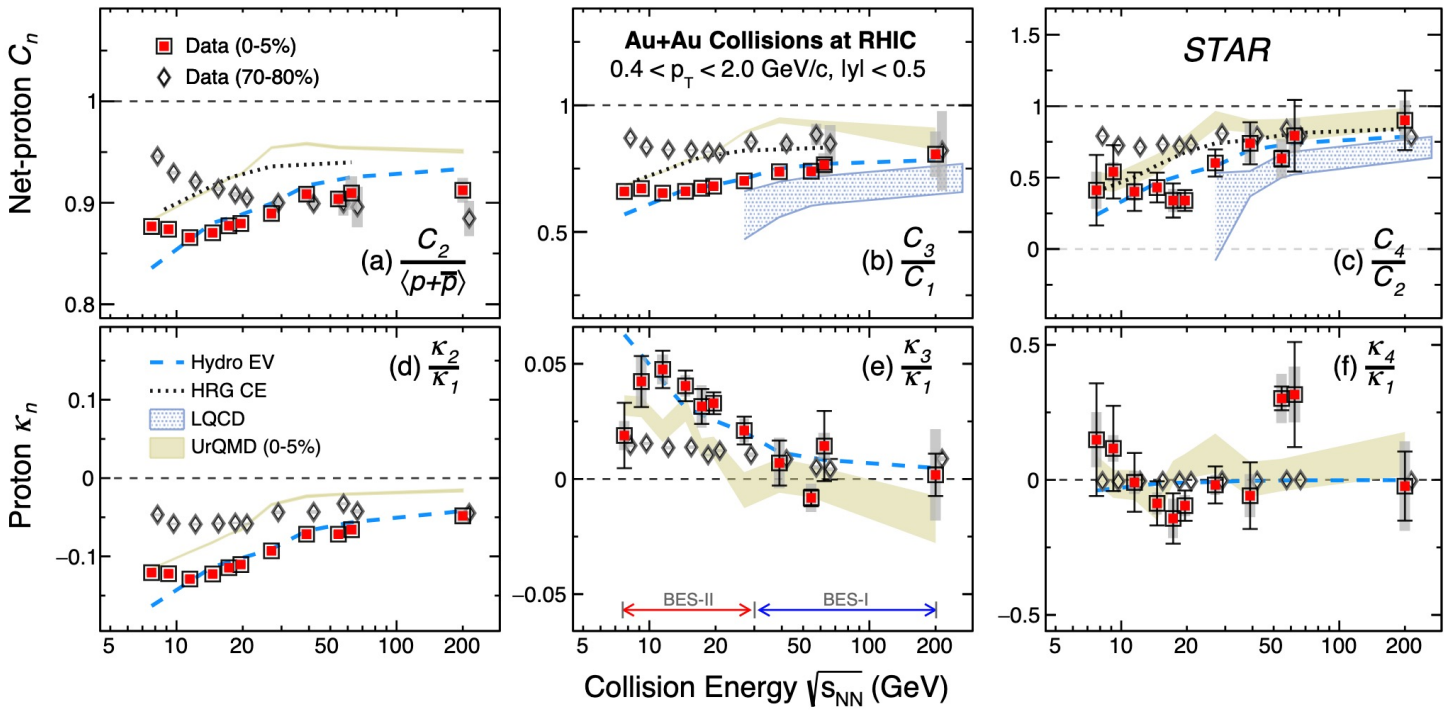
Collider Runs				Fixed-Target Runs			
	$\sqrt{s_{NN}}$ / GeV	events / million	μ_B / MeV		$\sqrt{s_{NN}}$ / GeV	event / million	μ_B / MeV
1	200	380	25	1	13.7 (100)	50	280
2	62.4	46	75	2	11.5 (70)	50	316
3	54.4	1200	85	3	9.2 (44.5)	50	372
4	39	86	112	4	7.7 (31.2)	260	420
5	27	585	156	5	7.2 (26.5)	470	440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

Large dataset taken at 4.2, 4.5, and 5.2 GeV in 2026

Au+Au Collisions at RHIC

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9	11.5	257	316	9	**4.2 (8.5)**	**New!**	600
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Results: Net-proton Cumulants

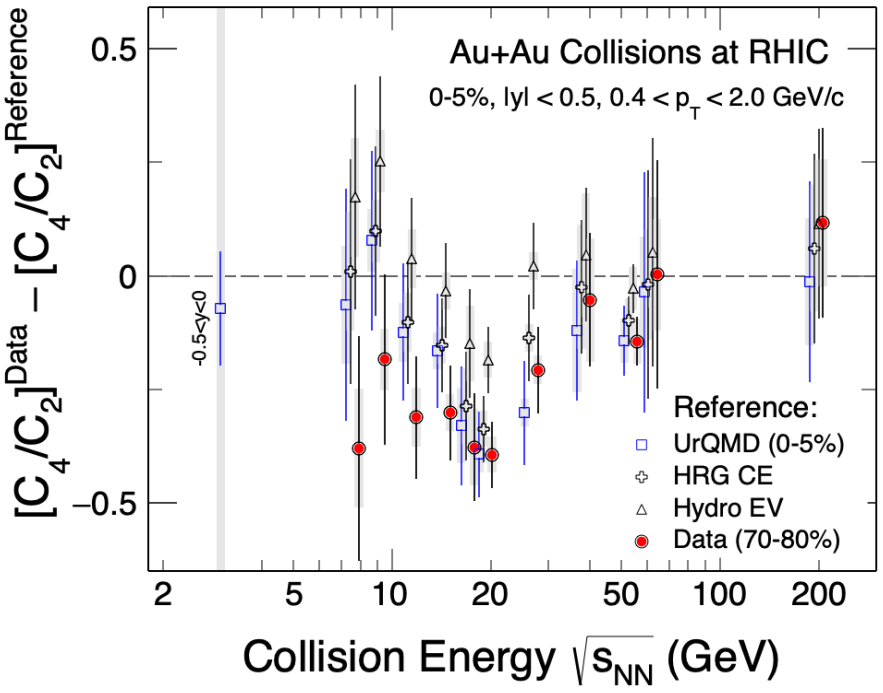


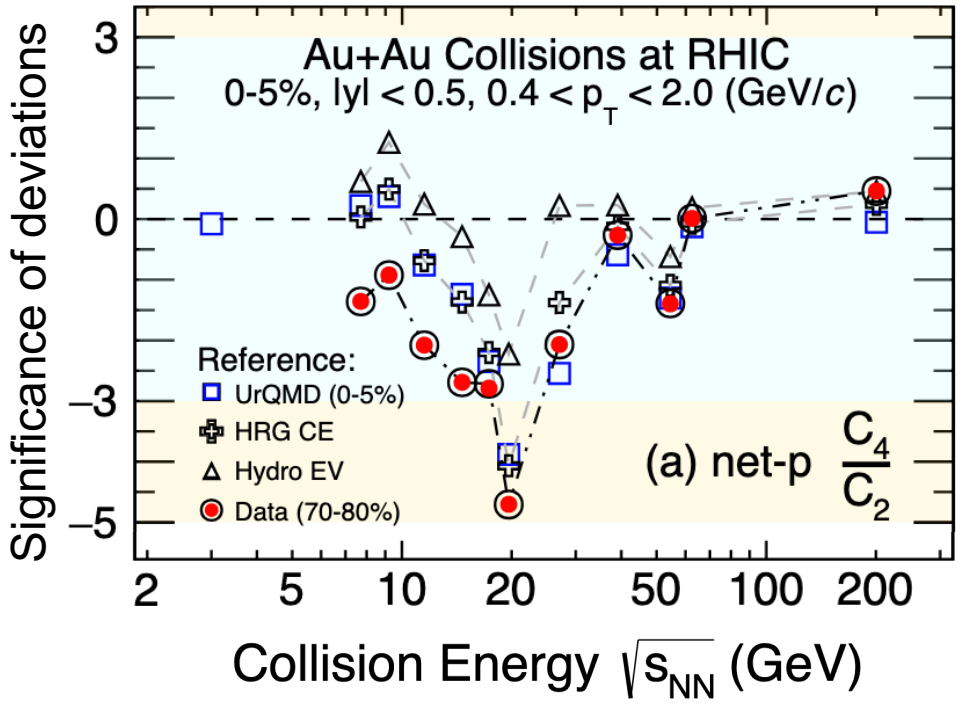
STAR, PRL 135.142301 (2025)
HRG CE: P. B. Munzinger et al, NPA 1008, 122141 (2021)

Hydro EV: V. Vovchenko et al, PRC 105, 014904 (2022)
LQCD: D. Bollweg et al, PRD 110, 054519 (2024)

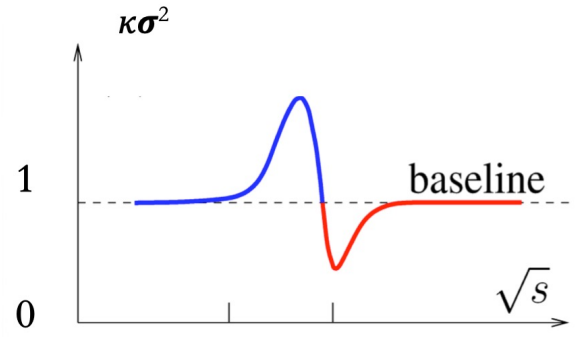
1. Net-proton $C_2/\langle p + \bar{p}\rangle$, C_3/C_1 and proton κ_2/κ_1 , κ_3/κ_1 also show deviations from no-CP models too, especially below 11.5 GeV.
2. In 0-5% central Au+Au collisions, net-proton C_4/C_2 shows deviation from no-CP models at around 20 GeV.
3. All models implement exact baryon number conservation and show monotonic trends.

