中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

QCD Critical Point and Net-proton Fluctuations

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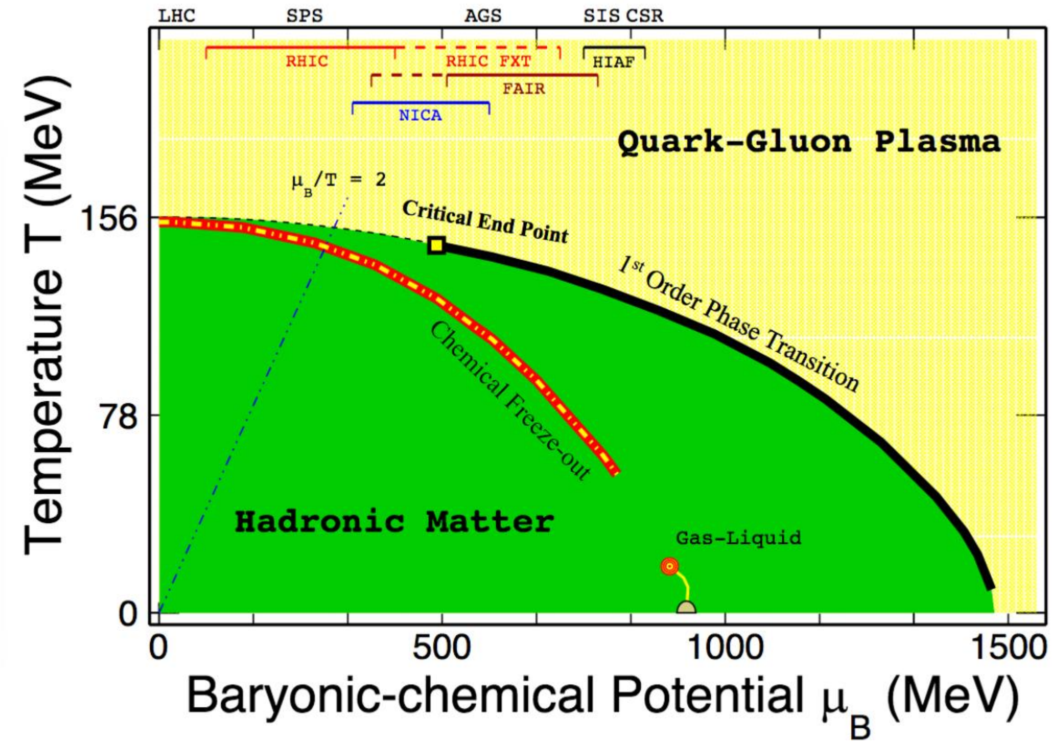
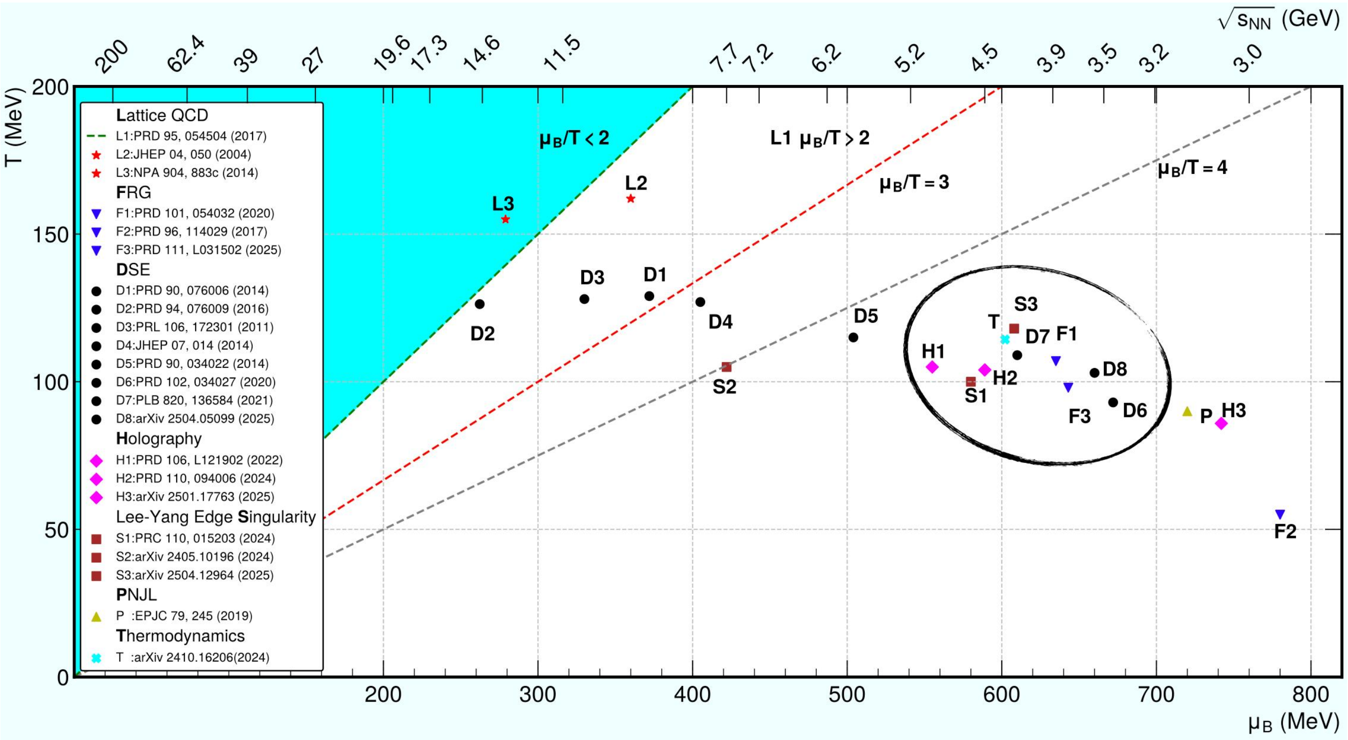
QCD Phase Diagram



1. Smooth crossover at $\mu_B = 0$ MeV by LQCD
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)

QCD Phase Diagram



- Recent theoretical predictions converge around high baryon density region, which is coverd by STAR fixed-target experiment !

