The 2nd China-Russia Joint Workshop on NICA Facility

Qingdao, 2024/9/11-13

Recent Results of the Experimental Study on CEP

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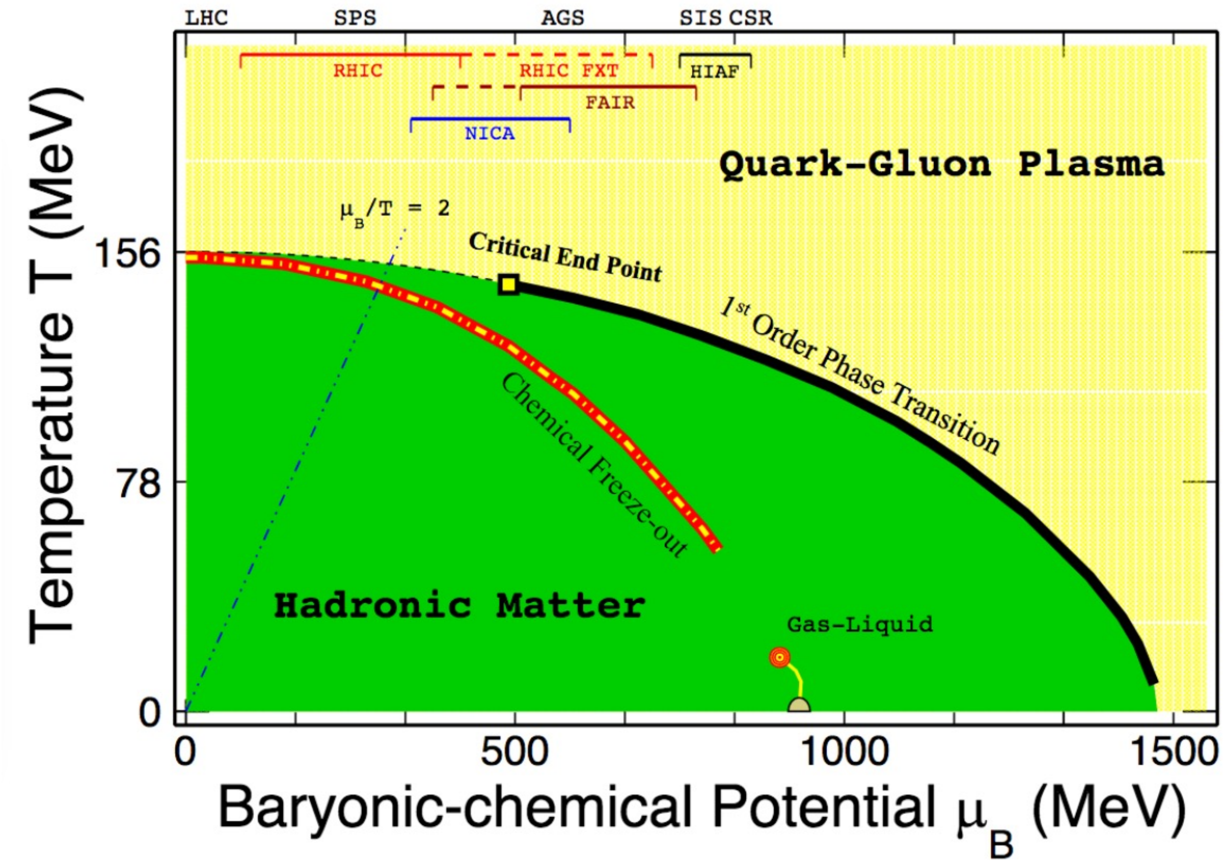
Outline

1. **Introduction**
2. **Selected Results from STAR**
   ① Baryon-strangeness Correlation
   ② Net-proton Cumulants
3. **Summary and Outlook**

Introduction

QCD Phase Diagram

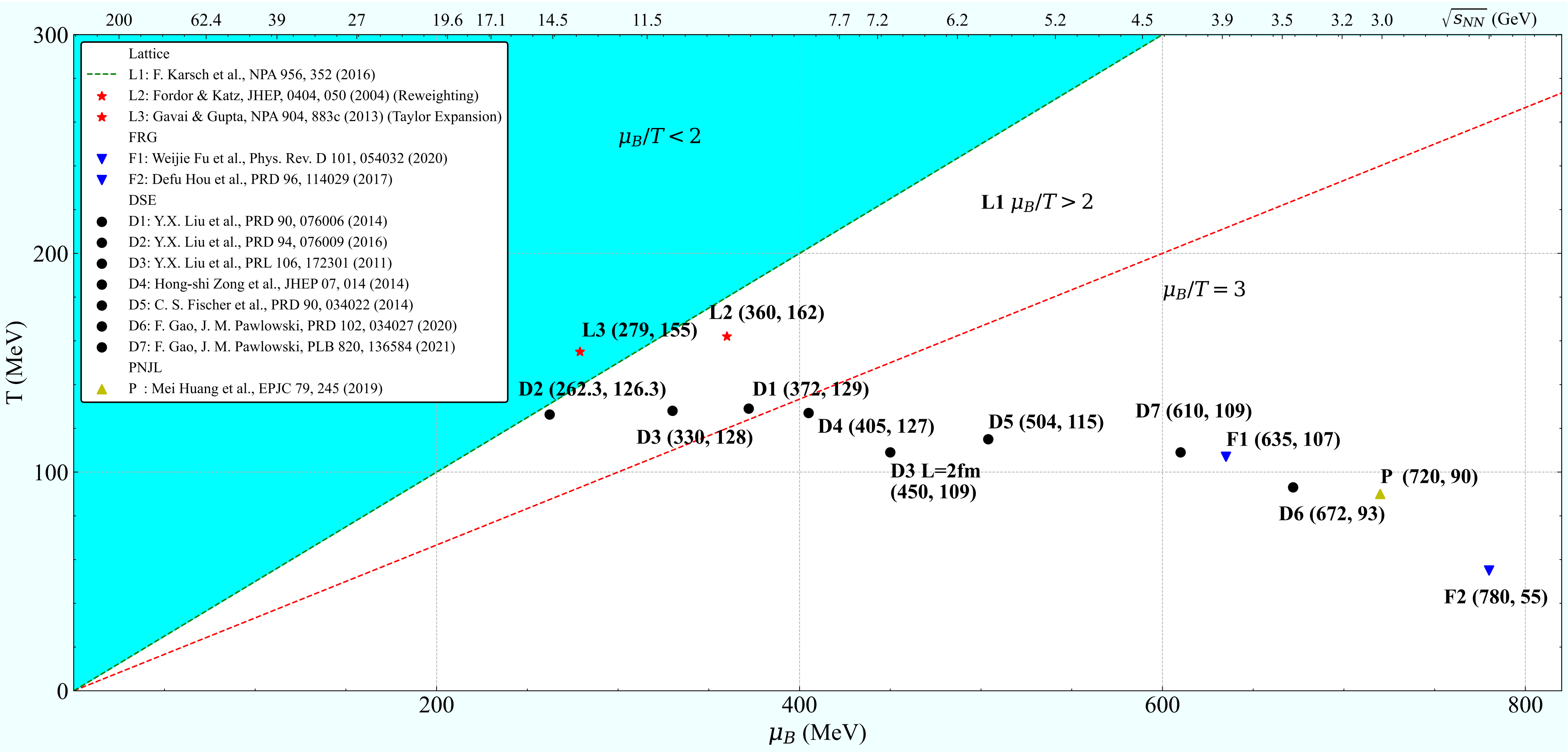


Predictions:

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

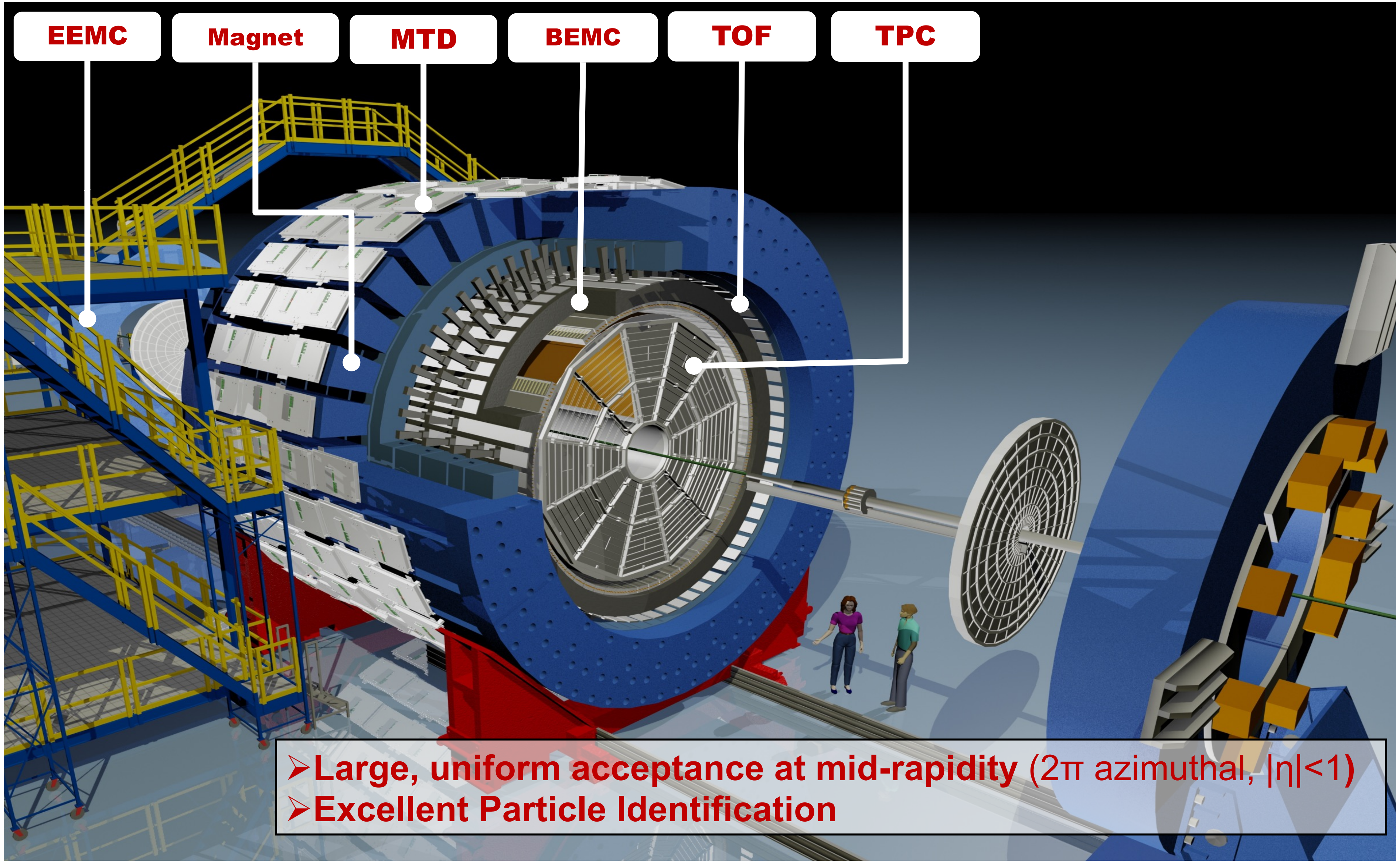
Y. Aoki et al, Nature 443, 675(2006)
A. Bzdak et al, Physics Reports 853,1-87(2020)
X. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017)
X. Luo, Q. Wang, N. Xu, P. F. Zhuang. Properties of QCD Matter at High Baryon Density. Springer, 2022, doi:10.1007/978-981-19-4441-3
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Theoretical Predictions

