

Exploring the QCD Phase Diagram through Conserved-Charge Fluctuations & Correlations at RHIC

华中师范大学 野中俊宏 (Toshihiro NONAKA)

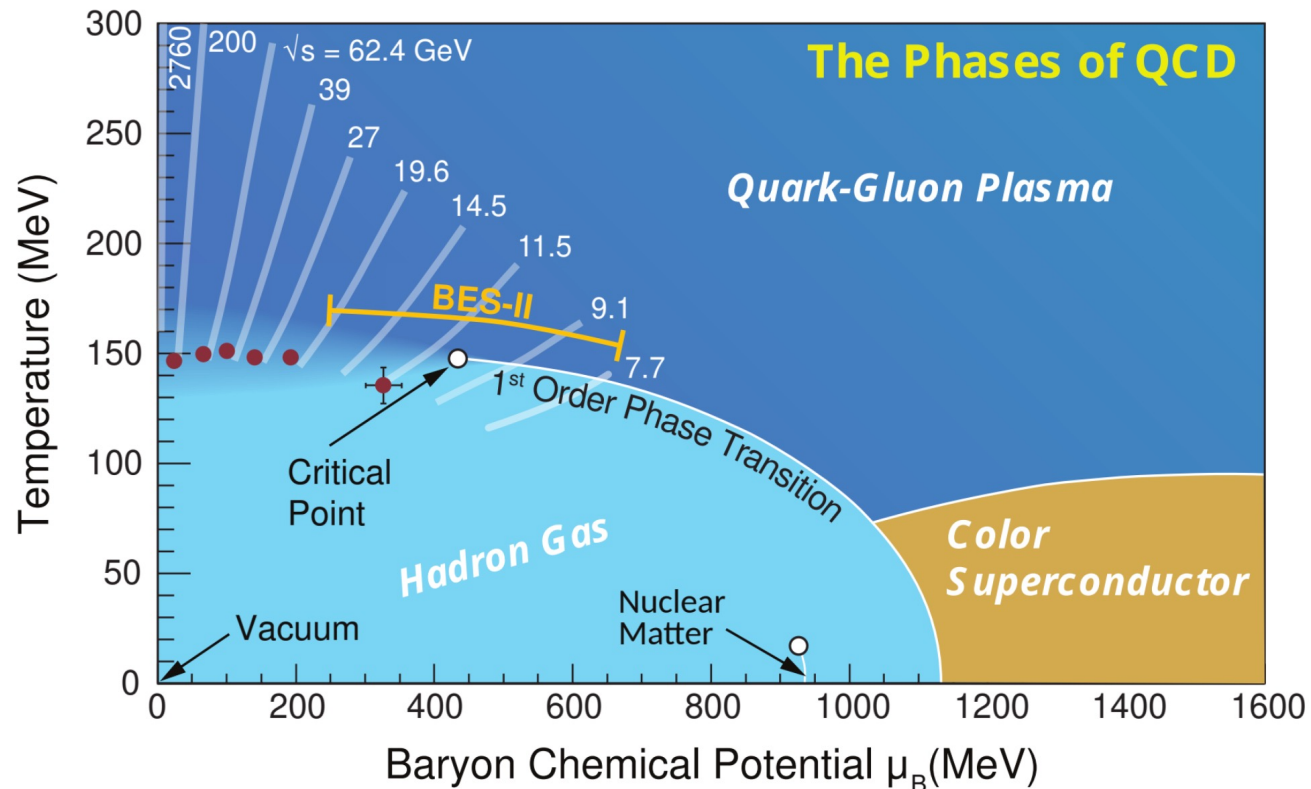
Spicy Gluons 2026 @ Wuhan

2026年10月18日

- Introduction
- Methodology
- Results
- Summary



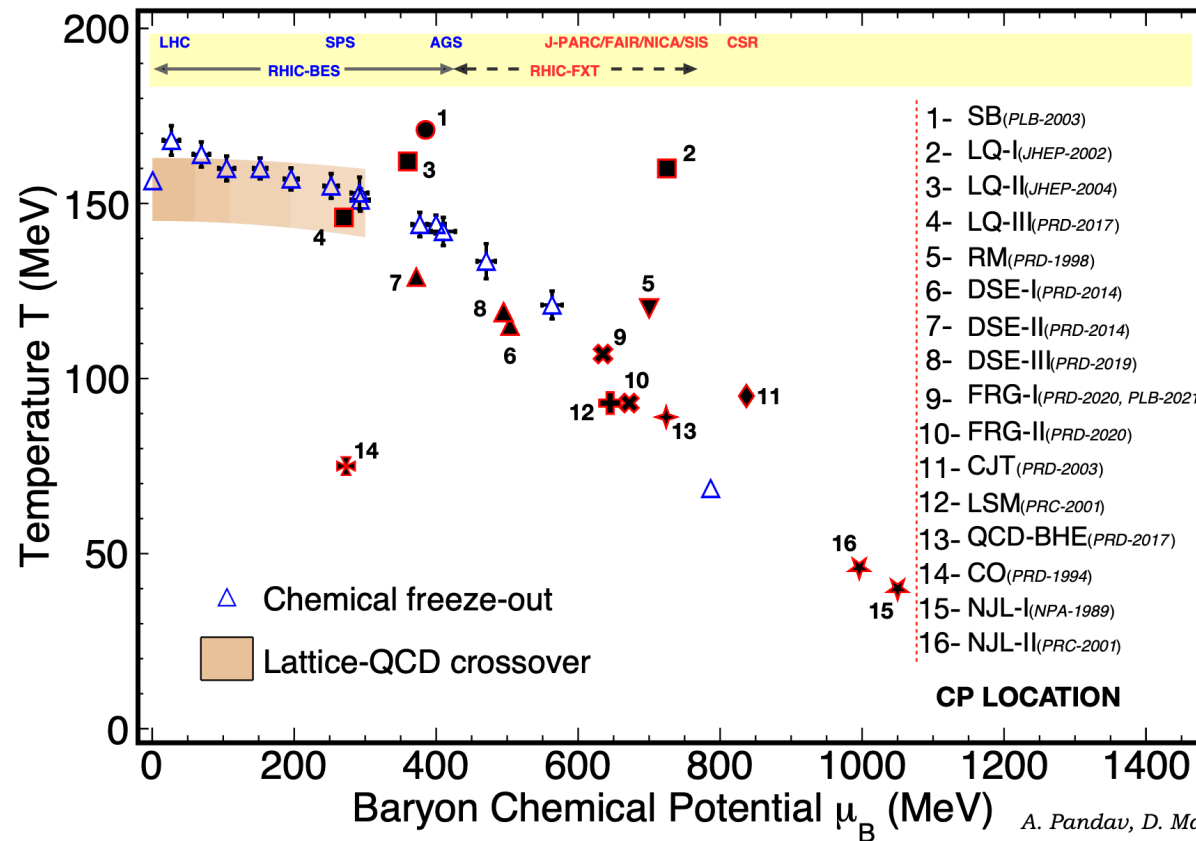
QCD phase diagram



A. Bzdak et al, Phys.Rep.853 pp1-87 (2020)

- Quark-Gluon Plasma (QGP) formation at high temperature region
- Crossover at $\mu_B = 0$ MeV
 - Y. Aoki et al, Nature 443,675(2006)
- 1st-order phase transition at large μ_B ?
- Critical point?

QCD critical point

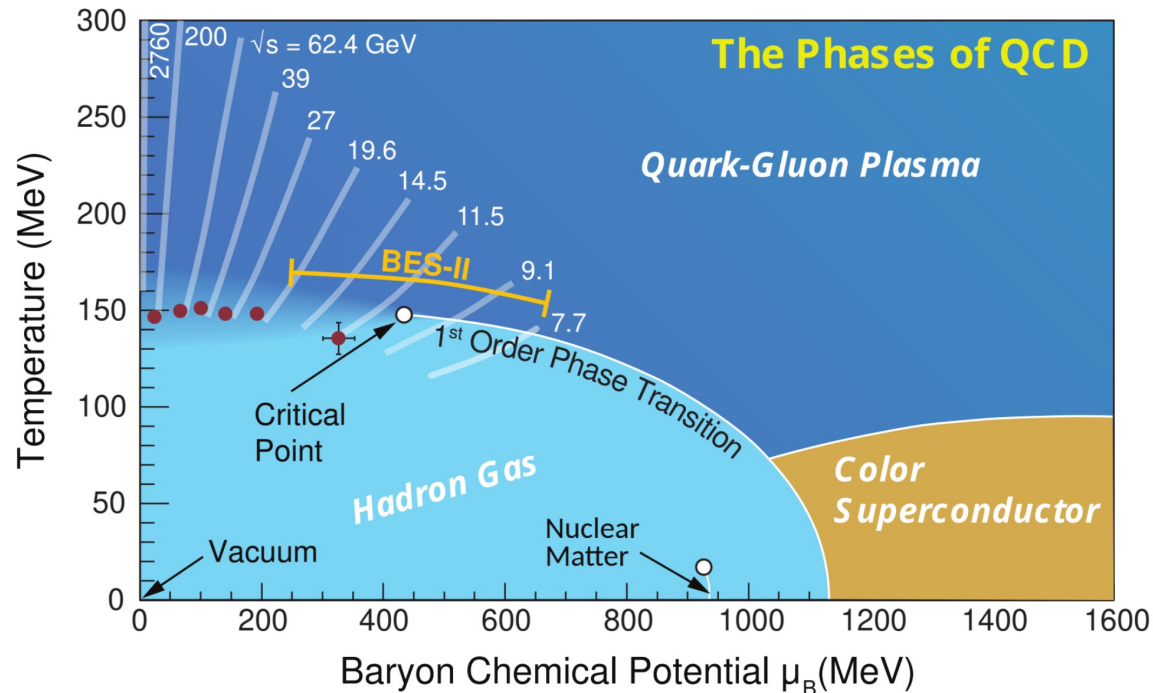


- Theoretical predictions vary widely in T - μ_B plane.
- Experimental search is crucial!

A. Pandav, QM2023

A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

Beam Energy Scan Phase-I (BES-I)

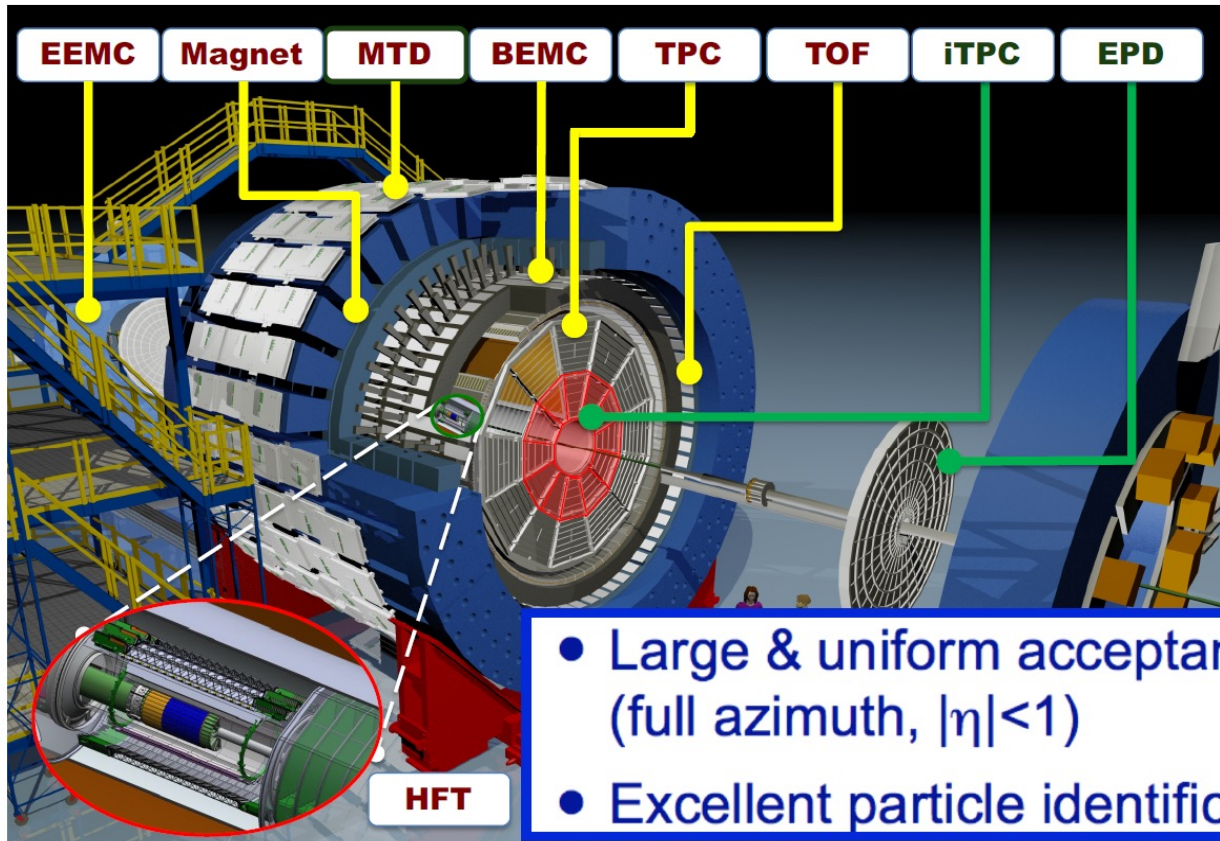


A. Bzdak et al, Phys.Rep.853 pp1-87 (2020)

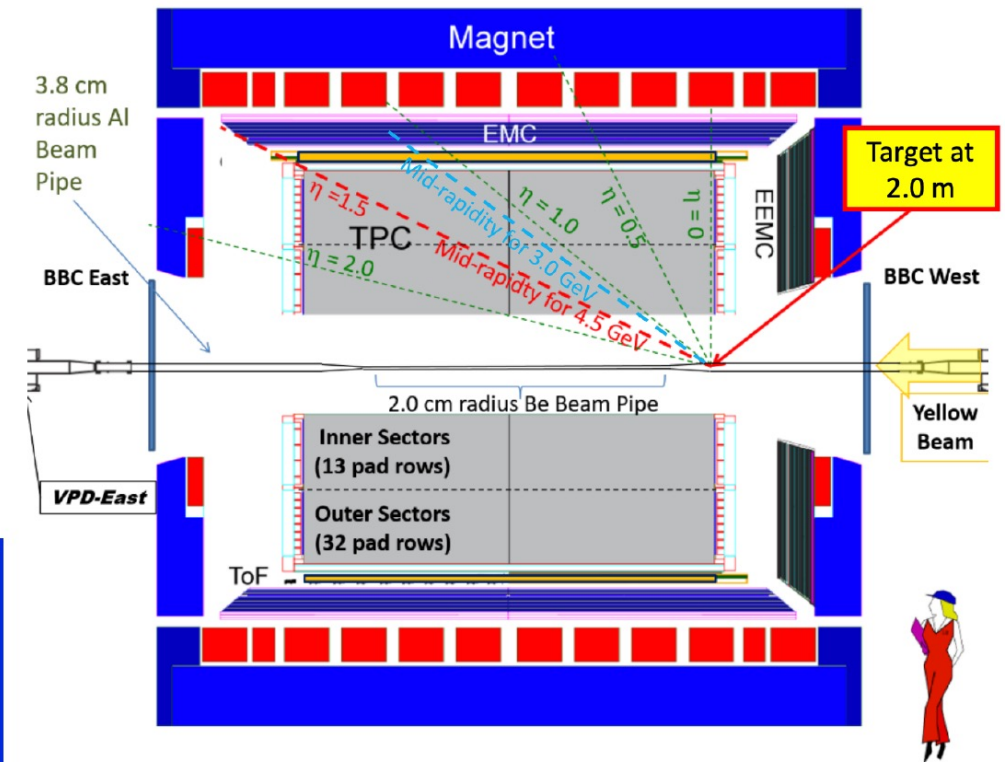
Fluctuations of conserved charges have been measured for BES data.