Observable: Cumulants of Conserved Quantities

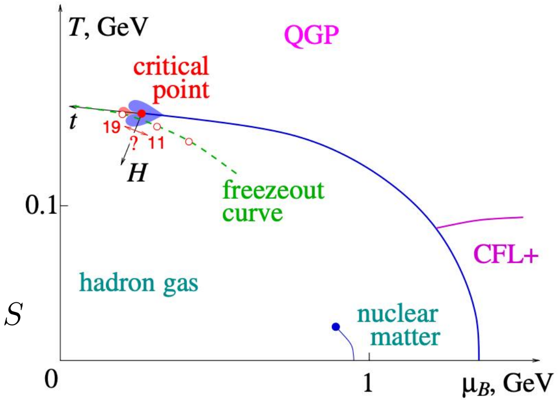
1. At around critical point, correlation length should diverge
2. Moments of Net-B, Net-Q, Net-S are
- sensitive to correlation length
- directly related to susceptibility ratios

$$C_3 = \langle (\delta N)^3 \rangle \sim \xi^{4.5}$$

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

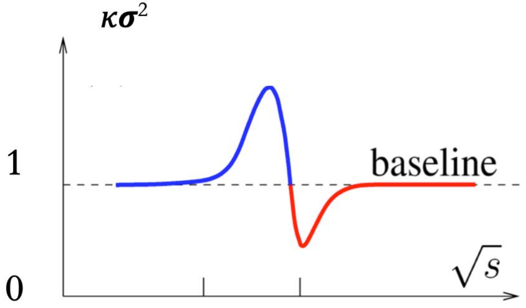
$$\frac{\chi_4^q}{\chi_2^q} = \kappa\sigma^2 = \frac{C_4^q}{C_2^q}, \quad \frac{\chi_3^q}{\chi_2^q} = S\sigma = \frac{C_3^q}{C_2^q}$$

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



Cumulants:

$$\begin{aligned}
&\text{mean: } M &&= \langle N \rangle &&= C_1 \\
&\text{variance: } \sigma^2 &&= \langle (\delta N)^2 \rangle &&= C_2 \\
&\text{skewness: } S &&= \langle (\delta N)^3 \rangle / \sigma^3 &&= C_3 / C_2^{\frac{3}{2}} \\
&\text{kurtosis: } \kappa &&= \langle (\delta N)^4 \rangle / \sigma^4 - 3 &&= C_4 / C_2^2
\end{aligned}$$



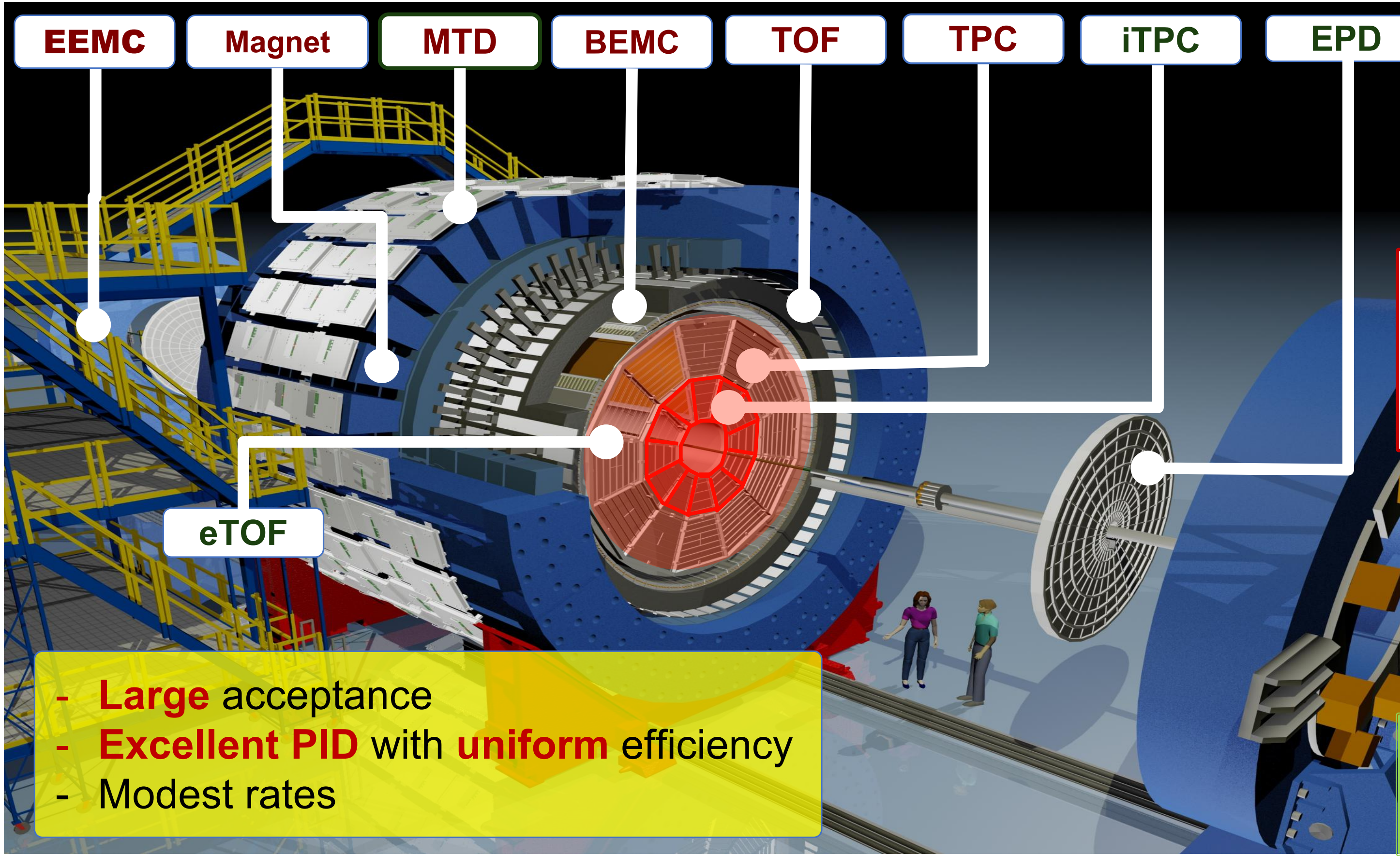
$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