Results: Data vs. No-CP models



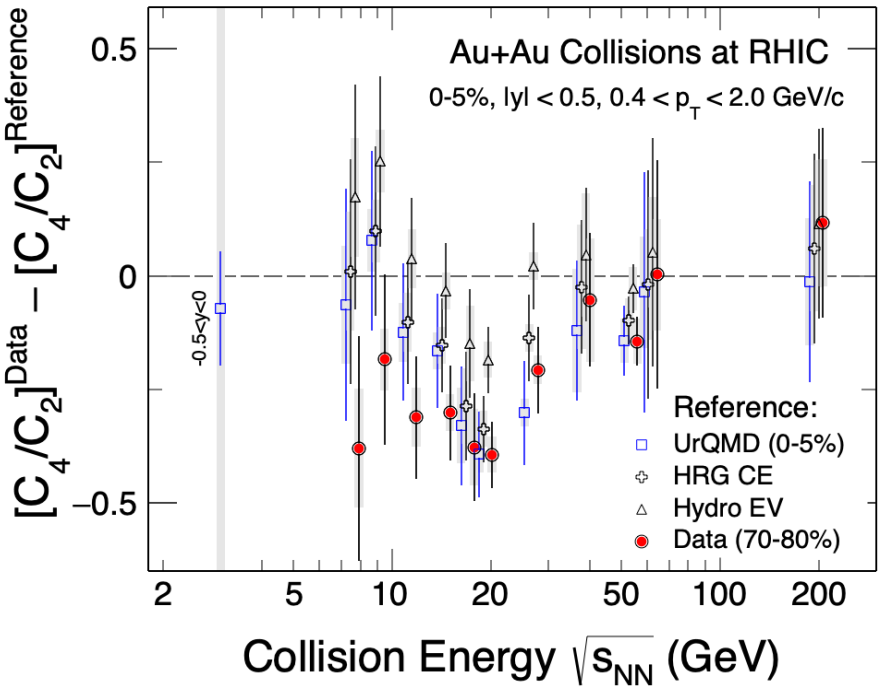


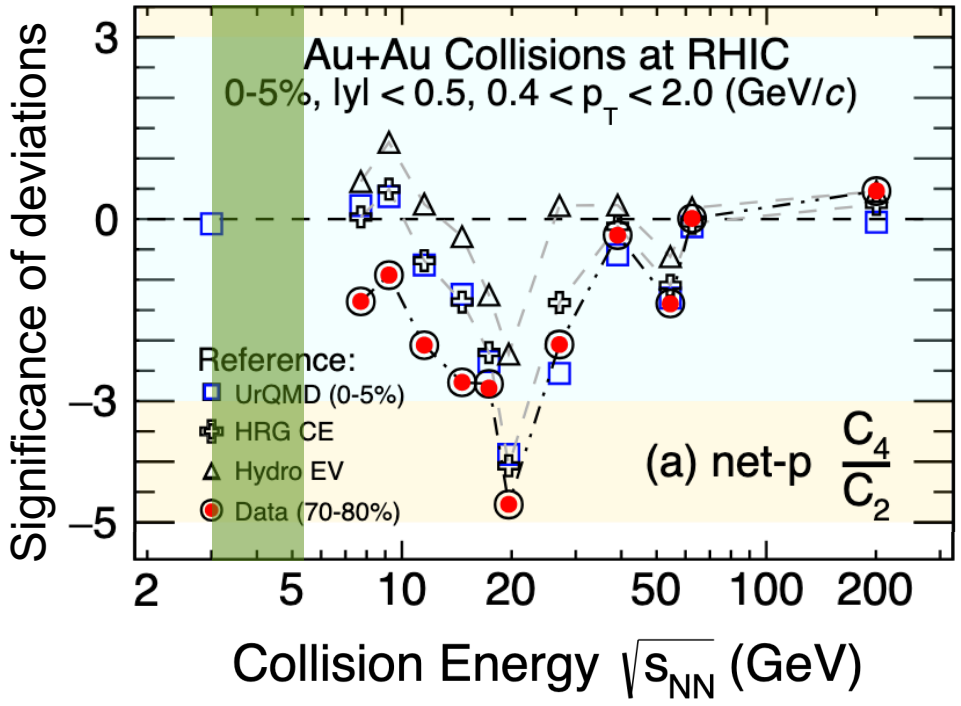
- Net-proton C4/C2 shows a minimum w.r.t no-CP models and peripheral data at ~20 GeV with 2-5σ significance.
- Qualitatively consistent with dip structure near QCD critical point.



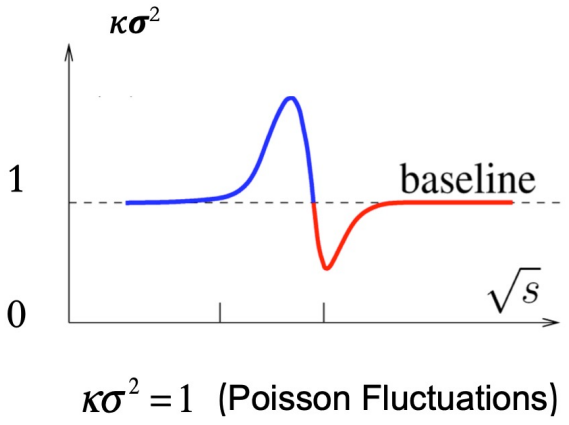
$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

Results: Data vs. No-CP models

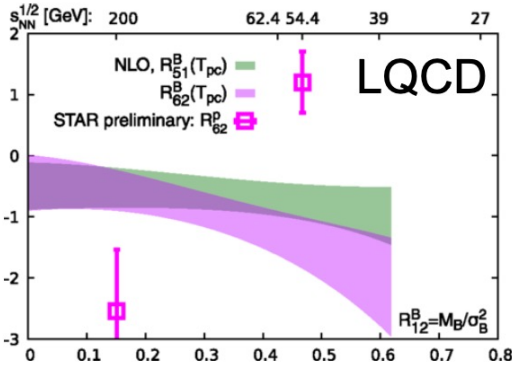




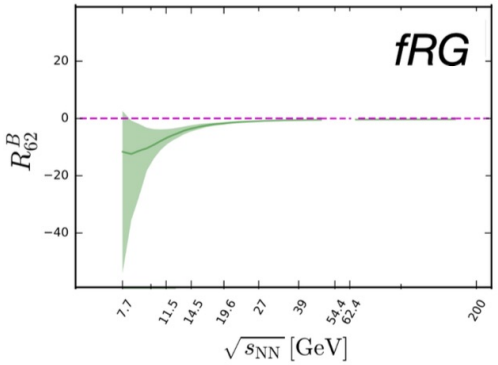
- Net-proton C4/C2 shows a minimum w.r.t no-CP models and peripheral data at ~20 GeV with 2-5σ significance.
- Qualitatively consistent with dip structure near QCD critical point.
- Analysis in FXT is important to confirm the oscillation structure.



Hyper-order Net-proton Measurements



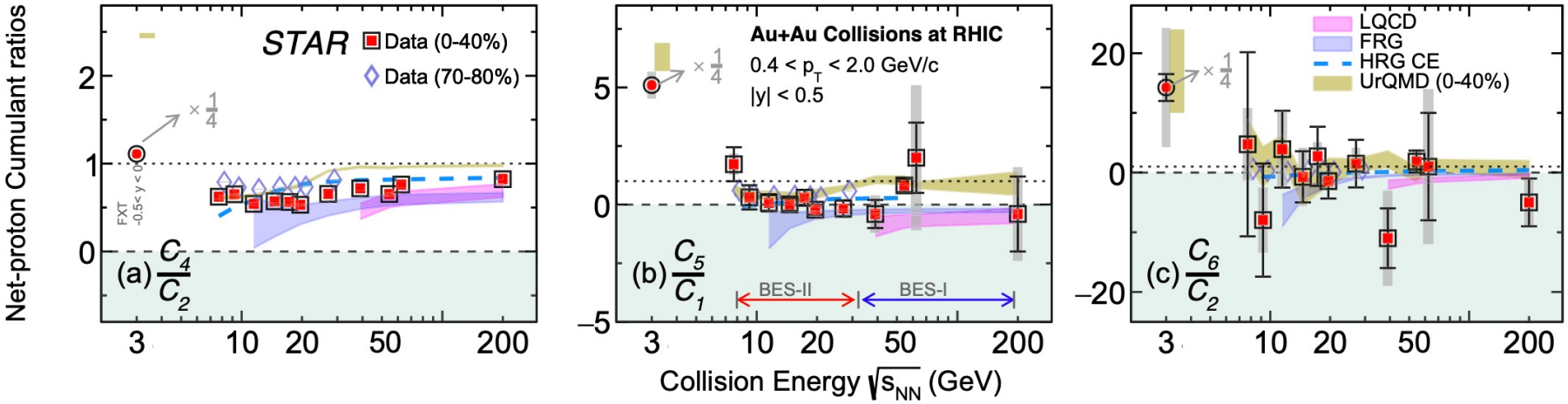
A. Bazavov et al. Phys. Rev. D 101, 074502



W. Fu, et al: PRD 104 094047 (2021)

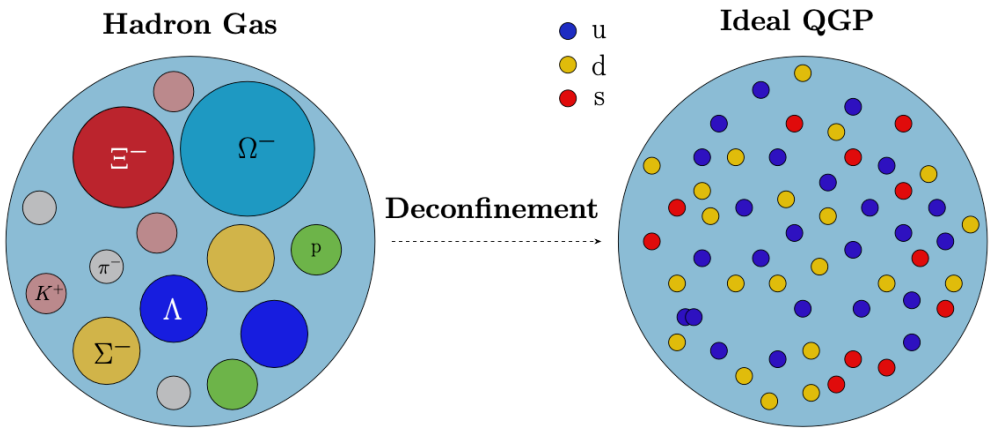
Negative sign in hyper-order cumulants (C_5 and C_6) indicates crossover transitions

STAR, Phys. Rev. C 113, L051901 (2026)



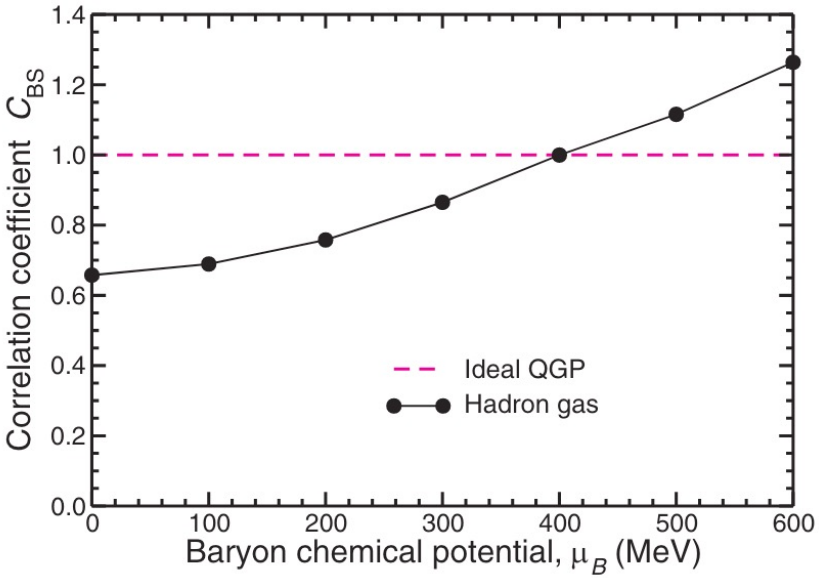
- BES-II measurement provides significant improved precision.
- In 0-40% central collisions, C_5/C_1 and C_6/C_2 fluctuate around zero.