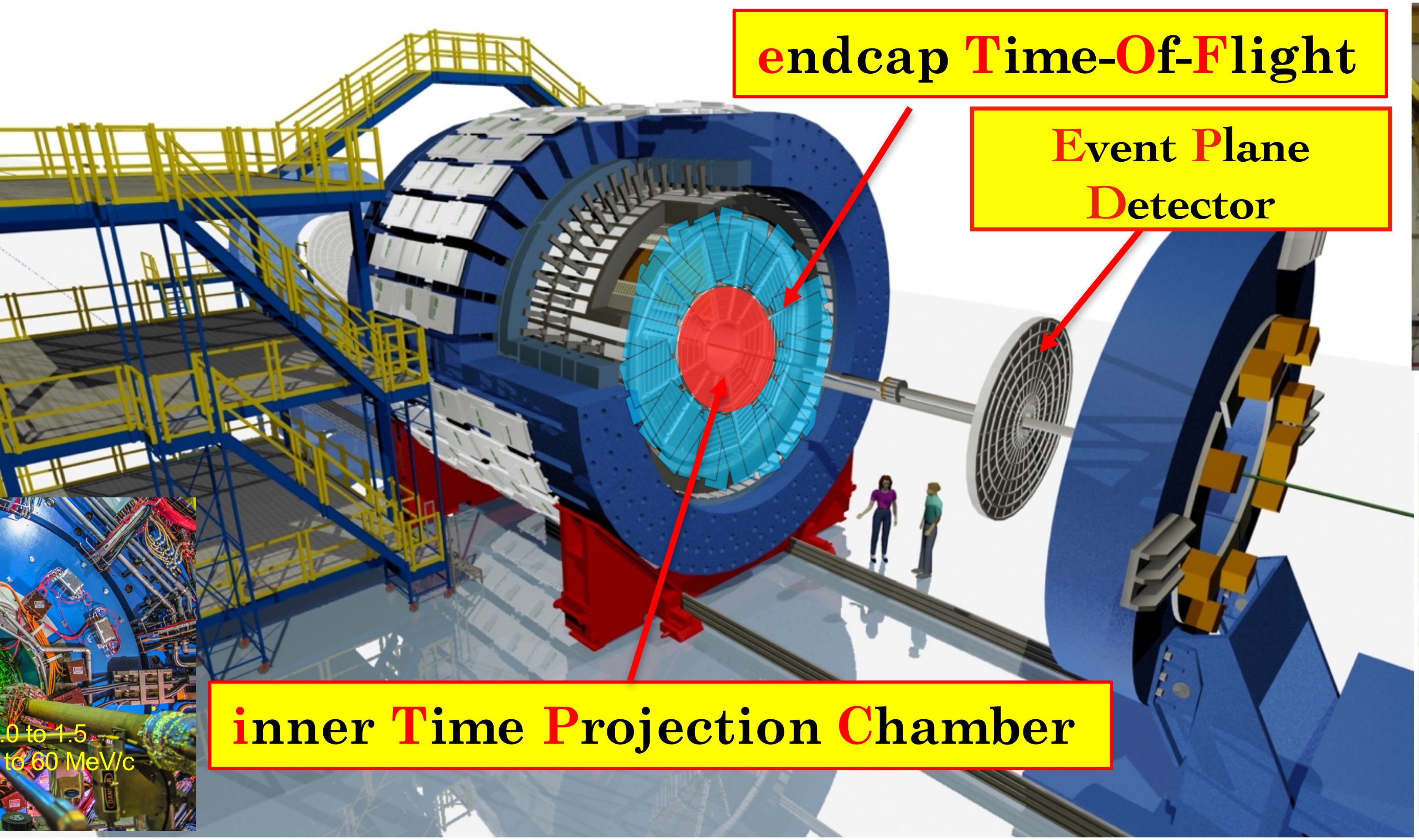


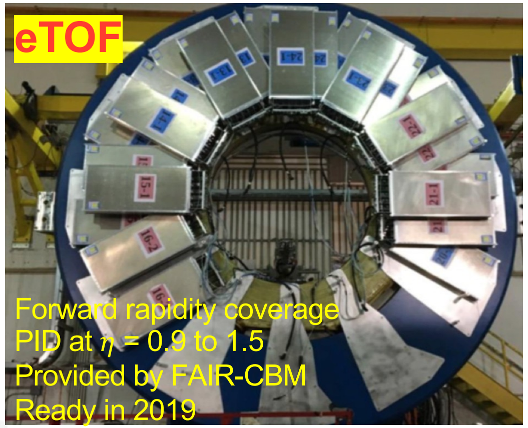
1. No consensus on the location of the critical point
2. Need confirmation from experiments!

STAR Detector System



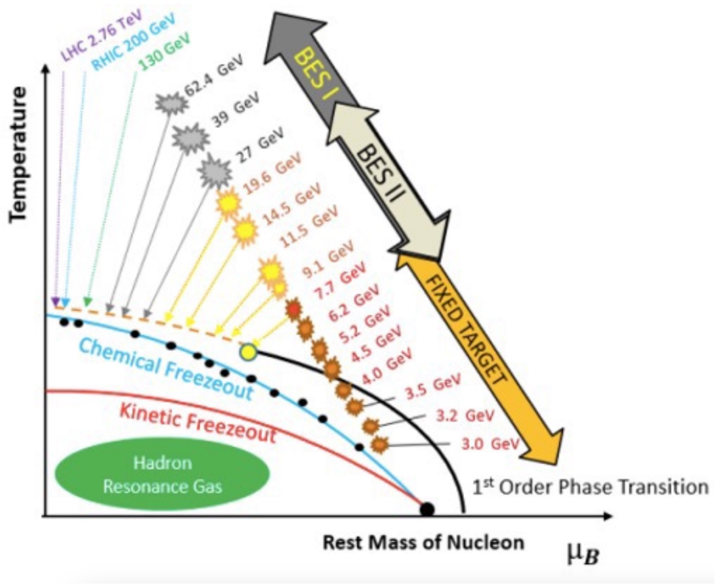
STAR Major Upgrades for BES-II

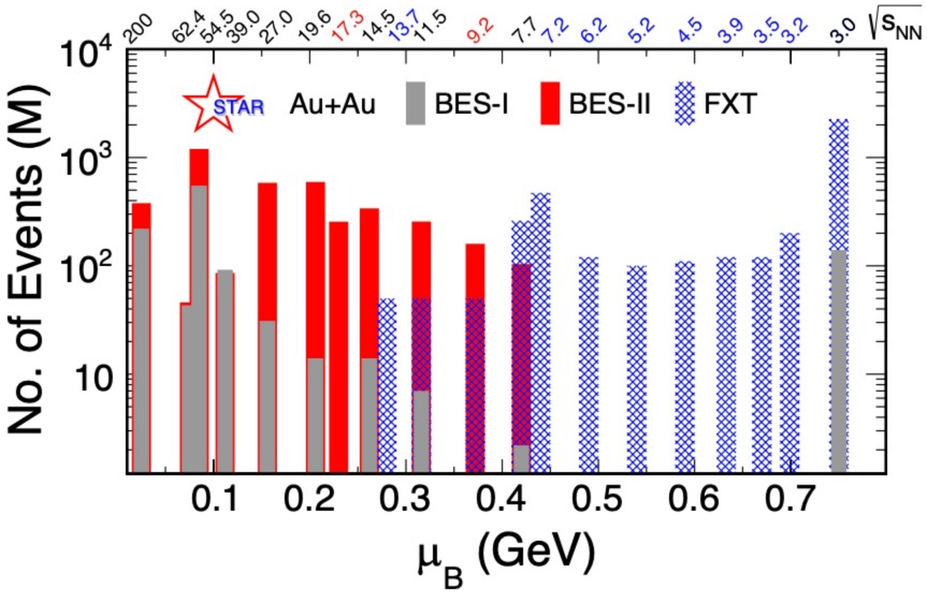




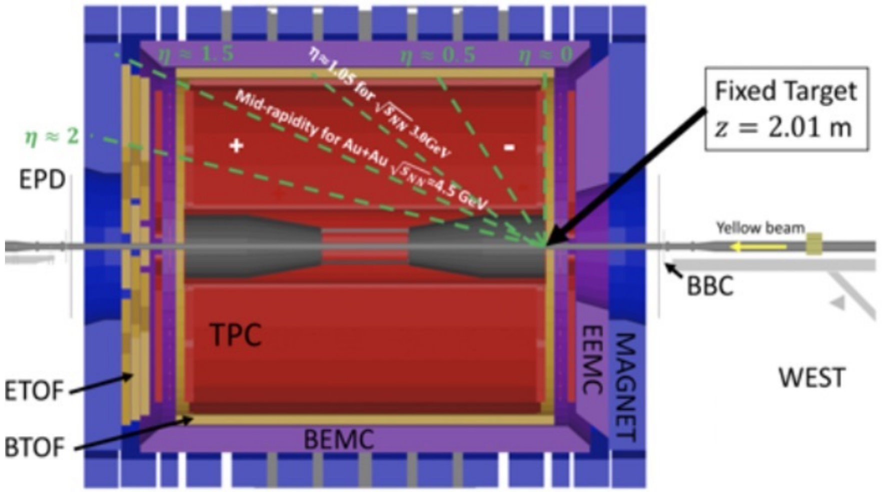
1. Improve dE/dx for particle identification, $p_T \geq 125$MeV/c → $p_T \geq 60$ MeV/c
2. Extend η coverage, $|\eta| \leq 1.0 \rightarrow |\eta| \leq 1.6$
3. Enable the fixed-target program $\mu_B \leq 420$ MeV → $\mu_B \leq 750$ MeV

RHIC Beam Energy Scan Program, 2010-2021





STAR Fixed-target Setup



1. BES-II collected 10-20 times larger statistics at collider energies with iTPC, eTOF, and EPD upgrades.
2. The STAR fixed-target program runs at 3.0 – 13.7 GeV, extends μ_B to ~750 MeV.

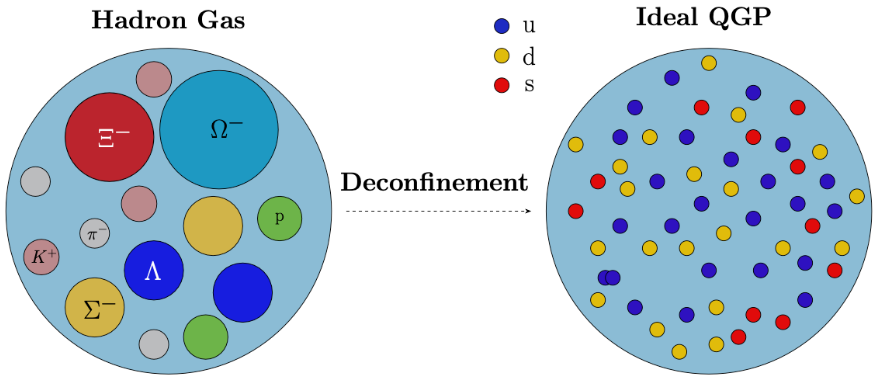
STAR, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Beam Energy Scan Data set

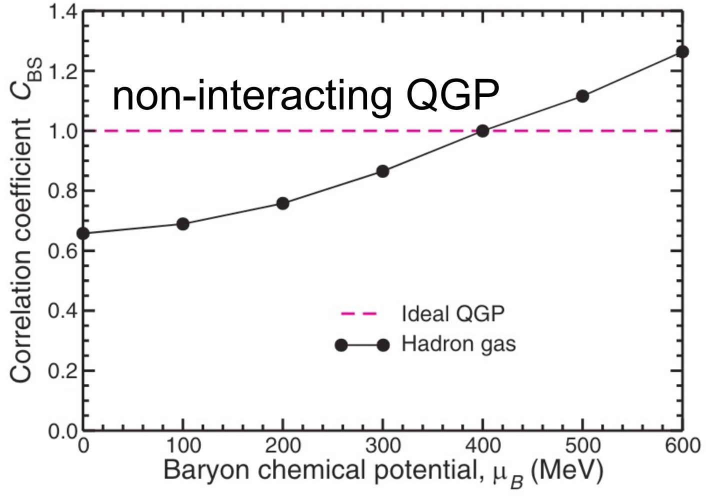
Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events (million)	μ_B (MeV)	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events (million)	μ_B (MeV)	y_{beam}	run
1	200	380	25	5.3	Run-10, 19	1	13.7 (100)	50	280	-2.69	Run-21
2	62.4	46	75	4.2	Run-10	2	11.5 (70)	50	320	-2.51	Run-21
3	54.4	1200	85	4.1	Run-17	3	9.2 (44.5)	50	370	-2.28	Run-21
4	39	86	112	3.7	Run-10	4	7.7 (31.2)	260	420	-2.1	Run-18, 19, 20
5	27	585	156	3.4	Run-11, 18	5	7.2 (26.5)	470	440	-2.02	Run-18, 20
6	19.6	595	206	3.1	Run-11, 19	6	6.2 (19.5)	120	490	1.87	Run-20
7	17.3	256	230	2.9	Run-21	7	5.2 (13.5)	100	540	-1.68	Run-20
8	14.6	340	262	2.7	Run-14, 19	8	4.5 (9.8)	110	590	-1.52	Run-20
9	11.5	57	316	2.5	Run-10, 20	9	3.9 (7.3)	120	633	-1.37	Run-20
10	9.2	160	372	2.3	Run-10, 20	10	3.5 (5.75)	120	670	-1.2	Run-20
11	7.7	104	420	2.1	Run-21	11	3.2 (4.59)	200	699	-1.13	Run-19
						12	3.0 (3.85)	2300	760	-1.05	Run-18, 21

- The STAR Beam energy scan program provides a wide range of data for CEP searches.