$\sqrt{s_{NN}}$ (GeV)	No. of events (million)	T_{ch} (MeV)	μ_B (MeV)
200	238	164.3	28
62.4	47	160.3	70
54.4	550	160.0	83
39	2010-2017	156.4	160
27		155.0	144
19.6		153.9	188
14.5	20	151.6	264
11.5	6.6	149.4	287
7.7	3	144.3	398

STAR detectors



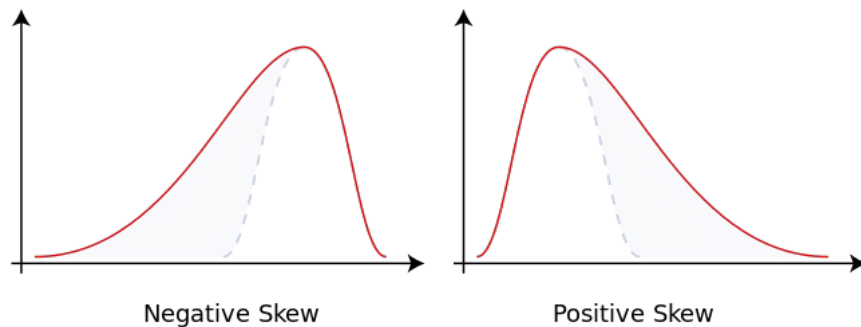
FXT mode : $\mu_B = 750$ MeV @ 3GeV



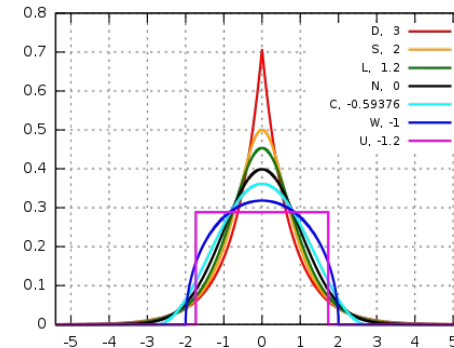
Higher-order fluctuation

- Moments and **cumulants** are mathematical measures of “shape” of a distribution, which probes fluctuations of an observable.

Skewness (S) → asymmetry



Kurtosis (κ) → sharpness



- Cumulant ↔ Central moment

$$C_1 = \langle N \rangle, \quad C_2 = \langle (\delta N)^2 \rangle \quad \delta N = N - \langle N \rangle$$

$$C_3 = \langle (\delta N)^3 \rangle \quad C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2$$

$$C_5 = \langle (\delta N)^5 \rangle - 10 \langle (\delta N)^2 \rangle \langle (\delta N)^3 \rangle$$

$$C_6 = \langle (\delta N)^6 \rangle + 30 \langle (\delta N)^2 \rangle^3 - 15 \langle (\delta N)^2 \rangle \langle (\delta N)^4 \rangle$$

- Cumulants have additivity : **proportional to the system volume**

$$C_n(X + Y) = C_n(X) + C_n(Y)$$

Cumulants of conserved charges

- Measure event-by-event distributions of **net-baryon**, **net-charge**, and **net-strangeness** number

$$\Delta N_q = N_q - N_{\bar{q}}, \quad q = B, Q, S$$

(1) Sensitive to the correlation length

$$C_2 = \langle (\delta N)^2 \rangle_c \approx \xi^2 \quad C_5 = \langle (\delta N)^5 \rangle_c \approx \xi^{9.5}$$

$$C_3 = \langle (\delta N)^3 \rangle_c \approx \xi^{4.5} \quad C_6 = \langle (\delta N)^6 \rangle_c \approx \xi^{12}$$

$$C_4 = \langle (\delta N)^4 \rangle_c \approx \xi^7$$

M. A. Stephanov, PRL102.032301(2009), PRL107.052301(2011)

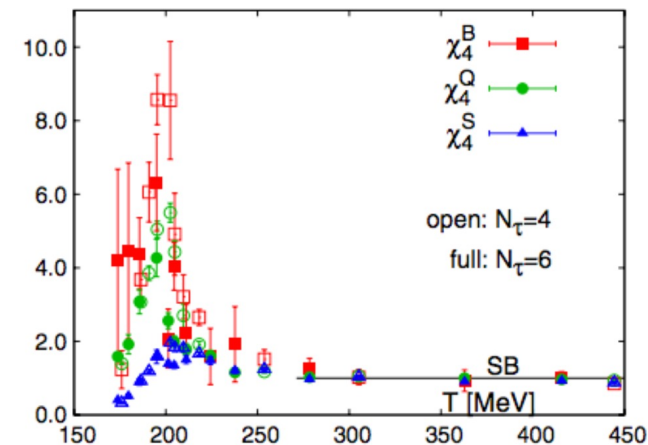
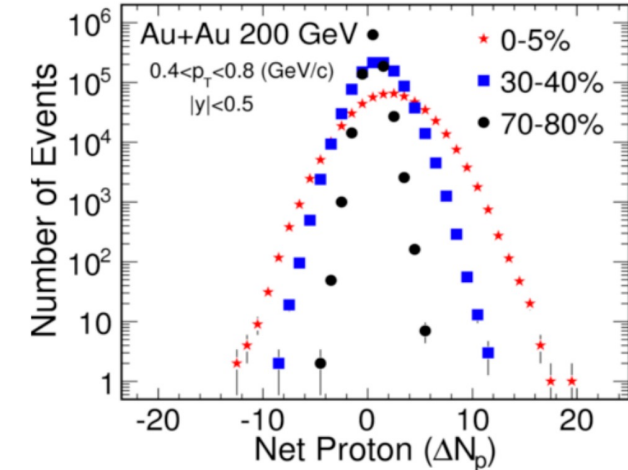
M. Asakawa, S. Ejiri, and M. Kitazawa, PRL103.262301(2009)

(2) Comparison with susceptibilities

$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \quad \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$

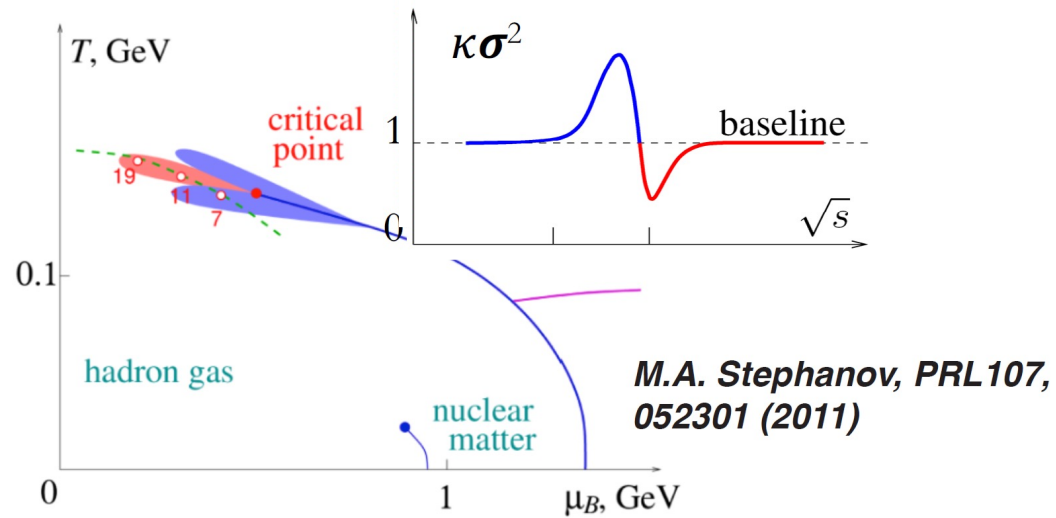
STAR, PRL105.022302(2010)



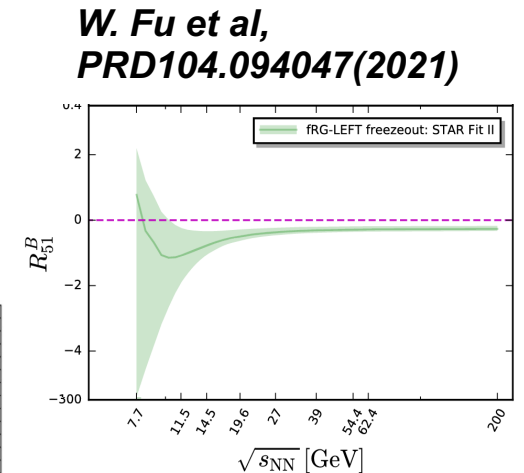
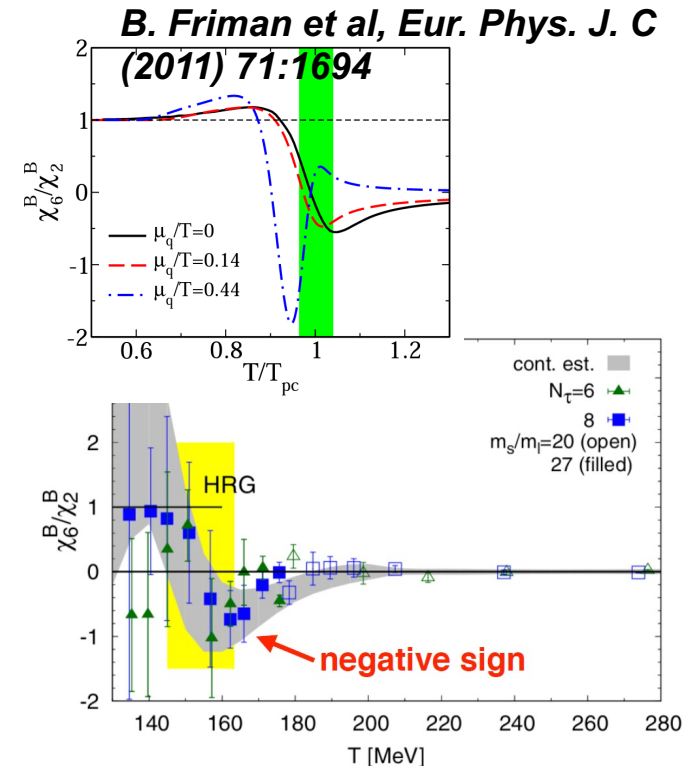
*M.Cheng et al,
PRD79.074505(2009)*

Theoretical predictions

Critical point : Nonmonotonic beam energy dependence of net-baryon C_4/C_2 w.r.t the baseline

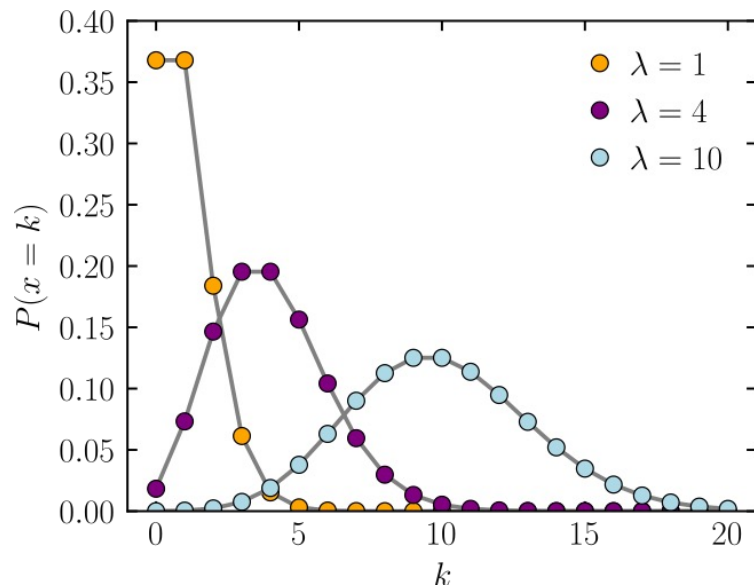


Crossover : Negative sign of C_5 and C_6



A. Bazavov et al, PRD95.054504(2017)

Baseline: Statistical fluctuation



Poisson distribution

$$P_{\lambda}(m) = \frac{\lambda^m}{m!} e^{-\lambda}$$

- Skellam distribution
 - “Statistical” baseline:
 - (Poisson) – (Poisson) = (Skellam)
 - $C_1 = C_3 = C_5 = \mu_1 - \mu_2$
 - $C_2 = C_4 = C_6 = \mu_1 + \mu_2$
- Non-critical baseline
 - Initial volume fluctuation, baryon number conservation...

$$C_3/C_1 = C_4/C_2 = C_6/C_2 = 1$$

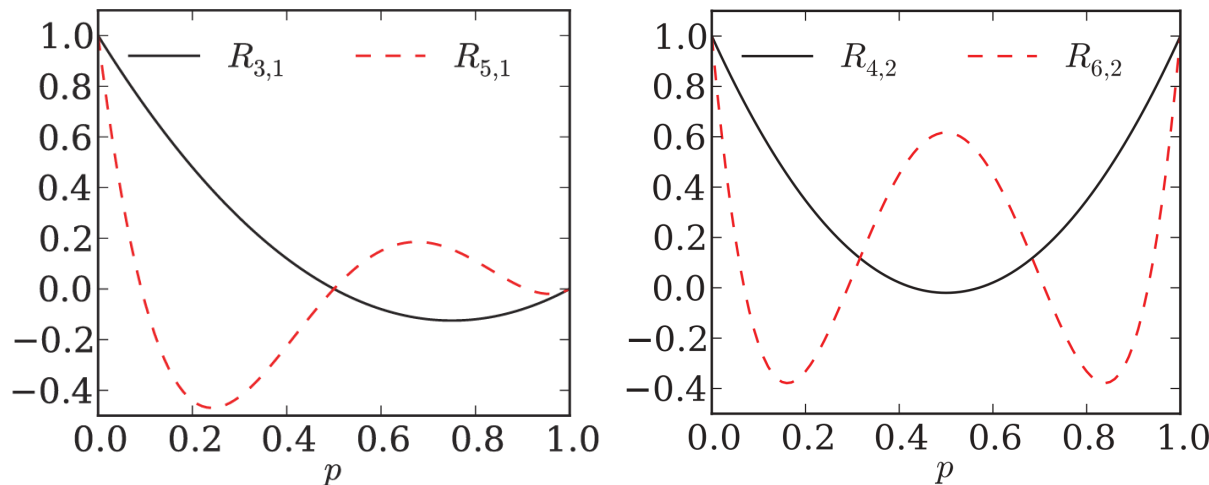
Skellam distribution

$$S_{\lambda_1, \lambda_2}(m) = e^{-(\lambda_1 + \lambda_2)} \left(\frac{\lambda_1}{\lambda_2} \right) I_m \left(2\sqrt{\lambda_1 \lambda_2} \right)$$

Baryon number conservation

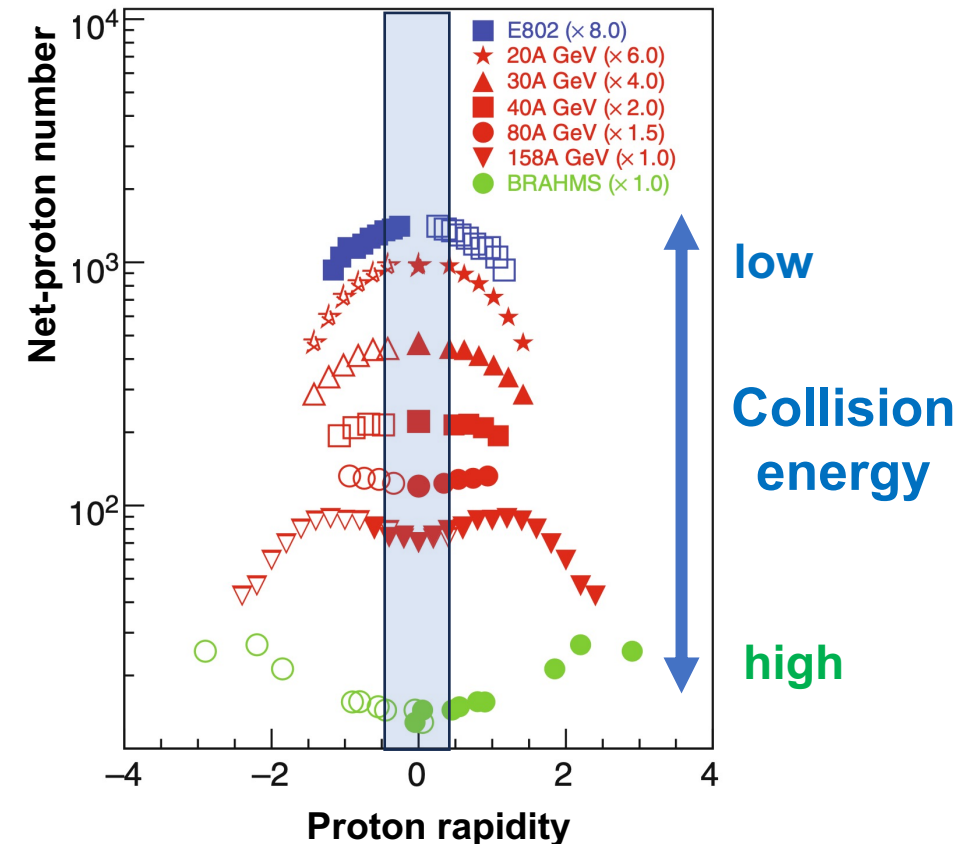
- The effect of baryon number conservation becomes more prominent with decreasing the collision energy.
- The baseline effectively changes.

