ゆらぎで探る原子核物質の相図

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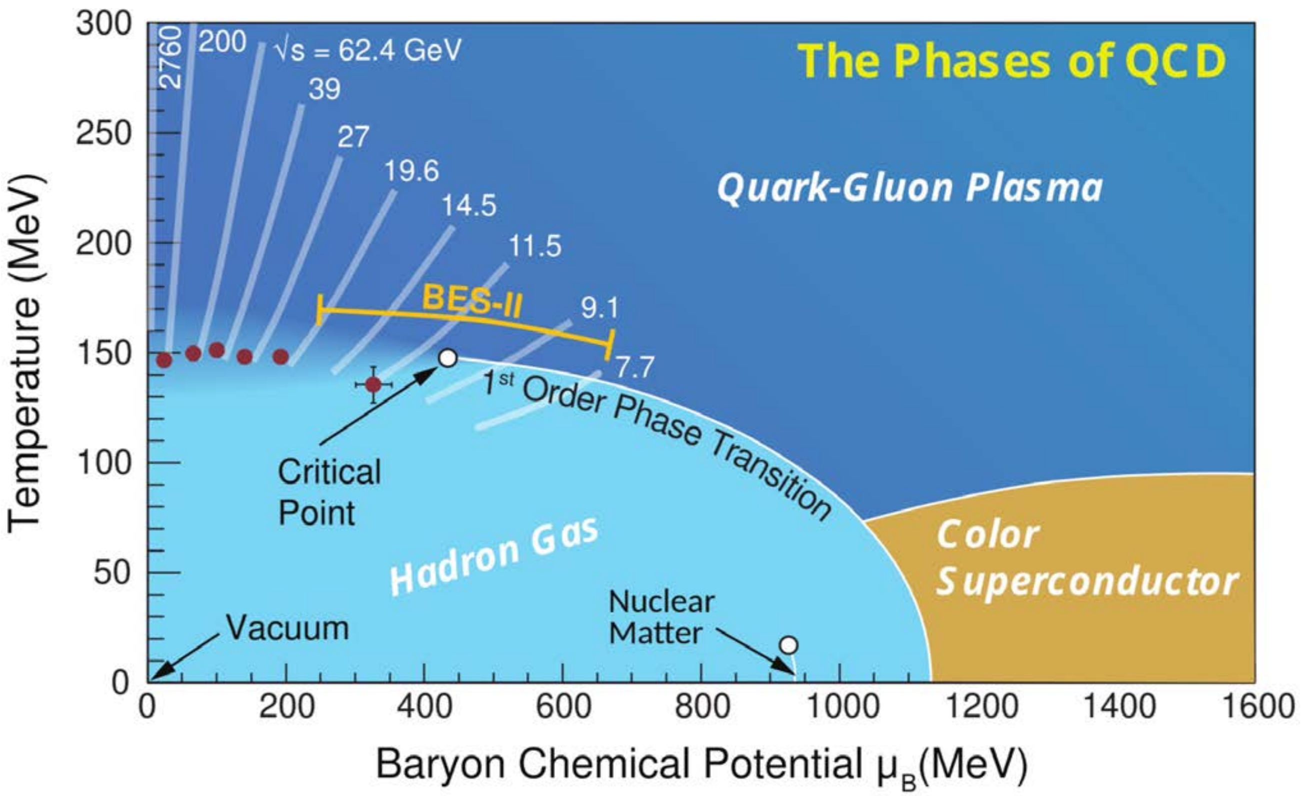
Outline

- Introduction
- Methodology
- Experimental results
  - Net-proton 4^{th}-order fluctuations from BES-I
  - New results from BES-II (A. Pandav, CPOD2024)
- Summary

Introduction

BES, STAR, Cumulant

“Conjectured” QCD phase diagram



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

- Crossover at μ_B = 0 MeV
  - Y. Aoki et al, Nature 443,675(2006)
- 1st-order phase transition at large μ_B?
- Critical point?

Beam Energy Scan Phase-I (BES-I)

$\sqrt{s_{NN}}$ (GeV)	No. of events (million)	$T_{\rm ch}$ (MeV)	$\mu_{\rm B}$ (MeV)
200	238	164.3	28
62.4	47	160.3	70
54.4	550	160.0	83
39	86	156.4	160
27	30	155.0	144
19.6	15	153.9	188
14.5	20	151.6	264
11.5	6.6	149.4	287
7.7	3	144.3	398

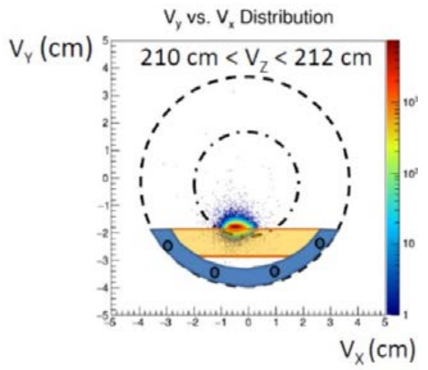
2010-2017

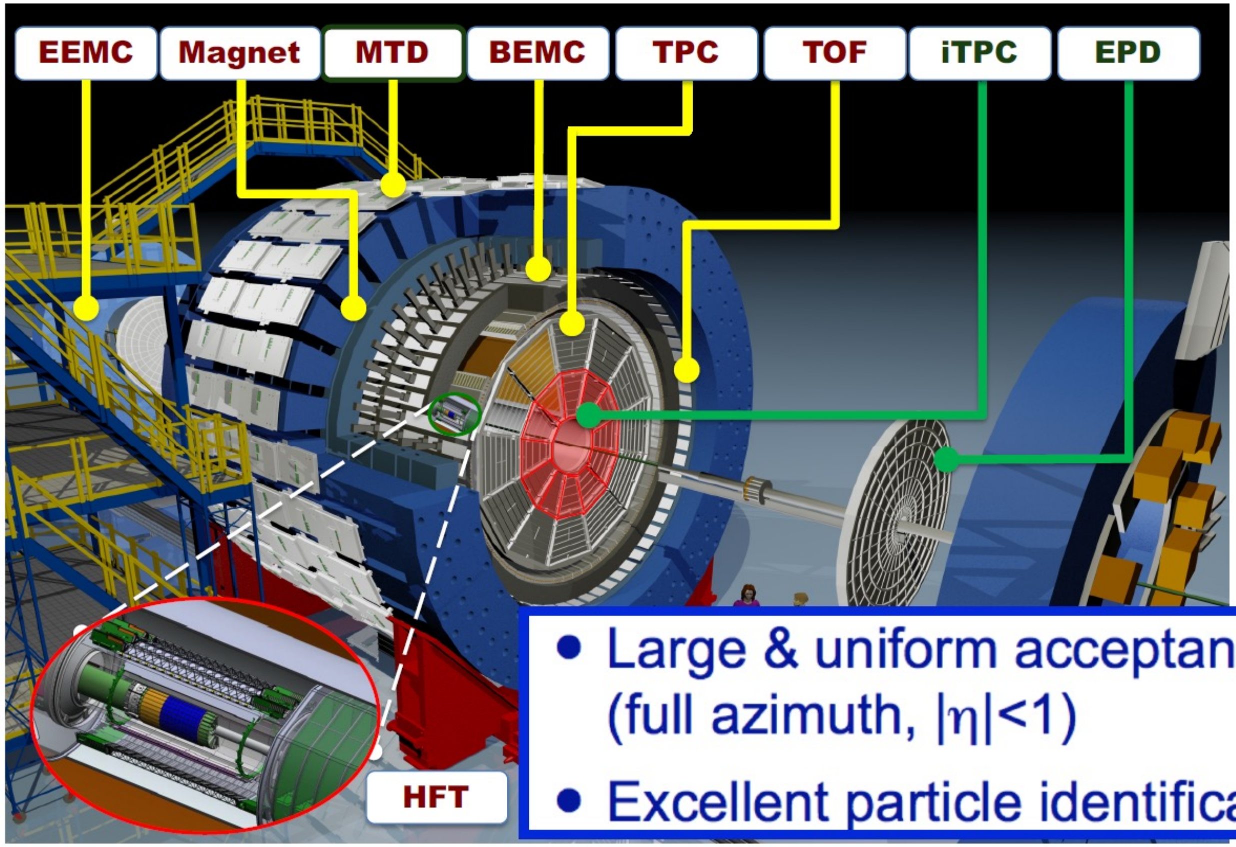
- Crossover at μ_B = 0 MeV
  - Y. Aoki et al, Nature 443,675(2006)
- 1st-order phase transition at large μ_B?
- Critical point?