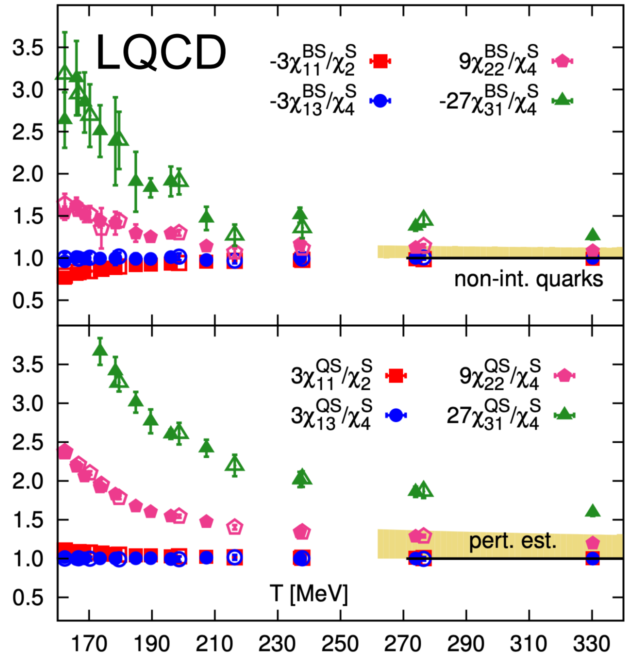
Baryon-strangeness Correlation



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



A. Bazavov et al, PRL 111, 082301 (2013).
H.-T. Ding, et al, EPJA 57,202 (2021)



Definition:

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

$$S = -\Delta s$$

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

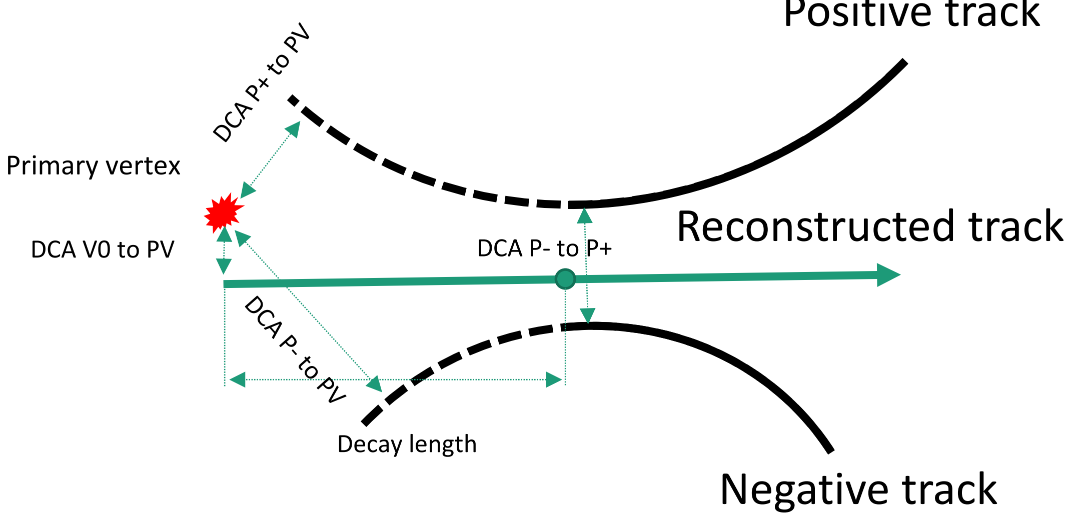
ideal QGP: $B = \frac{1}{3}(U + D - S)$

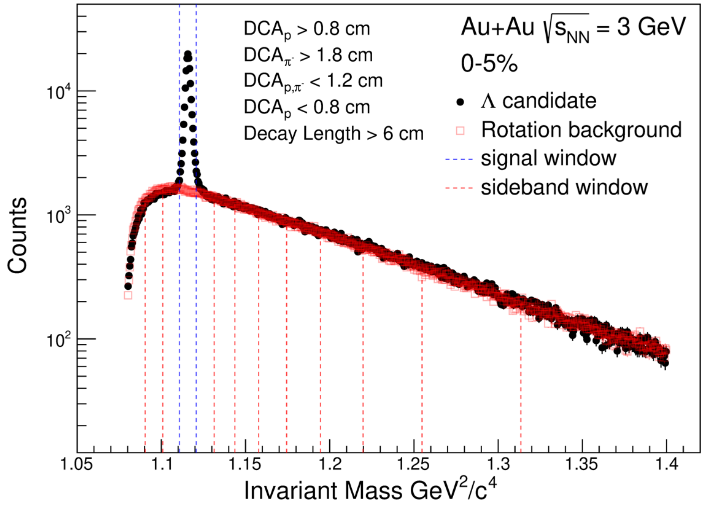
if quark flavors are uncorrelated $\sigma_{BS} = -\frac{1}{3}\sigma_{S^2} \rightarrow C_{BS} = 1$

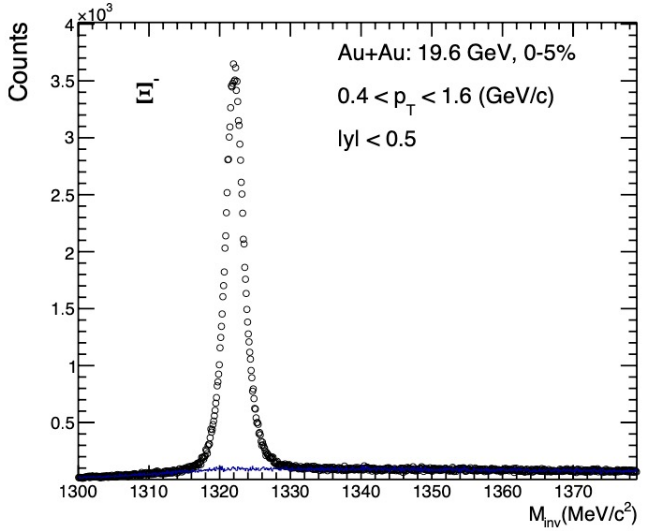
1. Sensitive to the degree of freedom of strongly interacting matter
2. Used to study the onset of deconfinement

Event-by-event Analysis

Λ decay topology





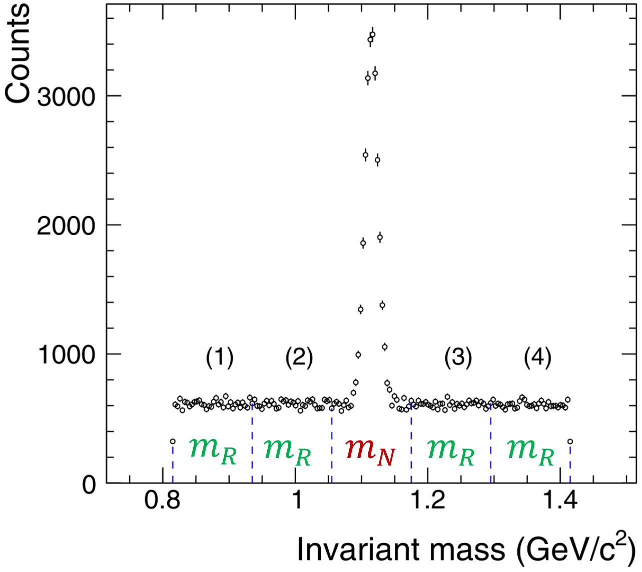


Particles measured in analysis:

① Baryon: p, Λ, Ξ^-

② Strangeness: $K^{\pm}$, Λ, Ξ^-

Purity correction:



- Subtract the combinatorial background for reconstructed particles

signal

background, not measurable

$$\langle m_S^2\rangle_c = \langle m_{SN}^2\rangle_c - \langle m_N^2\rangle_c - 2\langle m_S m_N\rangle_c$$

↓

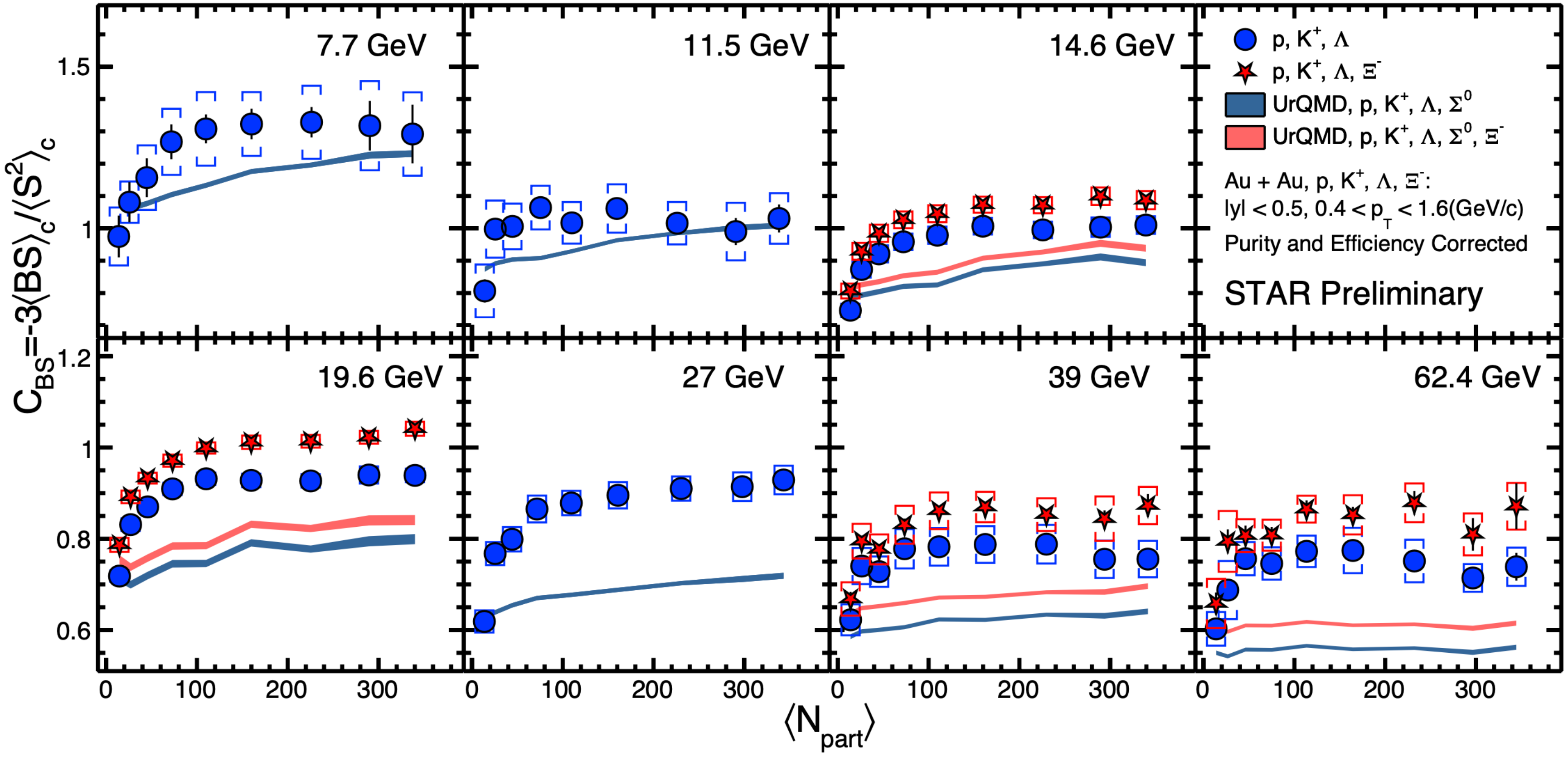
sidebands, measurable

$$\langle m_S^2\rangle_c = \langle m_{SN}^2\rangle_c - \langle m_{R,i}^2\rangle_c - 2\langle m_{SN} m_{R,i}\rangle_c + 2\langle m_{R,i} m_{R,j}\rangle_c$$

T. Nonaka, NIM A 1039 (2022) 167171,

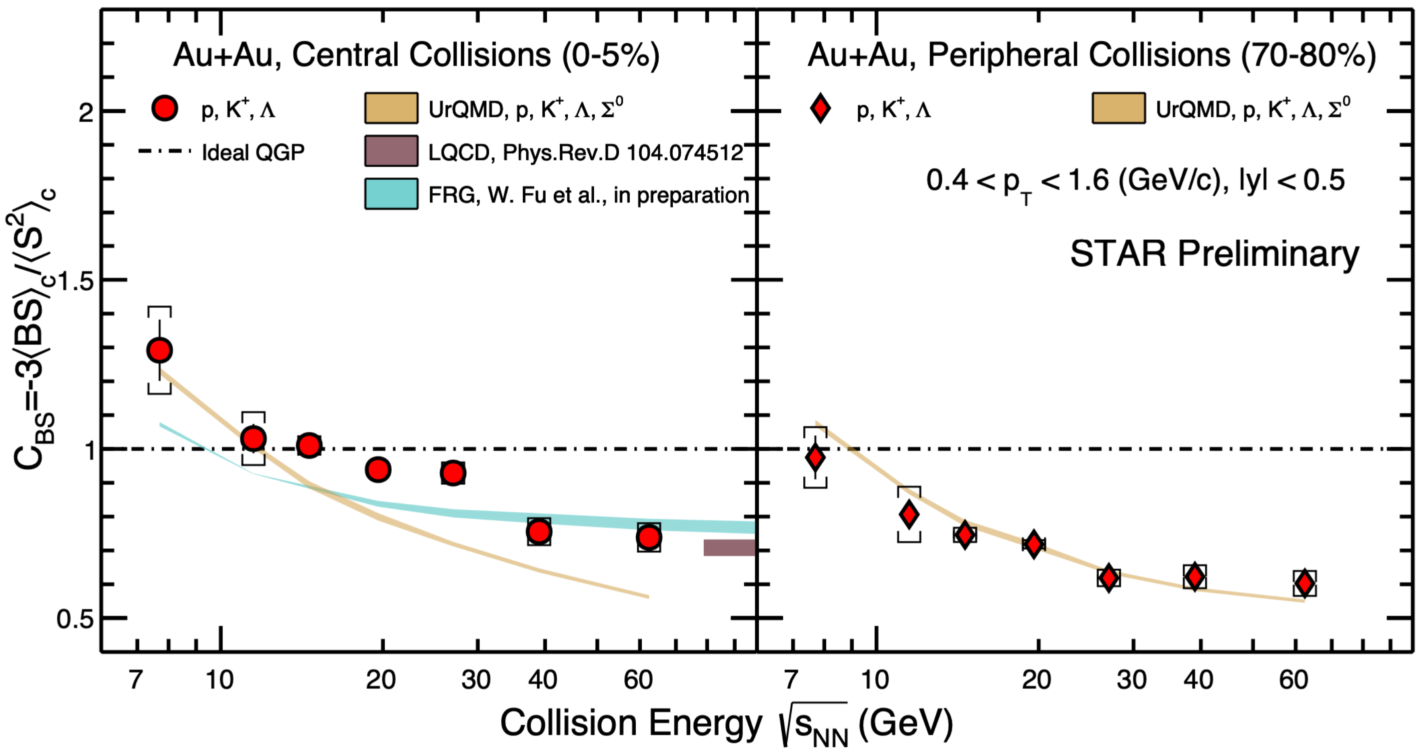
X. Luo, T. Nonaka , PRC 99, 044917 (2019), T. Nonaka, NIMA 1039,167171 (2022)