A. Bzdak et al, PRC 87 (2013) 014901



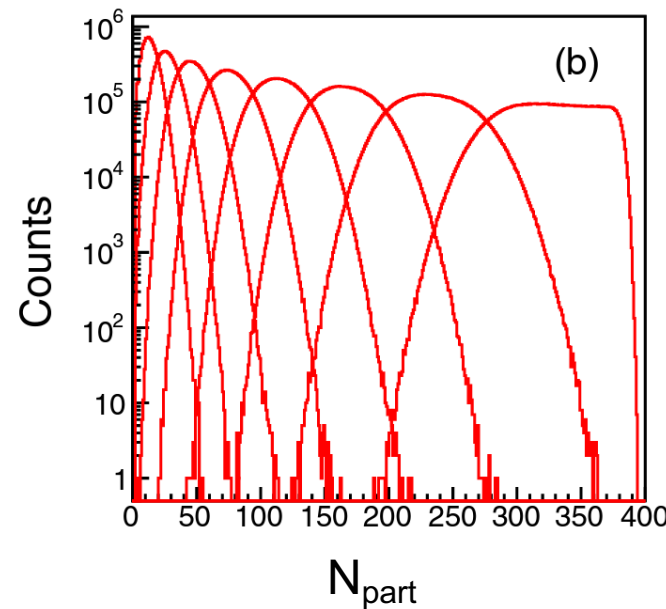
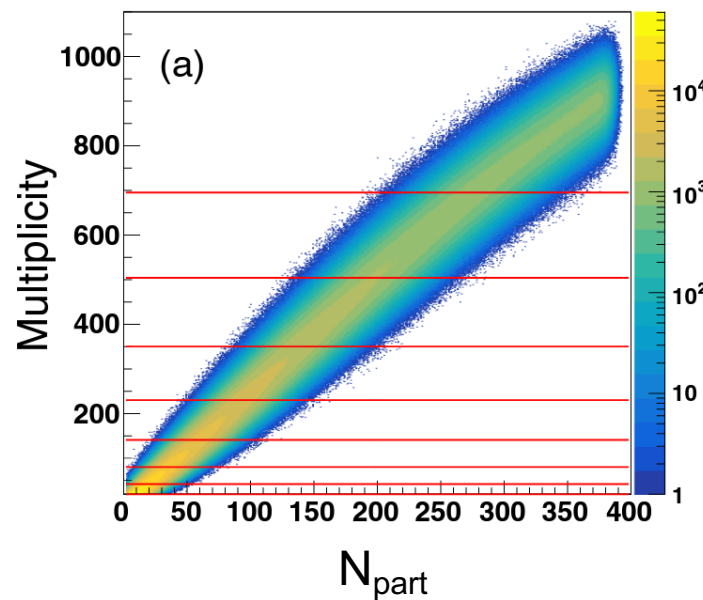
Fraction of measured particles

high Collision energy low



Initial volume fluctuation

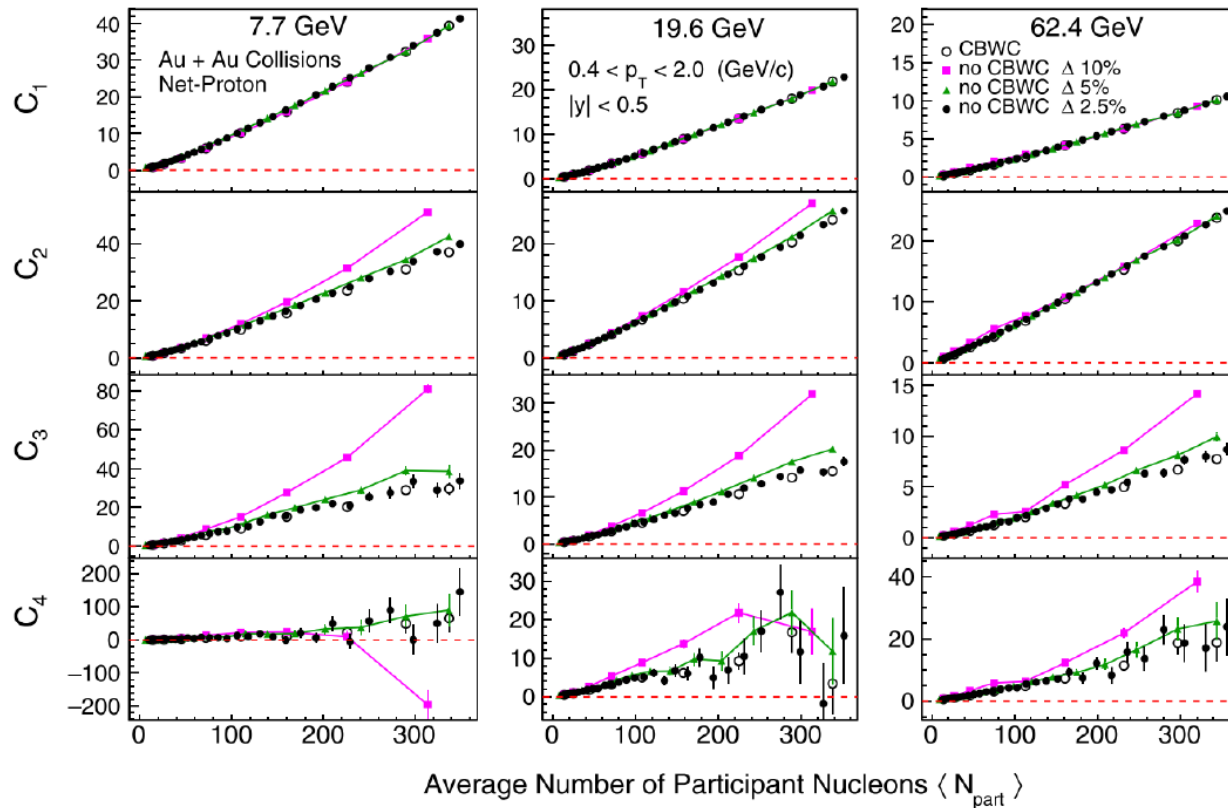
- Initial and final state variables are not one-to-one corresponding, which is referred to as the initial volume fluctuations.
- How does it affect the cumulant measurements?



UrQMD study fitted by
Glauber+two-component model

T. Sugiura et al., PRC.100.044904(2019)

Centrality Bin Width Correction (CBWC)



■ no CBWC Δ 10%
▲ no CBWC Δ 5%
● no CBWC Δ 2.5%
○ CBWC

↑ Centrality bin width for cumulant calculations

- Initial volume fluctuations can be partly suppressed by CBWC.

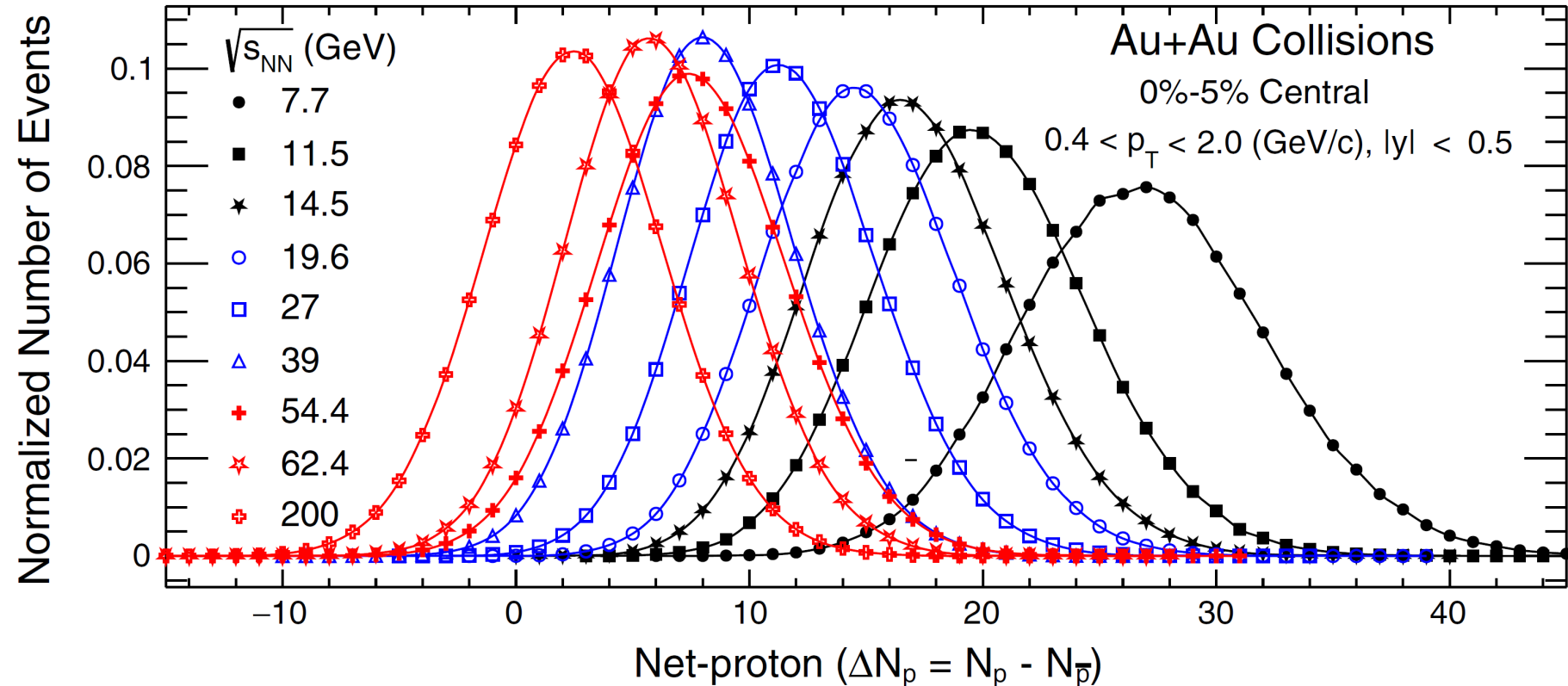
X. Luo et al., J. Phys. G40.105104 (2013)

- Purely data-driven, but cannot eliminate initial volume fluctuations.

STAR, PRC.104.024902(2021)

Raw net-proton multiplicity distribution

- Need to consider various experimental effects.



STAR, PRL126.092301(2021), PRC104.024902(2021)

Experimental challenges

- Detector efficiency correction

- **Binomial distribution**

- *M. Kitazawa and M. Asakawa, PRC86.024904(2012), A. Bzdak and V. Koch, PRC86.044904(2012), X. Luo, PRC91.034907(2016),*
 - *T. Nonaka, M. Kitazawa, S. Esumi, PRC95.064912(2017), X. Luo and T. Nonaka, PRC99.044917(2019)*

- **Non-binomial distribution**

- *T. Nonaka, M. Kitazawa, S. Esumi, NIMA906 10-17(2018)*
 - *S. Esumi, K. Nakagawa, T. Nonaka, NIMA987.164802(2021)*

- Initial volume fluctuation

- *M. I. Gorenstein and M. Gaździcki, PRC84.014904 (2011), V. Skokov, B. Friman, and K. Redlich, PRC88,034911 (2013)*
 - *X. Luo, J. Xu, B. Mohanty, N. Xu, J. Phys. G40.105104 (2013), P. Munzinger, A. Rustamov, and J. Stachel, NPA960.114 (2017)*
 - *T. Sugiura, T. Nonaka, and S. Esumi, PRC100.044904 (2019)*

- Pileup events

- *S. Sombun et al, J.Phys.G45.025101(2018), P. Garg and D. Mishra, PRC96.044908(2017)*
 - *T. Nonaka, M. Kitazawa, S. Esumi, NIMA984.164632(2020), Y. Zhang, Y. Huang, T. Nonaka, X. Luo, NIMA1026.166246(2022)*

- Identity method

- *M. Gaździcki, K. Grebieszko, M. Maćkowiak, and S. Mrówczyński, PRC83.054907 (2011)*
 - *A. Rustamov and M. I. Gorenstein, PRC86.044906 (2012), M. I. Gorenstein, PRC84.024902 (2018)*
 - *M. Arslanovic and A. Rustamov, NIMA946.162622 (2019)*

- More to be resolved...

- Net-proton≠net-baryon, purity correction, acceptance dependence for comparison with theory, ...

***Not all important studies are listed here**

Efficiency correction: Binomial model

- Correction formulas were derived based on the assumption that detector efficiencies follow the binomial distribution.