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

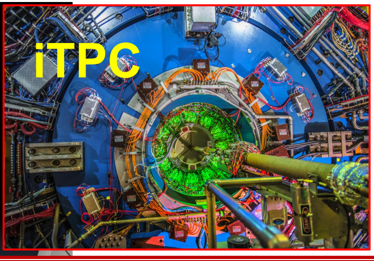
Factorial cumulants:

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

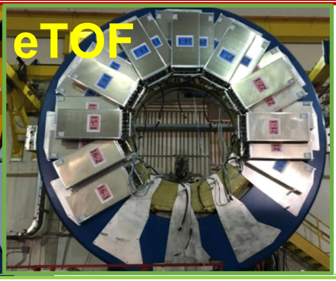
STAR Detector in BES-II



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



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

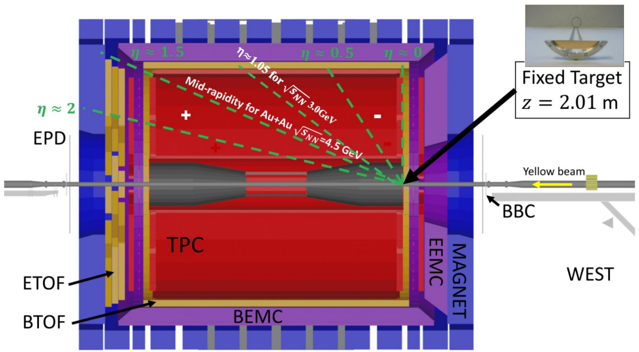


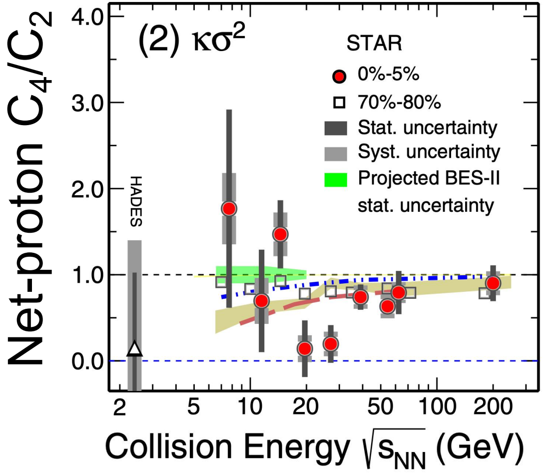
Forward rapidity coverage
PID at η = 0.9 to 1.5
Provided by FAIR-CBM

High statistics data from BES-II (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

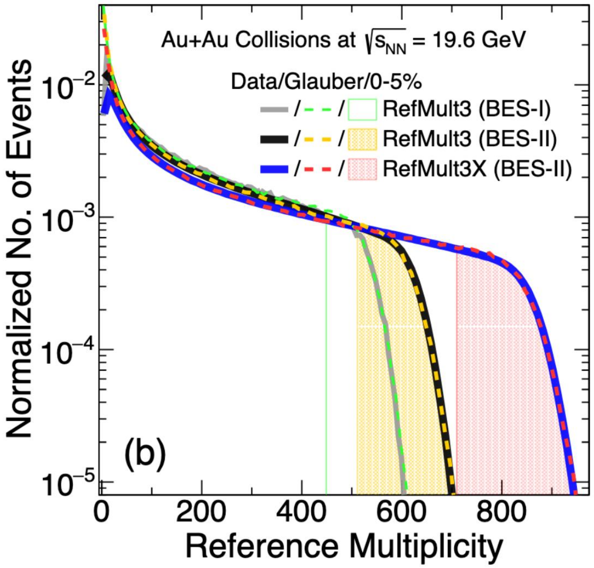




STAR, BES-I, PRL 126.092301(2021)