Baryon-strangeness Correlation



1. Diagnose the change of phases of matter created in heavy-ion collisions
2. Check in experiment the turn-off of QGP

V. Koch et al, PRL 95, 182301(2005)



Definition:

$$B = \frac{1}{3}(\Delta u + \Delta d + \Delta s)$$

$$Q = \frac{2}{3}\Delta u - \frac{1}{3}\Delta d - \frac{1}{3}\Delta s$$

$$S = -\Delta s$$

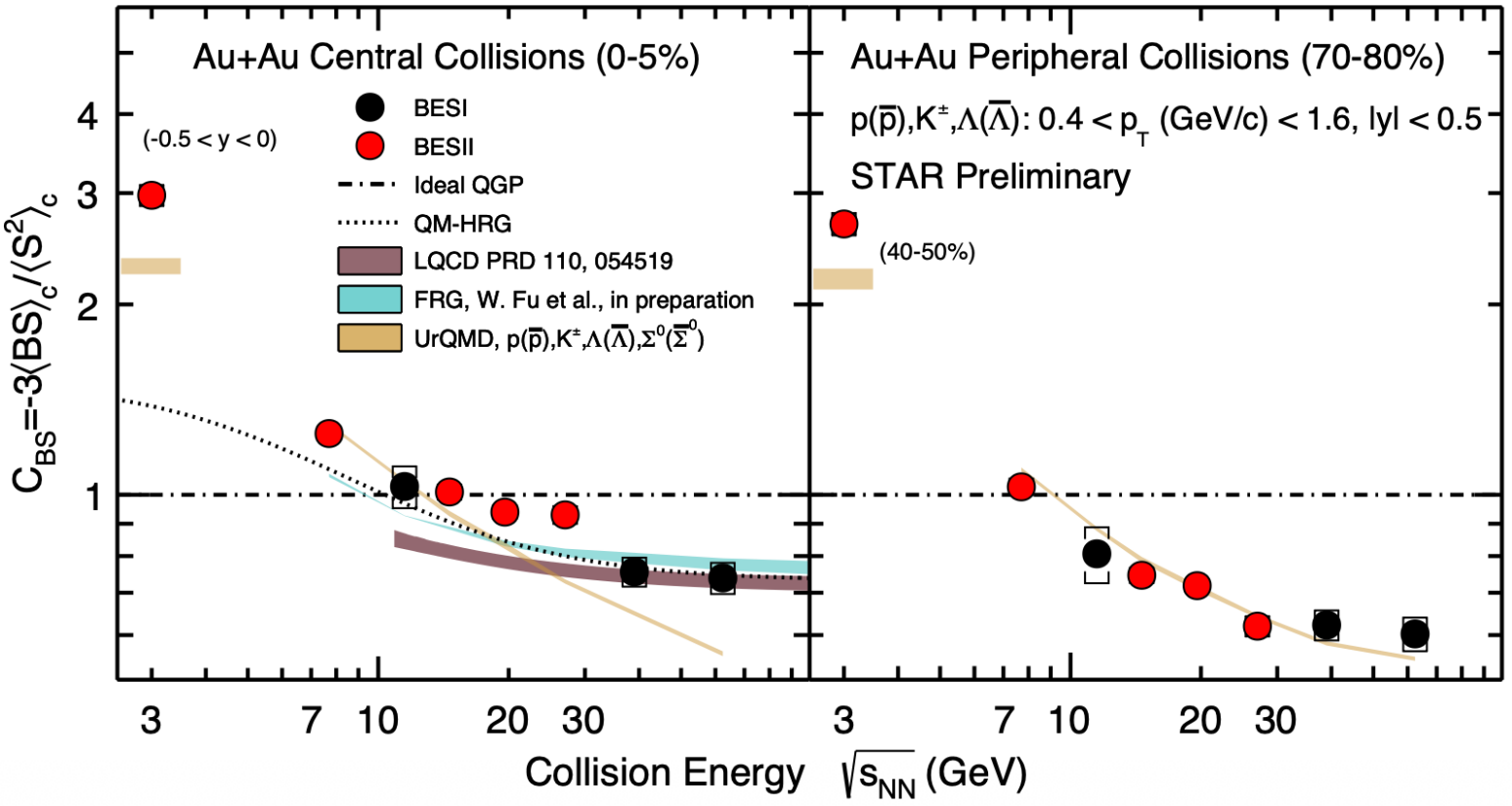
$$C_{BS} = -3\frac{\sigma_{BS}}{\sigma_S^2} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2}$$

if quark flavors are uncorrelated

$\sigma_{BS} = -\frac{1}{3}\sigma_{S^2} \rightarrow C_{BS} = 1$

Results: Baryon-strangeness correlation

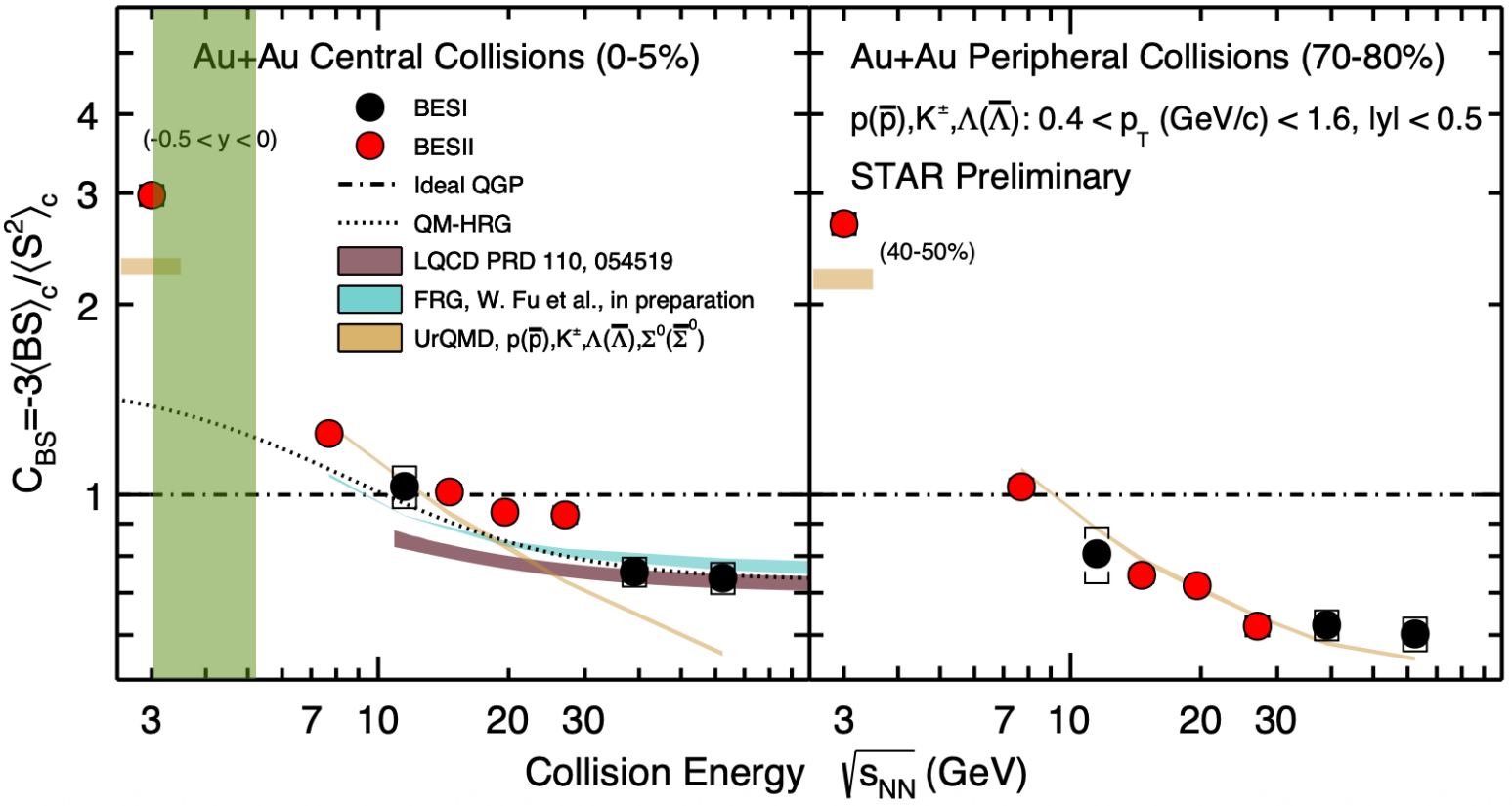
Hanwen Feng, Yu @ QM2025



- Central data are not fully described by any single model, while peripheral data is consistent with UrQMD.

Results: Baryon-strangeness correlation

Hanwen Feng, Yu @ QM2025



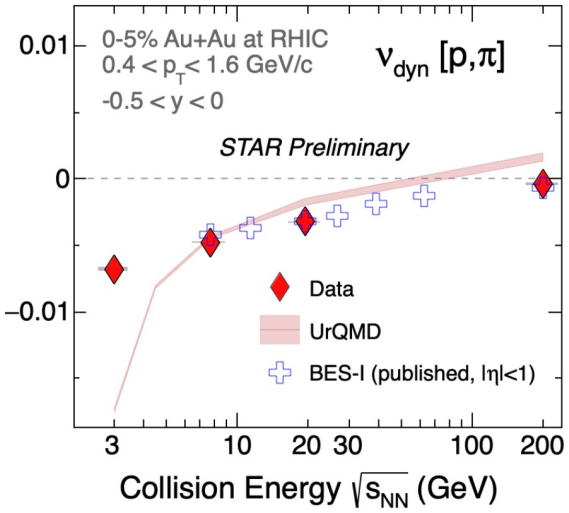
- Central data are not fully described by any single model, while peripheral data is consistent with UrQMD.
- Measurements are being extended to higher orders and to the high baryon density region (STAR FXT $\sqrt{s_{\mathrm{NN}}}$ = 3 - 5.2 GeV) !