Binomial response b/w generated and measured particles

$$B_{p,N}(n) = \frac{N!}{n!(N-n)!} p^n (1-p)^{N-n}$$

p: efficiency
N: generated particles
n: measured particles

$$q_{(r,s)} = q_{(a^r/p^s)} = \sum_{i=1}^M (a_i^r / p_i^s) n_i$$

M : # of efficiency bins
n : # of particles
p : efficiency
a : electric charge

$$\langle Q \rangle_c = \langle q_{(1,1)} \rangle_c, \quad (62)$$

$$\langle Q^2 \rangle_c = \langle q_{(1,1)}^2 \rangle_c + \langle q_{(2,1)} \rangle_c - \langle q_{(2,2)} \rangle_c, \quad (63)$$

$$\langle Q^3 \rangle_c = \langle q_{(1,1)}^3 \rangle_c + 3\langle q_{(1,1)}q_{(2,1)} \rangle_c - 3\langle q_{(1,1)}q_{(2,2)} \rangle_c + \langle q_{(3,1)} \rangle_c - 3\langle q_{(3,2)} \rangle_c + 2\langle q_{(3,3)} \rangle_c, \quad (64)$$

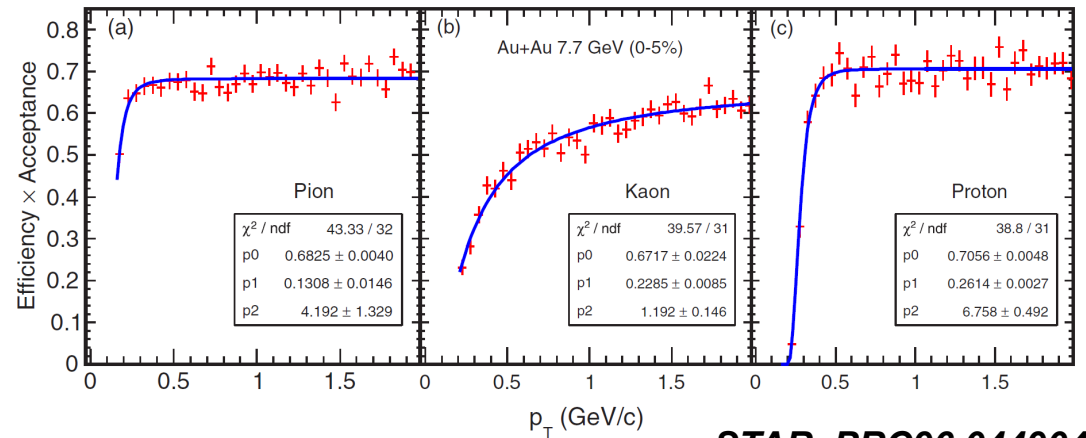
$$\langle Q^4 \rangle_c = \langle q_{(1,1)}^4 \rangle_c + 6\langle q_{(1,1)}^2q_{(2,1)} \rangle_c - 6\langle q_{(1,1)}^2q_{(2,2)} \rangle_c + 4\langle q_{(1,1)}q_{(3,1)} \rangle_c + 3\langle q_{(2,1)}^2 \rangle_c + 3\langle q_{(2,2)}^2 \rangle_c - 12\langle q_{(1,1)}q_{(3,2)} \rangle_c + 8\langle q_{(1,1)}q_{(3,3)} \rangle_c - 6\langle q_{(2,1)}q_{(2,2)} \rangle_c + \langle q_{(4,1)} \rangle_c - 7\langle q_{(4,2)} \rangle_c + 12\langle q_{(4,3)} \rangle_c - 6\langle q_{(4,4)} \rangle_c, \quad (65)$$

T. Nonaka, M. Kitazawa, S. Esumi, PRC95.064912(2017)

X. Luo and T. Nonaka, PRC99.044917(2019)

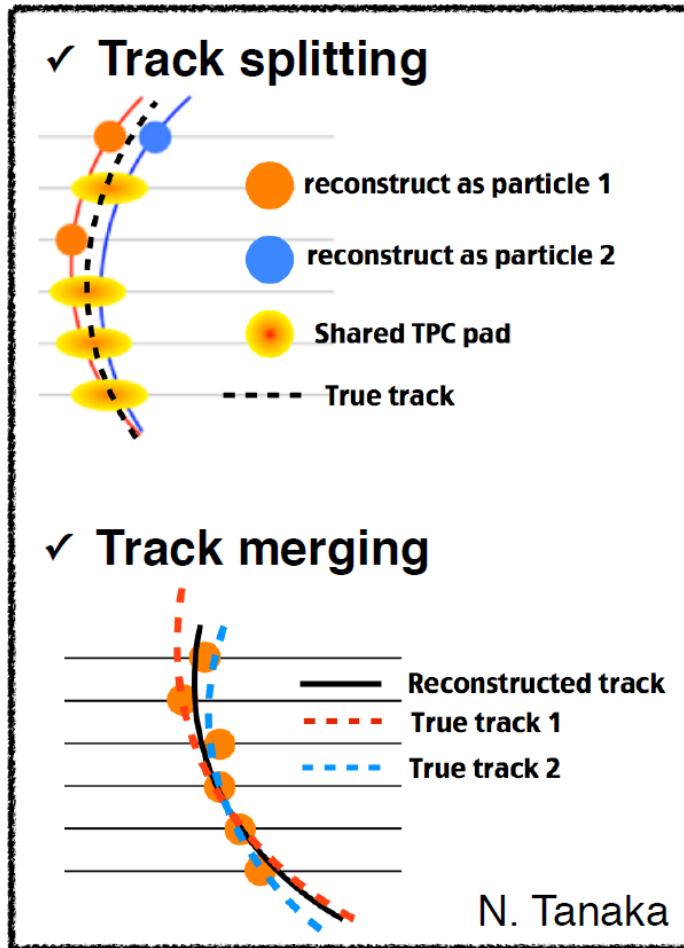
True and measured factorial cumulants

$$\langle n^m \rangle_{fc} = p^m \langle N^m \rangle_{fc}$$



STAR, PRC96.044904(2017)

Non-binomial efficiency

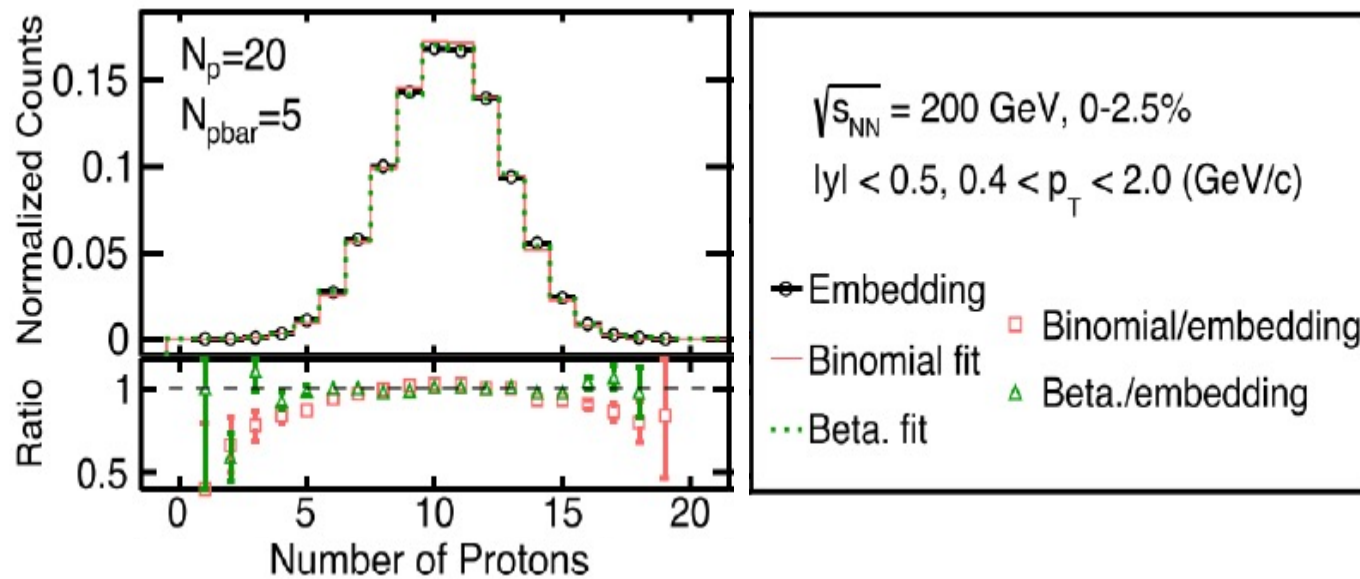


- Binomial efficiency is justified when efficiencies for all tracks are independent.
- Possible non-binomial effects:
 - Track splitting/merging
 - efficiency correlations
 - Multiplicity dependent efficiency
 - Time dependent efficiency

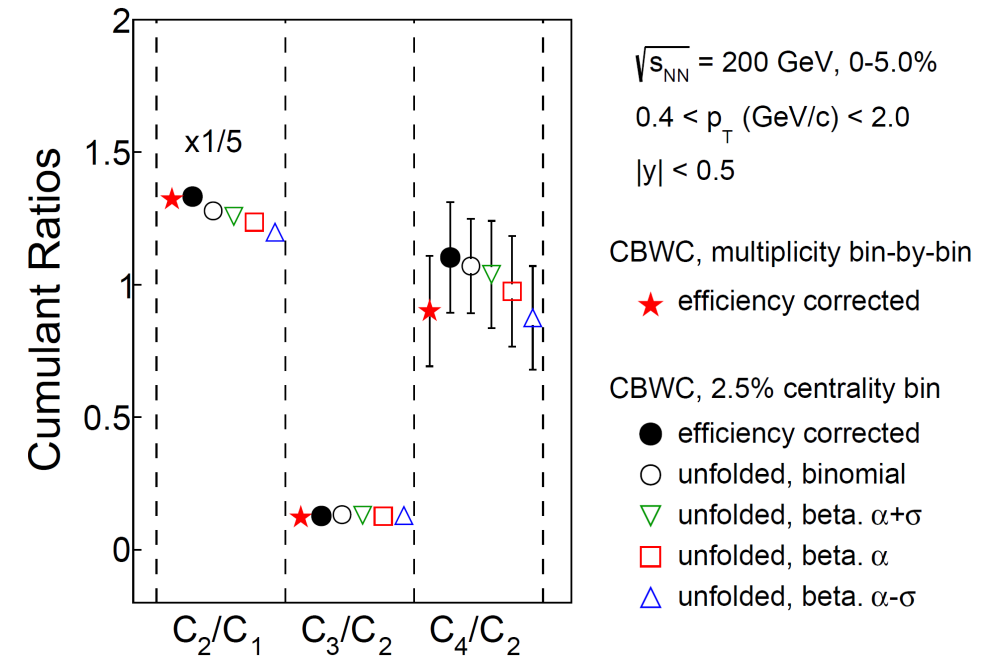
Efficiency distribution can be studied through detector simulations.

Effect of non-binomial efficiency

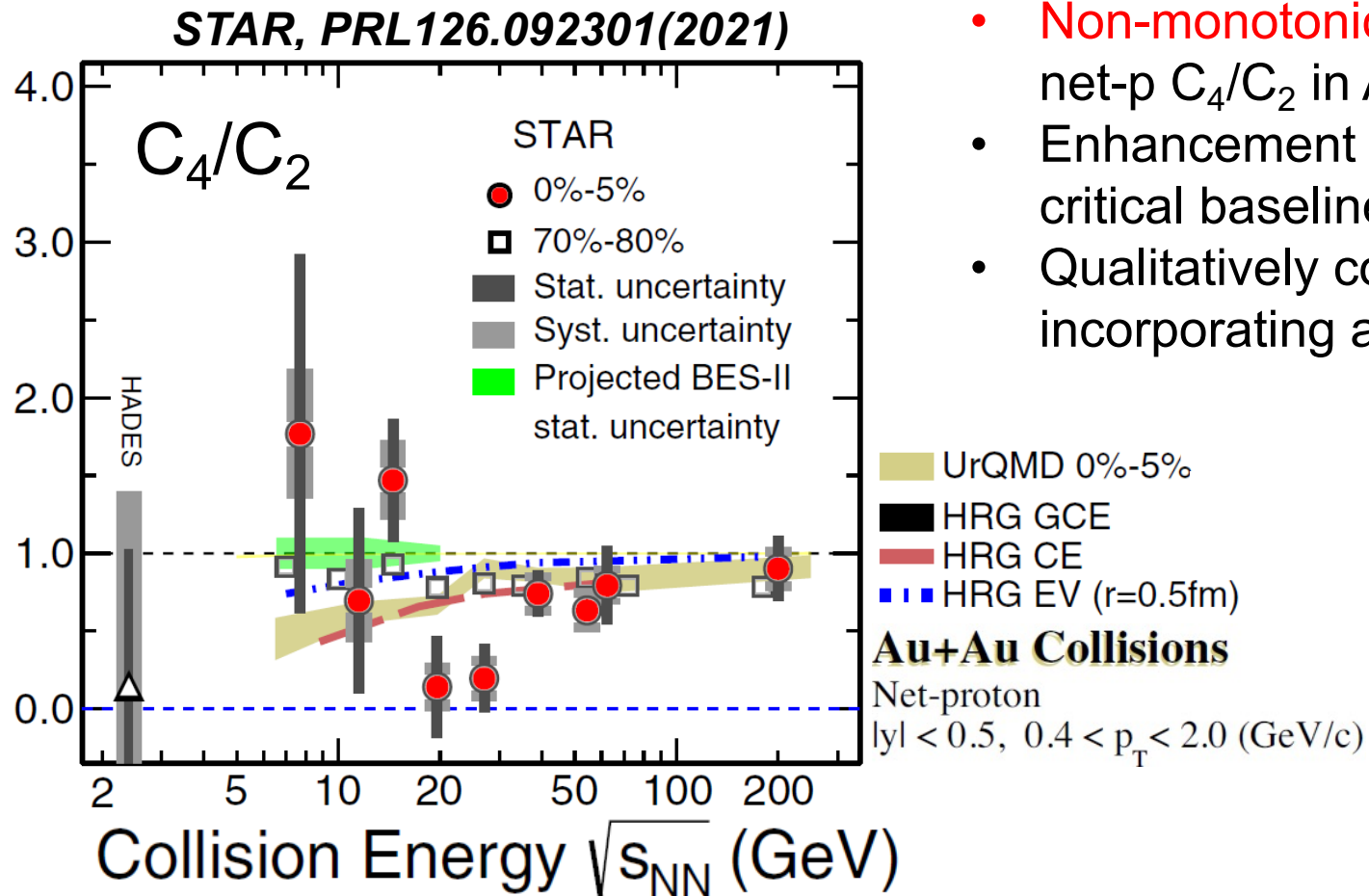
- Efficiency distribution was studied in embedding simulation, which was slight broader than the binomial.
- The effect on C_4/C_2 was within the statistical uncertainties.



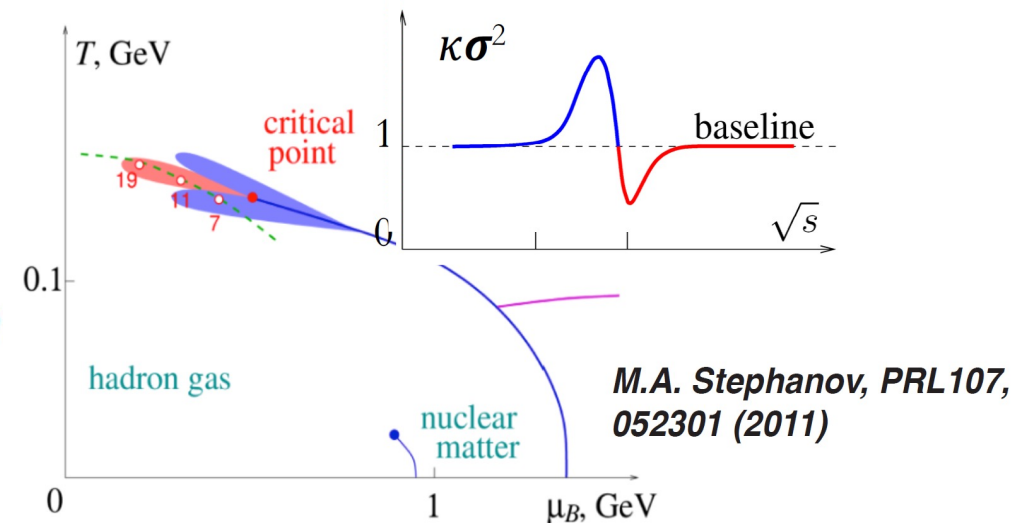
STAR, PRC.104.024902(2021)