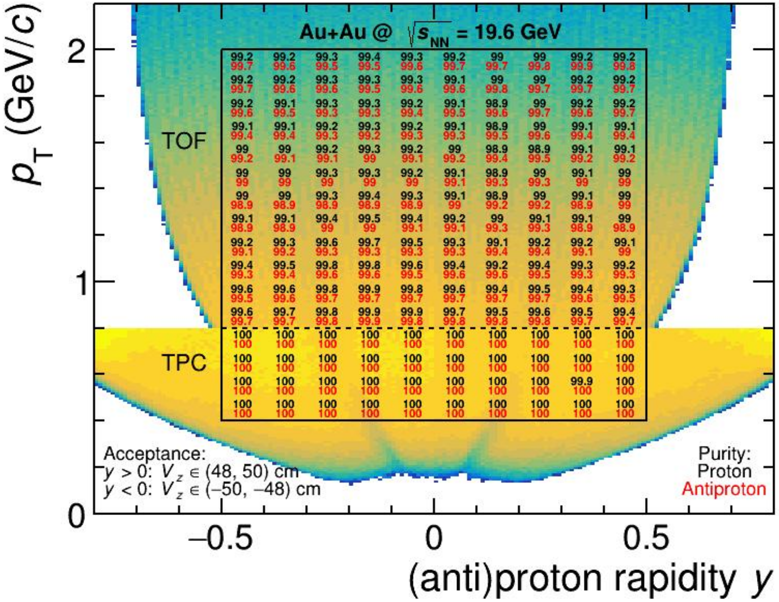
Analysis in BES-II collider energies

Collision Centrality



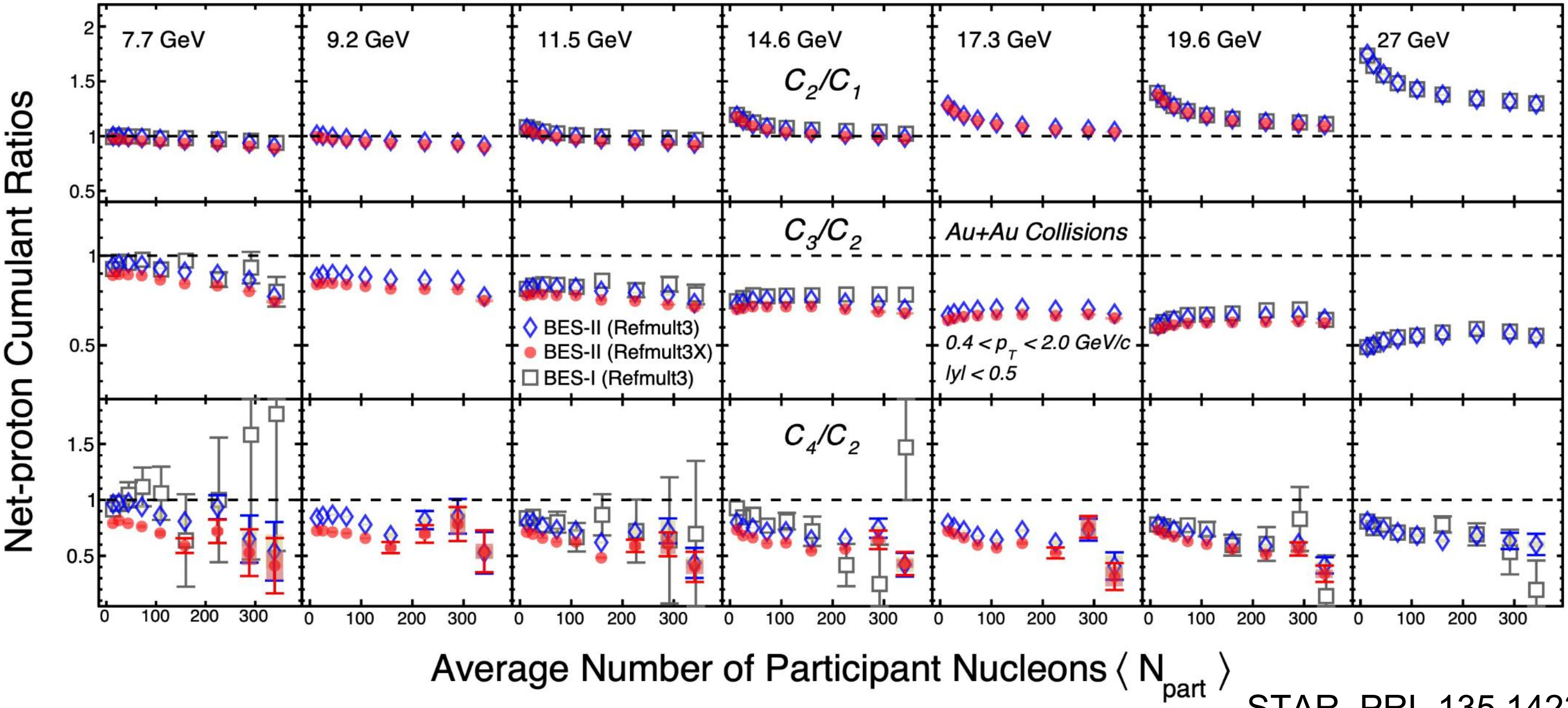
1. Charged particle multiplicity fit to MC Glauber to determine centrality
2. Better centrality resolution in BES-II analysis with extended detector coverage from $|\eta| \leq 1.0$ (BES-I) to $|\eta| \leq 1.6$ (BES-II)

Proton Identification



1. Uniform acceptance for (anti-) protons |y|<0.5
2. (anti-)protons identified using TPC dE/dx + TOF
3. Bin-by-bin purity > 99% in the full acceptance range and all energies

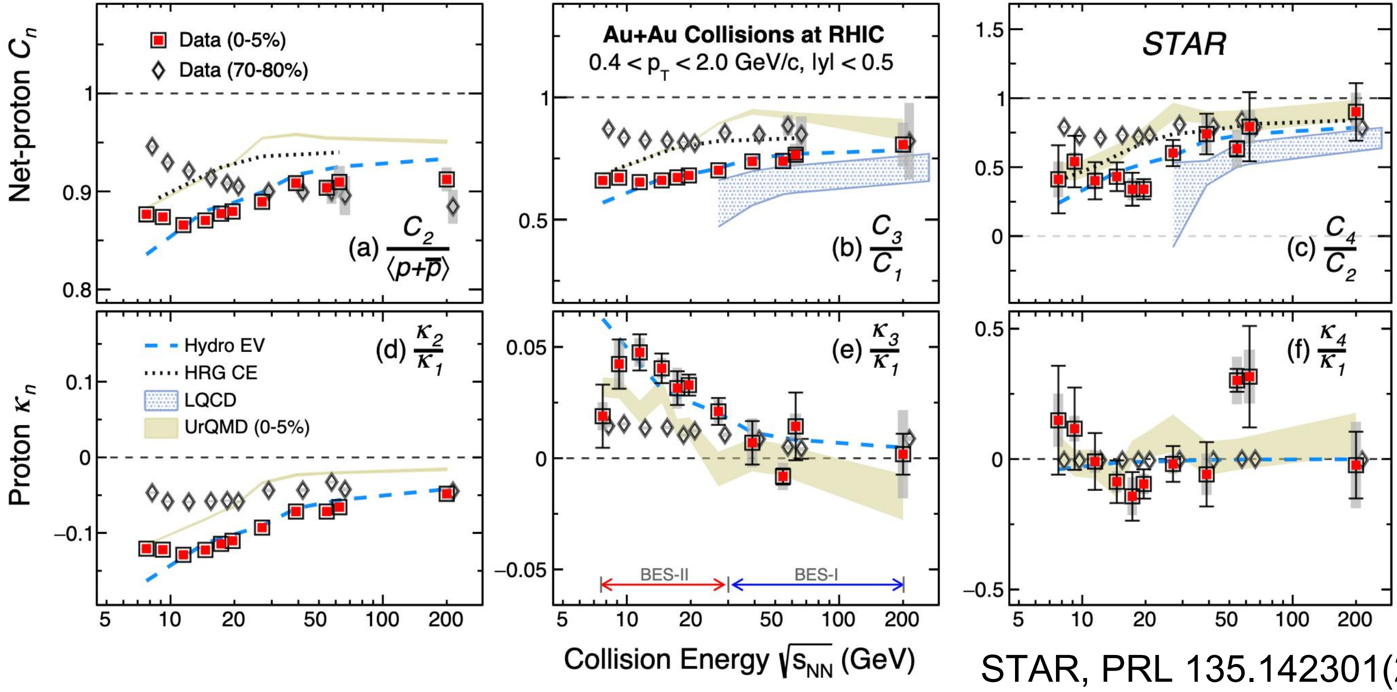
Net-proton cumulant ratios from BES-II



STAR, PRL 135.142301(2025)