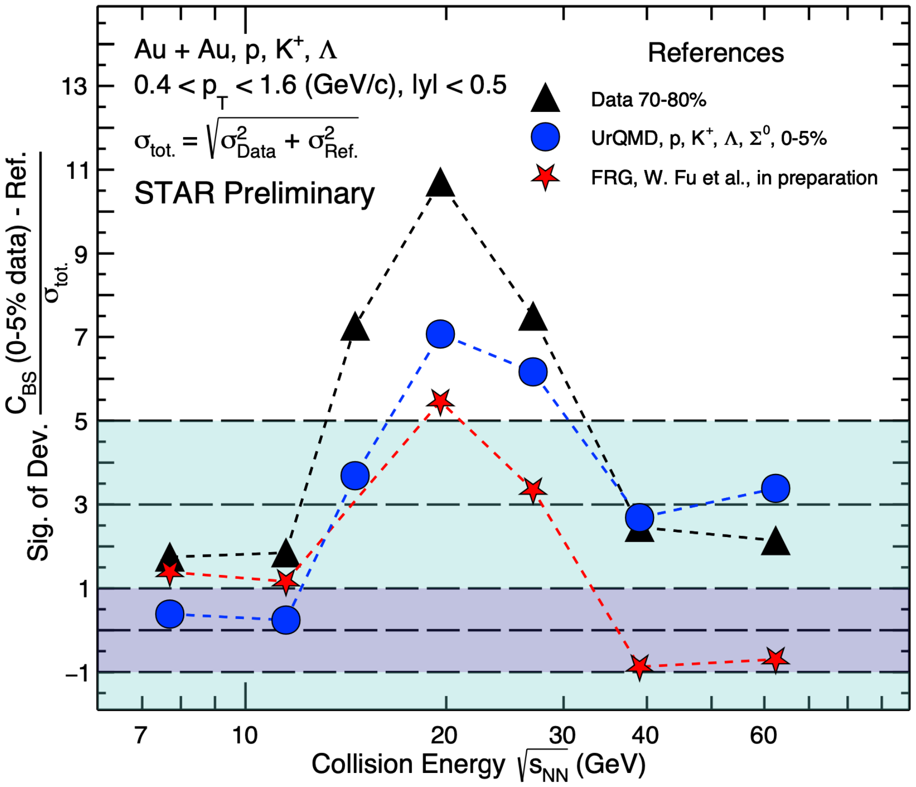
Centrality Dependence of C_{BS}



- The UrQMD calculation qualitatively describe 7.7 and 11.5 GeV while underestimates higher energy

Energy Dependence of C_{BS} from STAR





1. Central (0-5%): UrQMD qualitatively describes 7.7 and 11.5 GeV while underestimates other energies
2. Peripheral (70-80%): qualitatively described by UrQMD
3. At around 20 GeV, the deviation of 0-5% data reaches a maximum

Net-proton Cumulants

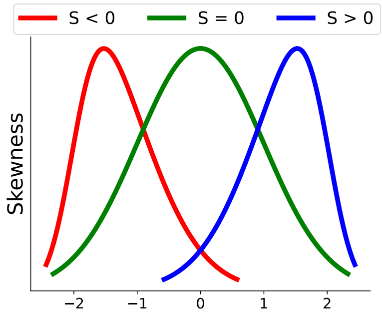
- Event-by-event on cumulants of conserved quantities

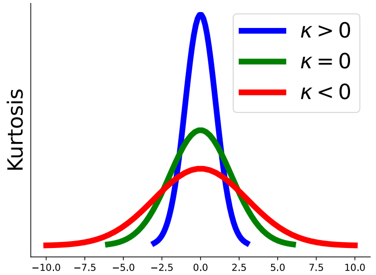
Net-baryon (B) (net-proton as proxy)
Net-electric charge (Q)
Net-strangeness (S) (net-kaon as proxy)

Cumulant (net-proton)

$$\delta N = N - \langle N \rangle$$
$$C_1 = \langle N \rangle = M$$
$$C_2 = \langle (\delta N)^2 \rangle = \sigma^2$$
$$C_3 = \langle (\delta N)^3 \rangle$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$
$$\frac{C_2}{C_1} = \frac{\sigma^2}{M}, \quad \frac{C_3}{C_2} = S\sigma$$
$$\frac{C_4}{C_2} = \kappa\sigma^2$$

N : event-wise net-particle multiplicity





Factorial cumulant (irreducible correlations, (anti)proton)

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

1. Sensitive to correlation length ξ

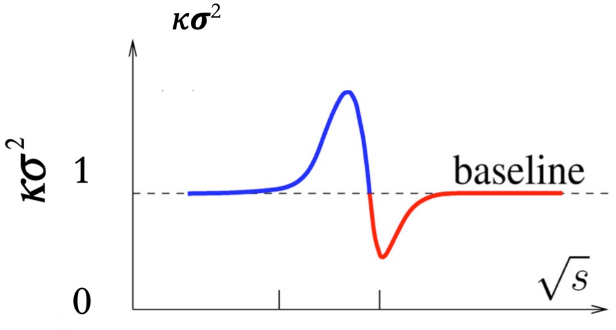
Near CP $\rightarrow$ $\xi \uparrow$ $\rightarrow P(\sigma)$ less gaussian

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

2. Related to susceptibility

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

3. Non-monotonic energy dependence of $\kappa\sigma^2$ (C_4/C_2) → existence of a critical point



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

M. A. Stephanov, PRL 102, 032301 (09);
M. Asakawa, S. Ejiri and M. Kitazawa, PRL 103, 262301 (09)
S.Ejiri et al, PLB 633, 275(06);
M. A. Stephanov, PRL 107, 052301 (11); F. Karsch and K. Redlich, PLB 695, 136 (11)

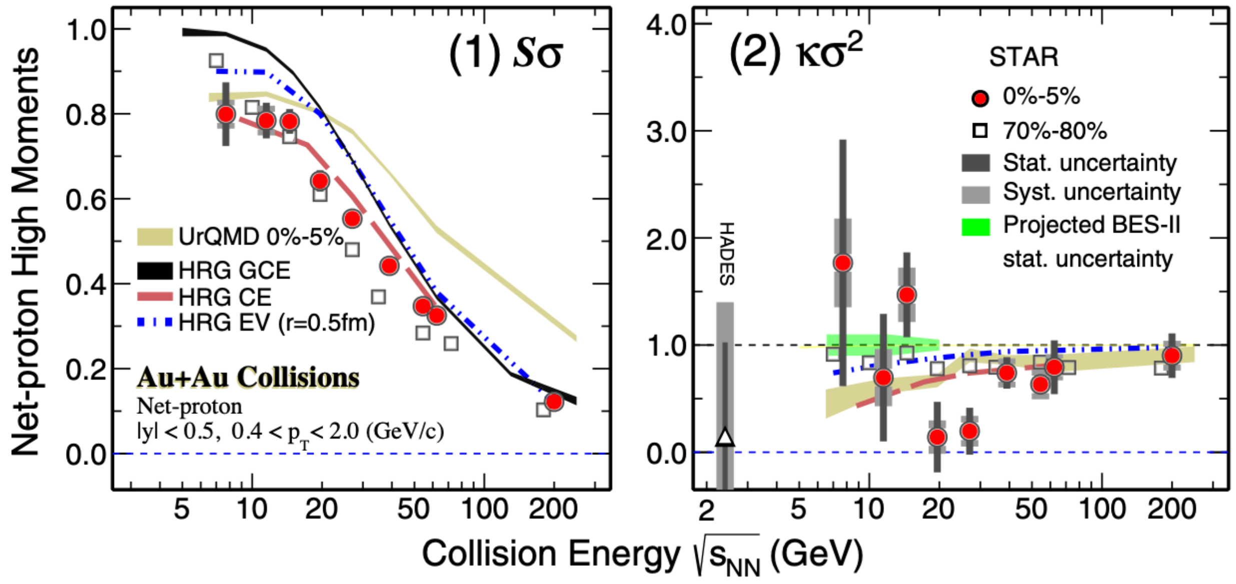
Measurement from STAR BES-I

STAR BES Program, Au+Au Collisions			
$\sqrt{s_{NN}}$ (GeV)	BES-I /10^6		μ_B (Mev)
200	220		25
62.4	43		75
54.4	550		85
39	92		112
27	31		156
19.6	14		206
17.3			230
14.5	14		264
11.5	7		315
9.2	-		372
7.7	3		420
3.0	-		750

μ_B from J. Cleymans et al, PRC 73,034905(2006)

BES-I, Net-proton Measurement

HADES, PRC 102(2020) 024914
STAR, PRL 126 (2021) 092301



1. Non-monotonic energy dependence trend with 3.1σ significance
2. High precision measurement can be made on BES-II datasets

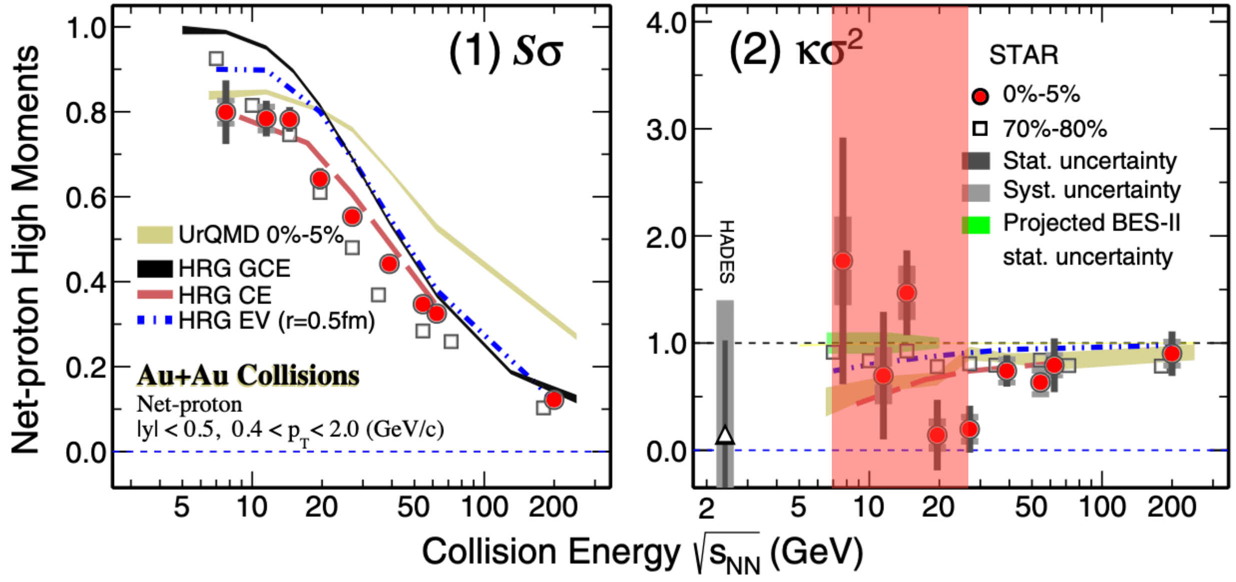
Measurement from STAR BES-I

STAR BES Program, Au+Au Collisions			
$\sqrt{s_{NN}}$ (GeV)	BES-I /10^6	**BES-II** /10^6	μ_B (Mev)
200	220	-	25
62.4	43	-	75
54.4	550	-	85
39	92	-	112
27	31	**220**	156
19.6	14	**270**	206
17.3		**116**	230
14.5	14	**178**	264
11.5	7	**110**	315
9.2	-	**78**	372
7.7	3	**45**	420
3.0	-	**140**	750

μ_B from J. Cleymans et al, PRC 73,034905(2006)