Net-proton C_4/C_2



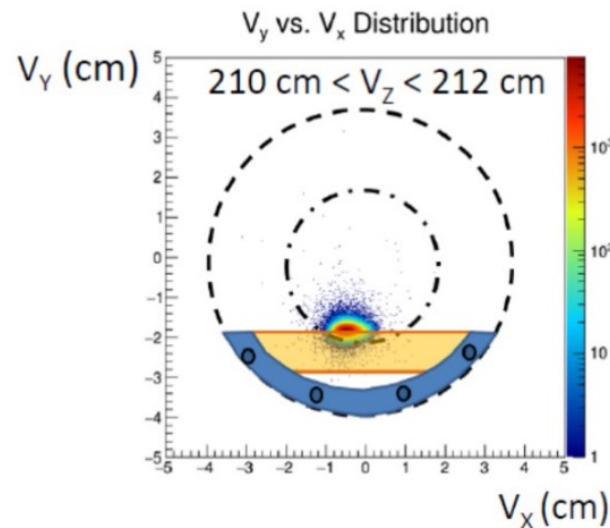
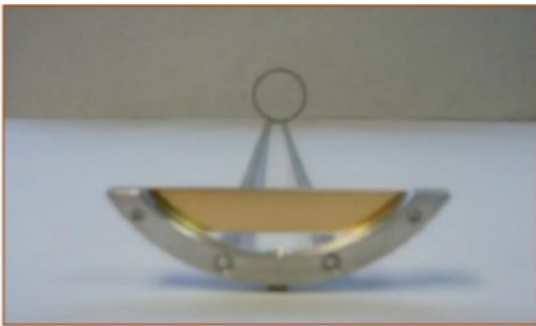
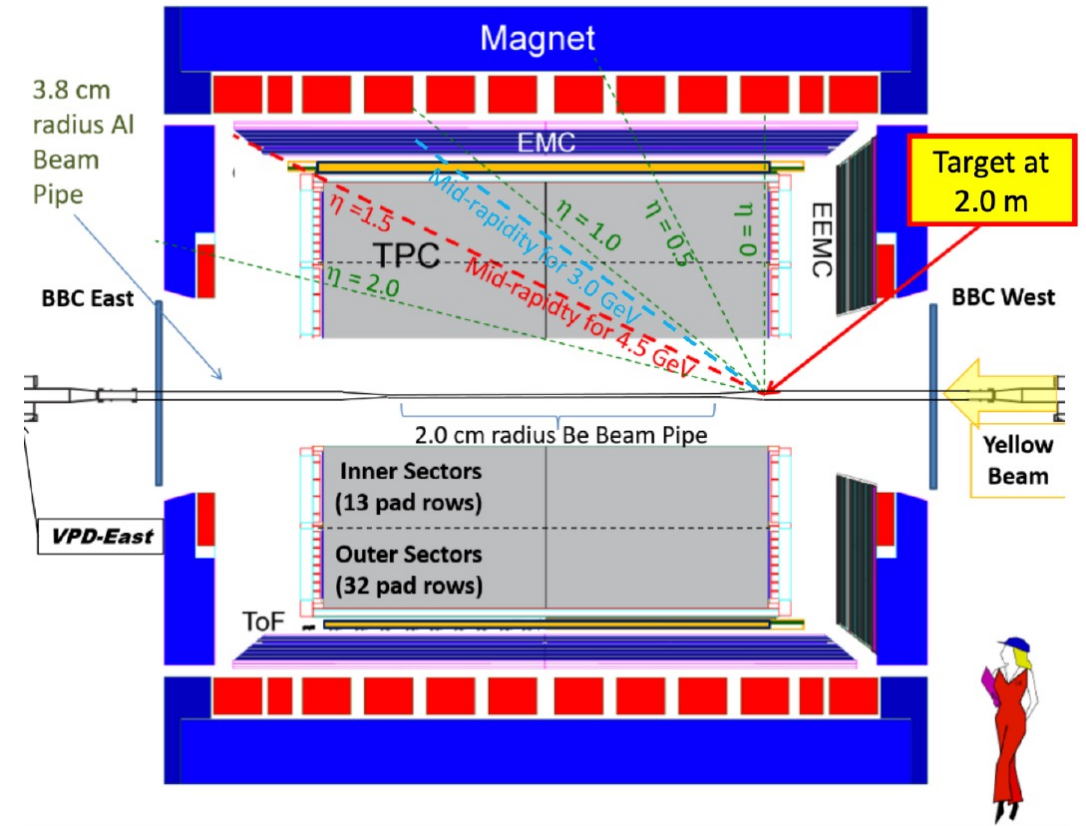
- **Non-monotonic beam energy dependence (3.1σ)** of net-p C_4/C_2 in Au+Au central collisions.
- Enhancement at ~ 7.7 GeV is not reproduced by non-critical baselines.
- Qualitatively consistent with the model prediction incorporating a critical point.



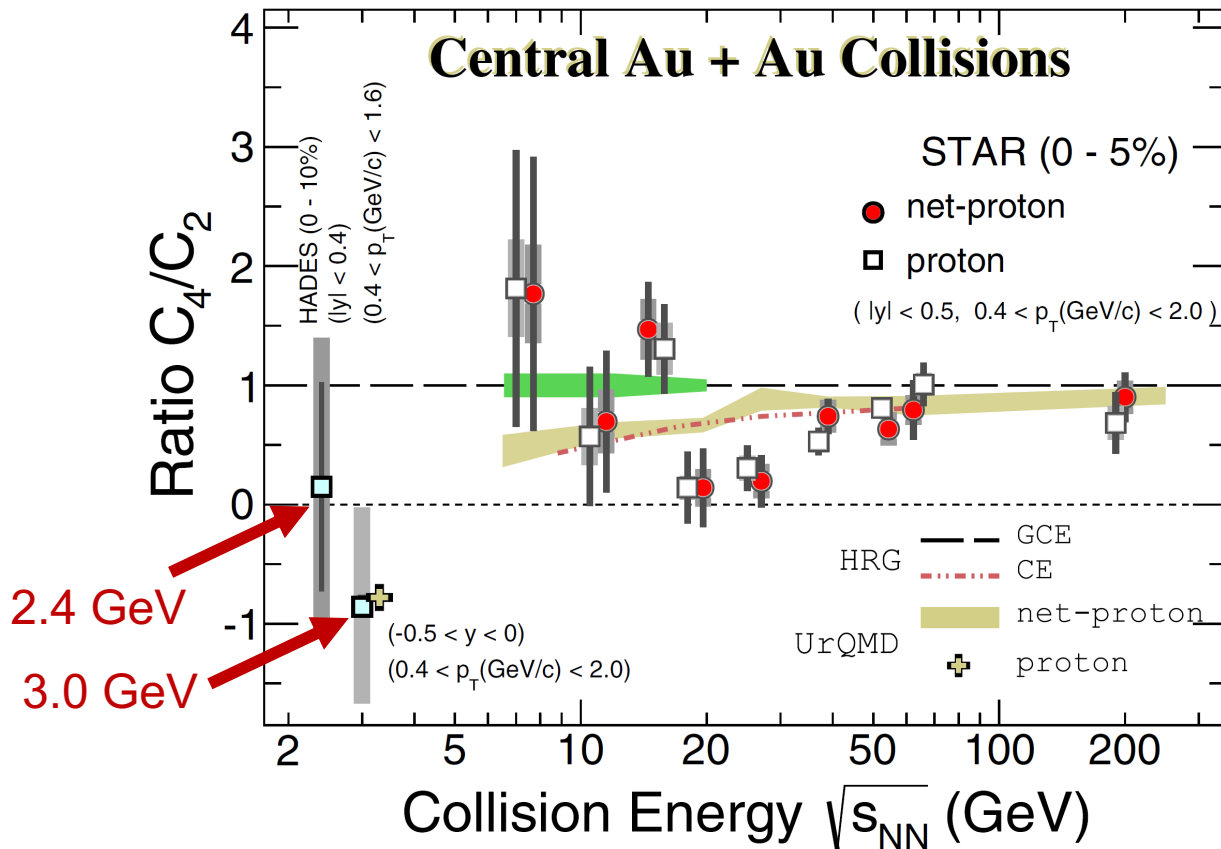
Fixed-target experiment

- Collide Au beam on the fixed Au target
→ much higher interaction rate

FXT mode : $\mu_B=750$ MeV @ 3GeV

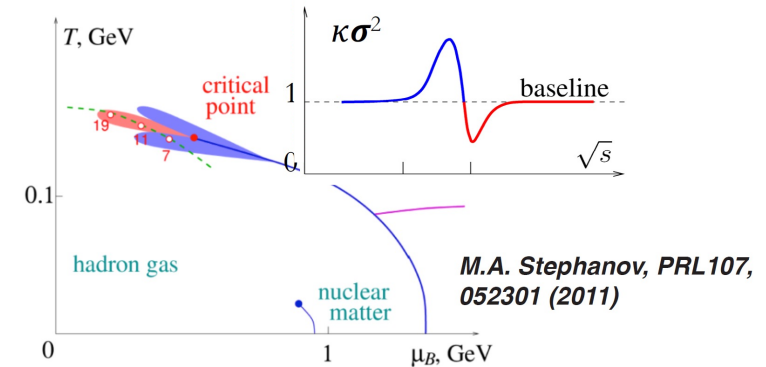


Collision energy dependence



HADES, PRC102.024914(2020)

STAR, PRL128.202303(2022), PRC107.024908(2023)



- No clear enhancement is observed for 2.4 and 3.0 GeV data from HADES and STAR.
- Negative value at 3 GeV is reproduced by UrQMD, which incorporates baryon number conservation.
- The data implies that the QCD critical region could only exist at energies $> 3\text{ GeV}$.

BES-II datasets

Au+Au Collisions at RHIC							
Collider Runs				Fixed-Target Runs			
Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)	Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	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
	BES-II collider results ready			12	3.0 (3.85)	260 + 2000	750

Events used for net-proton fluctuation studies (Collider runs)

BES-II vs BES-I

$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10 ⁶)	Events BES-II (10 ⁶)
7.7	3	45
9.2	-	78
11.5	7	110
14.5	20	178
17.3	-	116
19.6	15	270
27	30	220

~10-18 fold improvement in statistics
9.2 and 17.3 GeV added to energy scan

$$3 \leq \sqrt{s_{NN}} \text{ (GeV)} \leq 200 \rightarrow 750 \geq \mu_B \text{ (MeV)} \geq 25$$

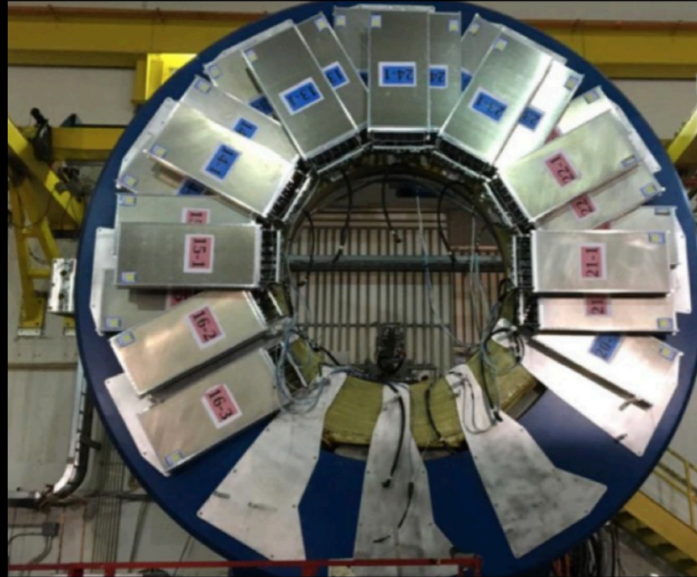
High precision, widest μ_B coverage to date

STAR Major Upgrades for BES-II



iTPC:

- Improves dE/dx
- Extends η coverage from 1.0 to 1.6
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019



eTOF:

- Forward rapidity coverage
- PID at $\eta = 1.05$ to 1.5
- Borrowed from CBM-FAIR
- Ready in 2019



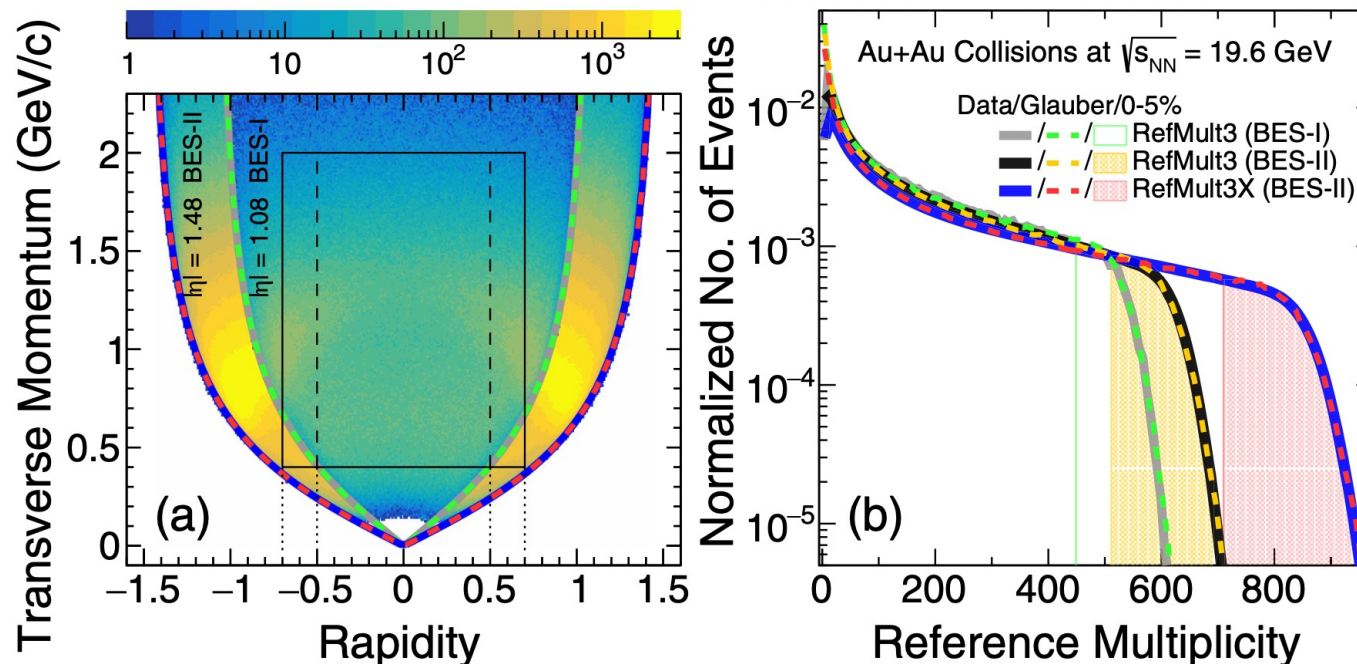
EPD:

- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

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

Centrality resolution

- The centrality resolution has been improved as more particles are measured due to wider acceptance.



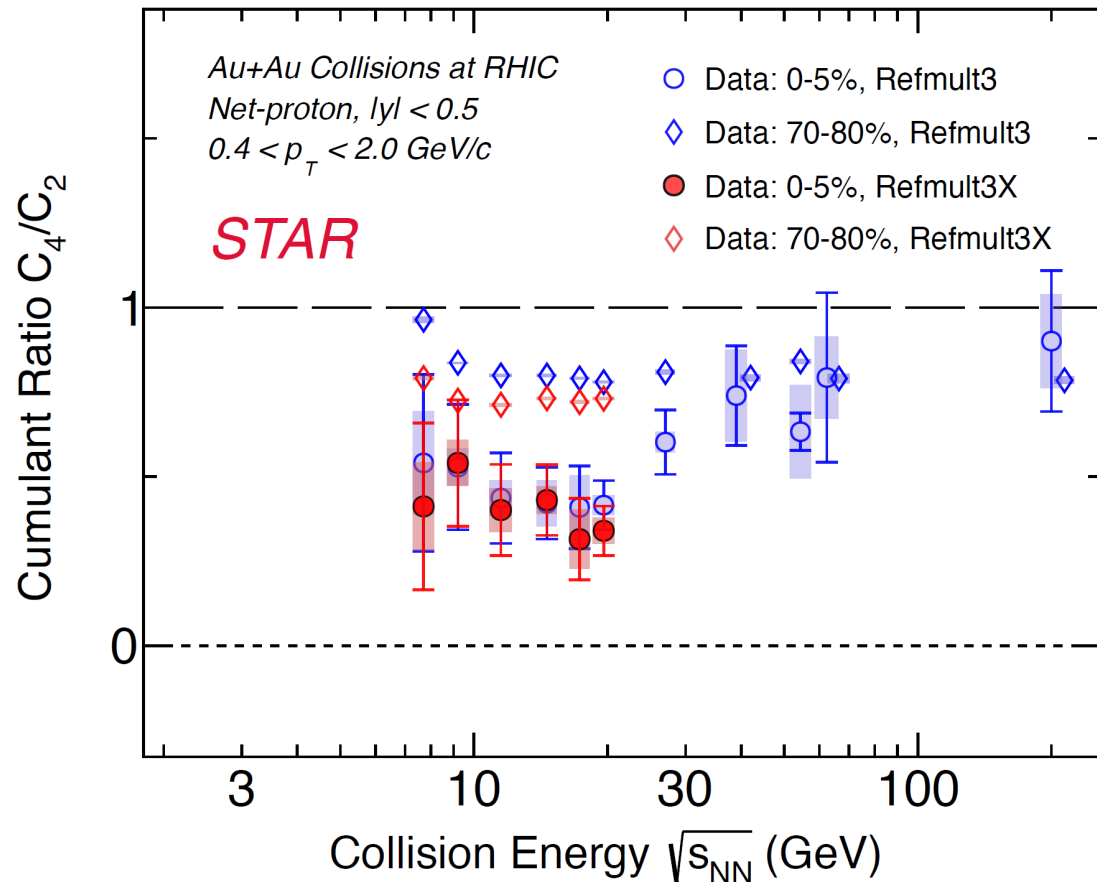
STAR, PRL135.142301(2025)