1. Significantly improved precision in BES-II measurements
2. C_4/C_2 in 0-5% centrality, results are consistent – weak centrality resolution effect

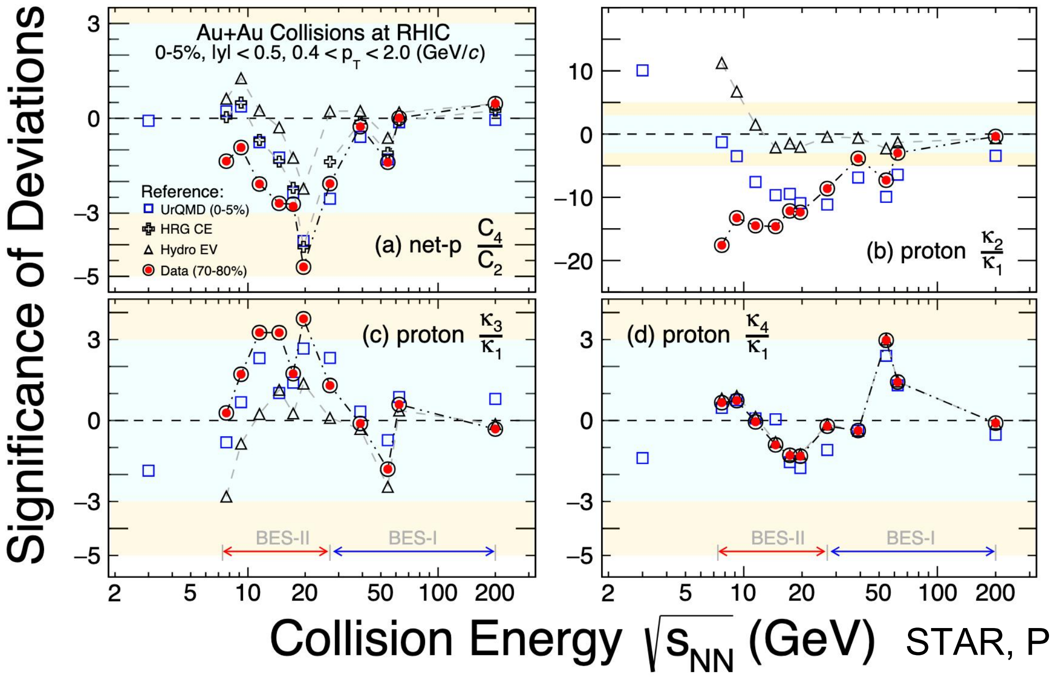
Net-proton fluctuations from BES-II



STAR, PRL 135.142301(2025)

1. In 0-5% central Au+Au collisions, net-proton C_4/C_2 shows deviation from non-critical references at around 20 GeV
2. 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 non-critical models too, especially below 11.5 GeV

Deviations from non-critical baselines

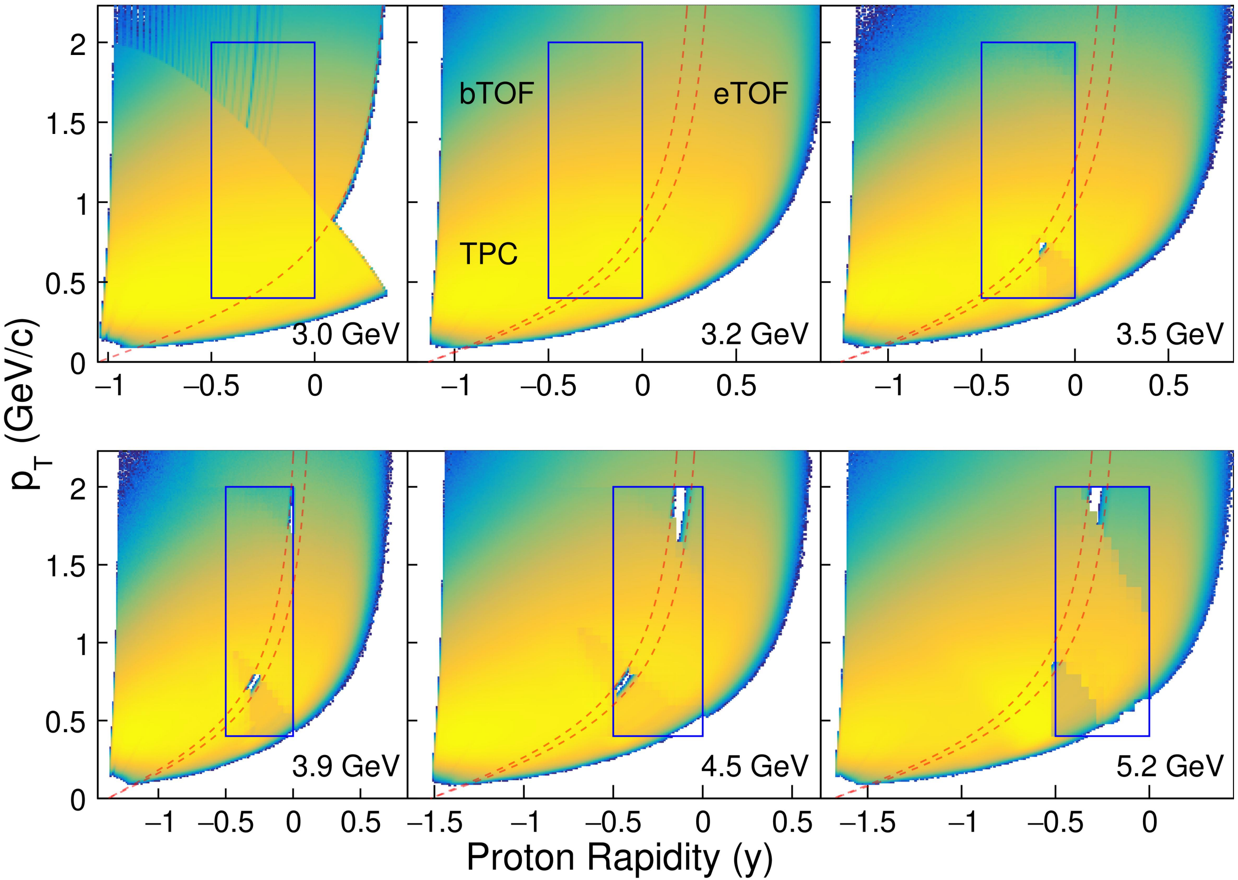


STAR, PRL 135.142301(2025)