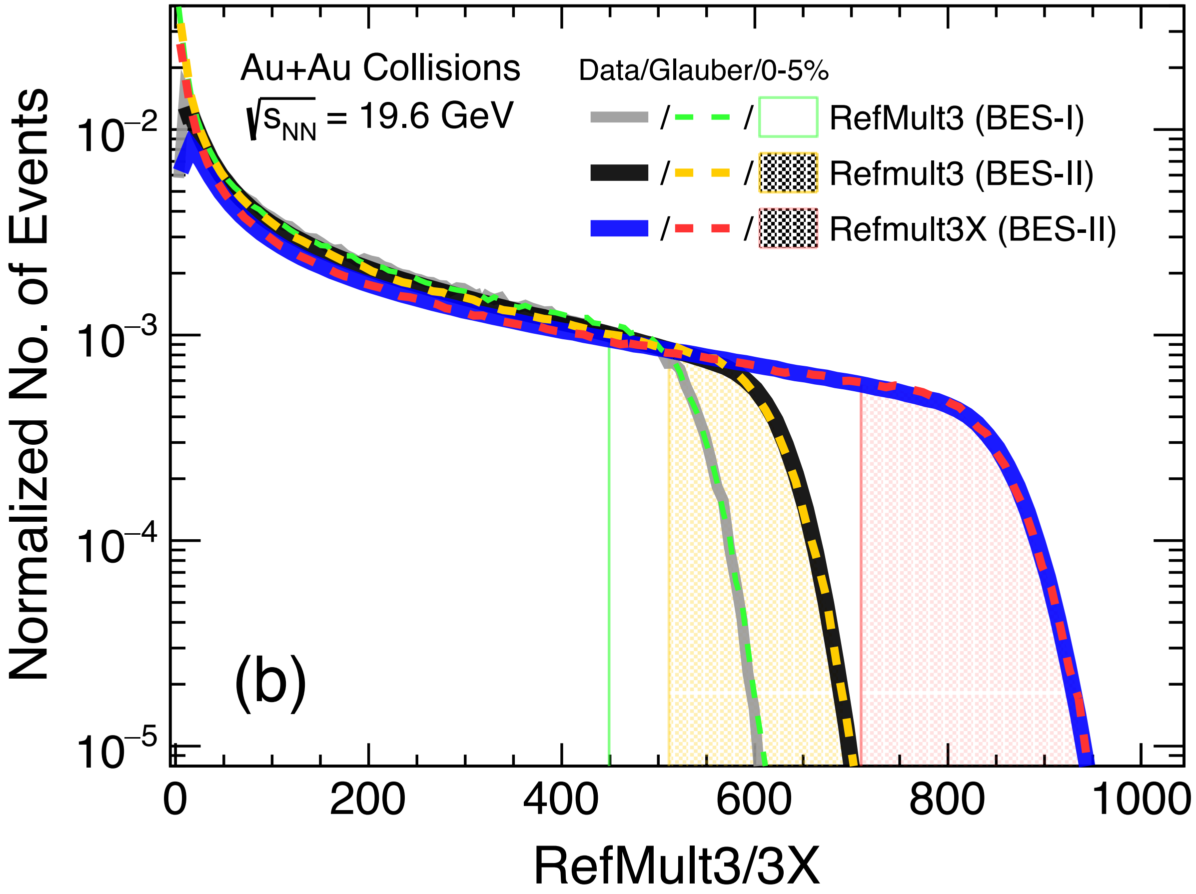
BES-I, Net-proton Measurement

HADES, PRC 102(2020) 024914
STAR, PRL 126 (2021) 092301



1. Non-monotonic energy dependence trend with 3.1σ significance
2. High precision measurement can be made on BES-II datasets

Centrality Determination



1. Centrality is defined using charged particle multiplicity
2. (Anti-)Protons are excluded to avoid self correlation

RefMult3: charged particles multiplicity excluding (anti)protons within $|\eta| \leq 1.0$

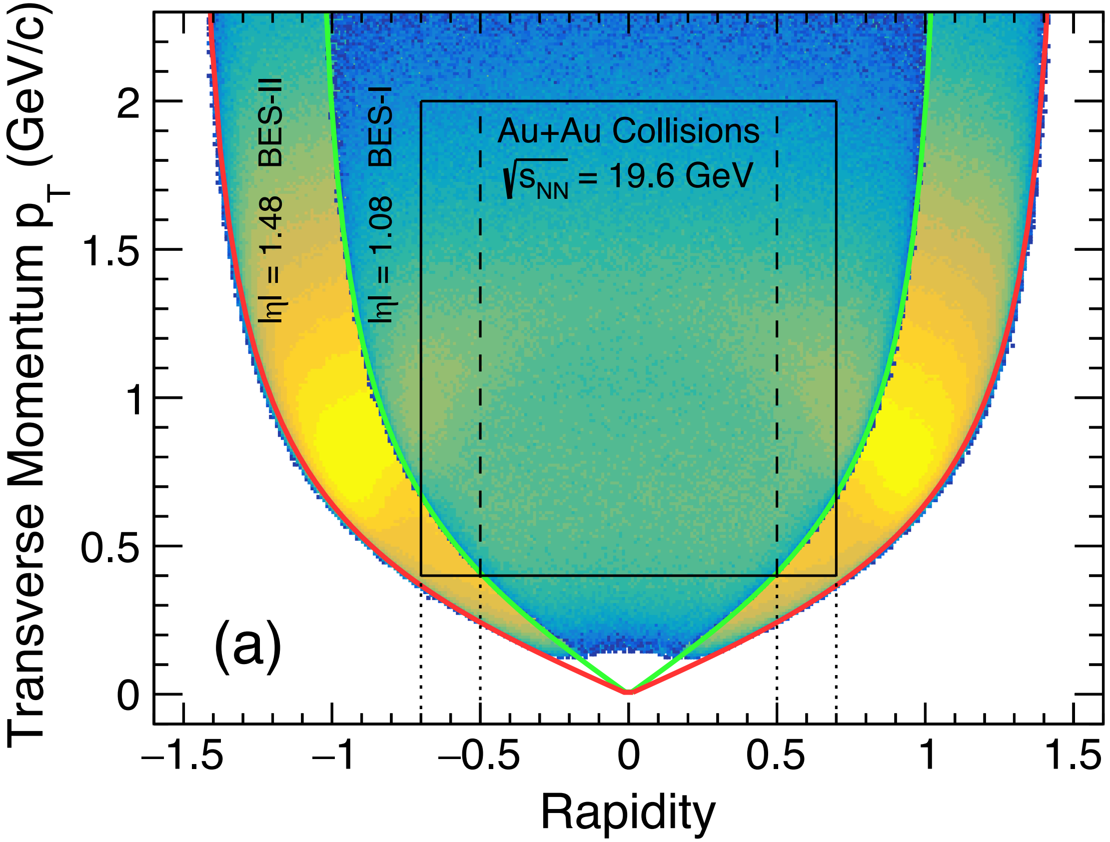
RefMult3X (additional in BES-II): charged particles multiplicity excluding (anti-)protons within $|\eta| \leq 1.6$

3. With larger multiplicity, we have better centrality resolution:

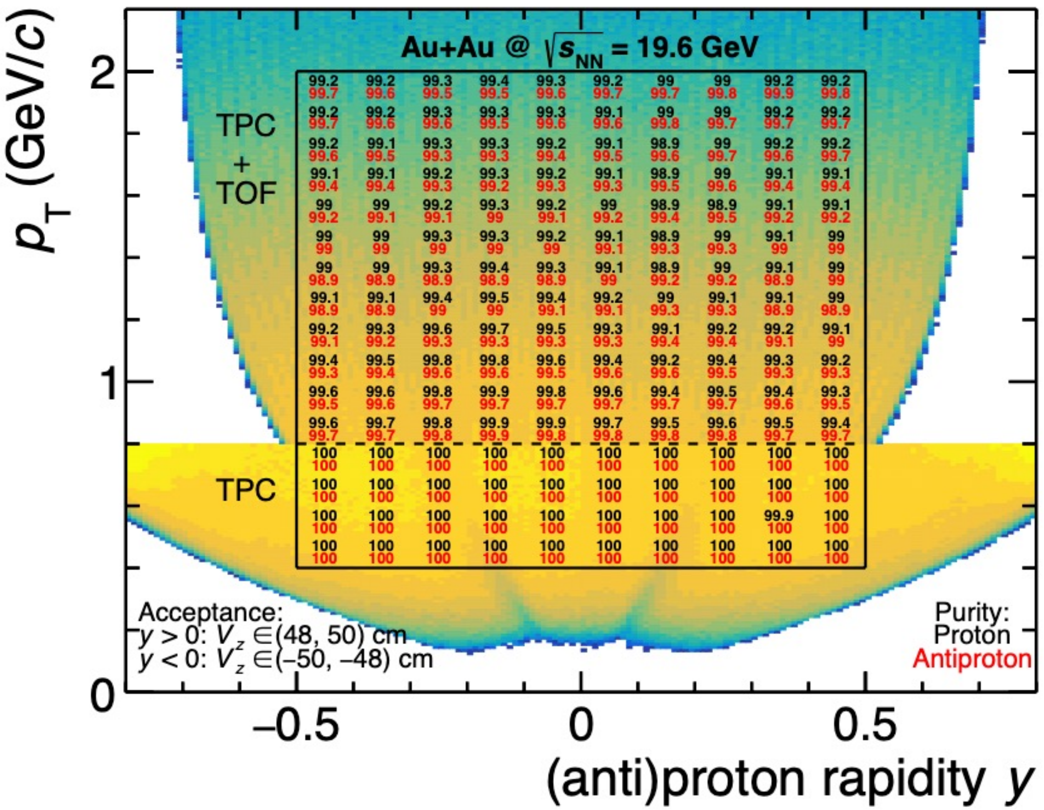
   RefMult3X(BES-II) > RefMult3(BES-II) > RefMult3(BES-I)