Charged particles except for
(anti)protons

Refmult3 : $|\eta| < 1.0$

Refmult3X : $|\eta| < 1.6$

Effect of centrality resolution

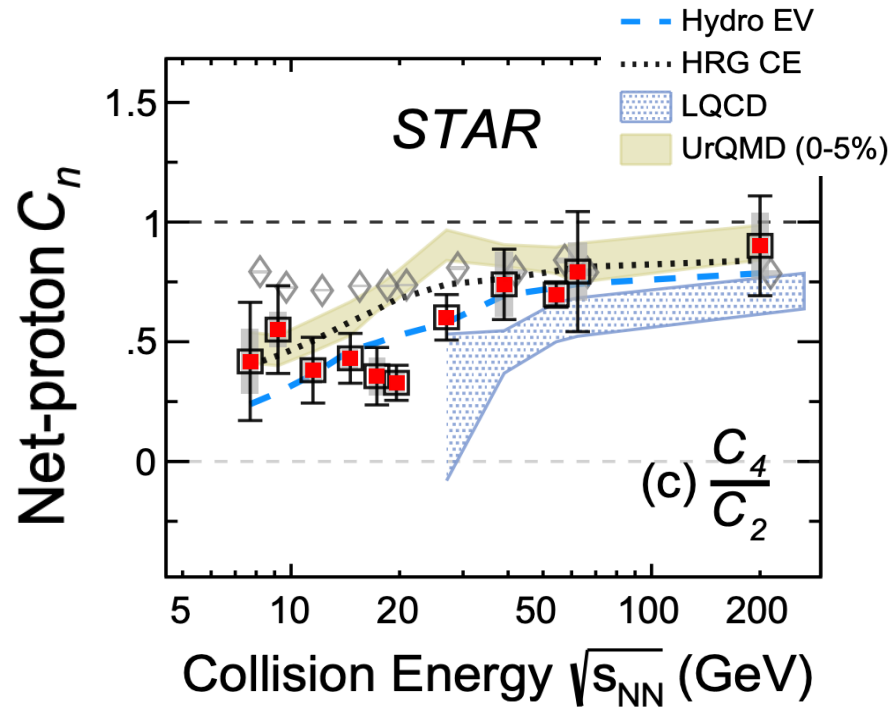


A. Pandav, CPOD2024

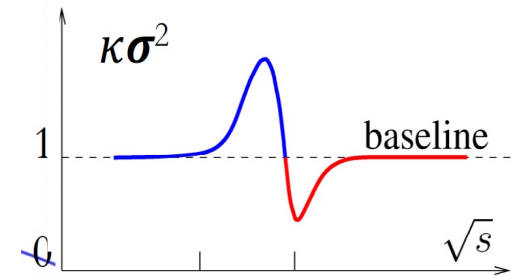
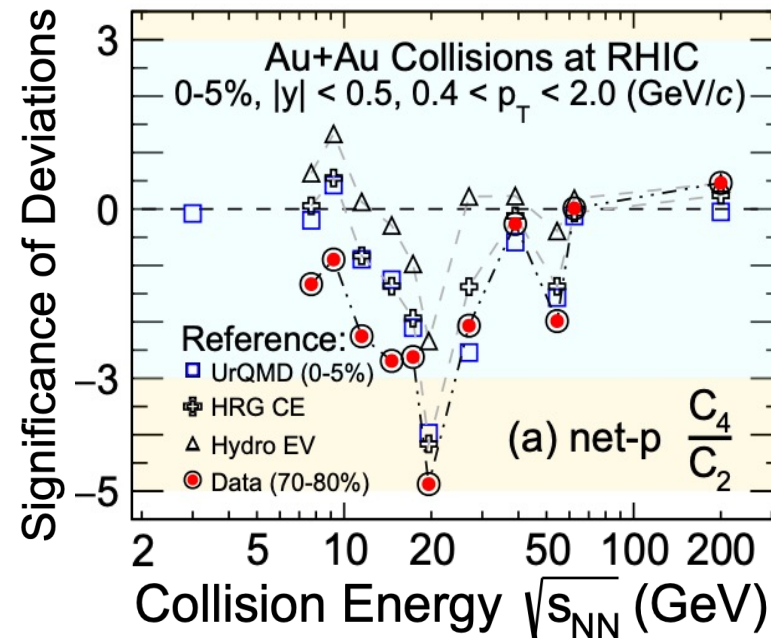
- The results show good agreement between Refmult3 and Refmult3X in the most central collisions.

Model comparison

- Significant deviation from non-critical baseline at 19.6 GeV.
- Dynamical model incorporating the critical point is needed.



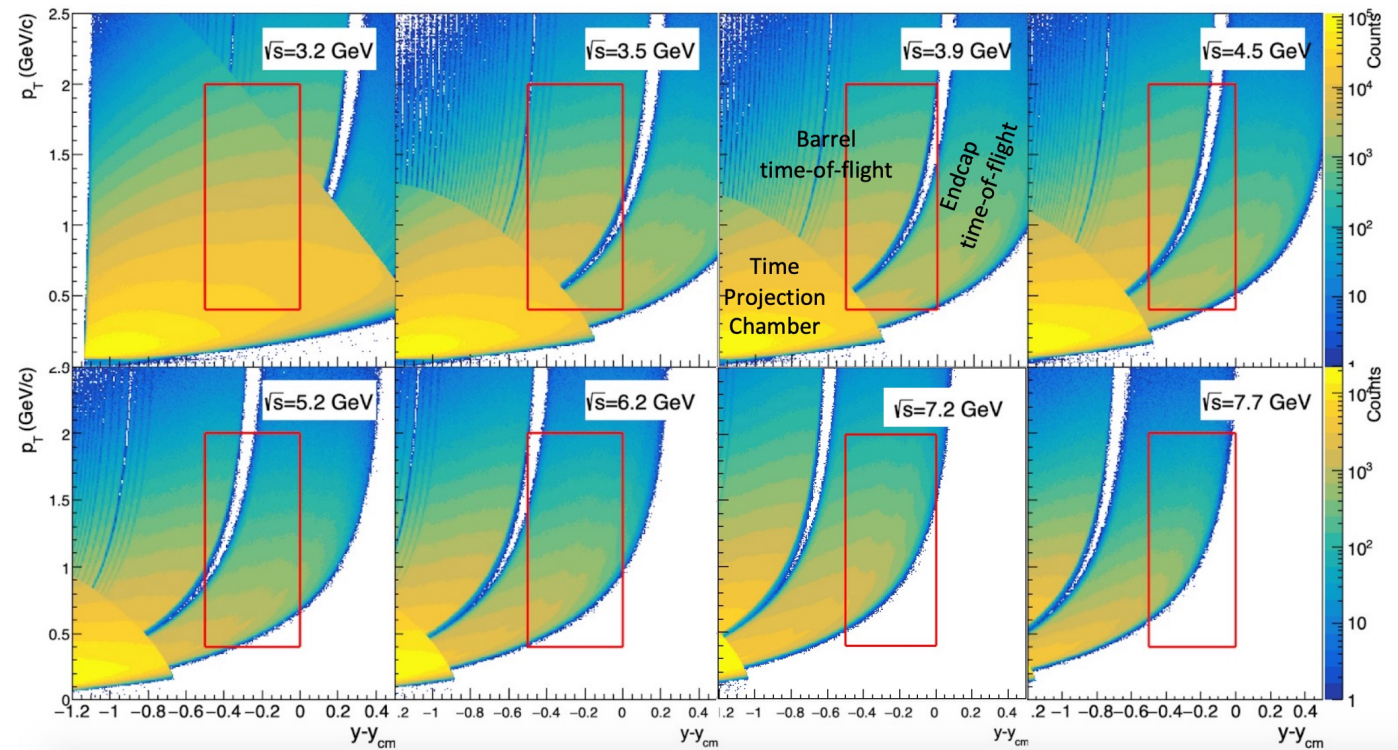
STAR, PRL135.142301(2025)



Fixed-target runs : proton acceptance

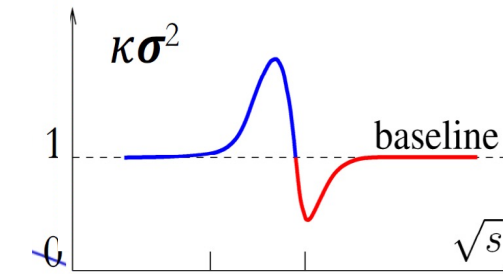
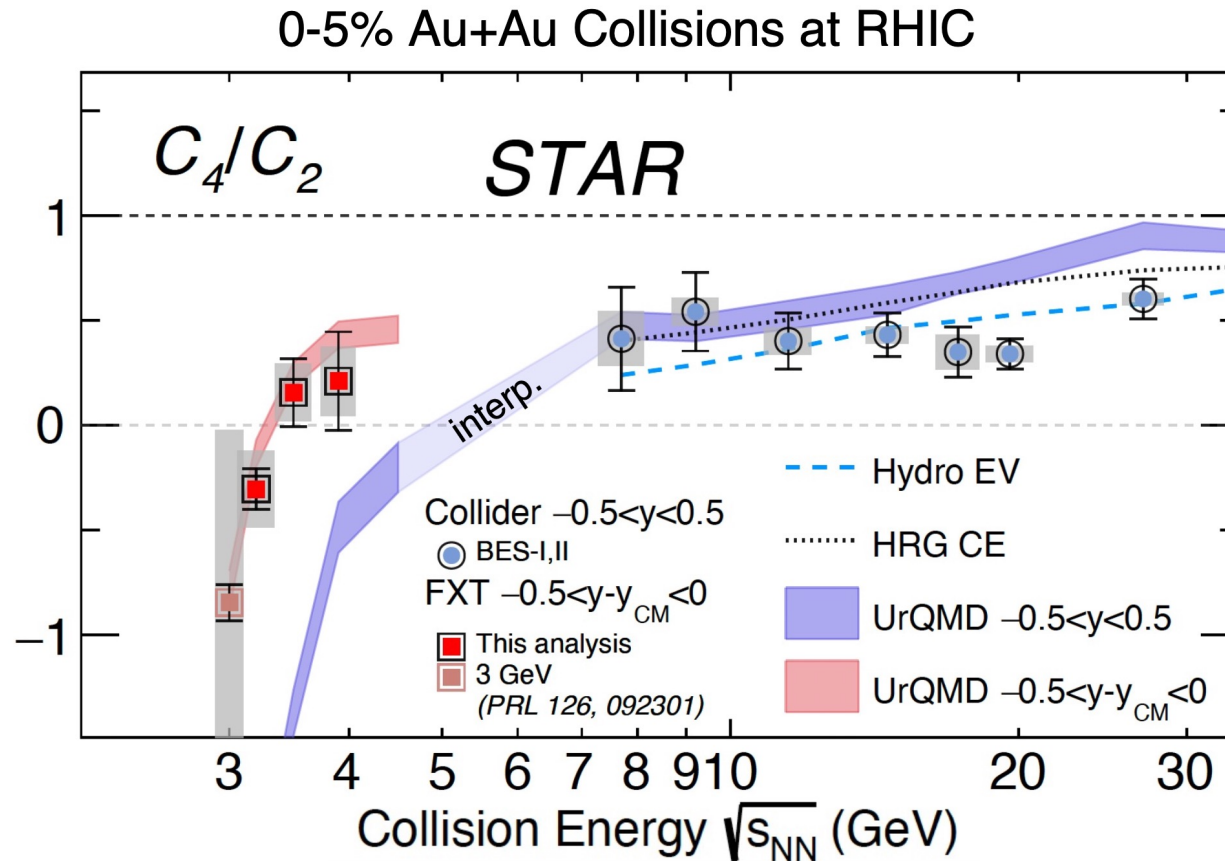
- The midrapidity cannot be covered in high energies.
- The gap between BTOF and ETOF are taken into account in UrQMD calculations.

Fixed-Target Runs			
Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)
1	13.7 (100)	50	280
2	11.5 (70)	50	316
3	9.2 (44.5)	50	372
4	7.7 (31.2)	260	420
5	7.2 (26.5)	470	440
6	6.2 (19.5)	120	490
7	5.2 (13.5)	100	540
8	4.5 (9.8)	110	590
9	3.9 (7.3)	120	633
10	3.5 (5.75)	120	670
11	3.2 (4.59)	200	699
12	3.0 (3.85)	260 + 2000	750



Z. Sweger, HAWAII23

Collision energy dependence



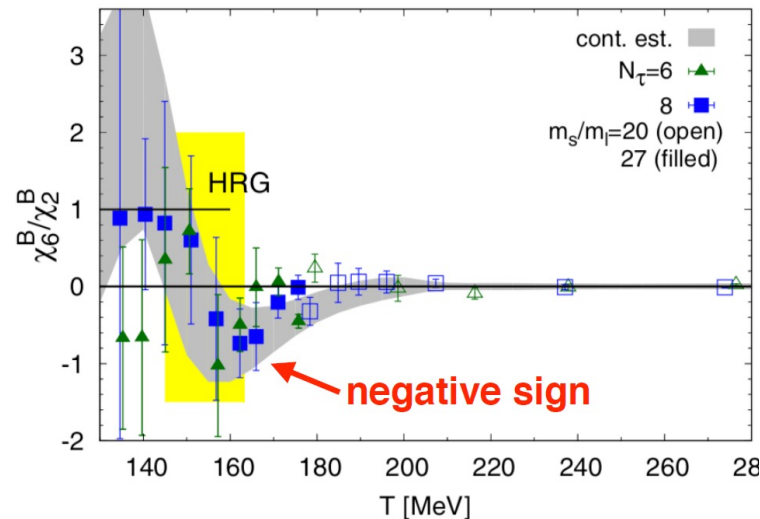
Z. Sweger, QM25

- Consistent with UrQMD calculations.
- Results from a few higher energies will be coming soon.

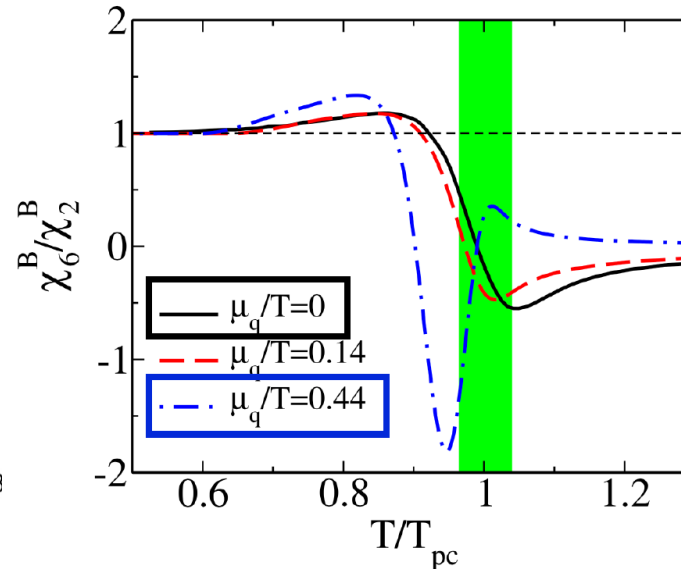
C_5 and C_6 for crossover search

- No direct experimental evidence for a smooth crossover at $\mu_B \sim 0$ MeV.
- $C_6/C_2 < 0$ is predicted as a sign of crossover transition
- High-statistics data sets at 27, 54.4, 200 GeV were analyzed.