Fluctuations of conserved charges have been measured for BES-I data.

Complementary measurements at RHIC: BES-II, FXT (2019-2022)

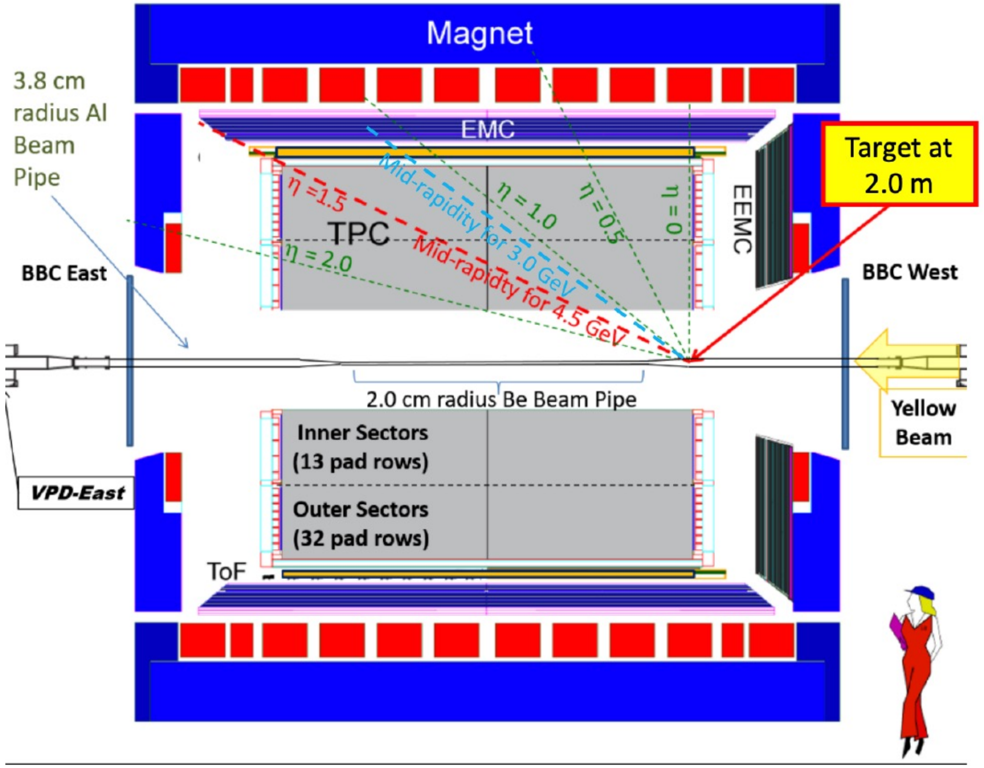
STAR detectors





- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

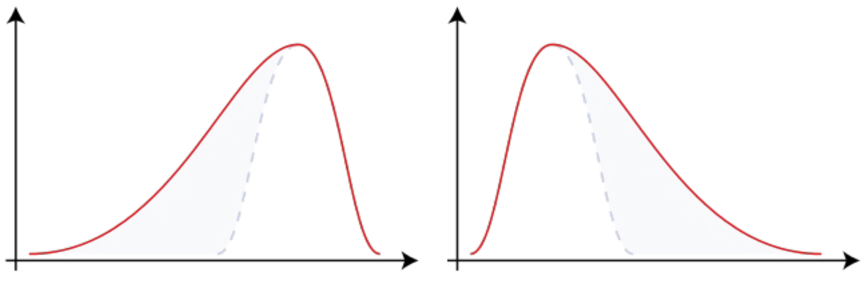
FXT mode : μ_B=750 MeV @ 3GeV



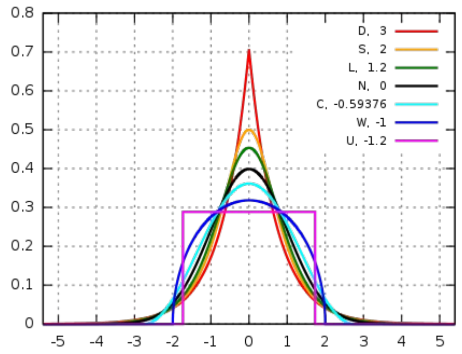
Higher-order fluctuation

- 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

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

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

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

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

- 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

$$C_2 = <(\delta N)^2>_c \approx \xi^2 \qquad C_5 = <(\delta N)^5>_c \approx \xi^{9.5}$$
$$C_3 = <(\delta N)^3>_c \approx \xi^{4.5} \qquad C_6 = <(\delta N)^6>_c \approx \xi^{12}$$
$$C_4 = <(\delta N)^4>_c \approx \xi^7$$

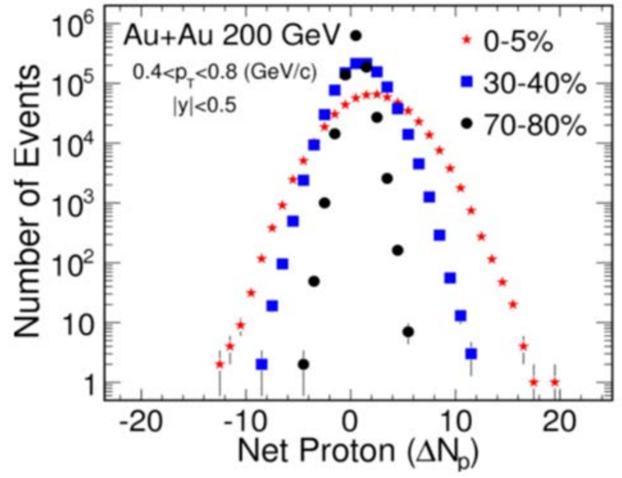
M. A. Stephanov, PRL102.032301(2009), PRL107.052301(2011)
M. Asakawa, S. Ejiri, and M. Kitazawa, PRL103262301(2009)

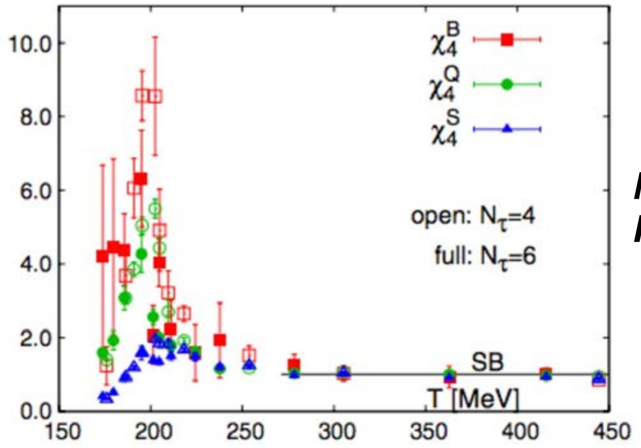
(2) Comparison with susceptibilities

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

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

STAR, PRL105.022302(2010)





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

Baselines

- Skellam distribution $p(k;\mu_1,\mu_2) = \Pr\{K=k\} = e^{-(\mu_1+\mu_2)}\left(\frac{\mu_1}{\mu_2}\right)^{k/2} I_k(2\sqrt{\mu_1\mu_2})$
  - "Statistical" baseline:
    - (Poisson) – (Poisson) = (Skellam)
  - $C_1 = C_3 = C_5 = \mu_1 - \mu_2$
  - $C_2 = C_4 = C_6 = \mu_1 + \mu_2$