Proton Identification

Proton Acceptance with TPC

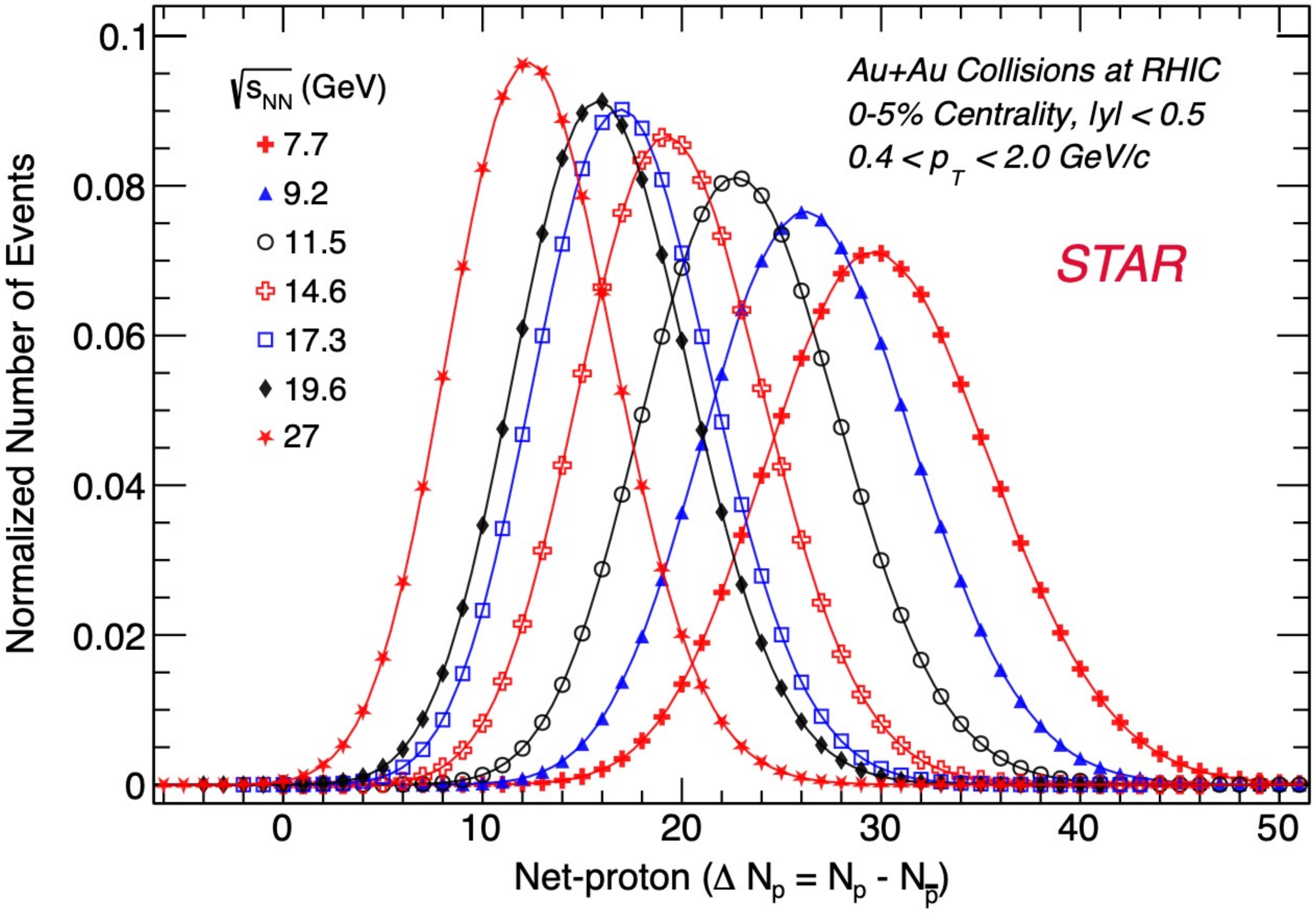


(Anti-)Proton Purity with TPC & TOF



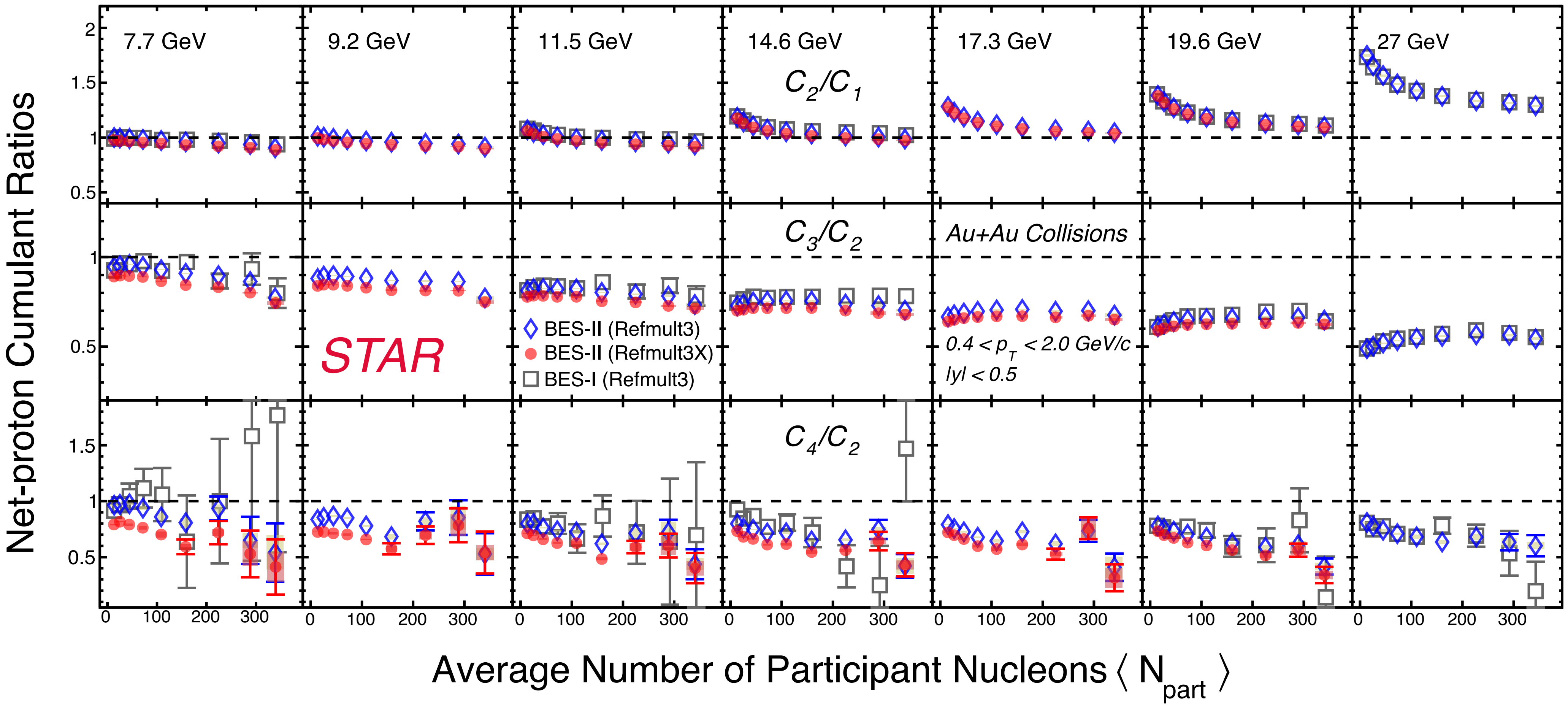
1. Proton rapidity coverage is extended to 0.7 in BES-II
2. TPC and TOF are combined to identify (anti)protons
3. (Anti)proton purity are better than 99% everywhere within analysis window, $0.4 < p_T < 2.0$ GeV/c, $|y| < 0.5$

Event-by-event Net-proton Number Distribution



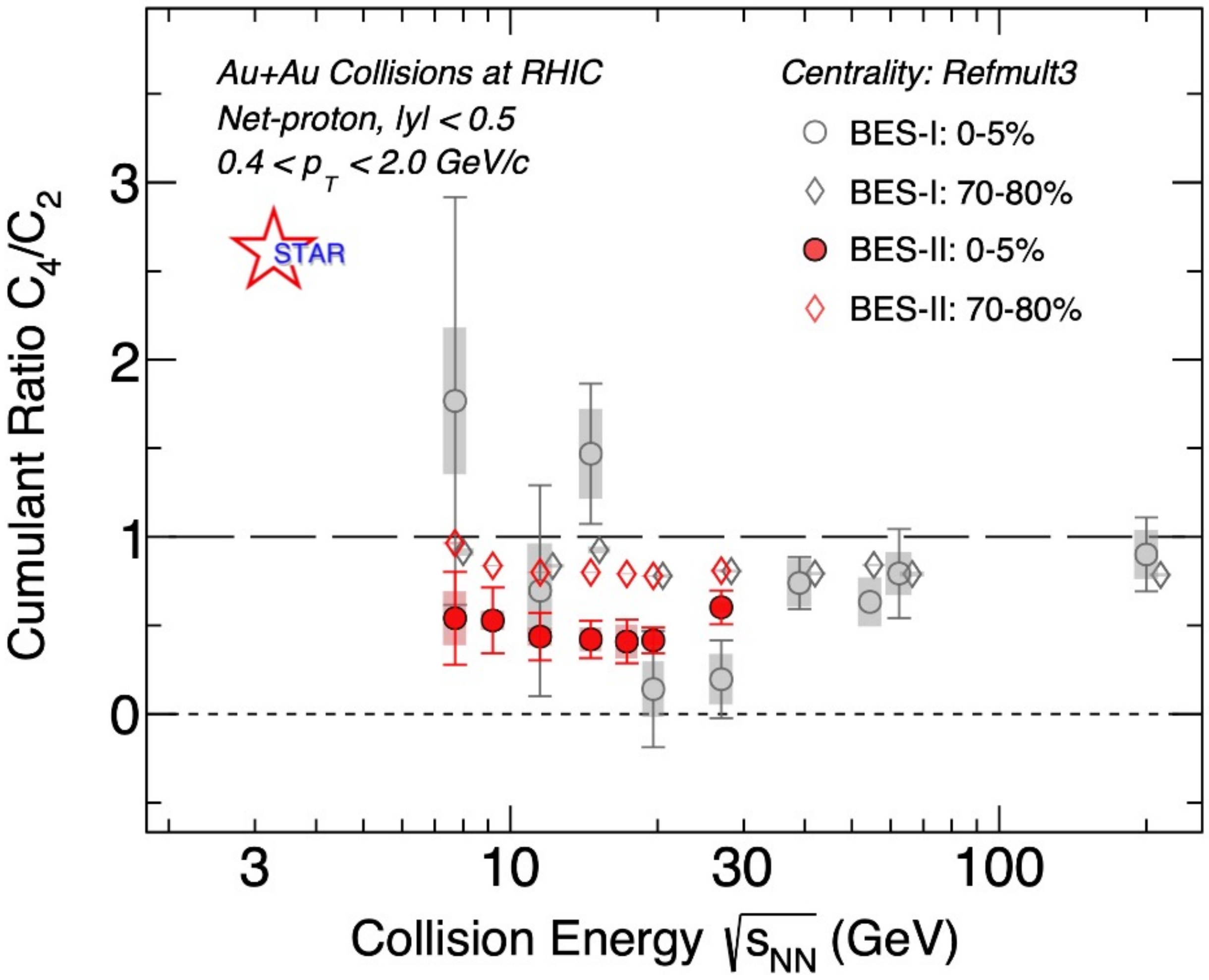
1. Not corrected for detector efficiency
2. Higher mean ΔN_p at lower energy → baryon stopping effect

Centrality Dependence of Cumulant Ratios



1. Observed smooth variation across centrality and collision energy
2. Higher centrality resolution leads to lower ratios values especially in most central collisions
3. For 0-5%, C4/C2 show weak dependence on centrality resolution

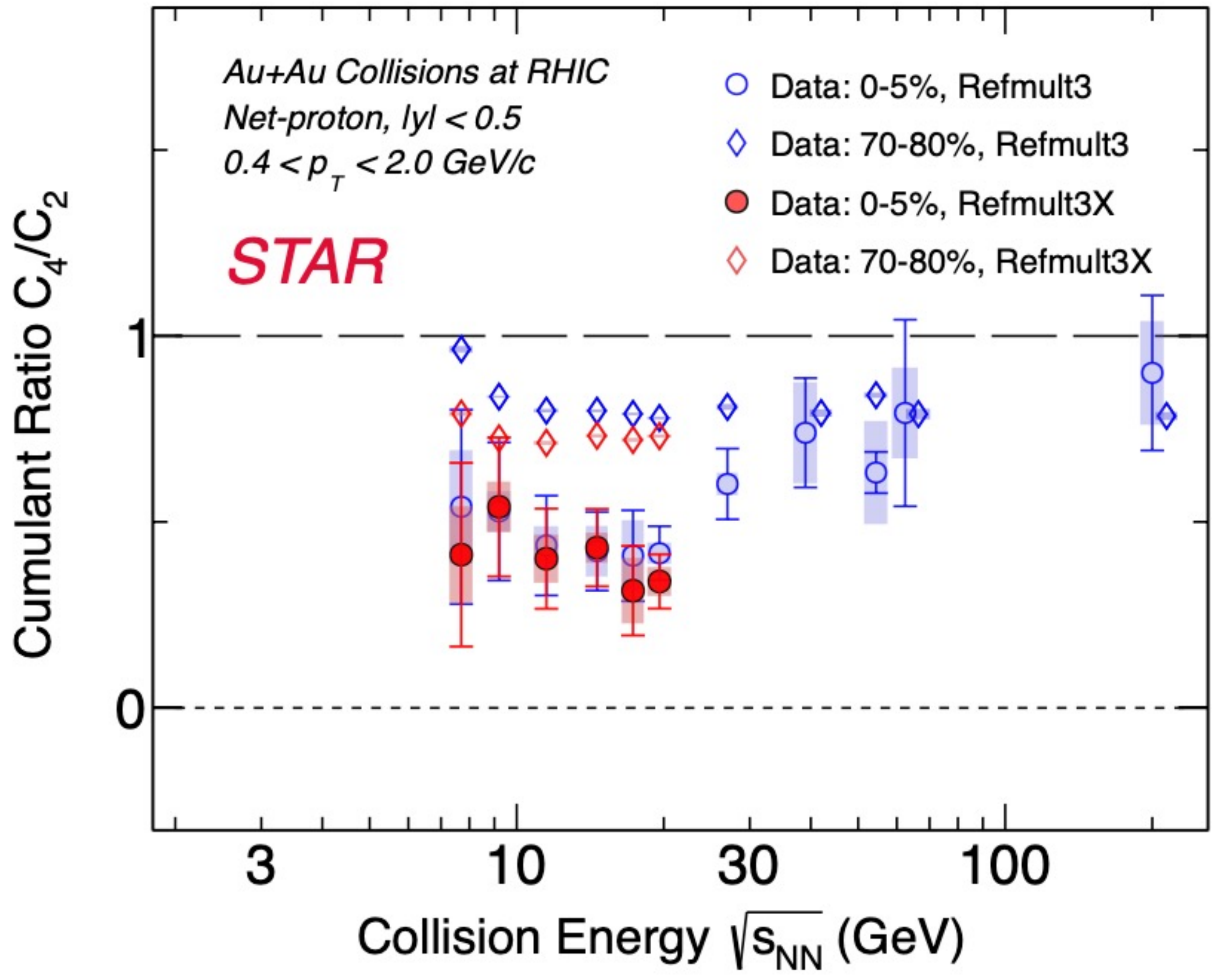
Comparison of C_4/C_2 with BES-I



Deviation between BES-I & BES-II		
Energy (GeV)	0-5%	70-80%
7.7	1.0σ	0.9σ
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.0σ
27	1.4σ	0.2σ

BES-II results (using RefMult3) are consistent with BES-I within uncertainties

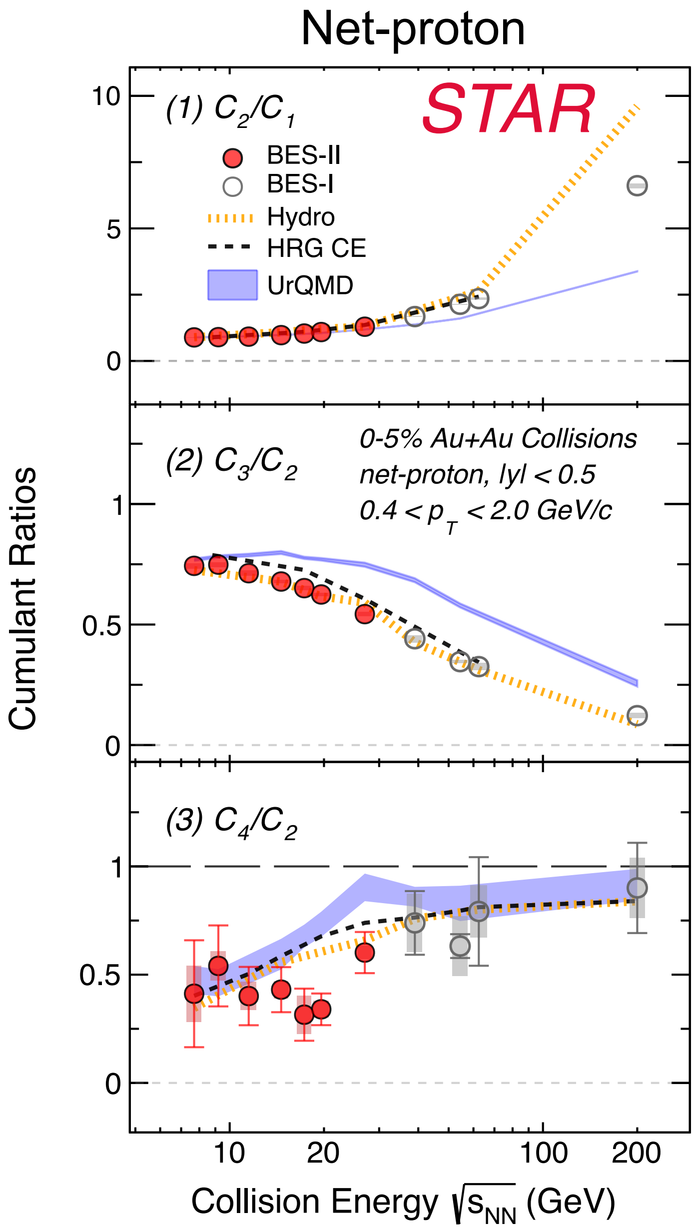
Improved Centrality Resolution with BES-II



① C_4/C_2 in 0-5% show weak dependence on centrality resolution

② BES-II results are shown with RefMult3X hereafter.