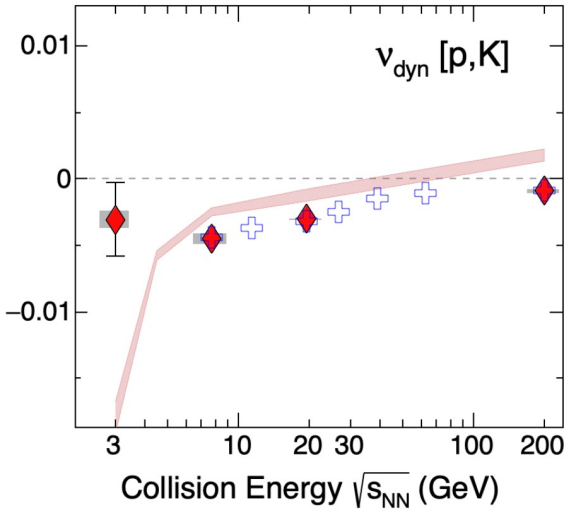
Particle Ratio Fluctuation

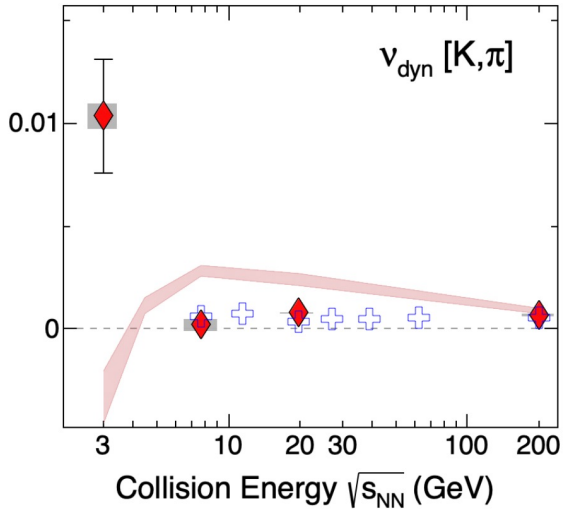
$$\nu_{dyn}[A,B] = \frac{\langle N_A\,(N_A-1)\rangle}{\langle N_A\rangle^2} + \frac{\langle N_B\,(N_B-1)\rangle}{\langle N_B\rangle^2} - 2\frac{\langle N_A N_B\rangle}{\langle N_A\rangle\,\langle N_B\rangle}$$

1. Combined measurement of two particles to construct a strongly intensive observable, which is stable to volume fluctuations
2. Looking for non-monotonic energy trend for the CP

A. Pandav @ CPOD 2026

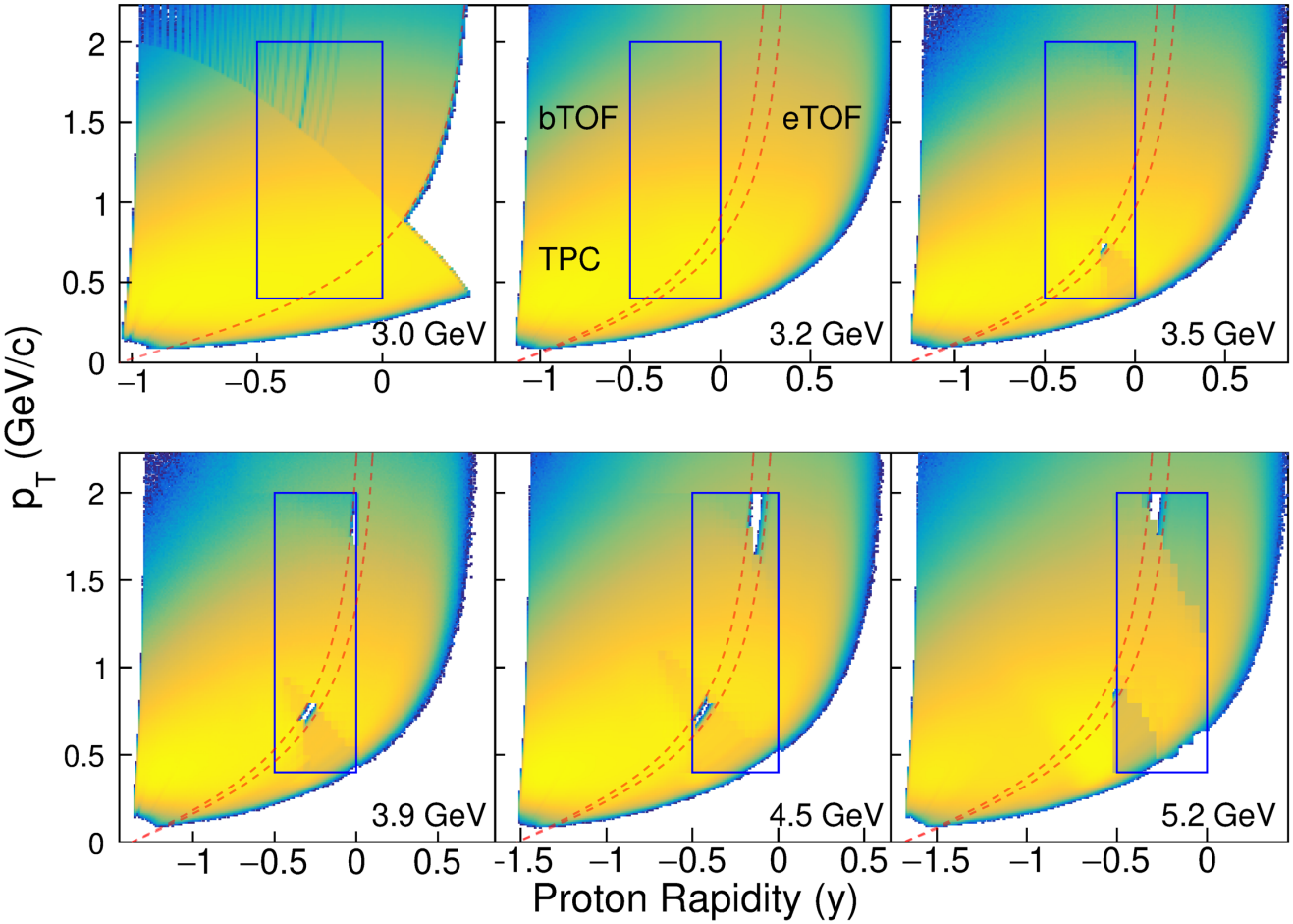






1. Data show a monotonically decreasing trend for υ_{dyn}[p, π] and υ_{dyn}[p, K], while υ_{dyn}[K,π] shows opposite trend.
2. UrQMD follows data but shows large difference at 3 GeV.

Analysis at FXT energies: Proton acceptance

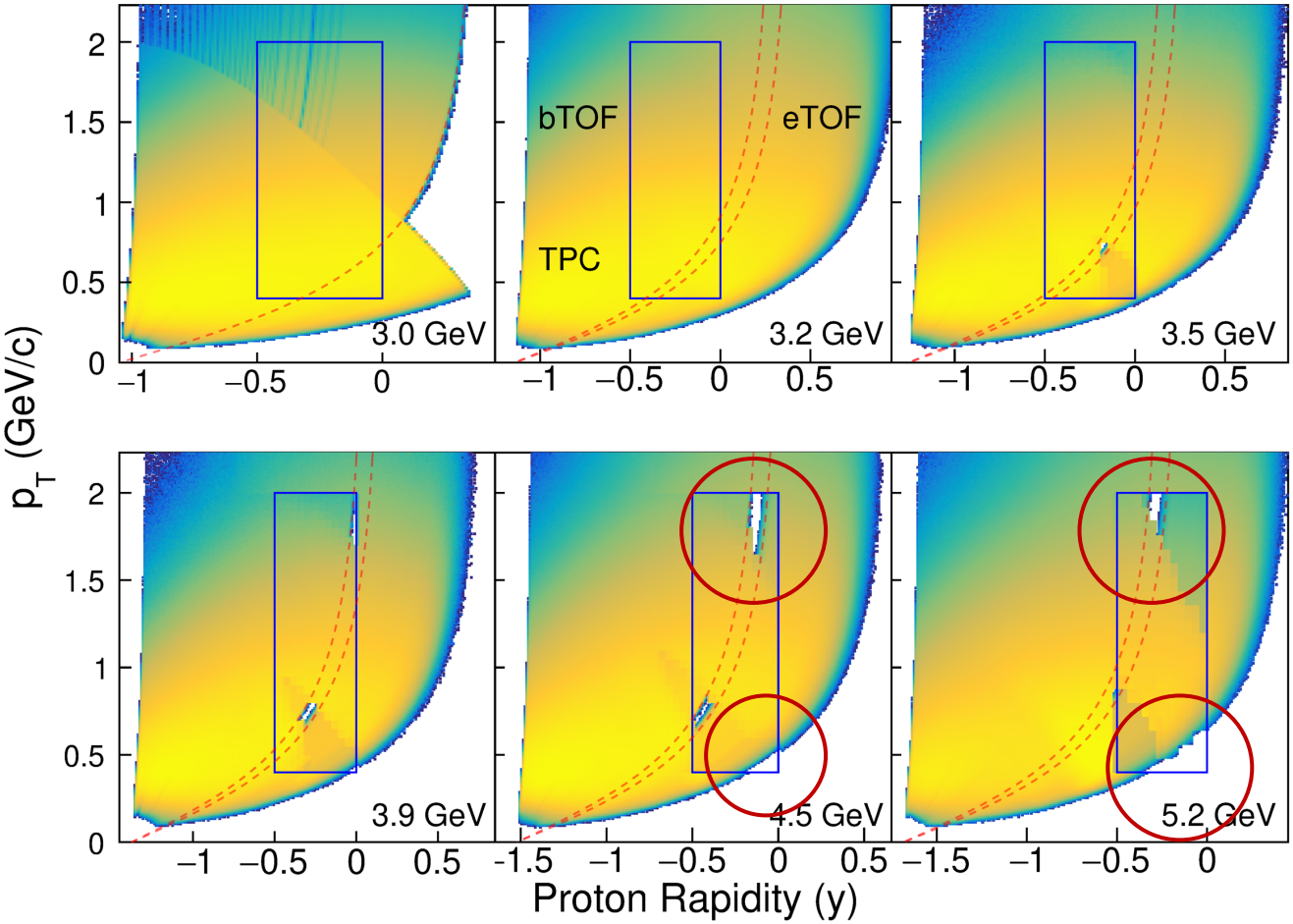


Mid-rapidity coverage:

-0.5 < y < 0

1. Combining TPC, bTOF/eTOF for PID, centrality, pileup
2. Evolving proton acceptance in different collision energies
3. Ongoing analysis at $\sqrt{s_{\mathrm{NN}}}$ = 3.0, 3.2, 3.5, 3.9, 4.5 and 5.2 GeV !

