Precision Measurement of (Net-)proton Number Fluctuations in Au+Au Collisions from BES-II Program at RHIC-STAR

Bappaditya Mondal for the STAR Collaboration

National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India

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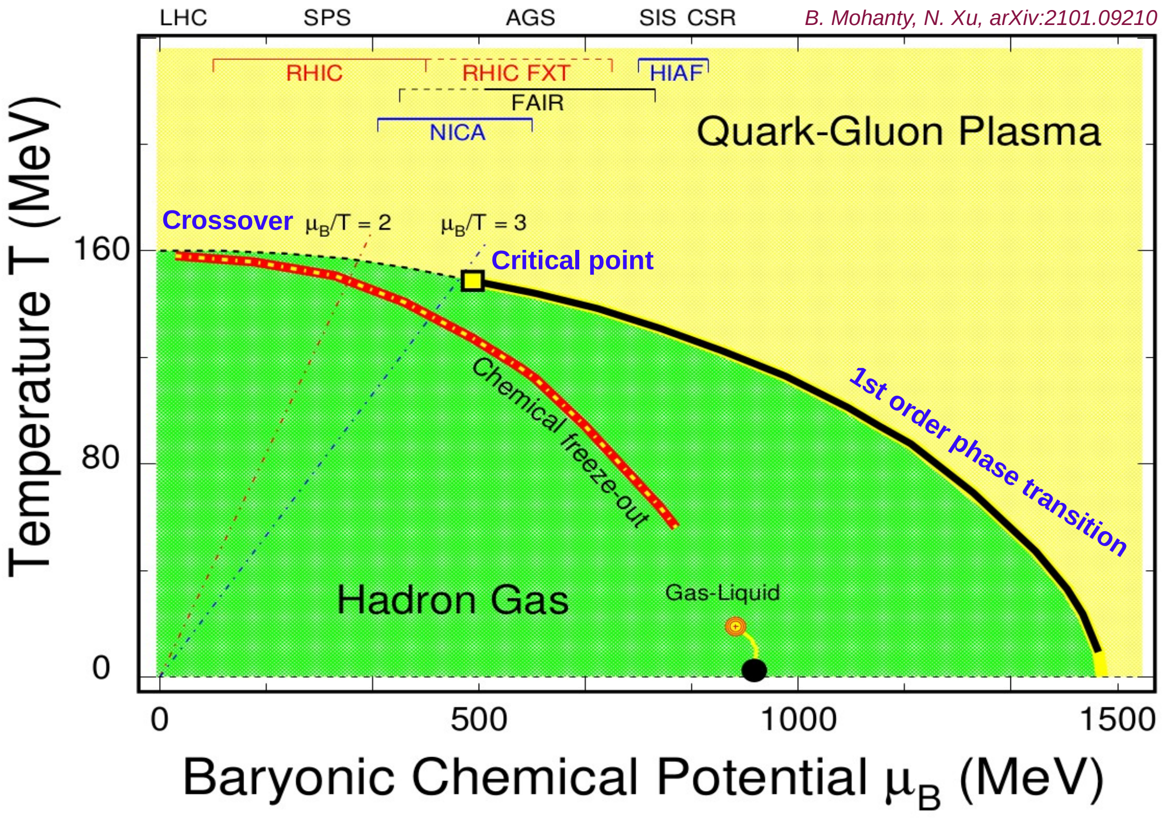
Outline :