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

- Non-critical baseline
  - Initial volume fluctuation, baryon number conservation…

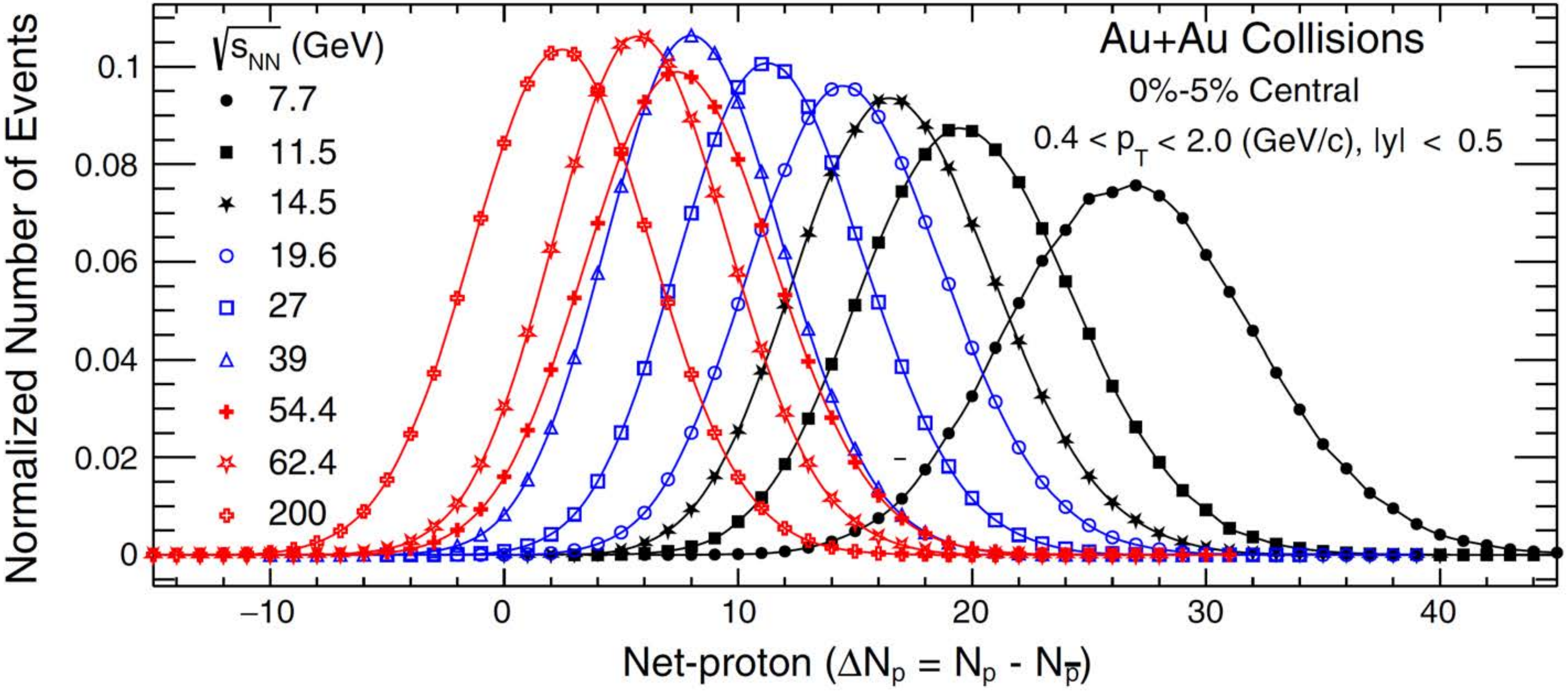
P.Braun-Munzinger et al, NPA982.307(2019), NPA1008.122141(2021)
A. Bzdak et al, EPJC77(2017)5.288, A. Bhattacharyya et al, PRC90.034909(2014)
A. Bzdak, V. Koch, V. Skokov, PRC87.014901(2013)

Methodology

Detector efficiency, Initial volume fluctuations, pileup corrections

Raw net-proton multiplicity distribution

- Need to consider various experimental effects.



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

Experimental challenges

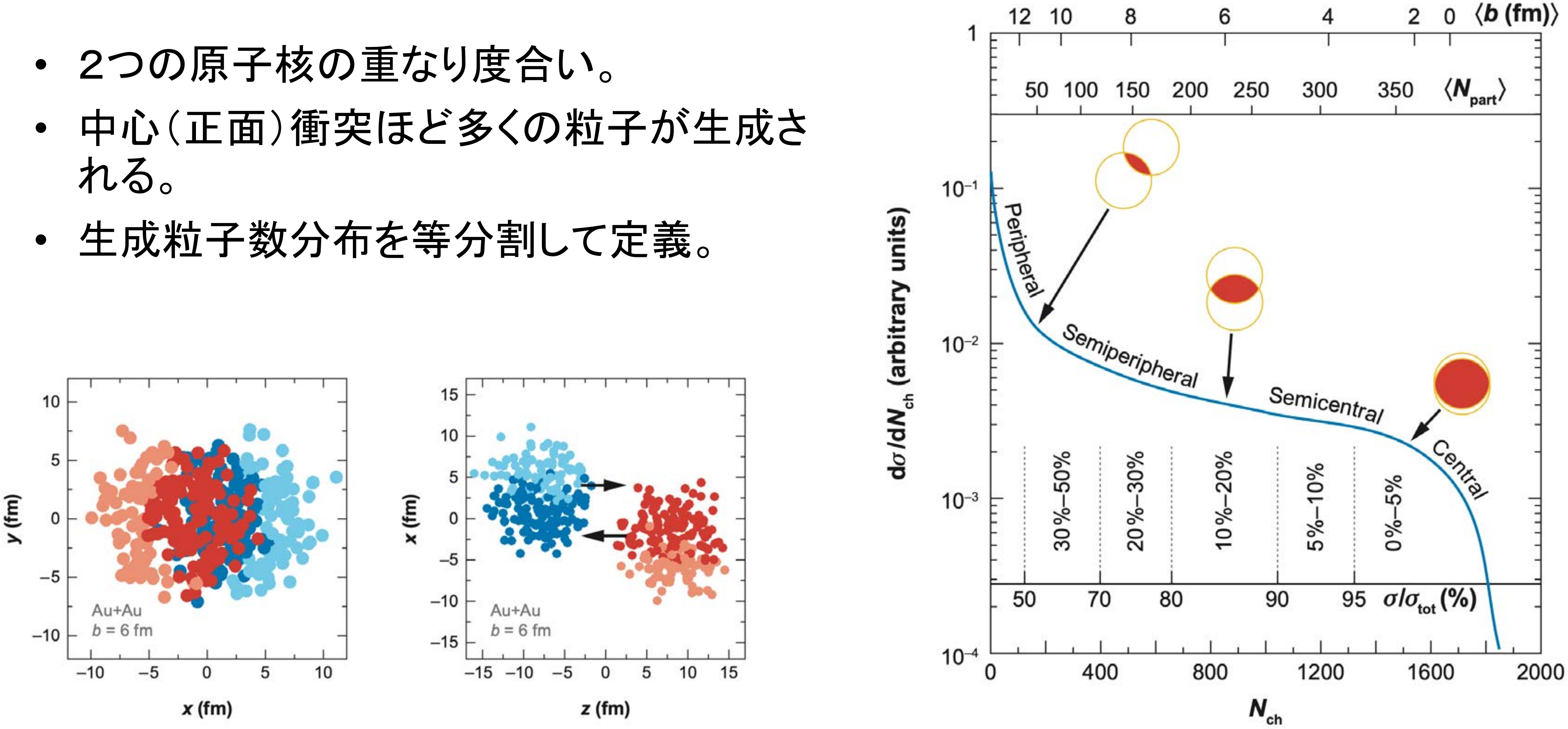
- Detector efficiency correction
  - ***Binomial distribution***
    - ***M. Kitazawa and M. Asakawa, PRC86.024904(2012), A. Bzdak and V. Koch, PRC86.044904(2012), X. Luo, PRC91.034907(2016),***
    - ***T. Nonaka, M. Kitazawa, S. Esumi, PRC95.064912(2017), X. Luo and T. Nonaka, PRC99.044917(2019)***
  - ***Non-binomial distribution***
    - ***T. Nonaka, M. Kitazawa, S. Esumi, NIMA906 10-17(2018)***
    - ***S. Esumi, K. Nakagawa, T. Nonaka, NIMA*****987.164802(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. Grebieszkow, M. Maćkowiak, and S. Mrówczyński, PRC83.054907 (2011)***
  - ***A. Rustamov and M. I. Gorenstein, PRC86.044906 (2012), M. I. Gorenstein, PRC84.024902 (2018)***
  - ***M. Arslandok 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**