Analysis at FXT energies: Proton acceptance



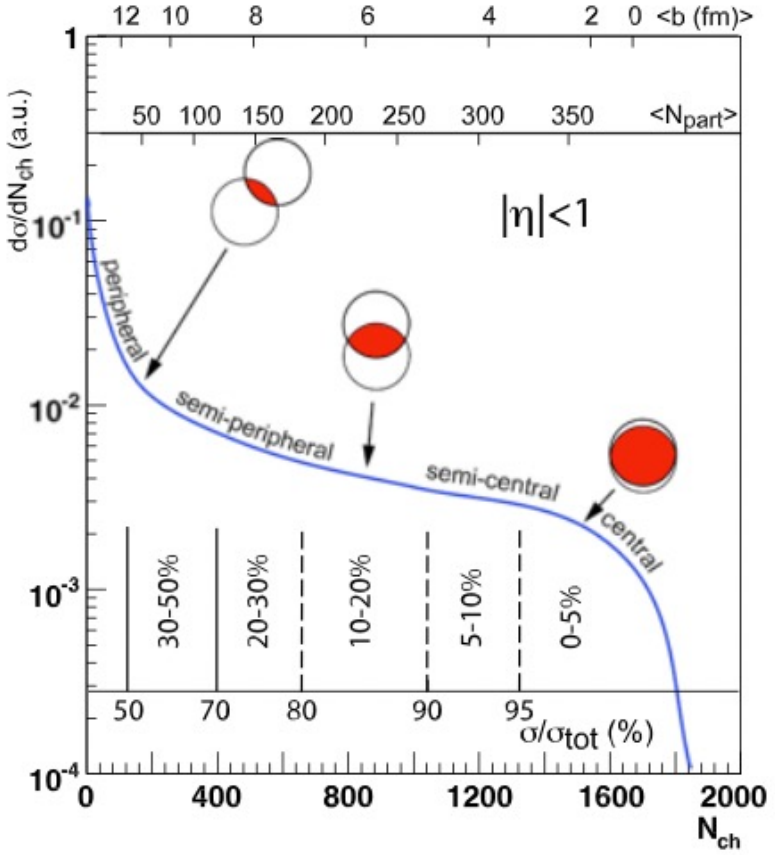
Mid-rapidity coverage:

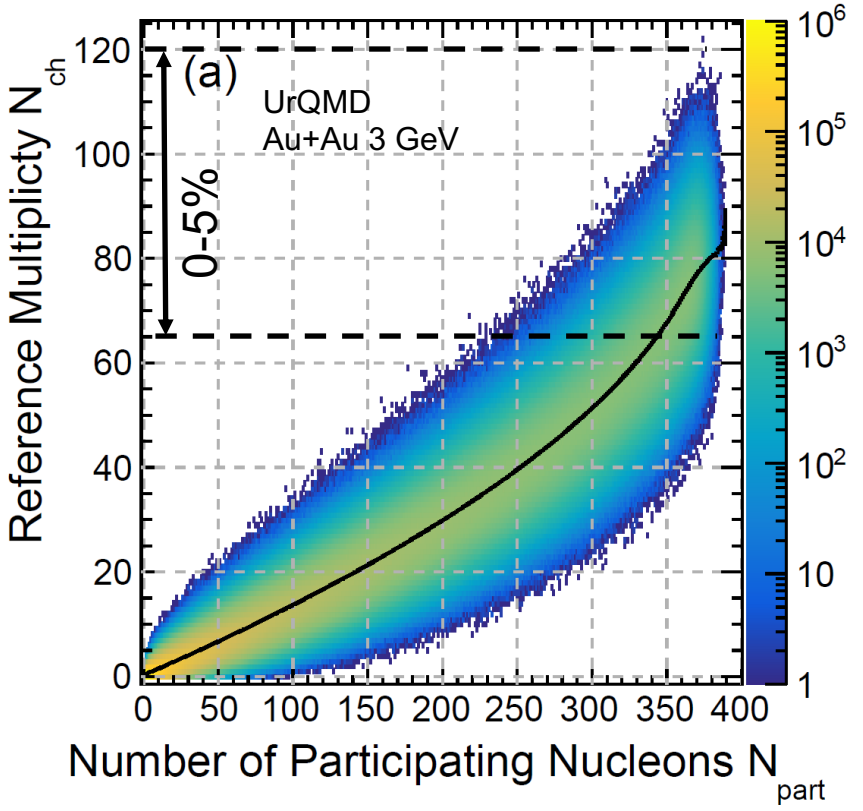
-0.5 < y < 0

Not fully covered at higher FXT energies

1. Combining TPC, bTOF/eTOF for PID, centrality, pileup
2. Evolving proton acceptance in different collision energies
3. Ongoing analysis at $\sqrt{s_{\mathrm{NN}}}$ = 3.0, 3.2, 3.5, 3.9, 4.5 and 5.2 GeV !

Challenge in FXT analysis: volume fluctuation





- Experimentally, charged particle multiplicity N_{ch}, is not in one to one correspondence with Npart or b.
- The spread of different collision volumes within same centrality class distort cumulants.

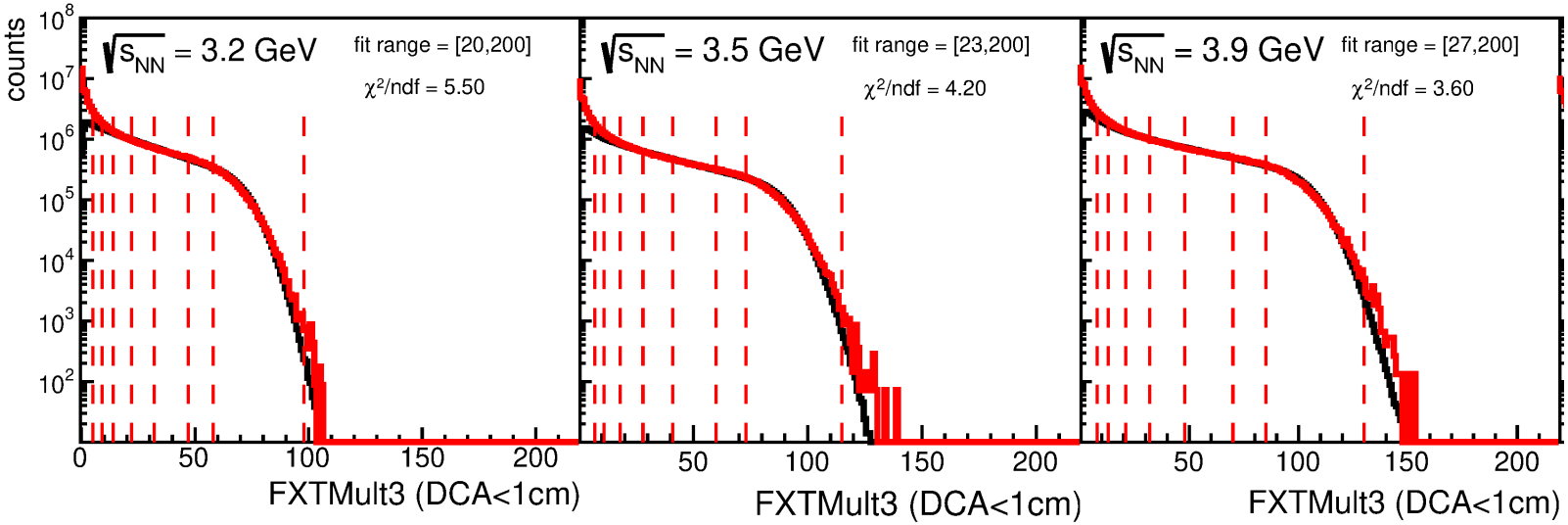
Limited multiplicity

→ Worse centrality resolution.

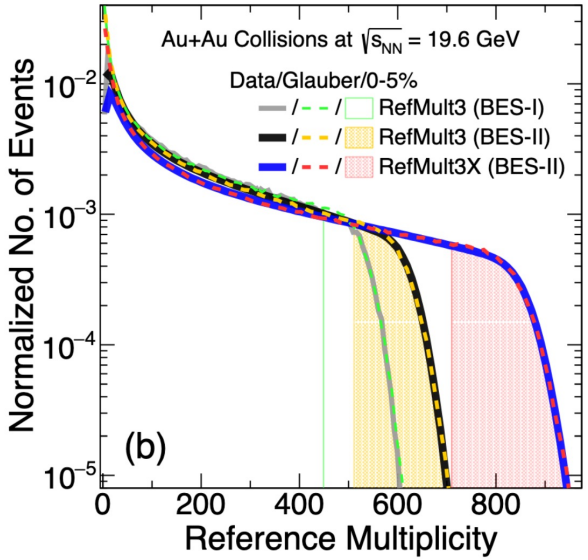
→ Large volume fluctuation.

Challenge in FXT analysis: volume fluctuation

FXT:



Collider:



Much smaller multiplicity at FXT energies than collider, hence a poorer centrality resolution.

Centrality bin width correction (CBWC): $C = \frac{\sum C*N}{\sum N}$

The CBWC method takes advantage of the high centrality resolution within each N_{ch} bin.

X. Luo et al, J. Phys. G: Nucl. Part. Phys. 40 105104

Possible Solutions (partial list)

Volume fluctuation correction:

V. Skokov, B. Friman, K. Redlich, Phys. Rev. C 88 (2013) 034911
P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 960 (2017) 114–130

Model-free corrections based on event mixing:

A. Rustamov, R. Holzmann, J. Stroth, NPA 1034 (2023) 122641
R. Holzmann, V. Koch, A. Rustamov, J. Stroth, Nucl. Phys. A 1050 (2024) 122924

Centrality Independent Analysis Method:

Z. Wang, X. Luo, PLB 871,139984(2025)

New centrality definitions with machine learning:

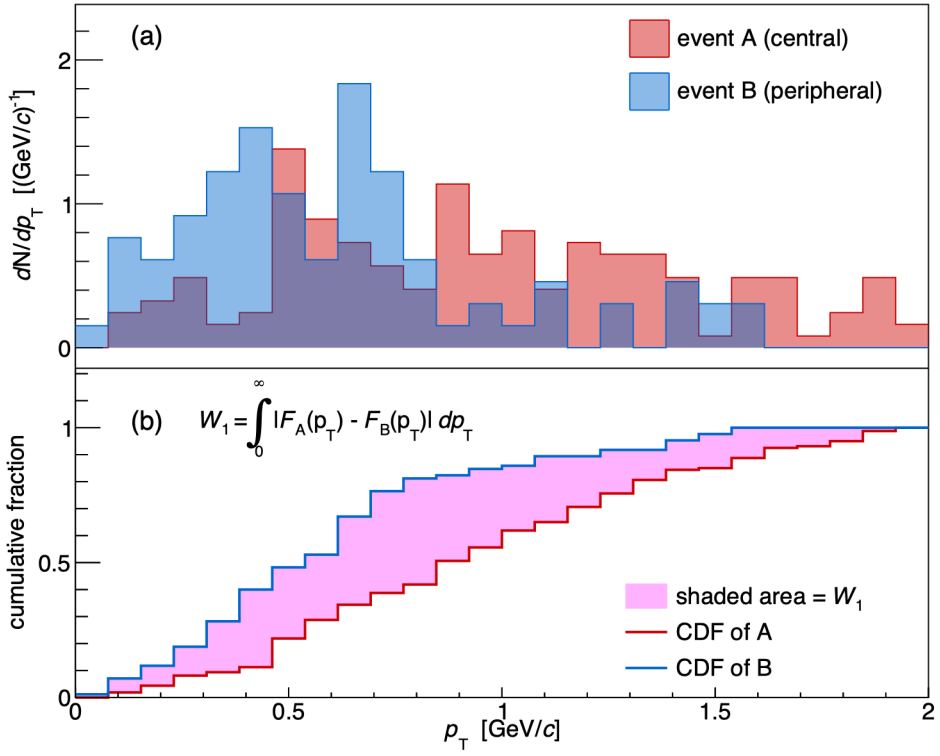
Y. Huang, arXiv: 2608.14045
S. Yang, Y. Zhang, arXiv: 2611.07465

New centrality definition with unsupervised machine learning

"Optimal-transport contrastive learning in centrality determination" S. Yang, Y. Zhang, arXiv: 2611.07465

The key idea is to use *Wasserstein distance* to distinguish collisions from different centrality.