A. Bazavov et al, PRD.95.054504



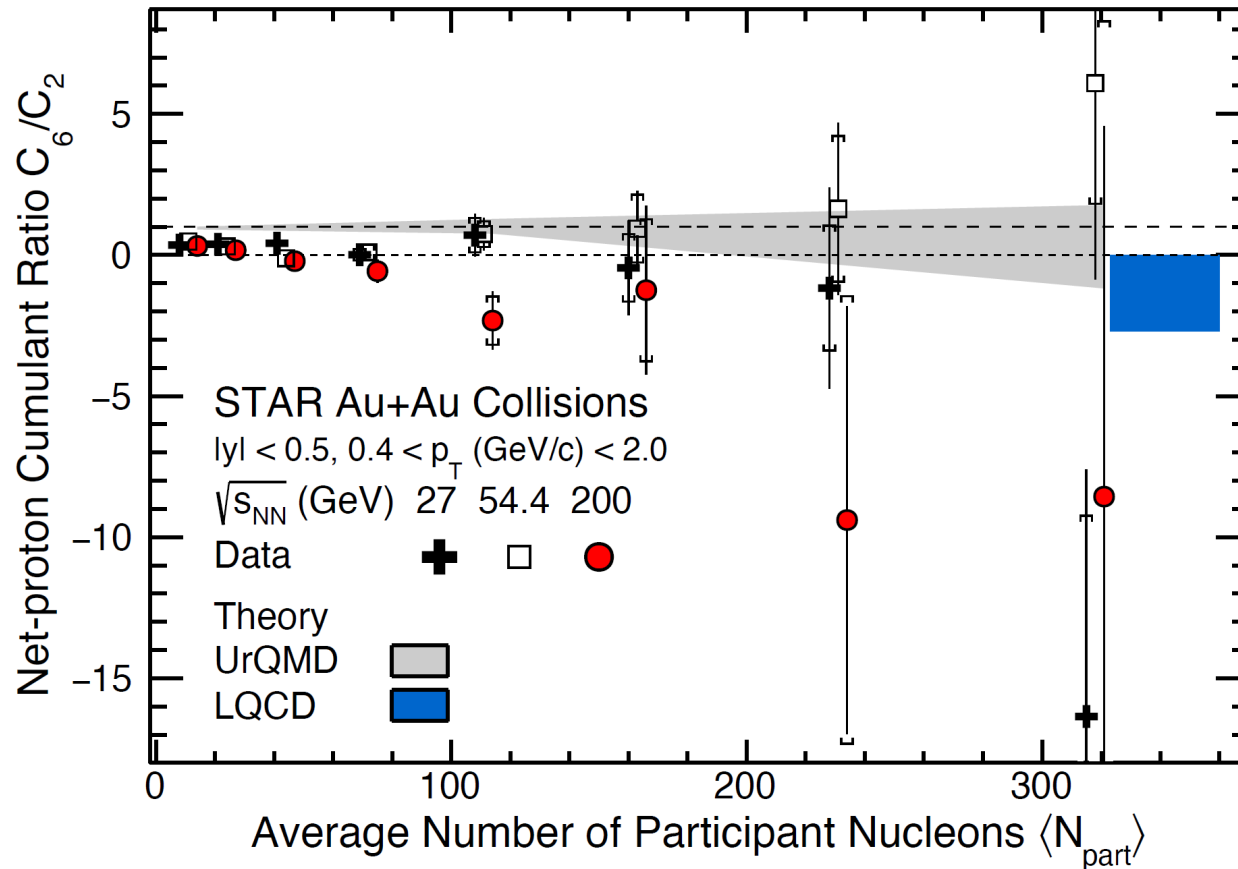
B. Friman et al, Eur. Phys. J. C (2011) 71:1694



Freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~ 2	~ 10
QCD: $T^{\text{freeze}}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~ 2	~ 10
QCD: $T^{\text{freeze}}/T_{pc} \simeq 1$	~ 0.5	< 0	~ 1	< 0

Predicted scenario for this measurement

Net-proton C_6/C_2 for crossover search

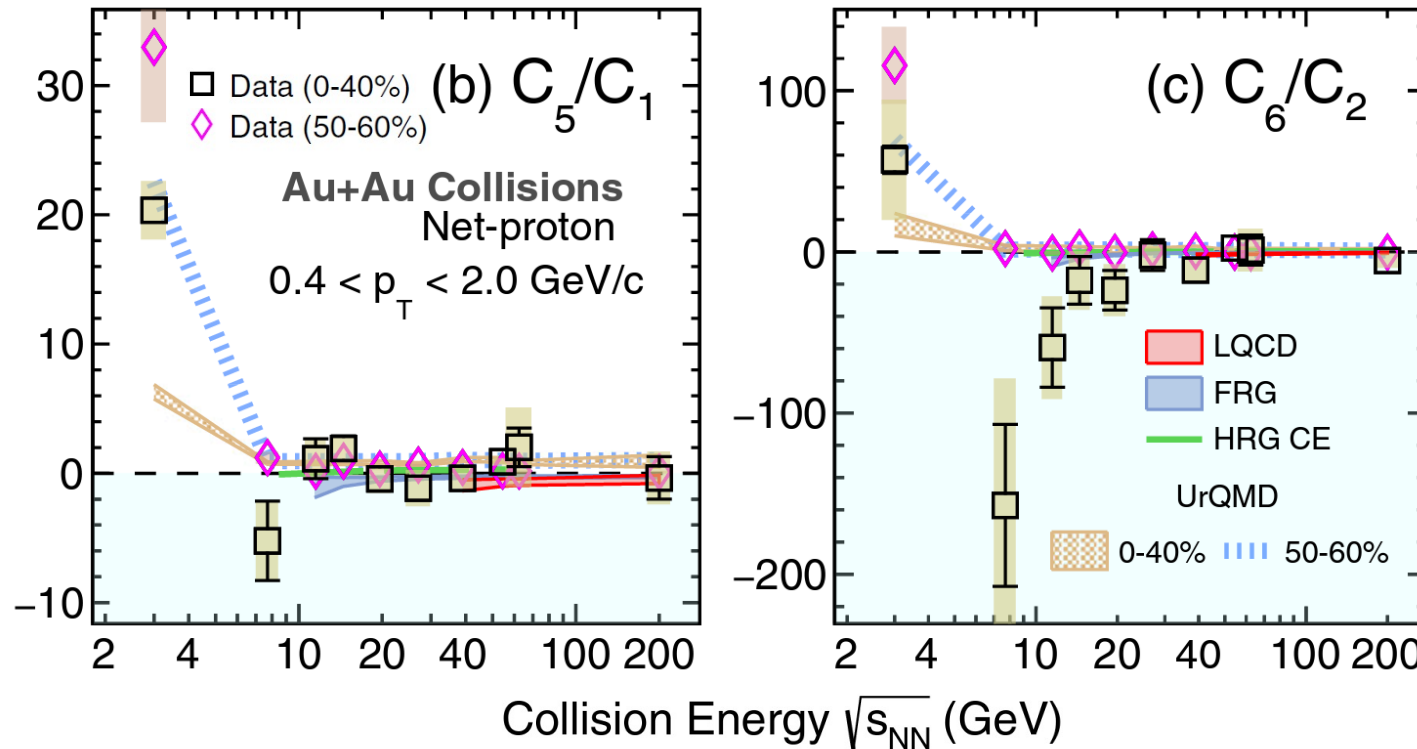


- C_6/C_2 values are progressively negative from peripheral to central collisions at 200 GeV, which is consistent with LQCD calculations.
- Could suggest a smooth crossover transition at top RHIC energy.

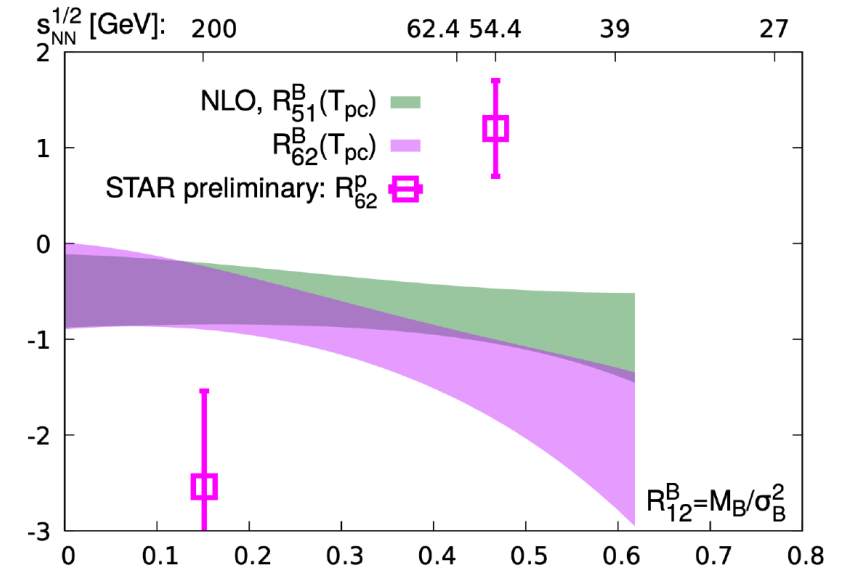
STAR, PRL127.262301(2021)

Energy dependence of C_5/C_1 and C_6/C_2

STAR, PRL130.082301(2023)



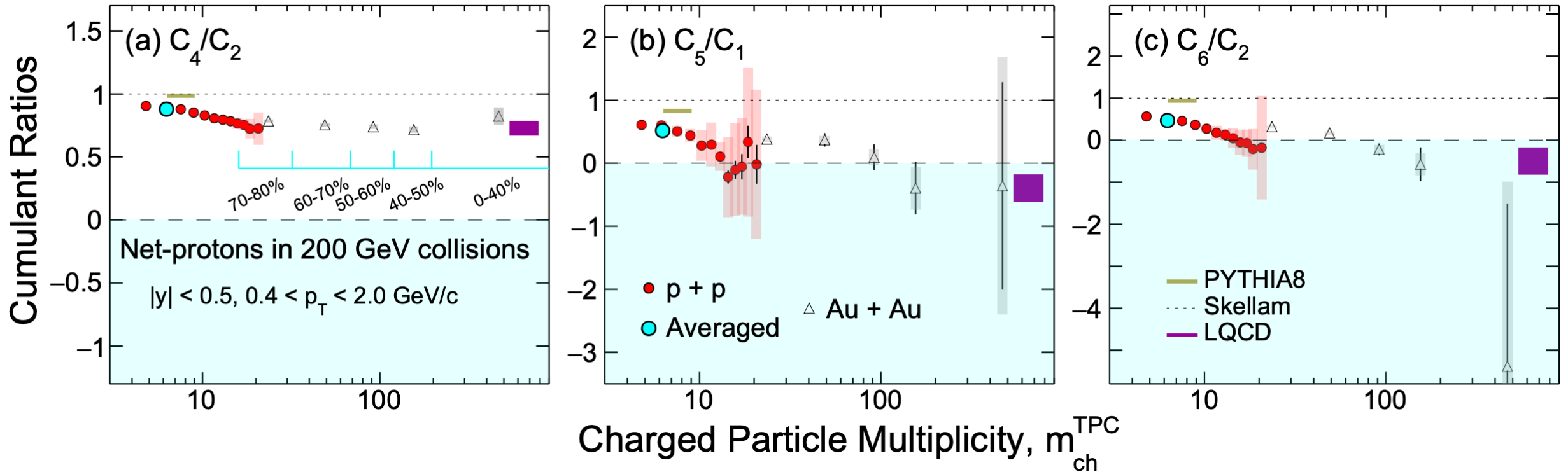
- Large negative signs have been observed for C_6/C_2 in low collision energies, which is quite similar to the LQCD calculation.



Bazavov et al, PRD101.074502(2020)

System size dependence

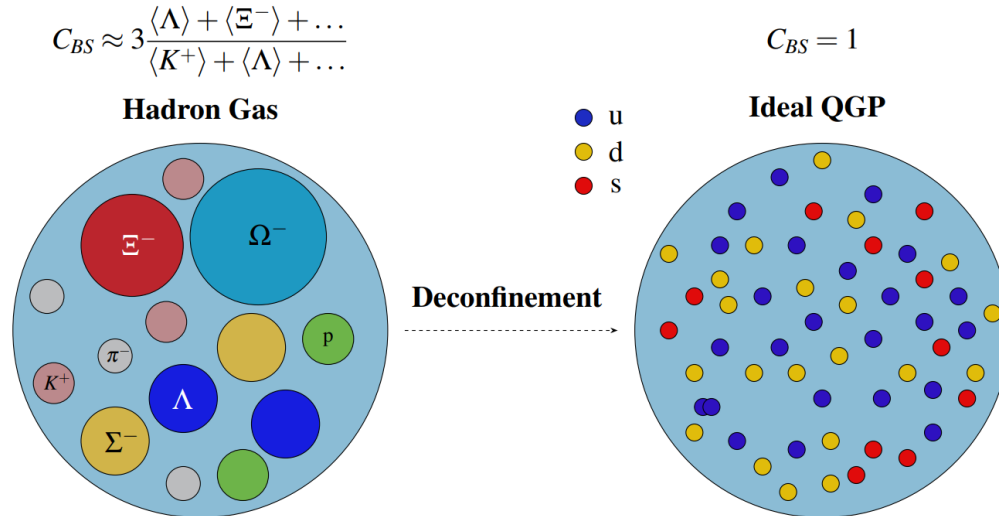
- Ratios approach LQCD calculations with increasing the multiplicity, which imply that the **created system approach thermalized medium at high multiplicity region.**



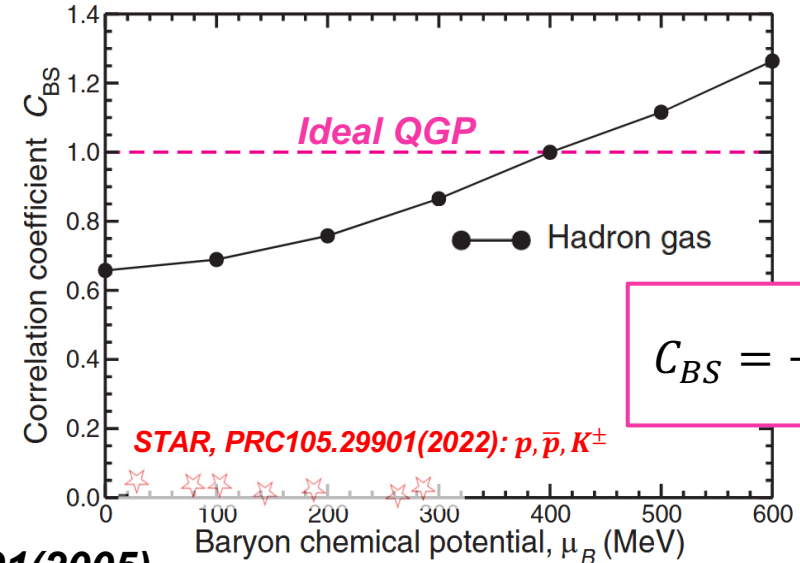
STAR, PLB 857(2024)138966

Baryon-strangeness correlations

- Strange quarks carry baryon number as well as strangeness, leading to direct BS correlation, $C_{BS}=1$, for the ideal QGP, while the C_{BS} strongly depends on the collision energy.