C_4/C_2 shows a minimum at ~20 GeV comparing to non-critical models or 70-80% data

- Maximum deviation: $2 – 5\sigma$ at 20 GeV ($1.3 – 2\sigma$ at BES-I)

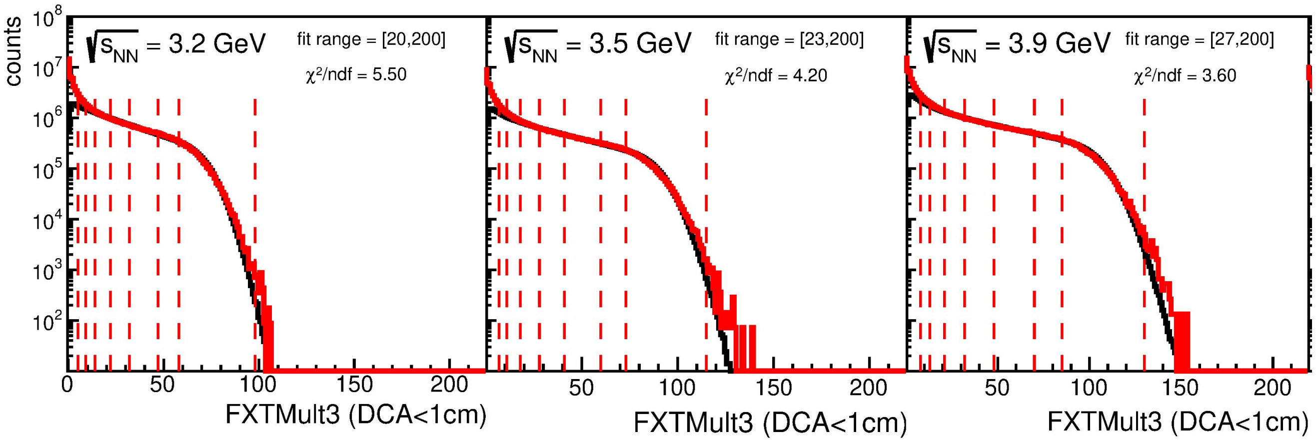
Analysis at FXT energies: Proton acceptance

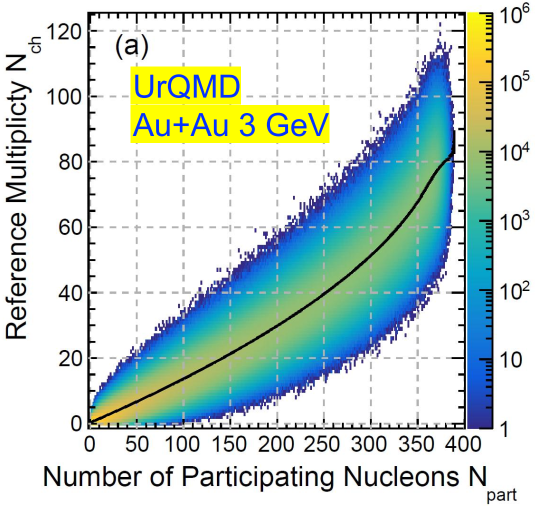


1. Combining TPC, bTOF/eTOF for PID, centrality, pileup
2. Evolving proton acceptance in different collision energies
3. Ongoing analysis at 3.0, 3.2, 3.5, 3.9, 4.5 and 5.2 GeV !

Analysis at FXT energies: Initial Volume Fluctuation

Experimental data





1. FXTMult3: All charged hadrons except protons within STAR detector
2. Smaller FXTMult3 with decreasing energy → worse centrality resolution

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

- Better resolution with fine binning on FXTMult3

Centrality Independent Analysis Method

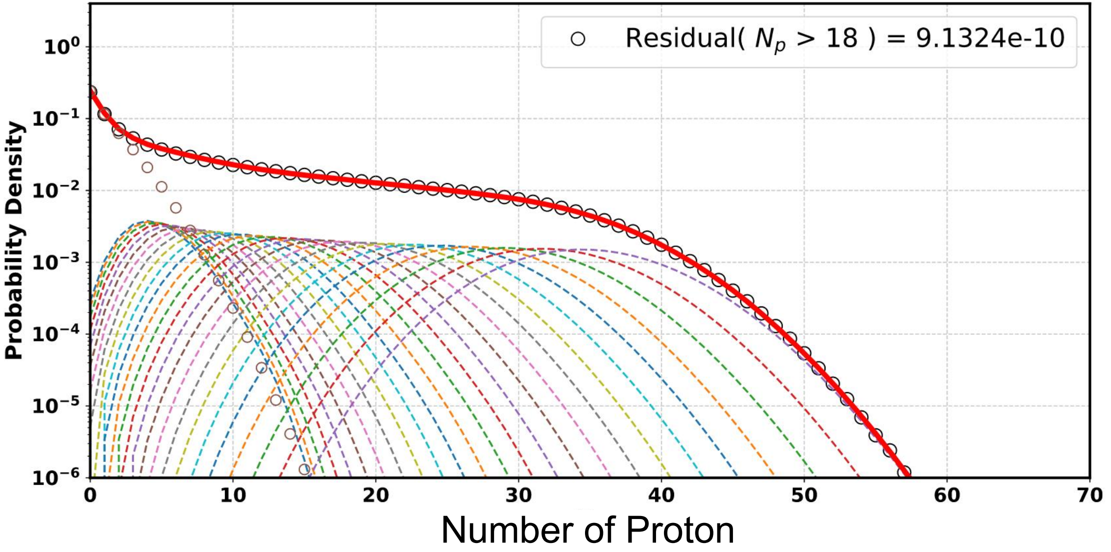
Z. Wang, X. Luo, PLB 871,139984(2025)