Wasserstein distance: the minimal cost of transforming one distribution into another

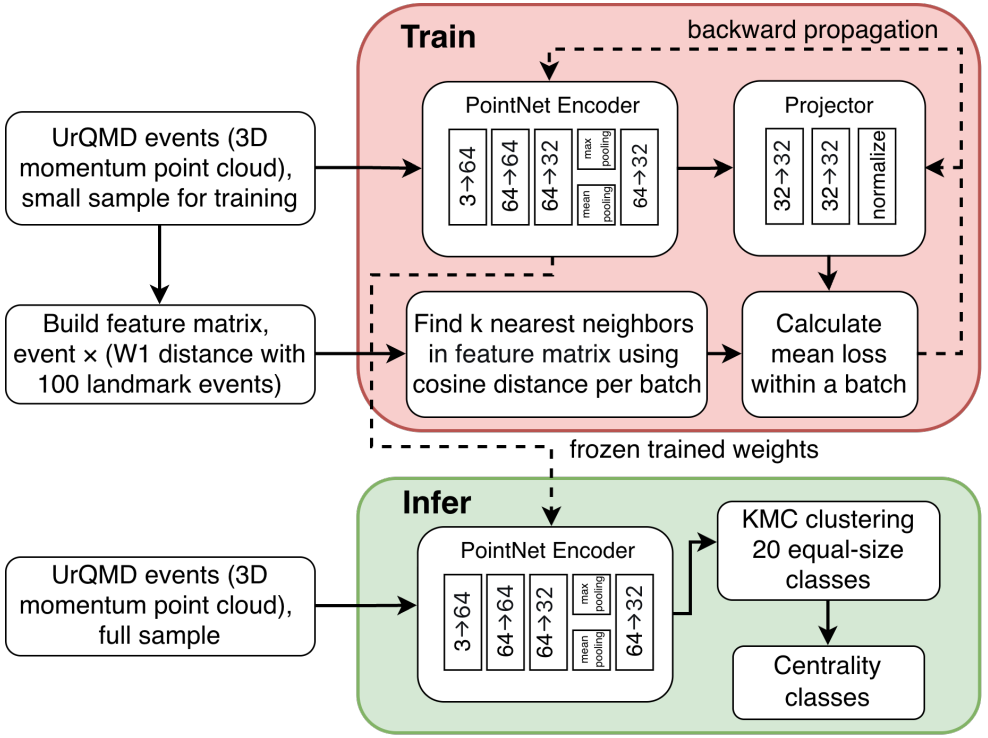


New centrality definition with unsupervised machine learning

"Optimal-transport contrastive learning in centrality determination" S. Yang, Y. Zhang, arXiv: 2611.07465

- We used calculate first-order Wasserstein distance (W1) on momentum distribution (px, py, pz)
- To avoid unrealistic calculation cost, a network of PointNet type is used to learn distinct feature between central and peripheral

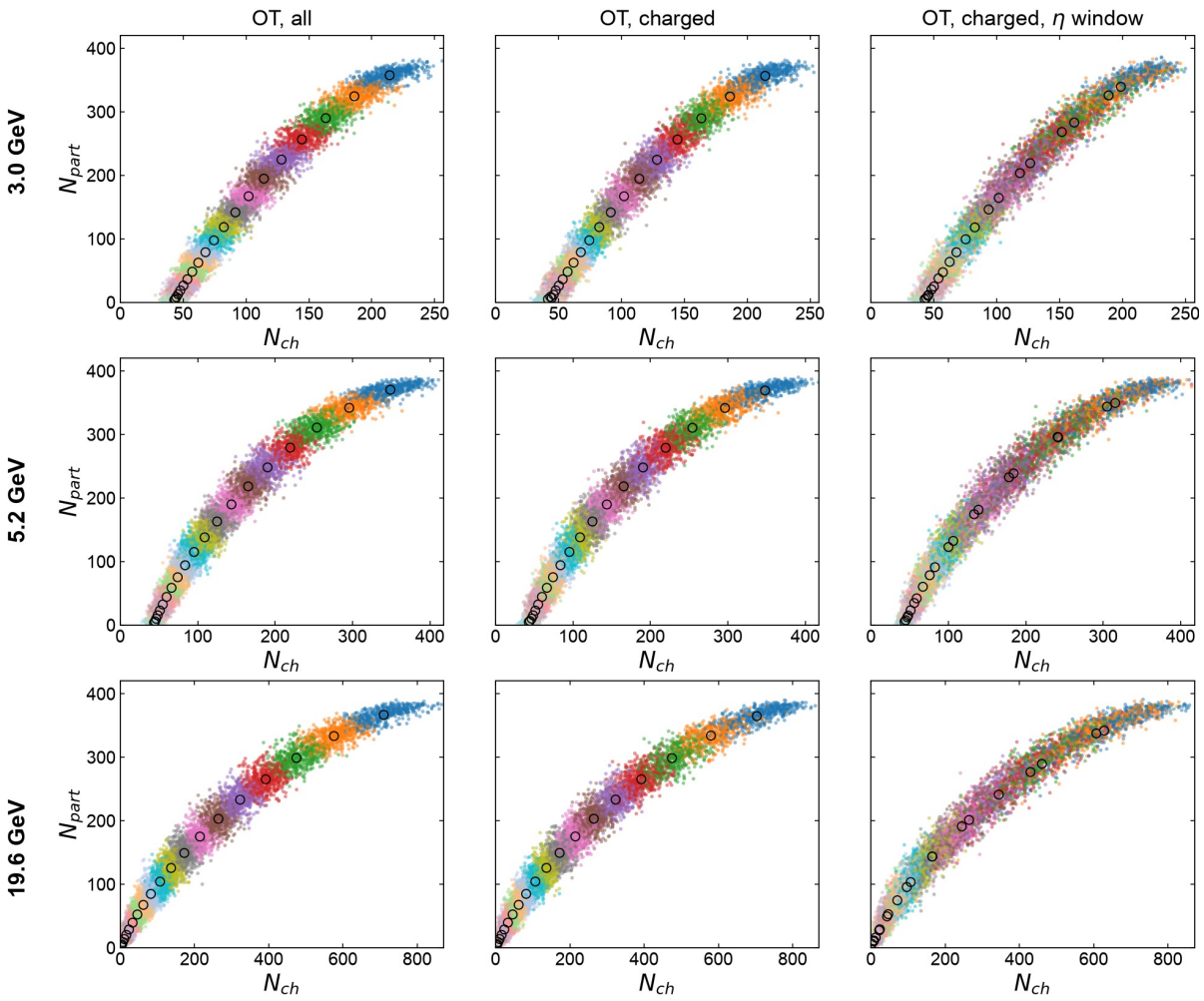
notation	Method to determine centrality classes
OT, all	OT-contrastive learning using all particles
OT, charged	OT-contrastive learning using charged particles
OT, charged, η	OT-contrastive learning using charged particles with η cut
$N_{\rm ch}$ slicing	Cutting $N_{\rm ch}$ distribution
$N_{\rm ch}$ slicing, η	Cutting $N_{\rm ch}$ distribution with η cut



$$\mathcal{L} = -\frac{1}{k}\sum_{i}\sum_{j\in\mathcal{N}_k(i)} \log \frac{\exp\left(\mathbf{z}_i\cdot\mathbf{z}_j/\tau\right)}{\sum_{m\neq i}\exp\left(\mathbf{z}_i\cdot\mathbf{z}_m/\tau\right)}$$

The training is to make each event close to its neighbors according to W1 distance, and away from other events.

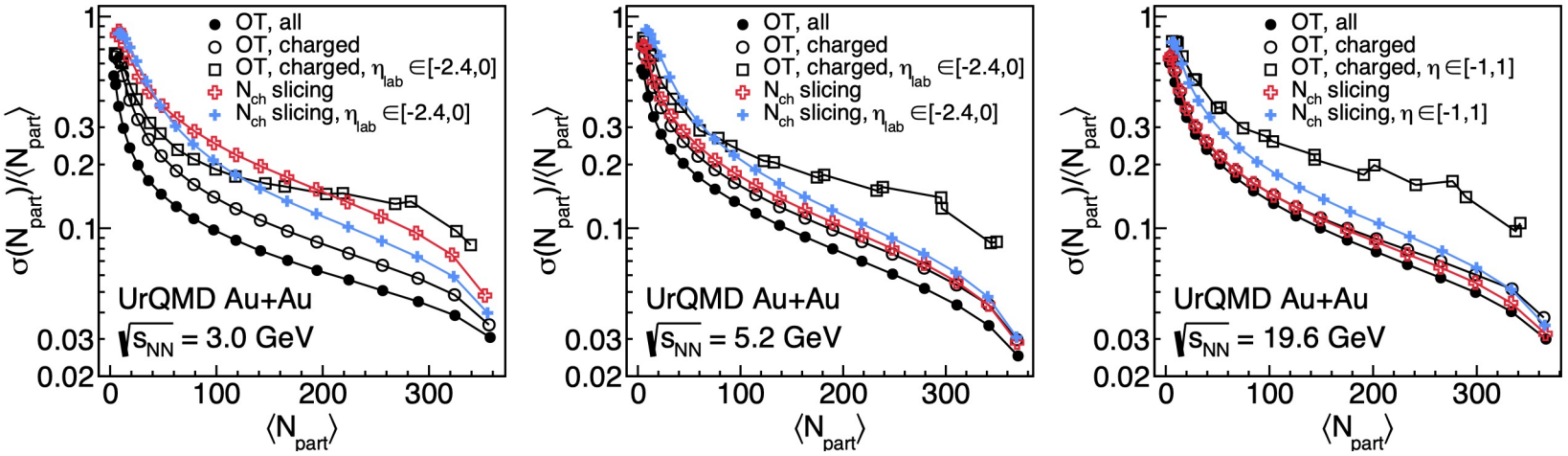
Performance test using UrQMD events



UrQMD Au+Au collisions			
$\sqrt{s_{NN}}$ / GeV	3.0	5.2	19.6
Training events	2k	2k	2k
Inference events	7.0M	6.1M	5.2M