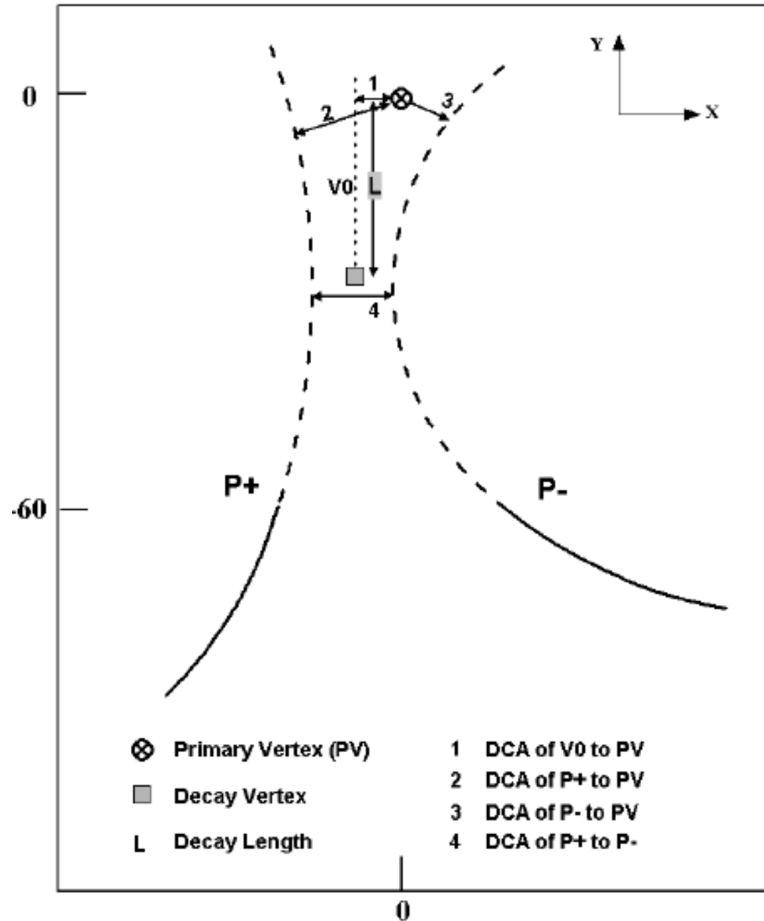
$$\langle XY \rangle_c = \langle XY \rangle - \langle X \rangle \langle Y \rangle : 2^{\text{nd}}\text{-order mix cumulant}$$



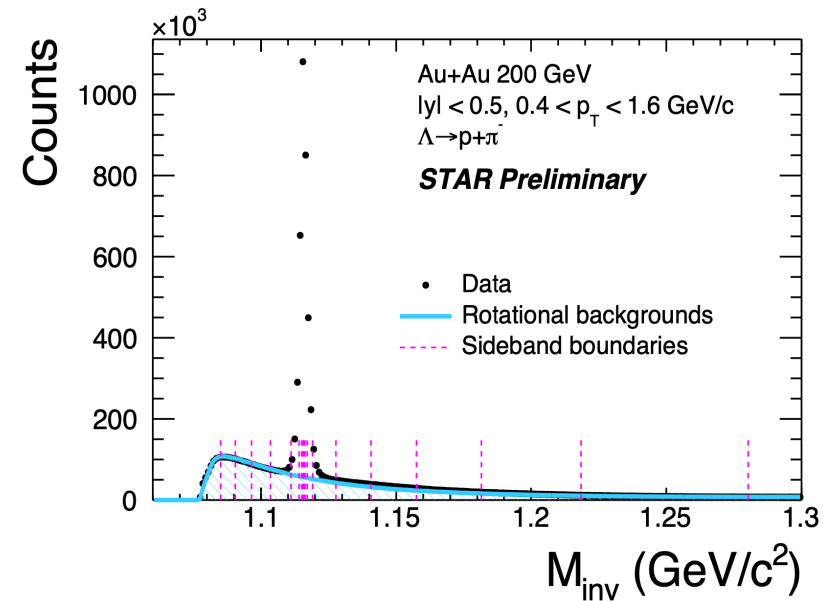
$$C_{BS} = -3 \frac{\langle BS \rangle_c}{\langle S^2 \rangle_c}$$

V. Koch et al, PRL95.182301(2005)

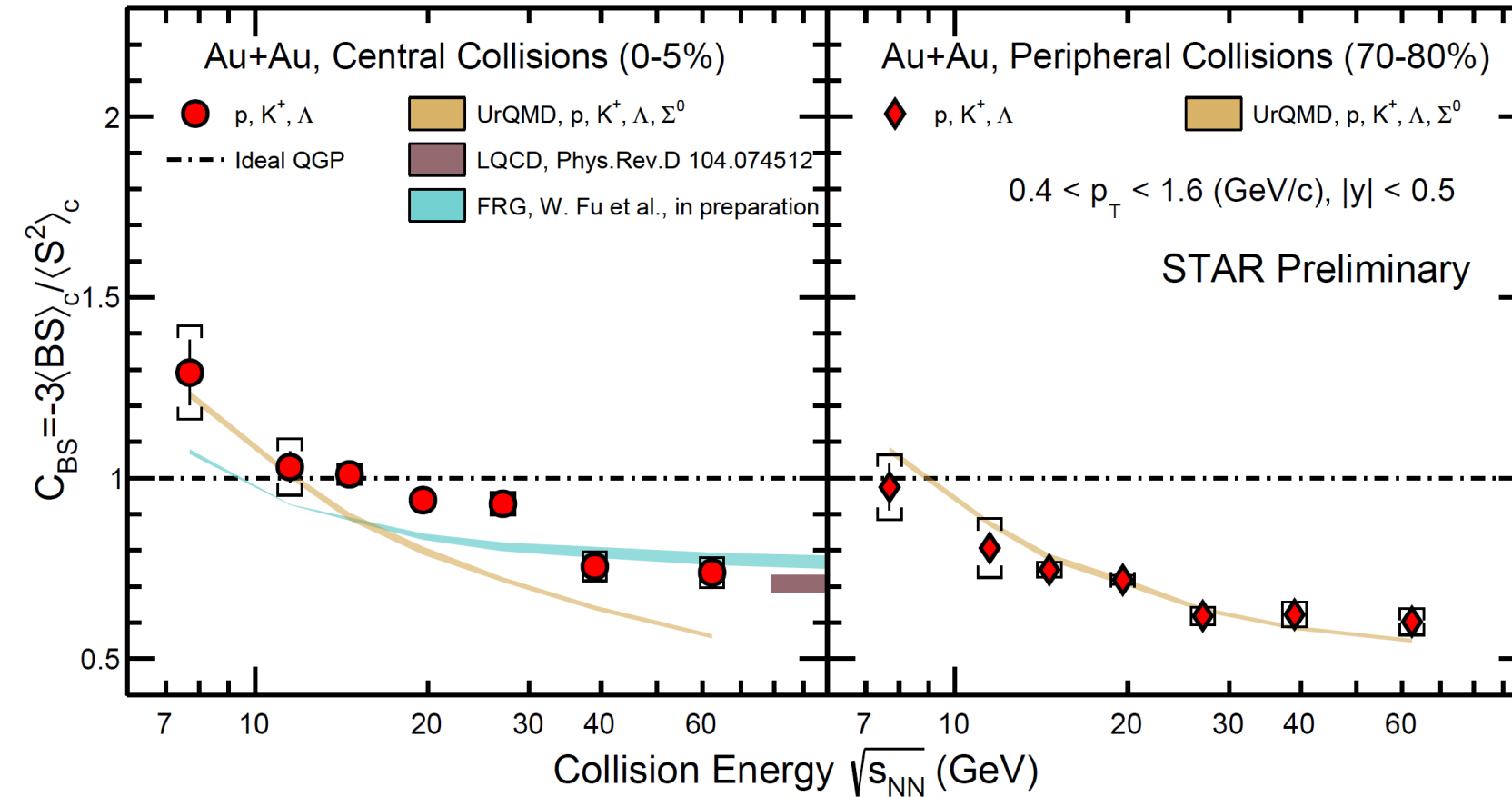
Hyperon reconstruction



- Hyperons are reconstructed by using the invariant mass technique.
- The signal peak suffers from the combinatorial backgrounds depending on the cut conditions.
- Purity correction approach has been developed for fluctuation measurements. *T. Nonaka, NIMA.1039.167171(2022)*



Baryon-strangeness correlation



H. Feng, QM2025

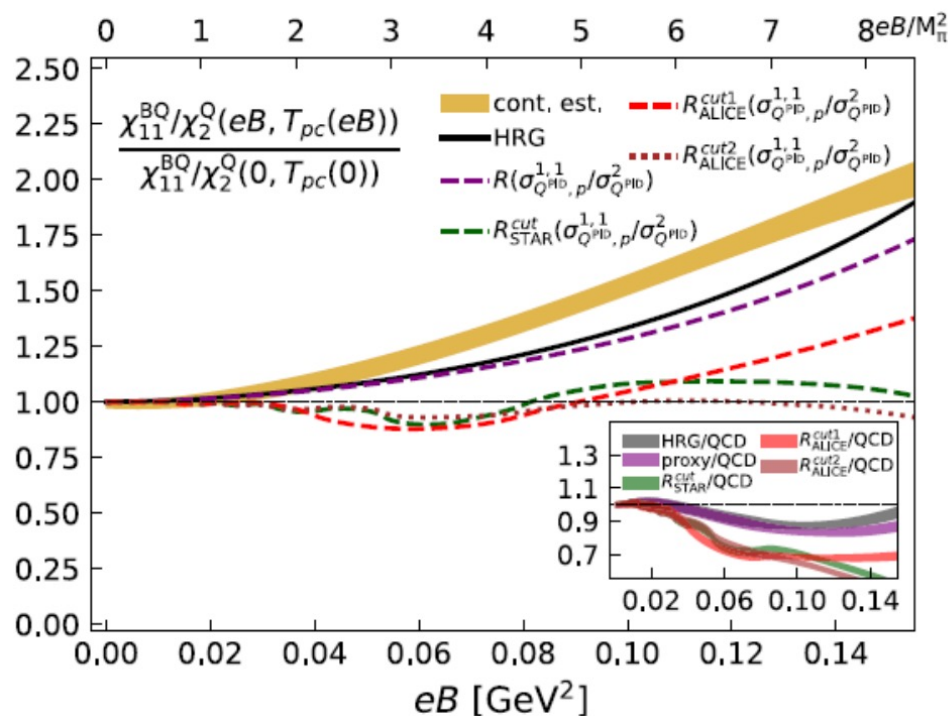
Central collisions:

- 39 and 62.4 GeV are consistent with functional renormalization group (FRG) and LQCD calculations.
- The results of 7.7 and 11.5 GeV are consistent with UrQMD.
- 14.6, 19.6 and 27 GeV cannot be reproduced by either UrQMD or FRG.

Peripheral collisions:

- The energy dependence can be well described by UrQMD.

Baryon-charge correlation



H.-T. Ding et al, PRL 111, 114522 (2025)

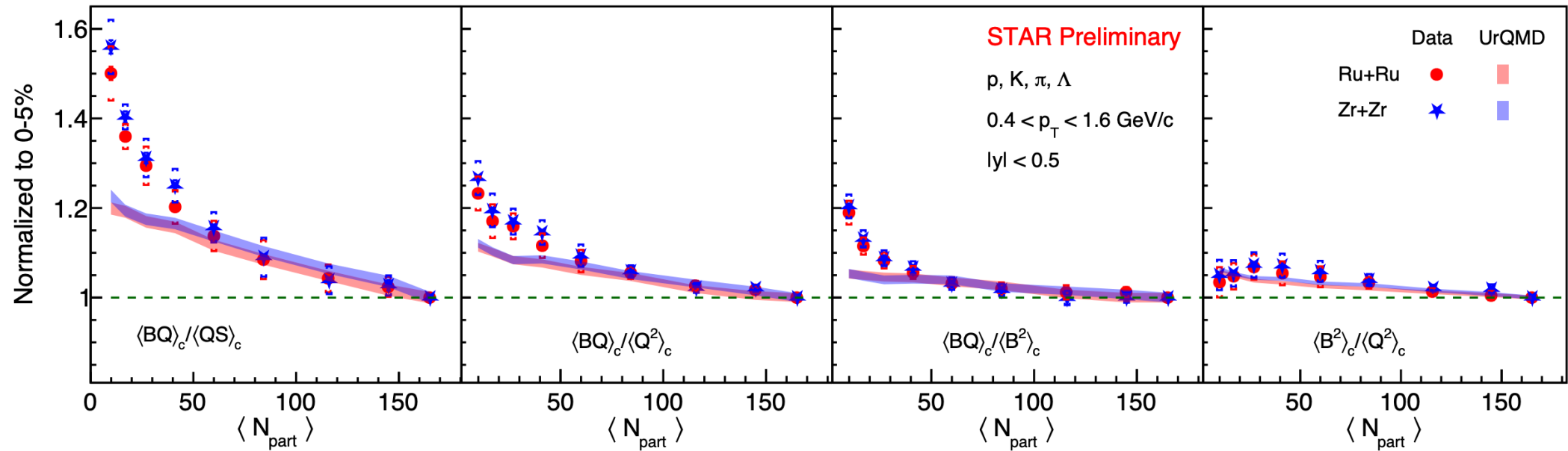
- LQCD predicts the sensitivity to the magnetic field is :

$$\frac{\langle BQ \rangle_c}{\langle QS \rangle_c} > \frac{\langle BQ \rangle_c}{\langle Q^2 \rangle_c} > \frac{\langle BQ \rangle_c}{\langle B^2 \rangle_c} > \frac{\langle B^2 \rangle_c}{\langle Q^2 \rangle_c}$$

Related topic will be presented by 帅杨

Baryon-Charge correlation

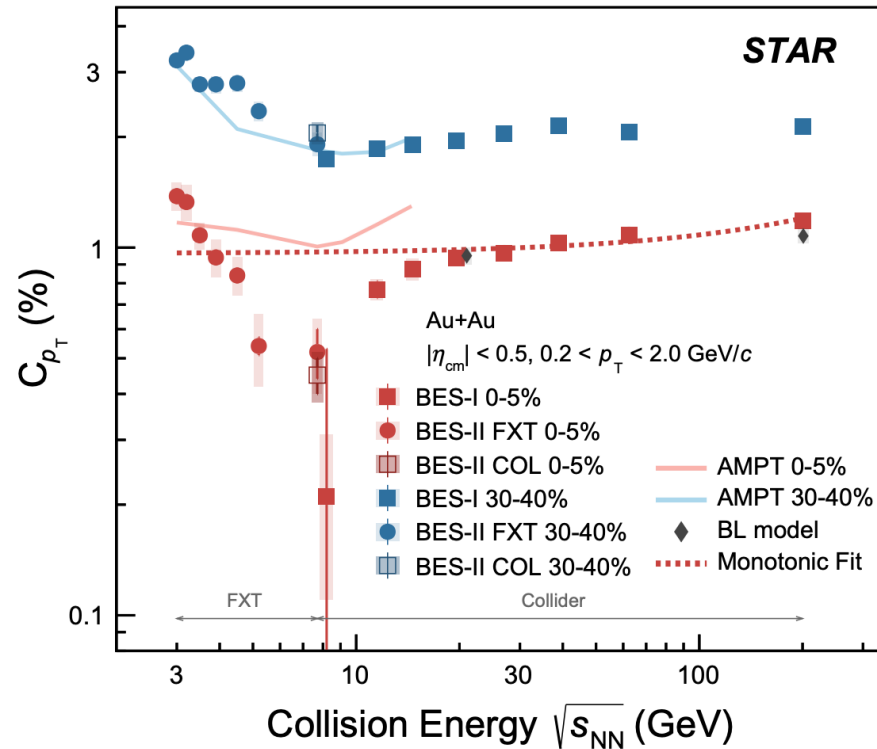
- The magnitude of the centrality dependence is consistent with the predicted ordering, but no difference between Ru+Ru and Zr+Zr.



C. Li, H. Feng, SQM2026

Mean p_T fluctuation

STAR, PRL.137.132301(2026)



- Nonmonotonic energy dependence observed in mean p_T fluctuation.
- Higher-order fluctuations are being analyzed in STAR.

See the next talk from Zheng Liu

Summary

- Net-proton
 - C_4/C_2 : A dip structure around 20 GeV $\rightarrow$ Critical point?
 - C_6/C_2 : Negative at Au+Au 200 GeV $\rightarrow$ Crossover?
 - C_6/C_2 : Approaching negative in multiplicity dependence p+p 200GeV $\rightarrow$ thermalized system at the highest multiplicity events?
- Baryon-Strangeness correlation
 - The largest deviation at 20-30 GeV, similar to net-proton C_4/C_2
- Baryon-Charge correlation
 - The results show the same ordering with LQCD prediction.

Thank you for your attention