中心衝突度

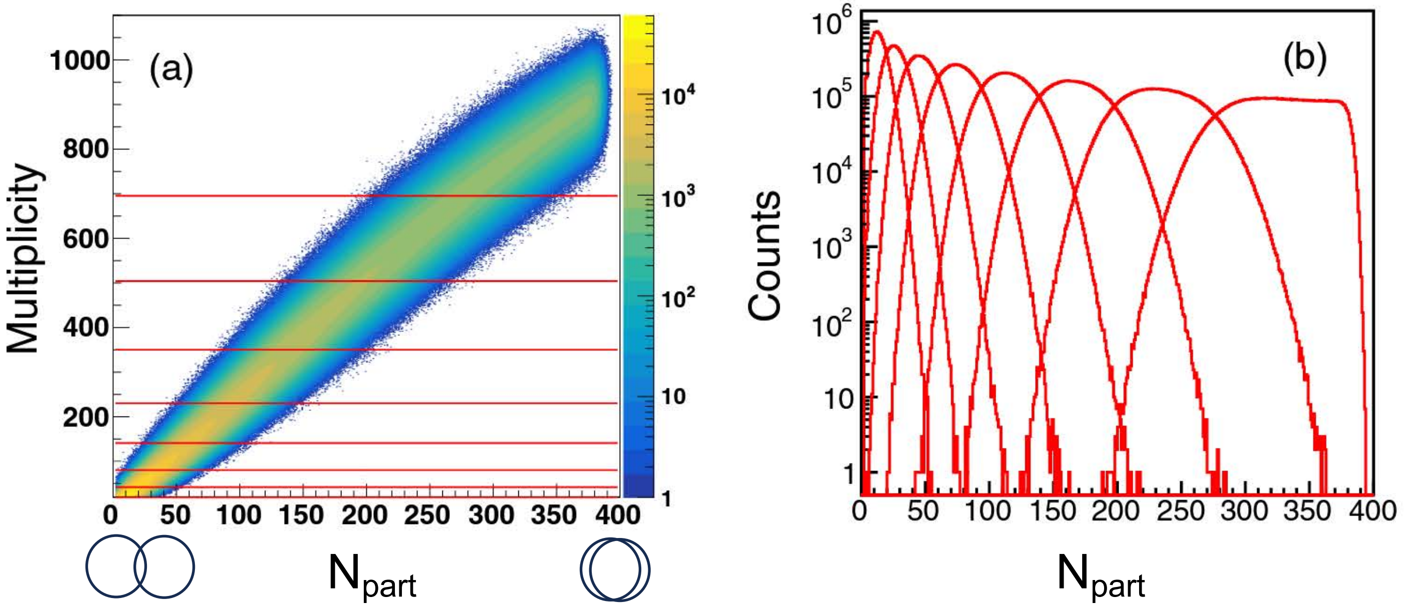
Impact parameter (b): 原子核の中心同士の距離
N_{part}: 衝突に参加した核子数
N_{ch}: 生成粒子数

- ２つの原子核の重なり度合い。
- 中心（正面）衝突ほど多くの粒子が生成される。
- 生成粒子数分布を等分割して定義。



Initial volume fluctuation

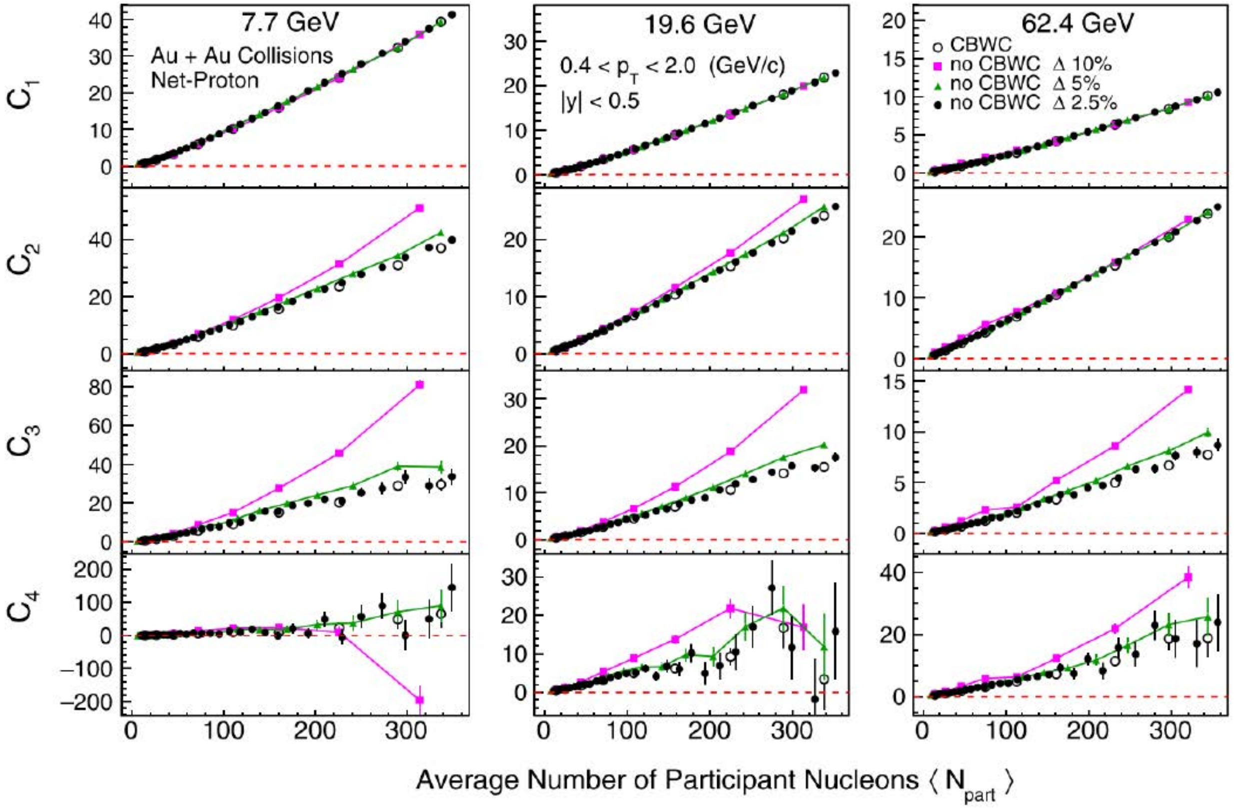
- Initial and final state variables are not one-to-one corresponding, which is referred to as the initial volume fluctuations.
- How does it affect the cumulant measurements?



UrQMD study fitted by Glauber+two-component model

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

Centrality Bin Width Correction (CBWC)



STAR, PRC.104.024902(2021)

Centrality bin width for cumulant calculations

- Initial volume fluctuations can be partly suppressed by CBWC.