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:

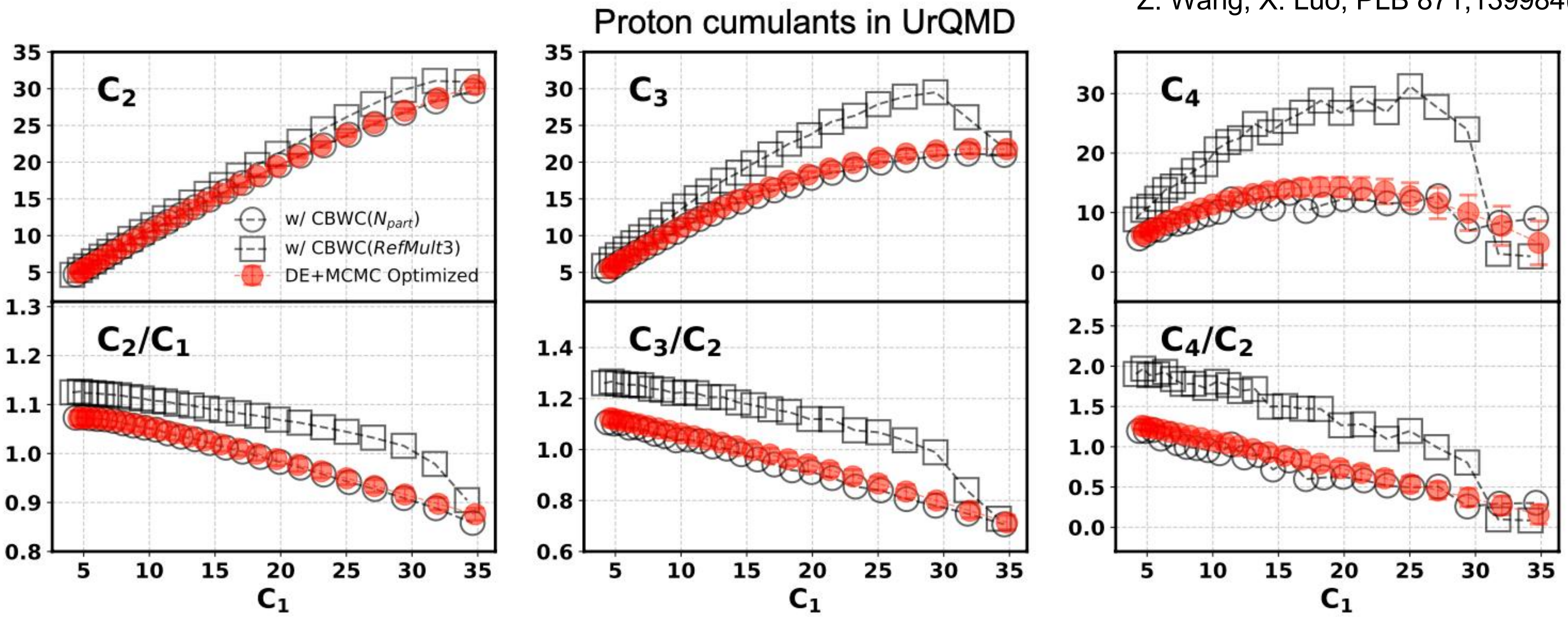
$$H_{e_n}(x) = (-1)^n exp(x^2/2)\frac{d^n}{dx^n}exp(-x^2/2)$$