Comparison with Non-critical Models



1. Smooth variation vs. collision energy in C_2/C_1 and C_3/C_2 observed. C_4/C_2 decreases within decreasing collision energy
2. Qualitative trend described by model but quantitative differences are observed between data and models

Non-critical models:

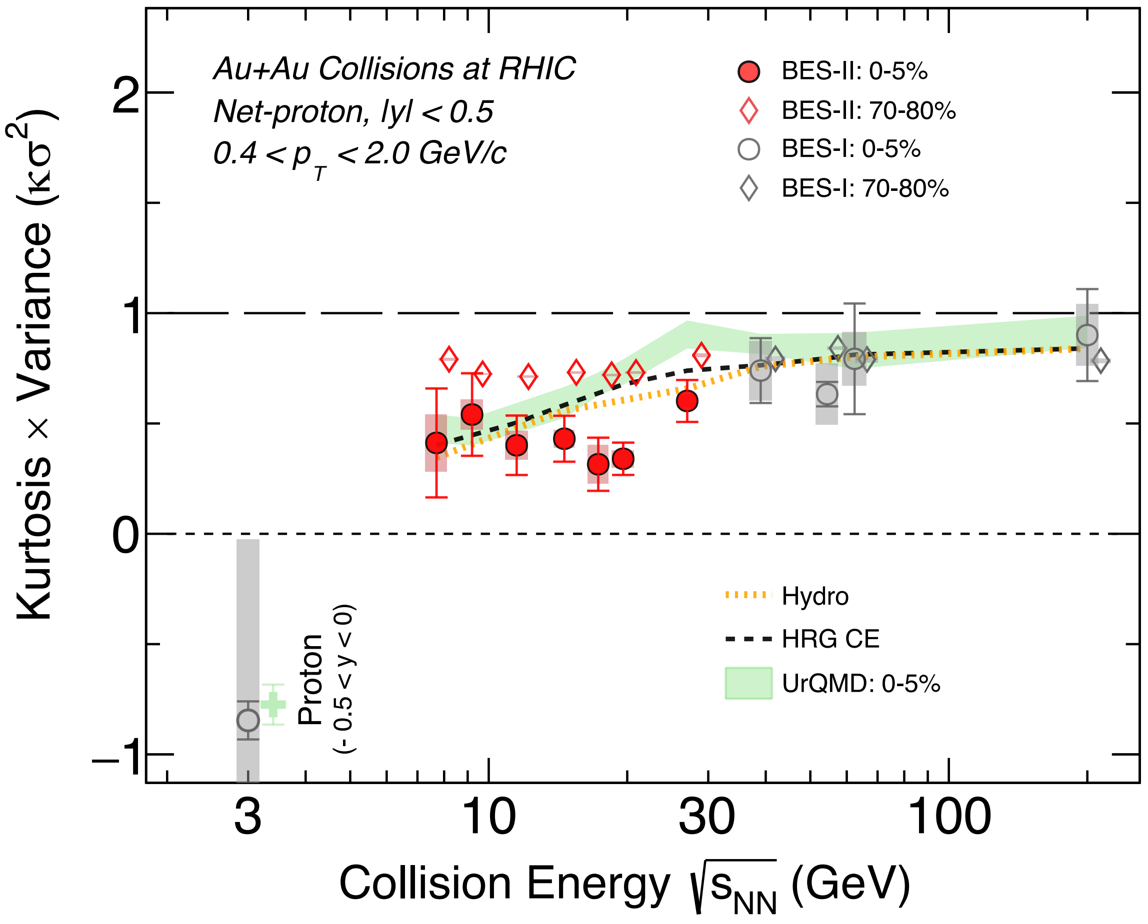
Hydro: hydrodynamical model

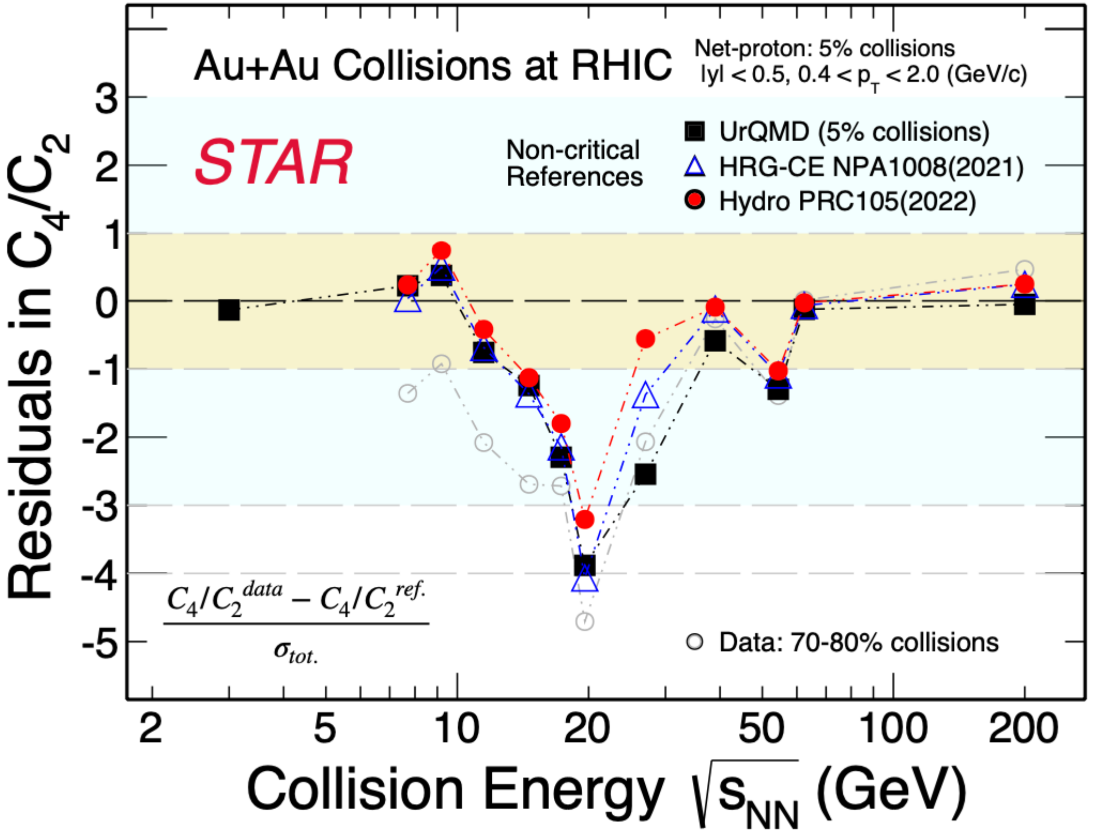
HRG CE: Thermal model with canonical treatment of baryon charge

UrQMD: hadronic transport model

All of them have implemented baryon number conservation

Quantify Difference with Non-critical Models

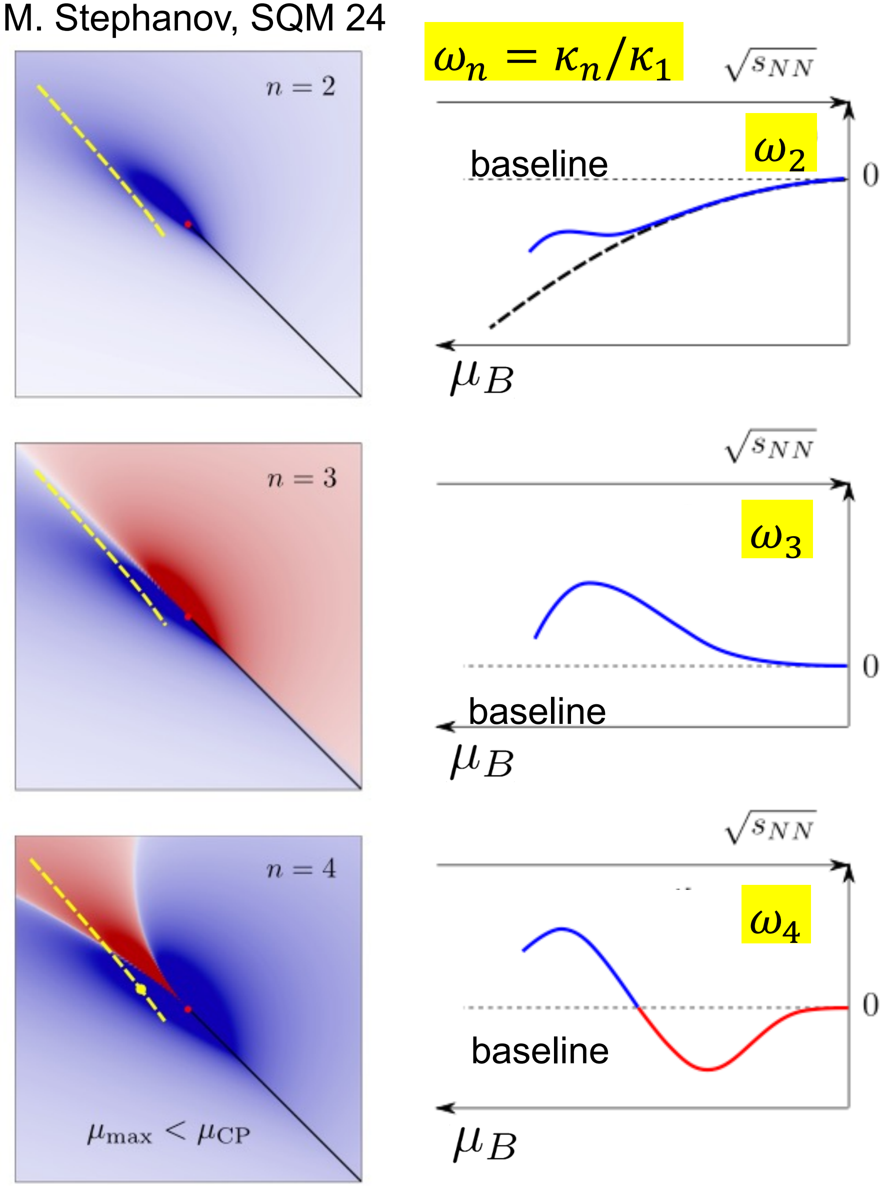




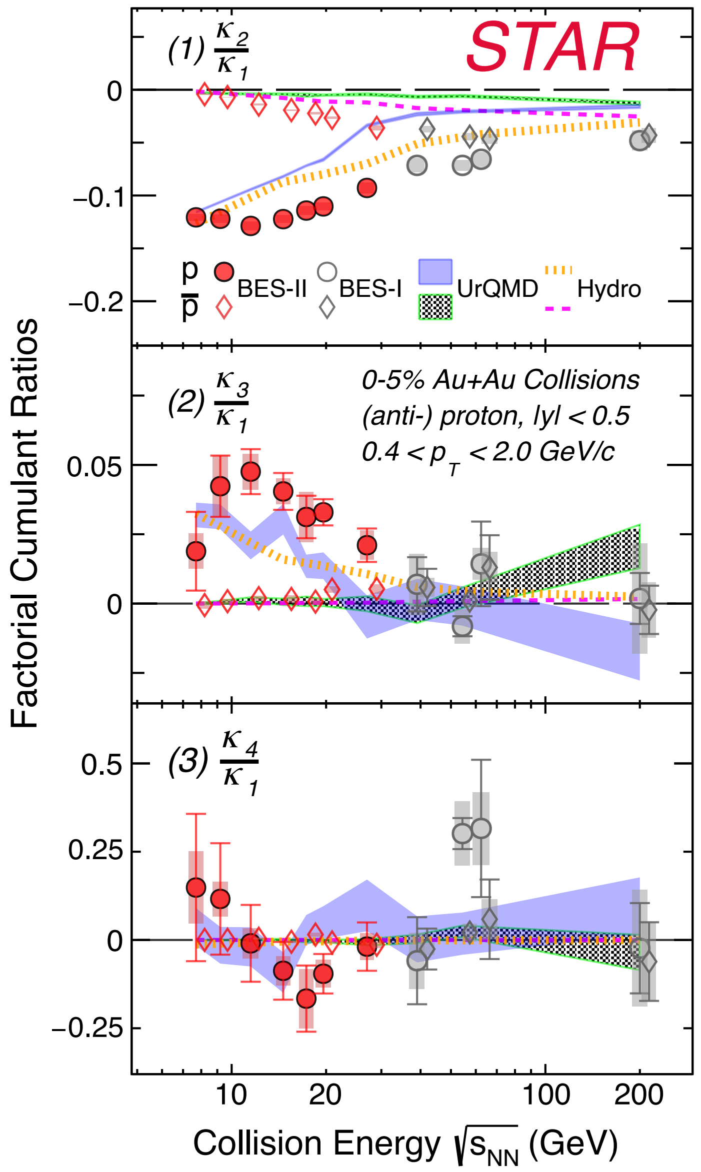
1. C_4/C_2 shows a minimum at around 20 GeV compared to non-CP models
2. Maximum deviation at **20 GeV: 3.2 – 4.7σ** which was **1.3 – 2σ at BES-I**
3. Overall deviation at **7.7 – 27 GeV: 1.9 – 5.4σ** which was **1.4 – 2.2σ at BES-I**