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

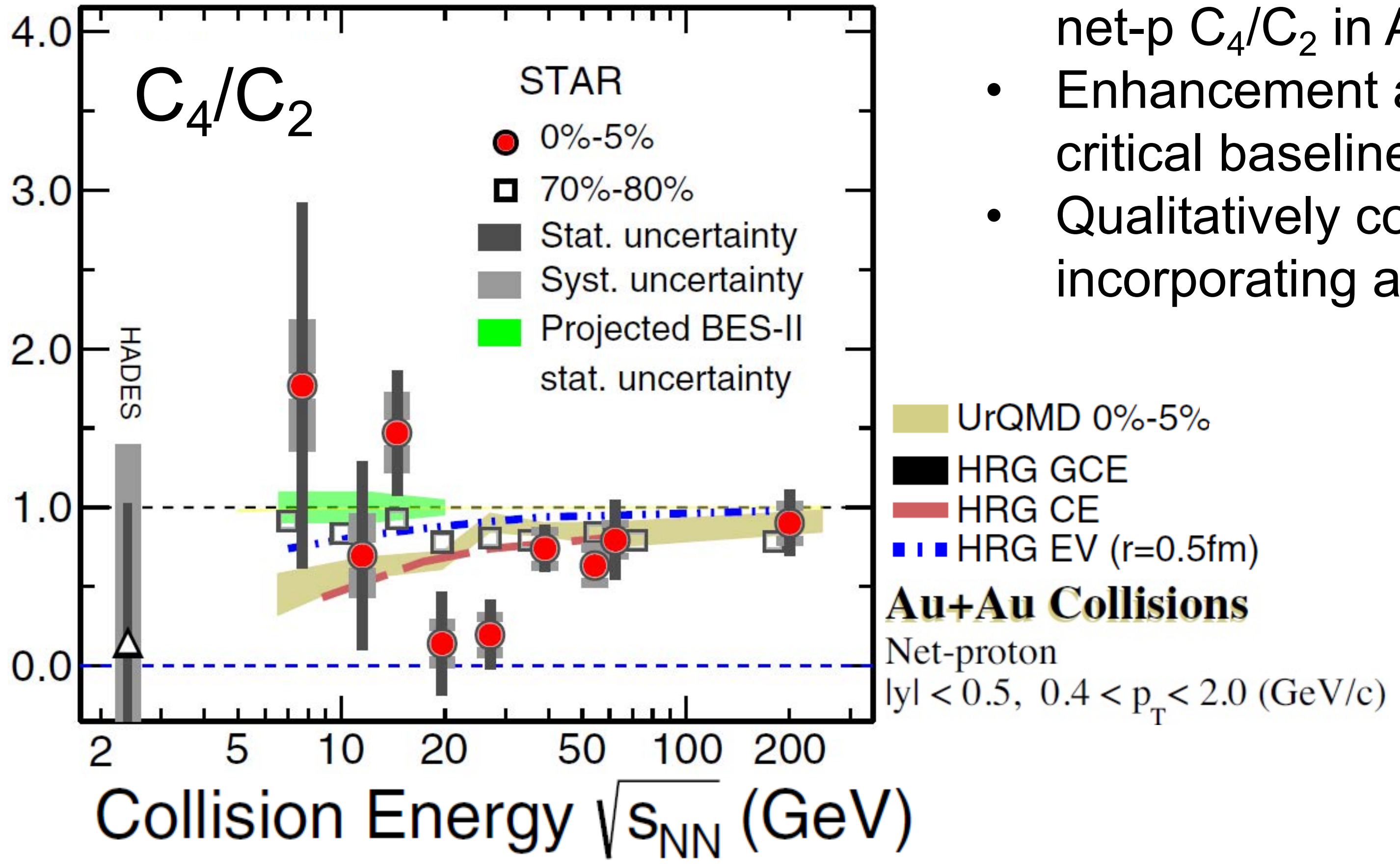
- Purely data-driven, but cannot eliminate initial volume fluctuations.

Experimental results

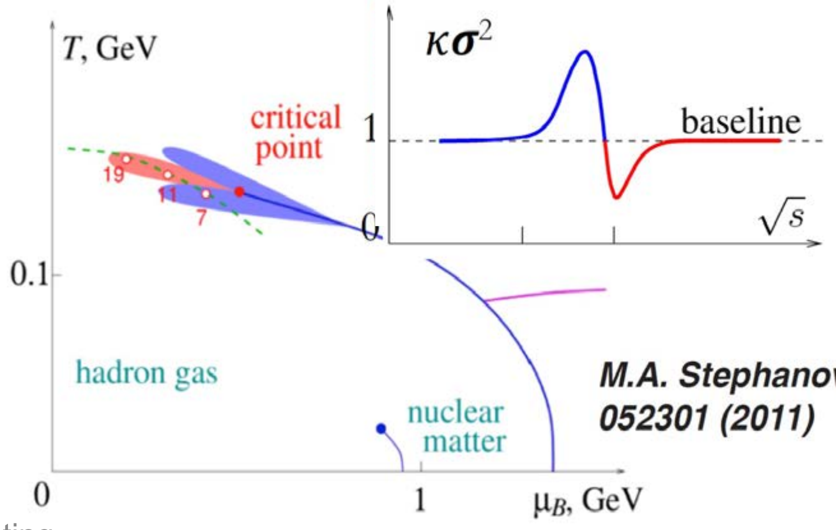
- 4^{th}-order fluctuations from BES-I and BES-II

Net-proton C_4/C_2

STAR, PRL126.092301(2021)