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

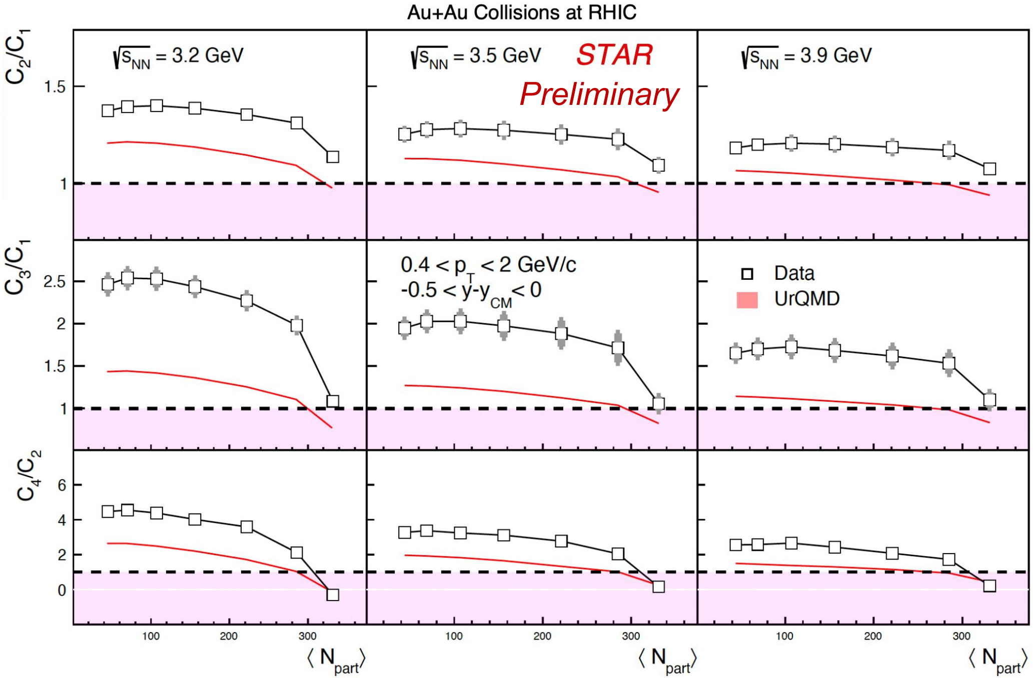
Centrality Independent Analysis Method

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



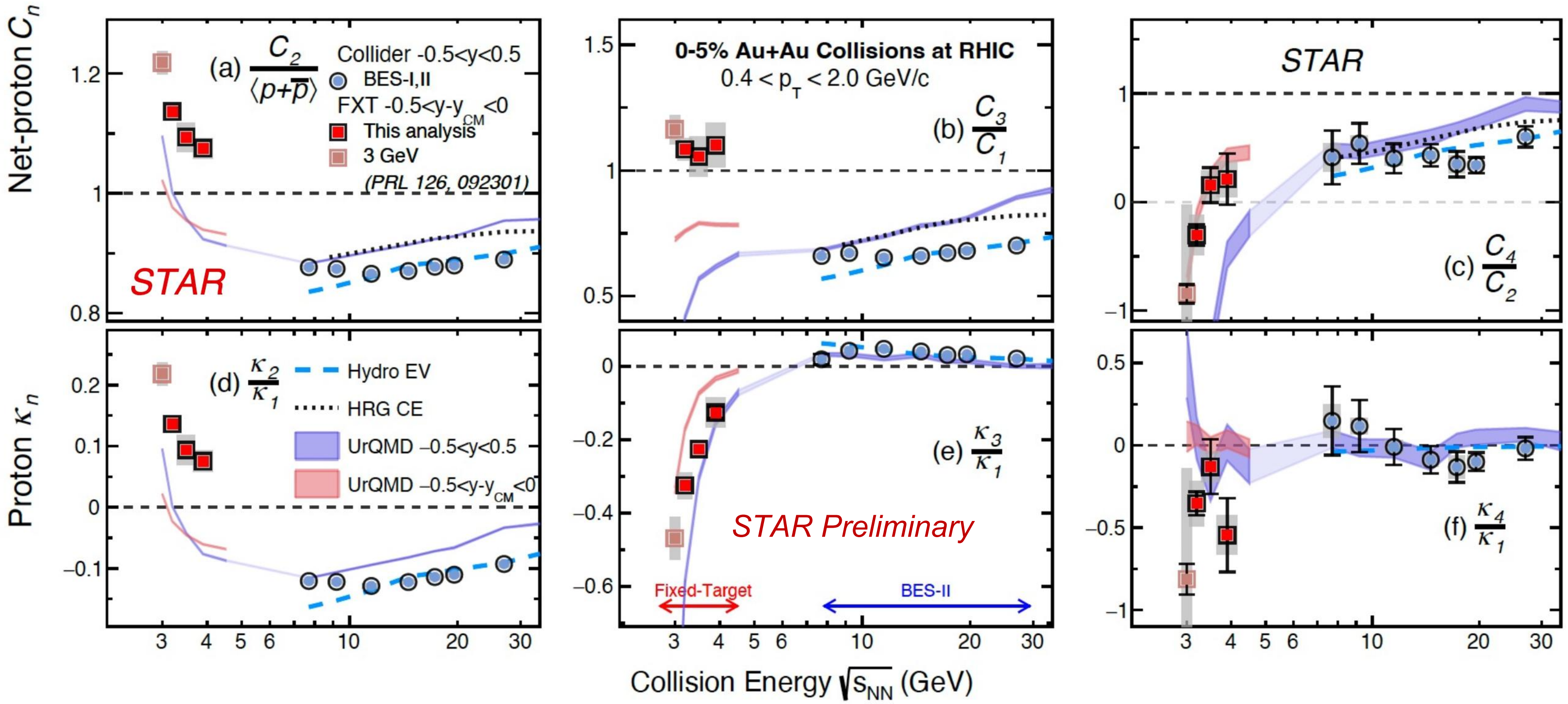
1. Model test shows good consistency with results binning on N_{part}
2. Being tested in FXT data to overcome volume fluctuation effect

Proton Cumulants at FXT Energies (CBWC)



1. The observed increase in ratios in peripheral collisions with decreasing collision energy suggests a growing influence of volume fluctuations at lower energies
2. The 0-5% most central collisions are the least affected by volume fluctuations, while caution is required when interpretating data

Energy Dependence of Cumulant Ratios (CBWC)



1. C_4/C_2 seems to follow the decreasing trend from high energy
2. C_2, C_3 ratios are above unity. Not suppressed by baryon number conservation?
3. Ongoing analysis at 3.0 to 5.2 GeV !

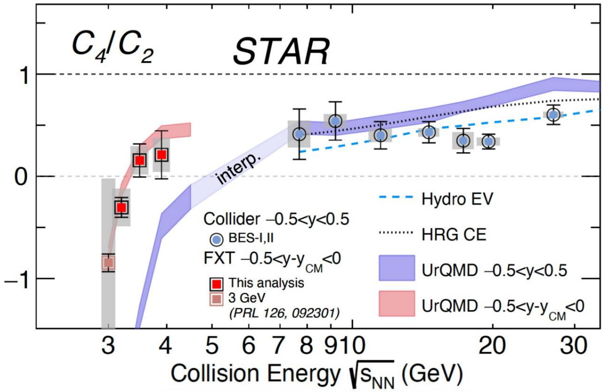
Summary

1. Measurements in BES-II collider data (7.7 - 27 GeV):
   - 2nd, 3rd order show deviations below 11 GeV
   - A maximum deviation of C_4/C_2 at 19.6 GeV from non-critical baselines

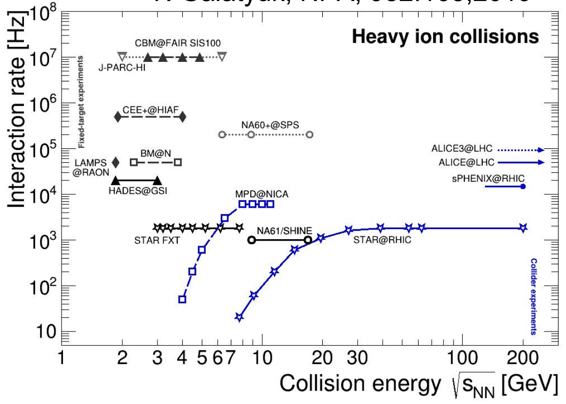
2. The analysis at FXT energies (3.0, 3.2, 3.5, 3.9, 4.5 and 5.2 GeV) are ongoing !

3. Looking forward to future facilities on the search of QCD critical point at high baryon density region

0-5% Au+Au Collisions at RHIC



T. Galatyuk, NPA, 982:163,2019



Thank you for your attention !

Many thanks to:

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