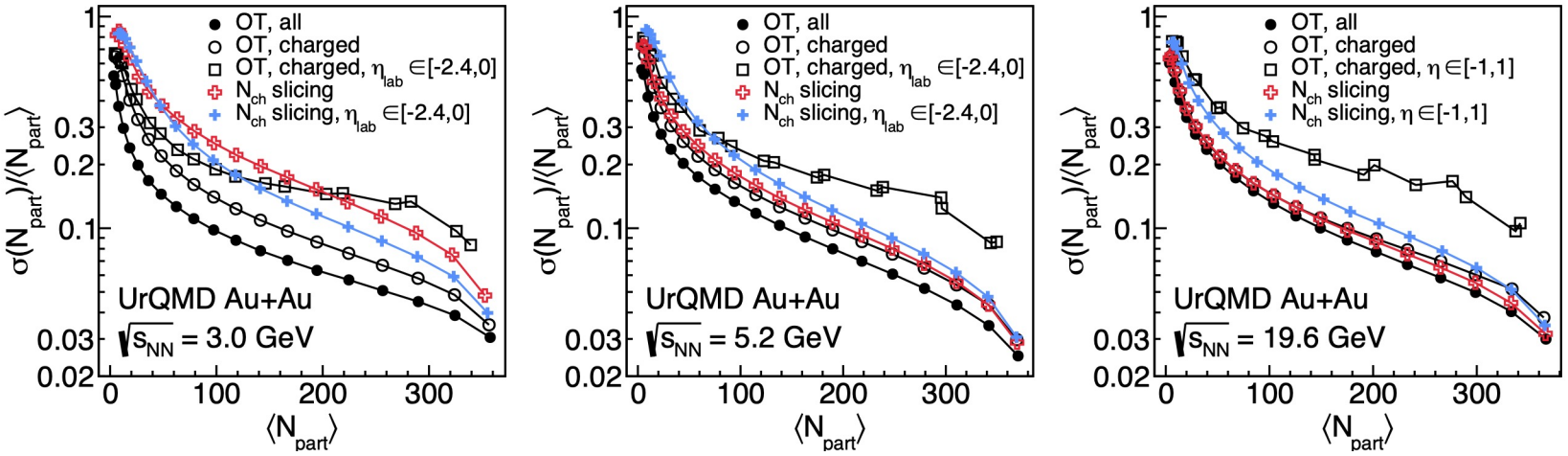
1. Three scenarios, using all particles, charged particles, charged particles with acceptance cut, are tested for the method.
2. Scenario “all particles”: Events are well separated and grouped with similar N_{part}.
3. But poor performance is seen in scenario “OT, charged, η”.

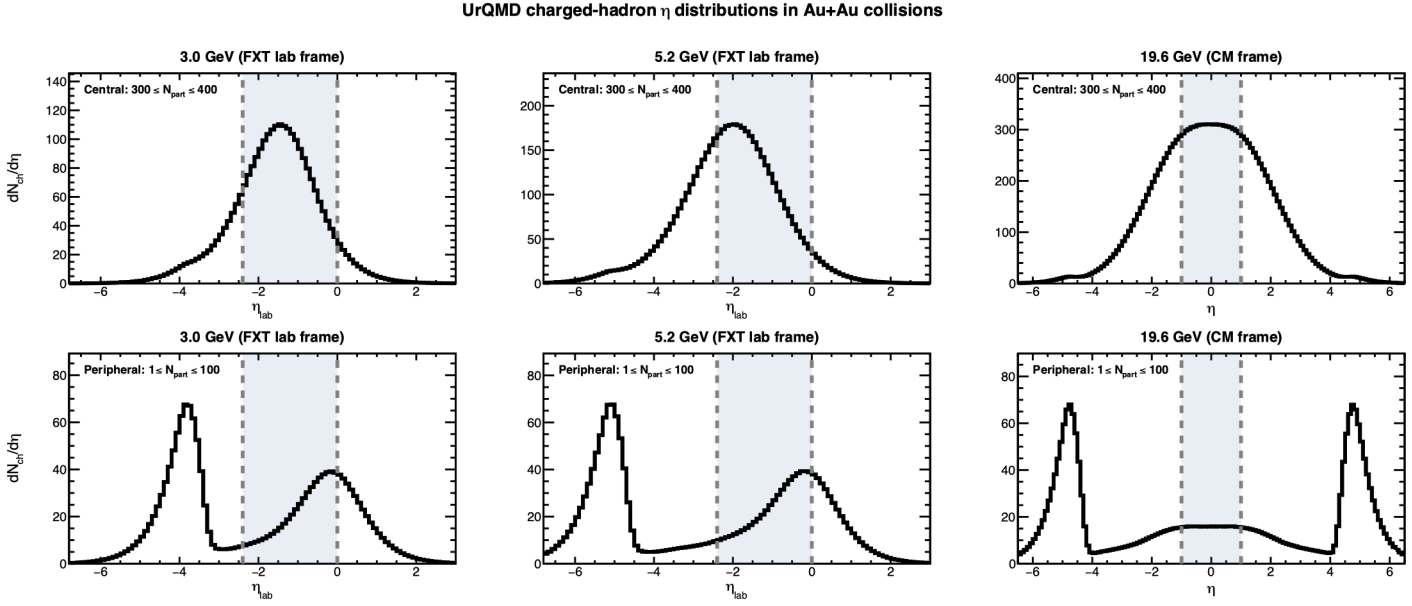
Performance test using UrQMD events



1. Improved centrality resolution, $\frac{\sigma(N_{part})}{\langle N_{part}\rangle}$, in "OT, all" compared with N_{ch} slicing
2. But poor performance is seen in scenario "OT, charged, η"

Performance test using UrQMD events





- Spectators are excluded, which leads to the poor performance
- Next step is to more precisely extract the shape feature with acceptance cut.

Centrality Independent Analysis Method

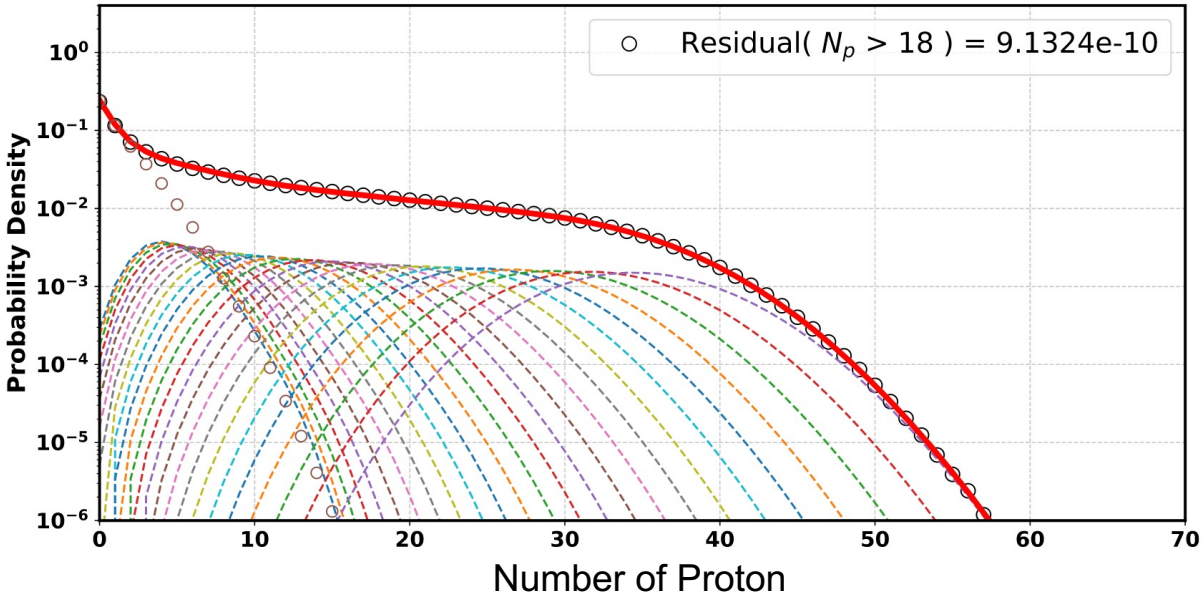
Z. Wang, X. Luo, PLB 871,139984(2025)

Edgeworth expansion:

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

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

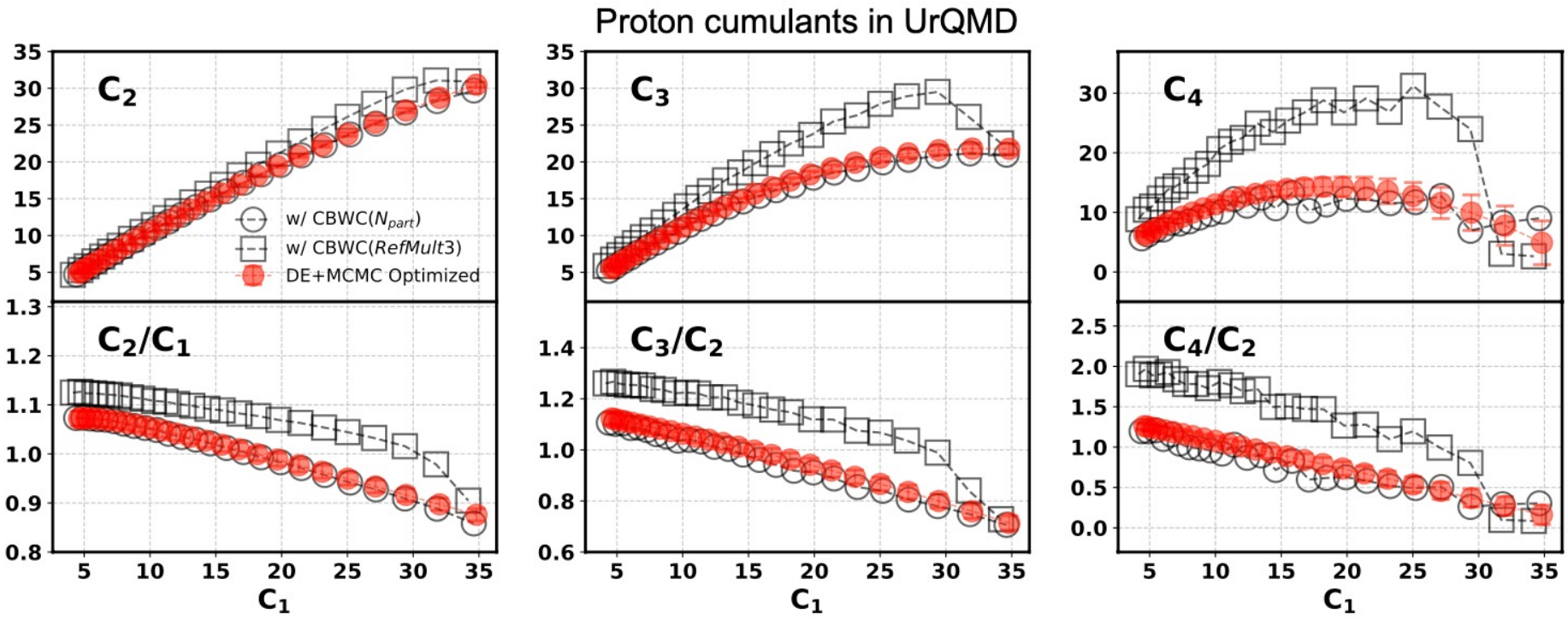
$$H_{e_n}(x) = (-1)^n exp(x^2/2)\frac{d^n}{dx^n}exp(-x^2/2)$$



1. Whenever a centrality observable is used in data analysis, volume fluctuation effect is involved in measurements
2. Use Edgeworth expansion to reconstruct proton distribution in finer centrality bins

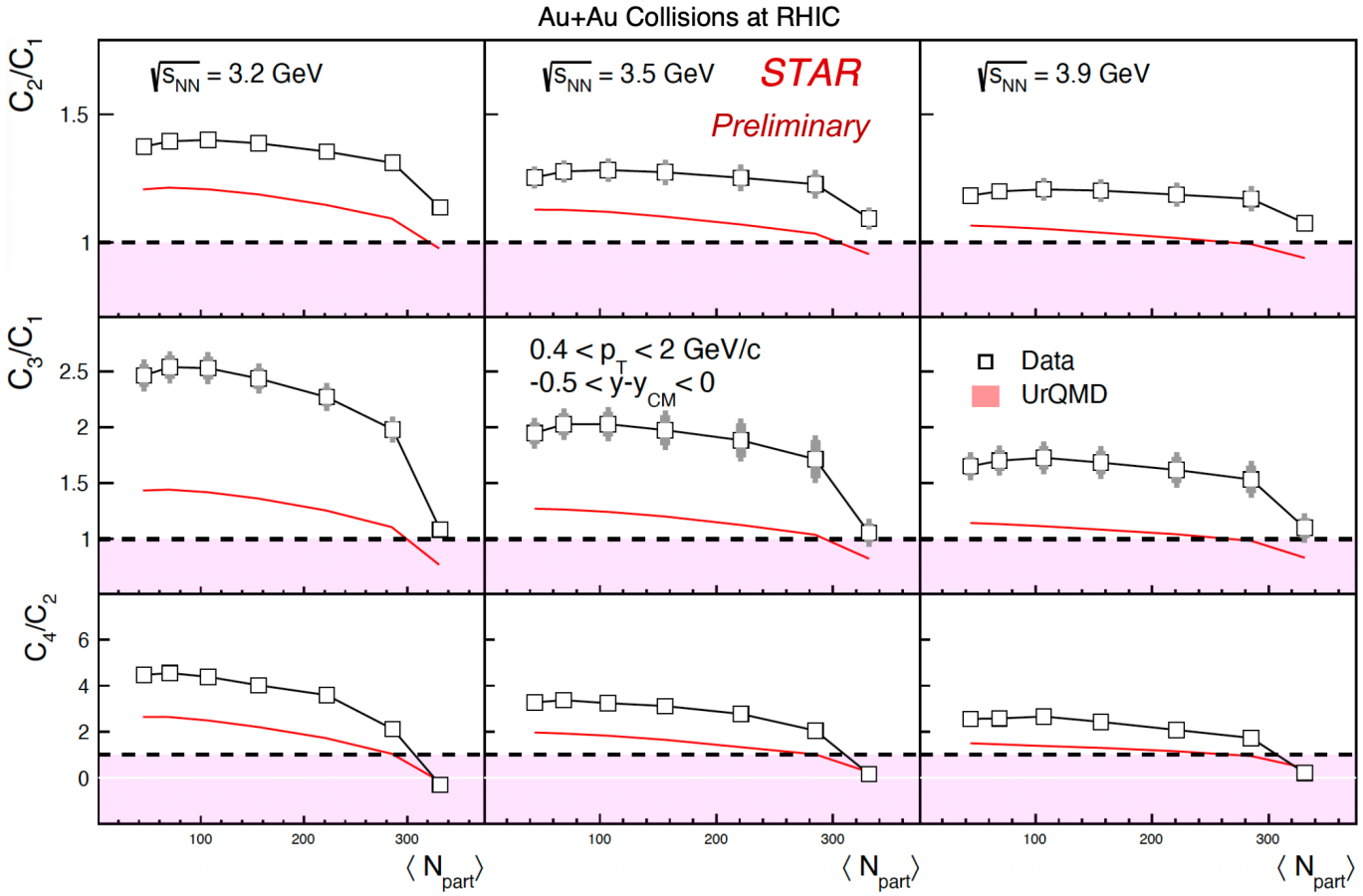
More details in Zhaohui's talk on Nov 12

Centrality Independent Analysis Method



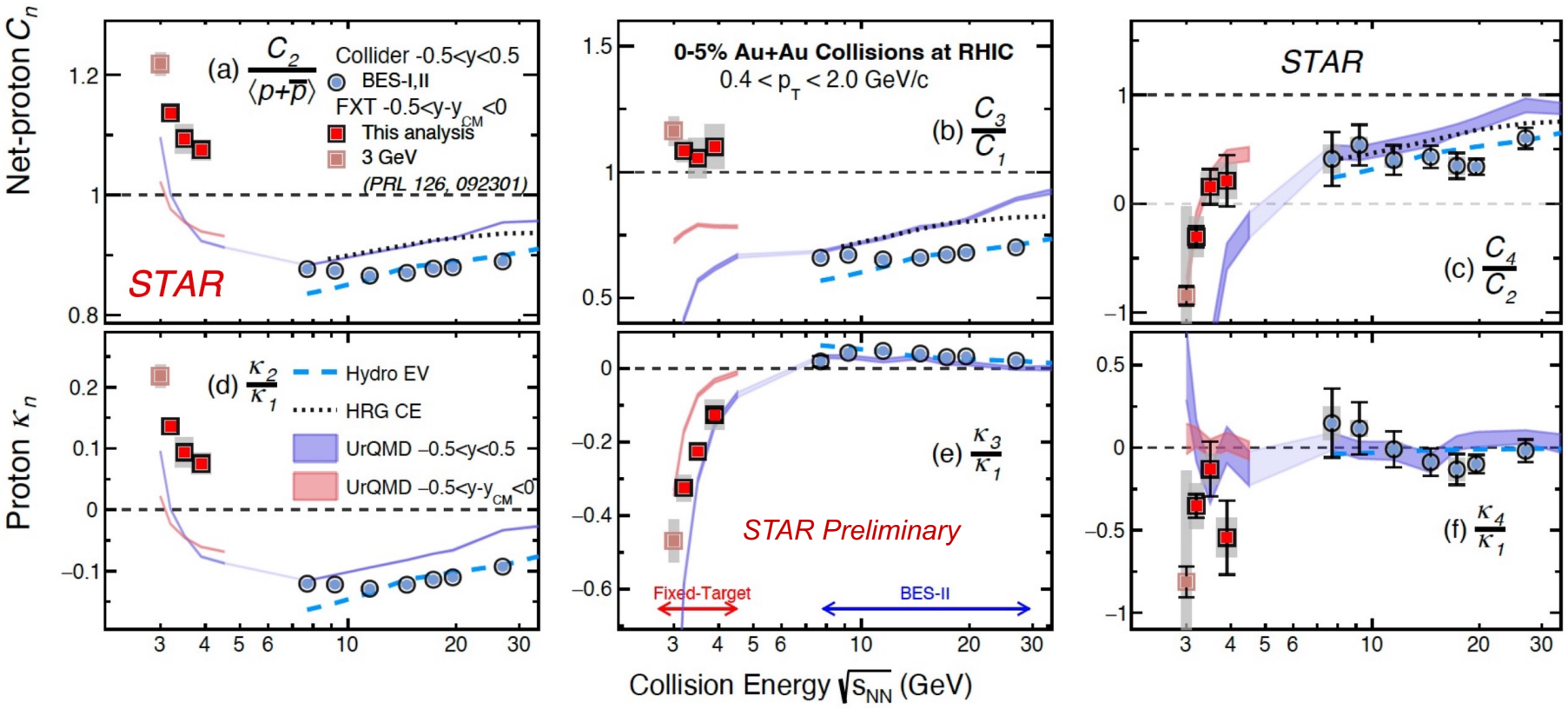
1. Model test shows good consistency with results binning on N_{part}
2. The method is being tested in FXT data analysis

Preliminary FXT results with CBWC method



1. Small statistical uncertainties up to fourth order.
2. The observed increase in ratios in peripheral collisions with decreasing collision energy suggests a growing influence of volume fluctuations at lower energies
3. The 0-5% most central collisions are the least affected by volume fluctuations.

Energy Dependence of Net-proton cumulant ratios



1. C_4/C_2 seems to follow the decreasing trend from high energy, consistent with UrQMD
2. Ongoing analysis at 3.0 to 5.2 GeV !

Summary

Net-proton C_4/C_2

- Central data shows a minimum w.r.t no-CP models around 20 GeV
- Ongoing analysis at 3.0– 5.2 GeV on FXT with several methods

Net-proton C_5/C_1 and C_6/C_2

- Significant improved precision; 0-40% data fluctuate around zero

Baryon-strangeness Correlation

- Central data is not completely described by any single model
- Ongoing analysis at 3.0– 5.2 GeV on FXT

Particle Ratio Fluctuation

- Monotonic energy dependence observed for υ_{dyn}[p, π], υ_{dyn}[p, K], and υ_{dyn}[K,π]
- Large difference from UrQMD observed at 3 GeV. Analysis on FXT energies.

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STAR Collaboration, Theory colleagues, Organizers of PHD meeting

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