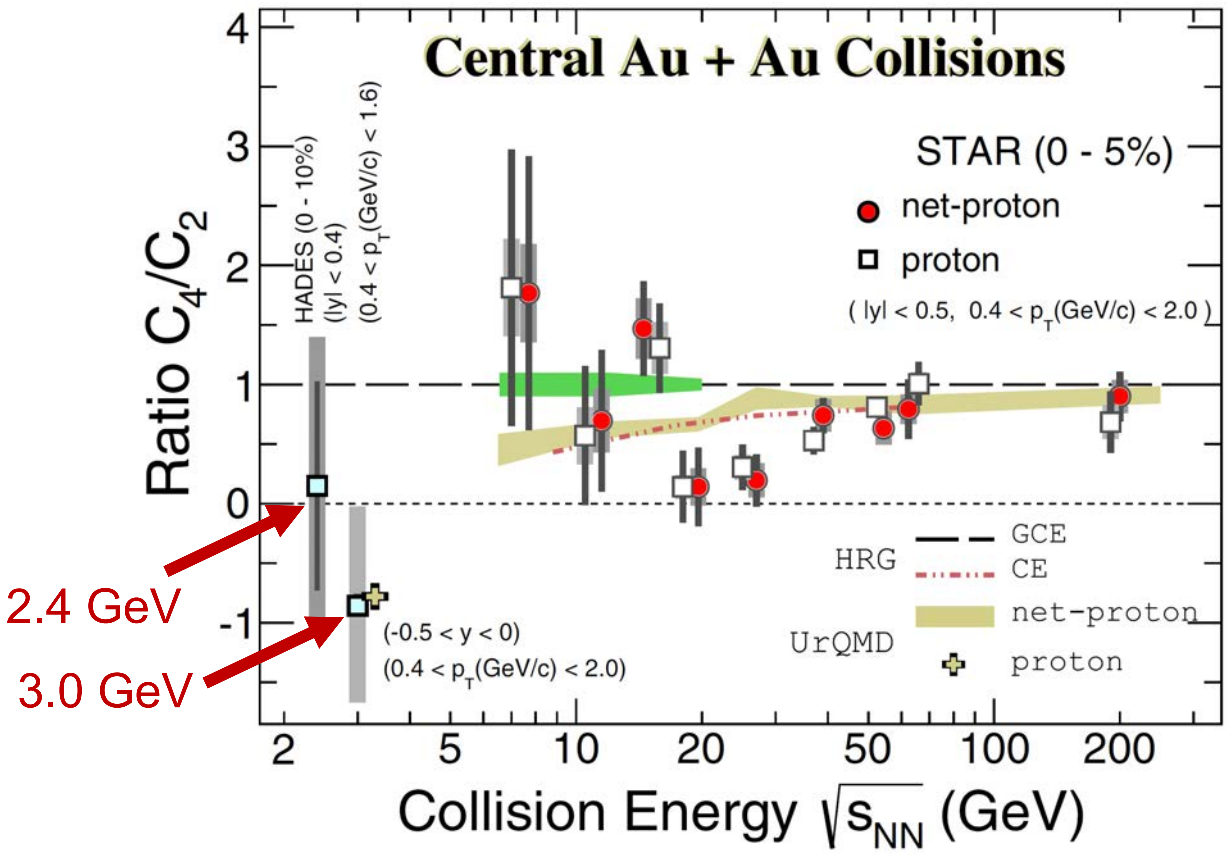


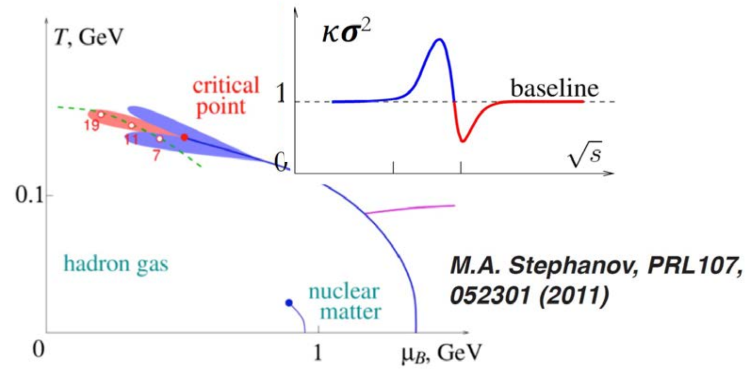
- Non-monotonic beam energy dependence (3.1σ) of net-p C_4/C_2 in Au+Au central collisions.
- Enhancement at ~7.7 GeV is not reproduced by non-critical baselines.
- Qualitatively consistent with the model prediction incorporating a critical point.



M.A. Stephanov, PRL107, 052301 (2011)

Collision energy dependence





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

HADES, PRC102.024914(2020)
STAR, PRL128.202303(2022), PRC107.024908(2023)

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

$3 \le \sqrt{s_{NN}}\ (GeV) \le 200 \rightarrow 750 \ge \mu_B\ (MeV) \ge 25$

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

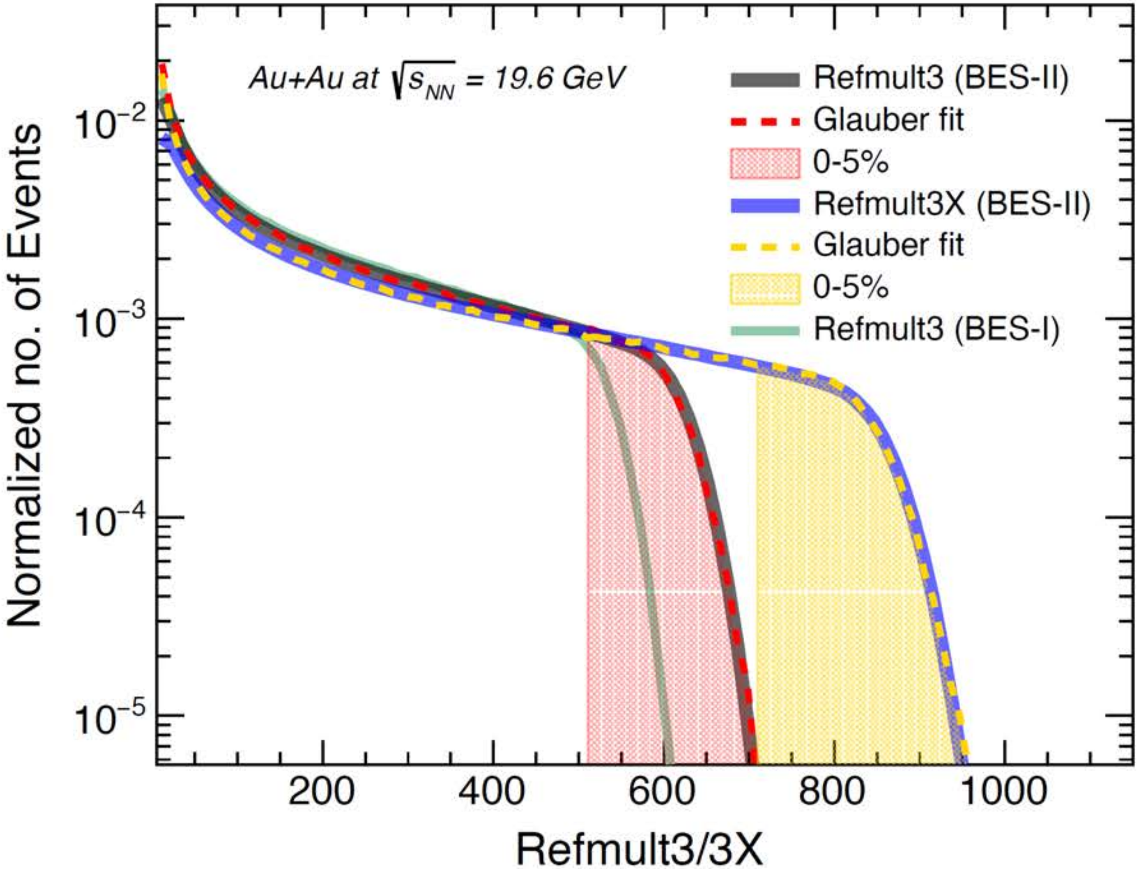
eTOF:
- Forward rapidity coverage
- PID at η = 1.05 to 1.5
- Borrowed from CBM-FAIR
- Ready in 2019

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: $p_T \geq 125$ MeV/c $\rightarrow p_T \geq 60$ MeV/c
3) Enhance centrality/event plane resolution, suppress auto correlations
4) Enable the fixed-target program: $\mu_B \leq 420$ **MeV** $\rightarrow \mu_B \leq 750$ **MeV**

Centrality

- Defined using charged particle multiplicity measured by STAR
- Exclude protons and antiprotons to avoid self correlation



Two choices of centrality

Refmult3: Charged particle multiplicity excluding protons measured within $|\eta| < 1.0$