Comparison of factorial cumulants with Models

M. Stephanov, SQM 24



(Anti-)Proton

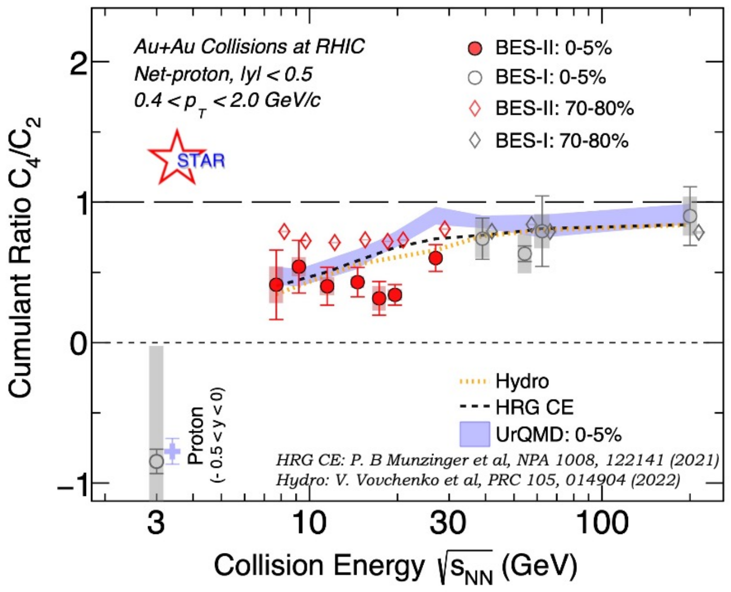


1. (Anti-) proton κ_2/κ_1 shows suppression at lower energies due to baryon number conservation
2. Anti-proton κ_3/κ_1 and κ_4/κ_1 are closer to zero
3. Proton κ_2/κ_1, κ_3/κ_1, and κ_4/κ_1 deviate from Poisson baseline (zero), qualitatively consistent with theoretical predictions of critical point

Expected signature: bump in ω_2 and ω_3, bump and dip in ω_4

Measurement at STAR Fixed-target Energies

STAR Fixed-Target Runs			
	$\sqrt{s_{NN}}$ / GeV	event / million	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



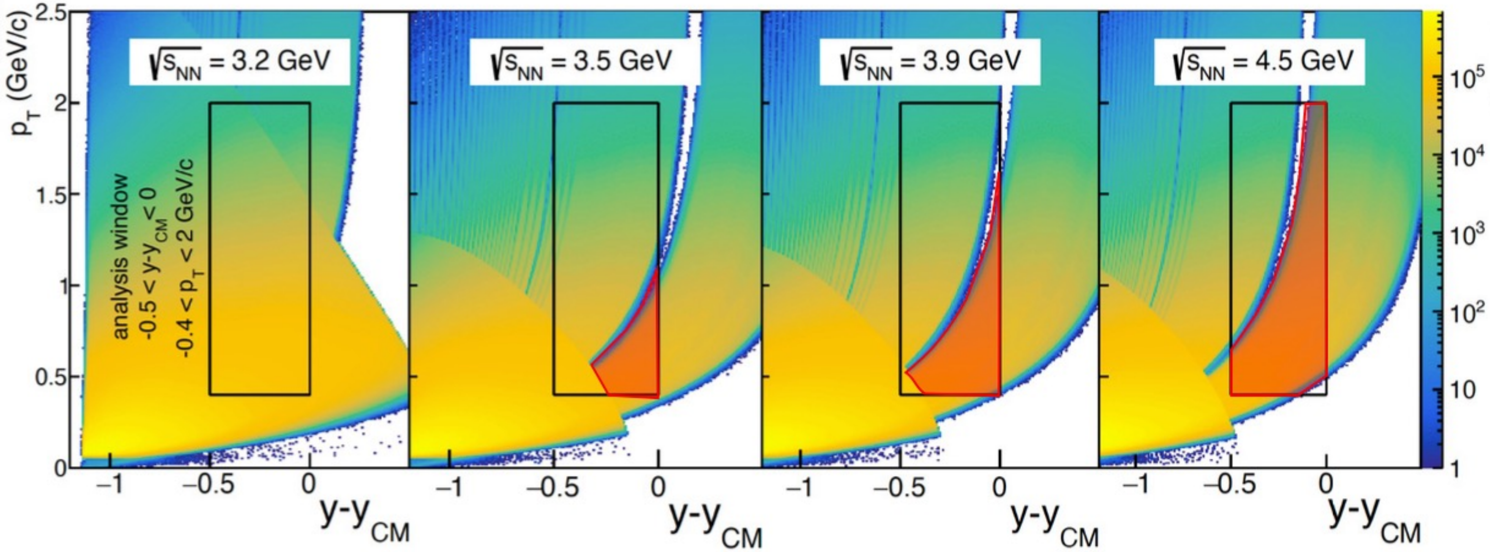
1. Finish FXT analysis and confirm the non-monotonic behavior
2. Looking at even higher order cumulants for crossover signal

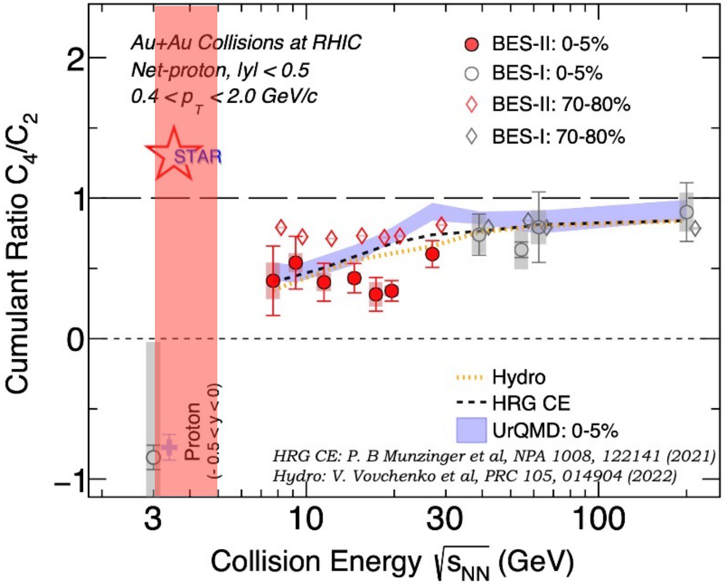
Measurement at STAR Fixed-target Energies

STAR Fixed-Target Runs			
	$\sqrt{s_{NN}}$ / GeV	event / million	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

Proton Acceptance

: ETOF coverage



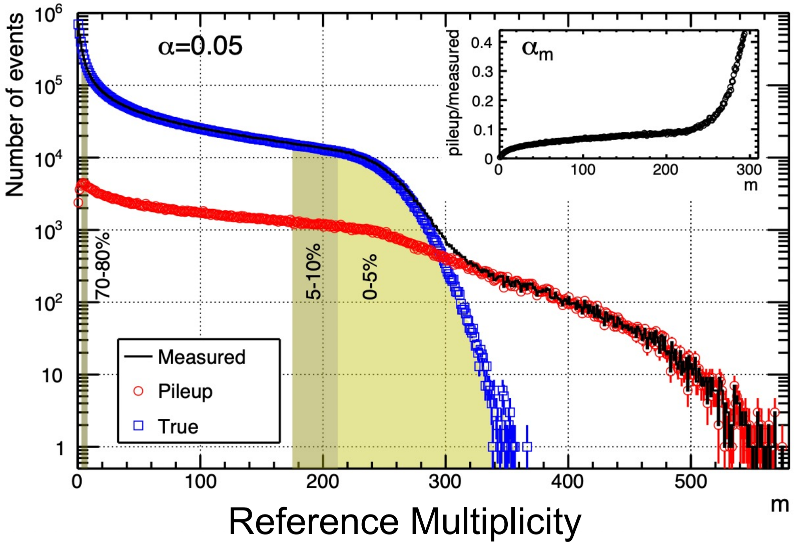


1. Finish FXT analysis and confirm the non-monotonic behavior
2. Looking at even higher order cumulants for crossover signal

Difficulties in FXT Measurement

1. Effect of event pileup

- Due to finite thickness of target
- Distort fluctuation measurement



construct probability: $$P(N) = (1-\alpha)P^{\mathrm{single}}(N) + \alpha P^{\mathrm{pileup}}(N)$$

corrected cumulant: $$\langle N^r \rangle_m^{\mathrm{t}} = \frac{\langle N^r \rangle_m - \alpha_m C_m^{(r)}}{1 - \alpha_m + 2\alpha_m w_{m,0}},$$

where $$C_m^{(r)} = \mu_m^{(r)} + \sum_{i,j>0} \delta_{m,i+j} w_{i,j} \langle N^r \rangle_{i,j}^{\mathrm{sub}}.$$

T. Nonaka et al, Nucl. Inst. Meth. A 984(2020)164632

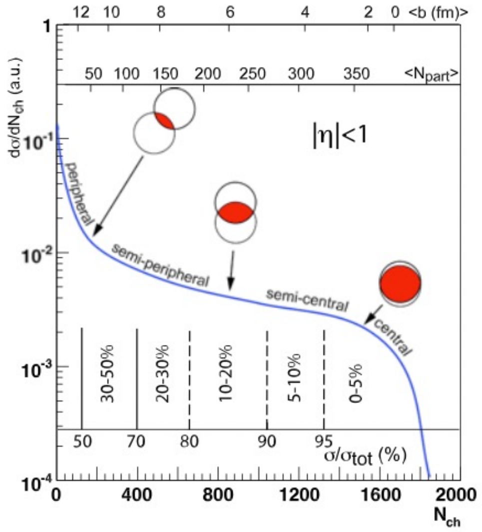
Y. Zhang et al. Nucl. Inst. Meth. A 1026(2022)166246

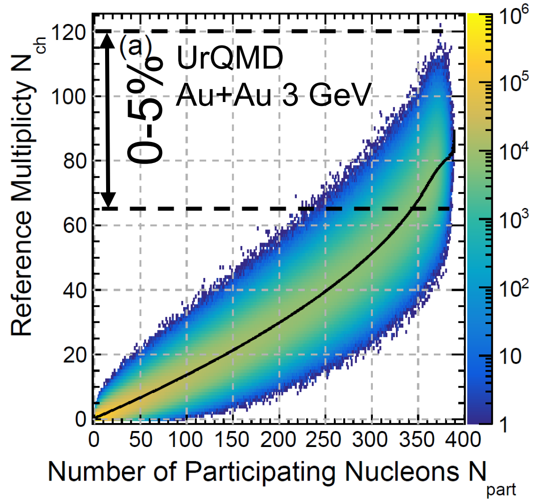
2. Volume fluctuation

Limited multiplicity

→ Worse centrality resolution.

→ Large volume fluctuation.





Volume fluctuation correction:

Measured cumulant | True cumulant

Additional terms appears from the event by event participant fluctuation

$$\kappa_1(\Delta N) = \langle N_W \rangle \kappa_1(\Delta n)$$

$$\kappa_2(\Delta N) = \langle N_W \rangle \kappa_2(\Delta n) + \langle \Delta n \rangle^2 \kappa_2(N_W),$$

$$\kappa_3(\Delta N) = \langle N_W \rangle \kappa_3(\Delta n) + 3\langle \Delta n \rangle \kappa_2(\Delta n)\kappa_2(N_W) + \langle \Delta n \rangle^3 \kappa_3(N_W),$$

$$\kappa_4(\Delta N) = \langle N_W \rangle \kappa_4(\Delta n) + 4\langle \Delta n \rangle \kappa_3(\Delta n)\kappa_2(N_W) + 3\kappa_2^2(\Delta n)\kappa_2(N_W) + 6\langle \Delta n \rangle^2 \kappa_2(\Delta n)\kappa_3(N_W) + \langle \Delta n \rangle^4 \kappa_4(N_W).$$

P. Braun-Munzinger et al, NPA 960 (2017) 114–130

A. Rustamov et al, NPA 1034 (2023) 122641

R. Holzmann et al, arXiv: 2403.03598

Summary

1. Precision measurement of (net, anti-)proton cumulants and factorial cumulants on STAR BES-II datasets (7.7 - 27 GeV)
2. Data show large deviation from dynamical model calculations in most central collisions at 19.6 GeV, which might be consistent with the scenario of QCD CEP
3. FXT data is crucial for the QCD CEP search

Thank you for your attention!