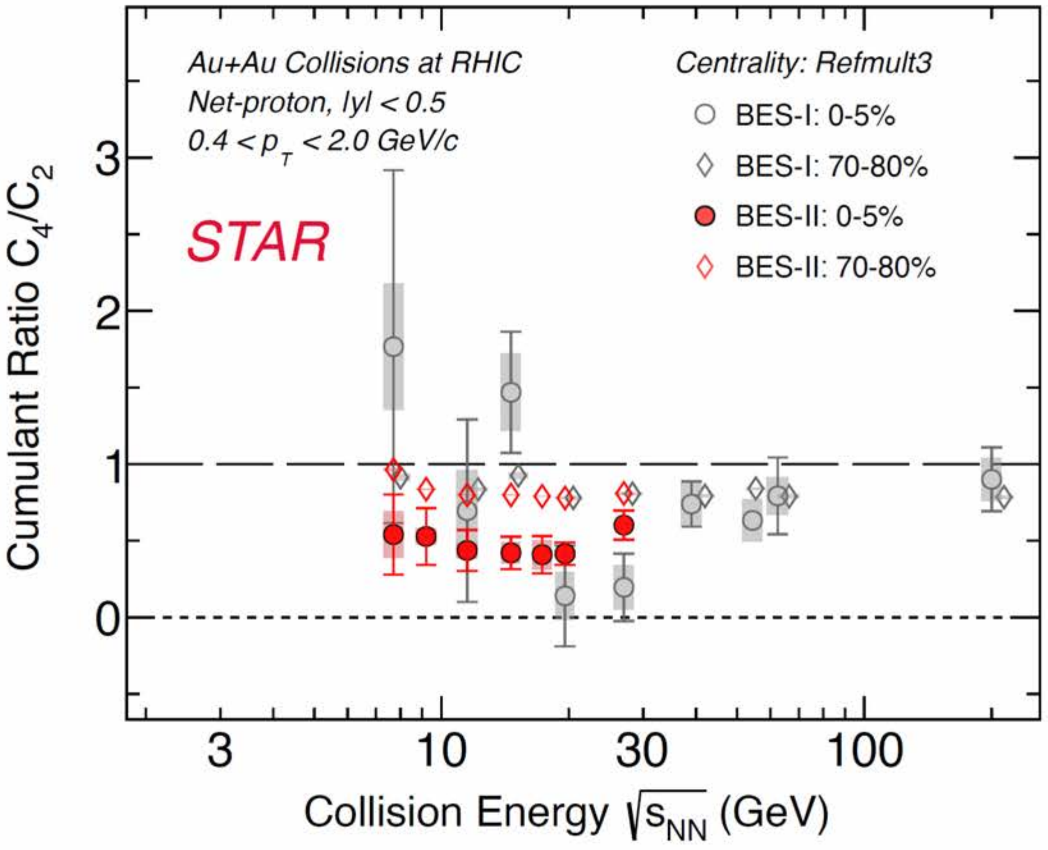
Refmult3X: Charged particle multiplicity excluding protons measured within $|\eta| < 1.6$

Possible due to iTPC upgrade

Larger multiplicity leads to better centrality resolution:

Refmult3X (BES-II) > Refmult3 (BES-II) > Refmult3 (BES-I)

New results from BES-II

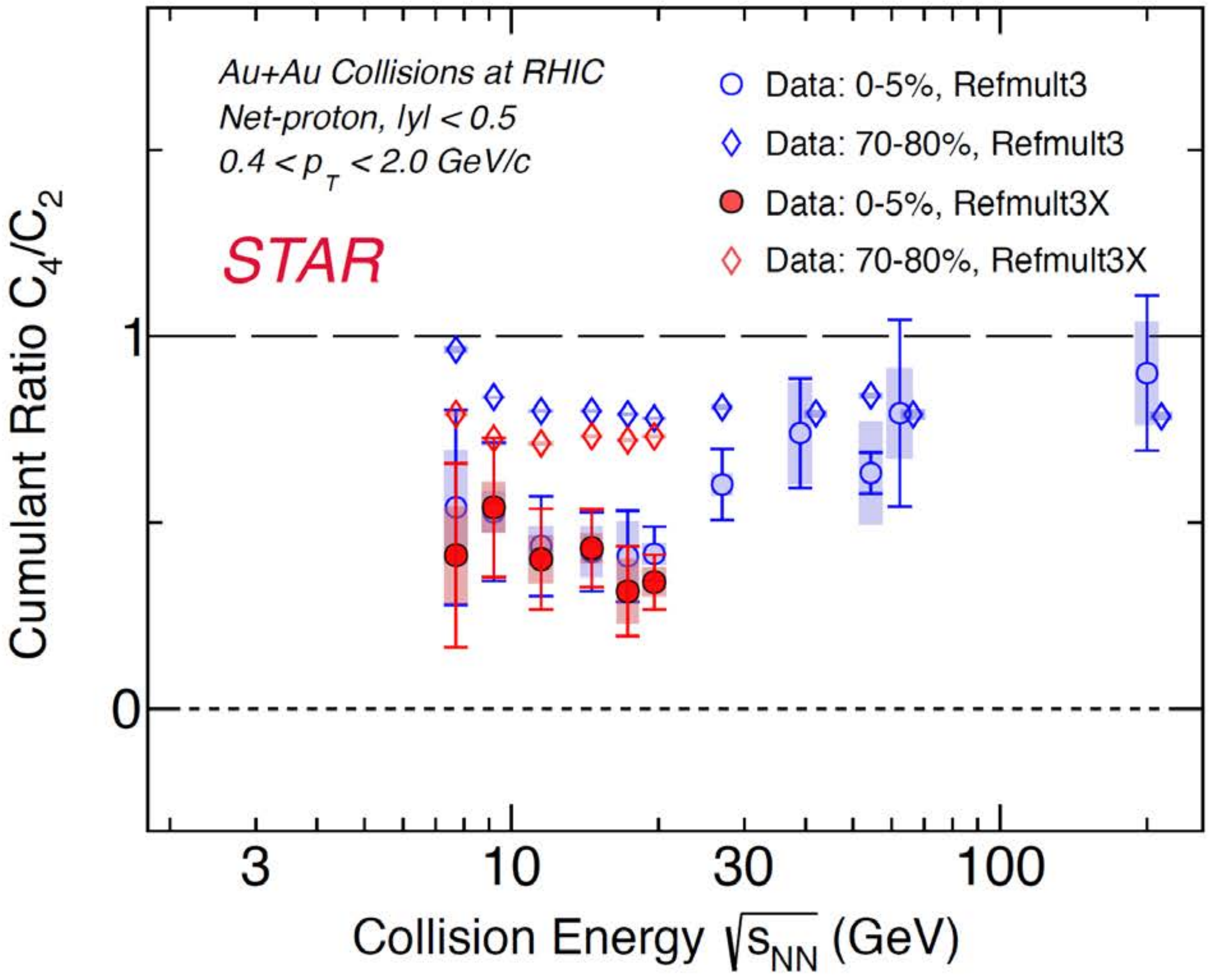


Deviation between BES-II and BES-I data

$\sqrt{s_{NN}}$ (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 consistent with BES-I within uncertainties.

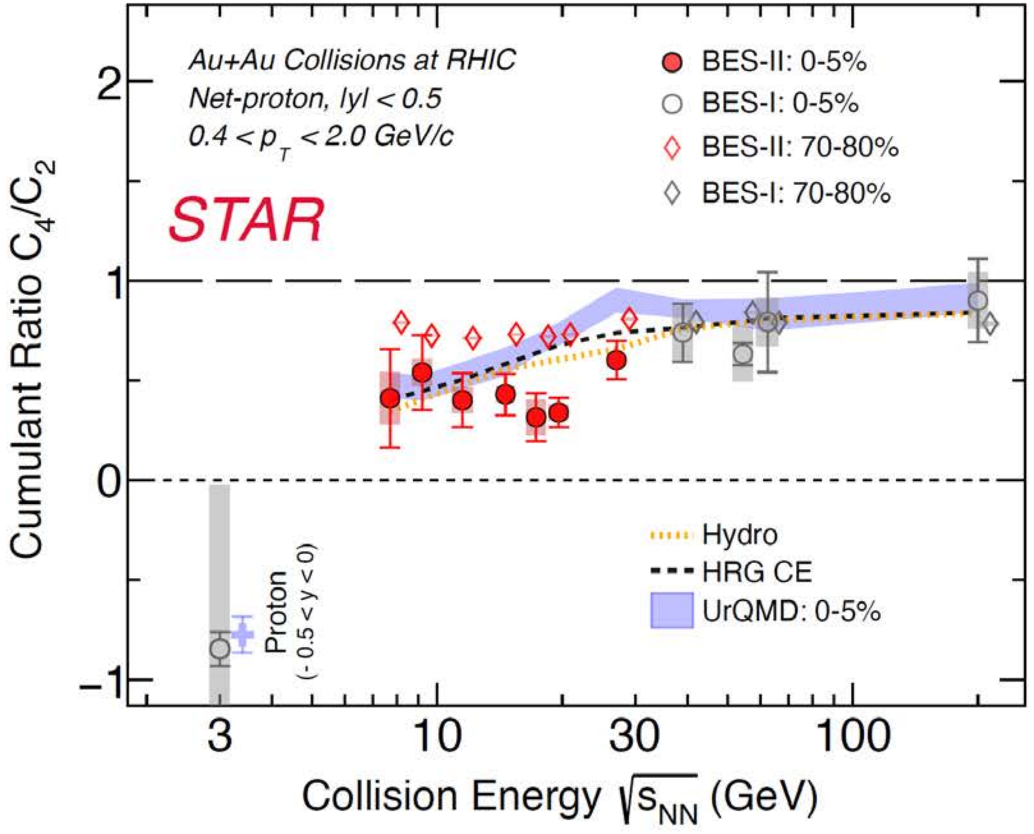
Effect of centrality resolution

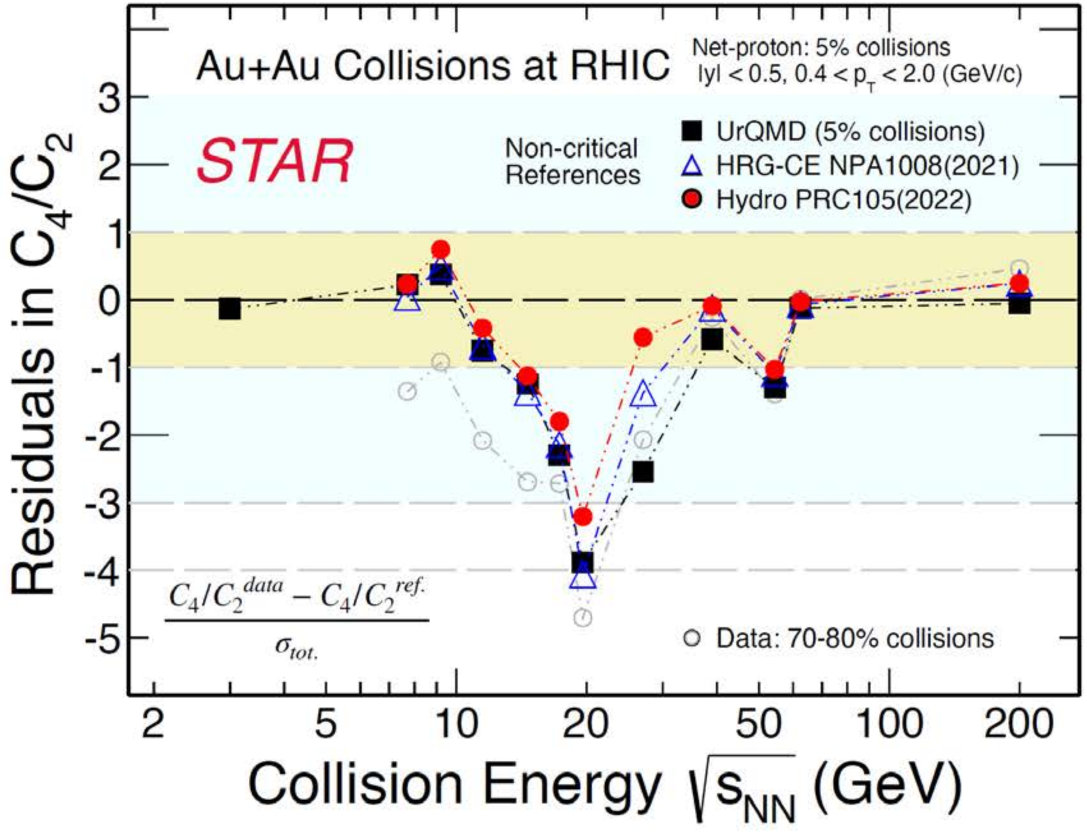


1. **0-5% centrality C_4/C_2** results show good agreement between Refmult3 and Refmult3X: **weak effect of centrality resolution.**

2. BES-II results shown hereafter are with Refmult3X

Model comparison





C_4/C_2 shows minimum around ~20 GeV comparing to non-CP models, 70-80% data

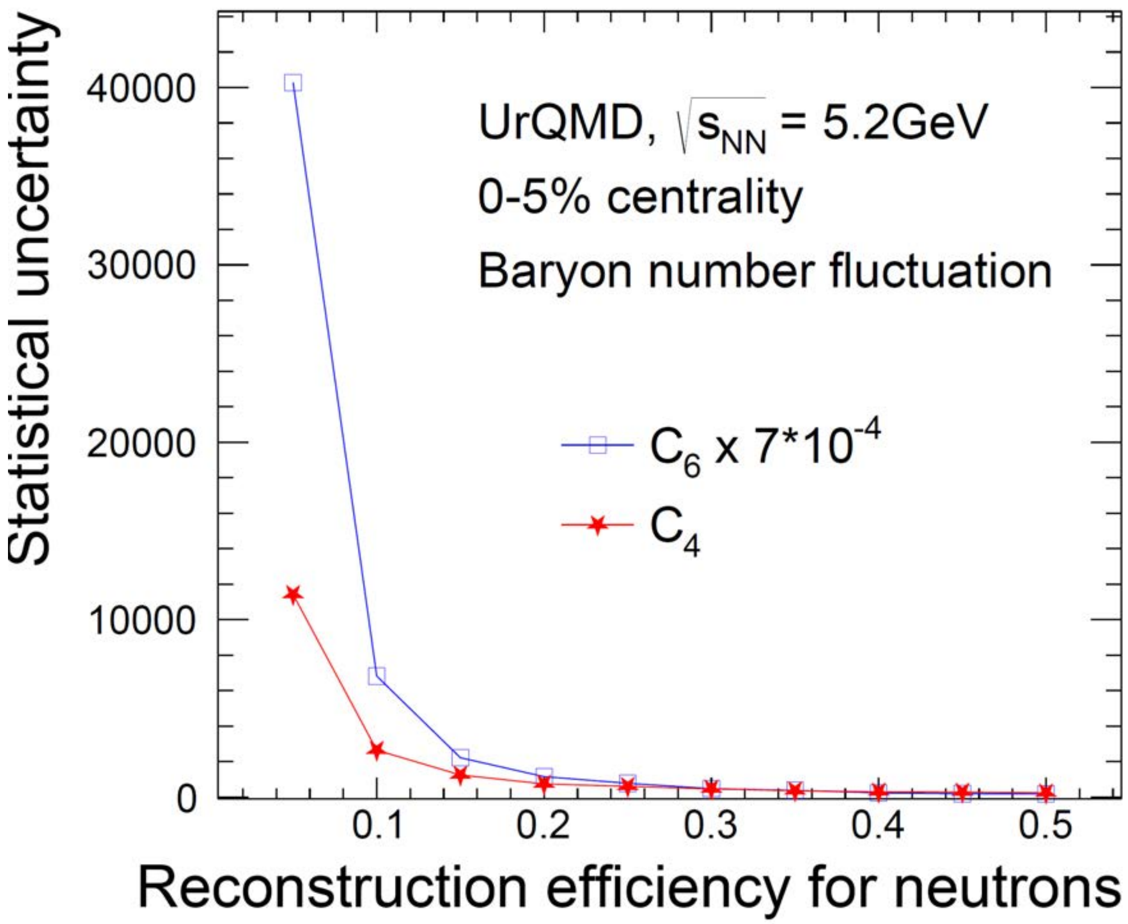
HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)

Summary

- Net-proton C_4/C_2 (BES-II) significant deviation from model expectations at ~20 GeV. Theoretical input is needed for interpretation.
- Results from FXT ($3.3<\sqrt{s_{NN}}<4.5$ GeV) will come in near future.

Thank you for your attention

Detector efficiency for neutrons



- Reconstruction efficiency for neutrons is varied to see the statistical uncertainties after efficiency correction.
- Statistical uncertainties for C_4 and C_6 drastically increase below <20% efficiency.
- More detailed requirement should be determined based on the required precision on final results and event statistics.