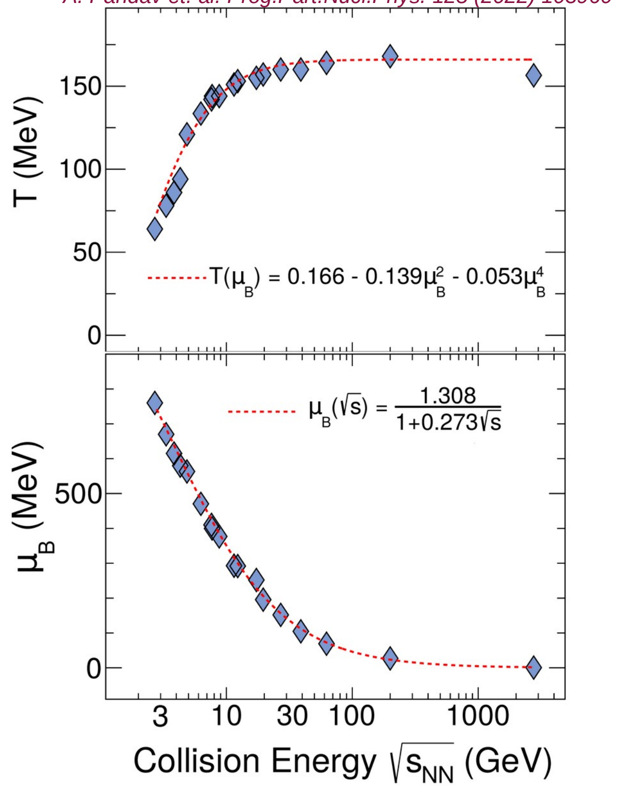
1) *Introduction : QCD Phase Diagram*
2) *Observables*
3) *Analysis details*
4) *Results*
5) *Summary and Outlook*

Introduction- QCD phase diagram

B. Mohanty, N. Xu, arXiv:2101.09210



P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302
A. Pandav et. al. Prog.Part.Nucl.Phys. 125 (2022) 103960



- **Goal:** To study QCD phase diagram -> search for Critical Point (CP).
- **Scan:** Varying collision energy changes Temperature (T) and Baryon Chemical Potential (μ_B).
- **Observables:** Fluctuation of conserved quantities are sensitive observables to study QCD phase diagram.

Observables

- Higher order cumulants of (net-) proton multiplicity distribution

Cumulants

$C_1 = \langle N \rangle$

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

$C_3 = \langle (\delta N)^3 \rangle$

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

Factorial Cumulants

$\kappa_1 = C_1$

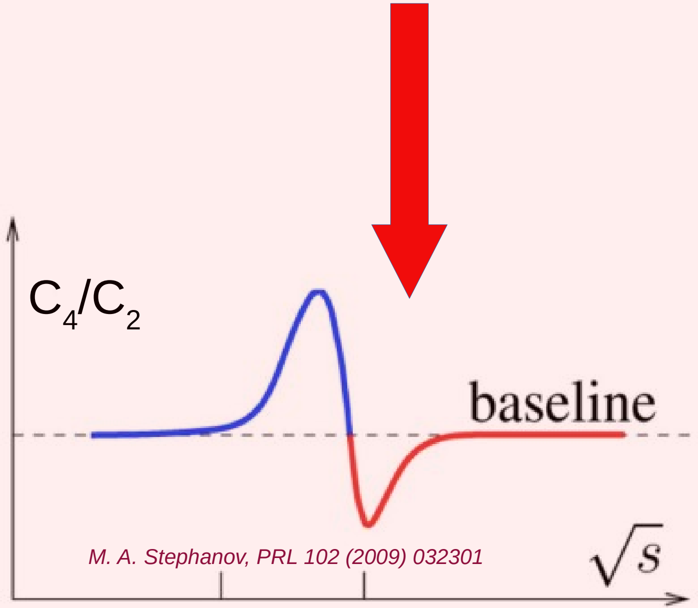
$\kappa_2 = -C_1 + C_2$

$\kappa_3 = 2C_1 - 3C_2 + C_3$

$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$

Theory expectation

Presence of critical point -> non-monotonic collision energy dependence of C_4/C_2



- **Related to correlation length:** $C_2 \sim \xi^2 \quad C_4 \sim \xi^7$

  finite size/time effects reduce ξ

  Higher order -> More sensitive

- **Related to Susceptibility:** $\frac{C_4}{C_2} = \kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}}$

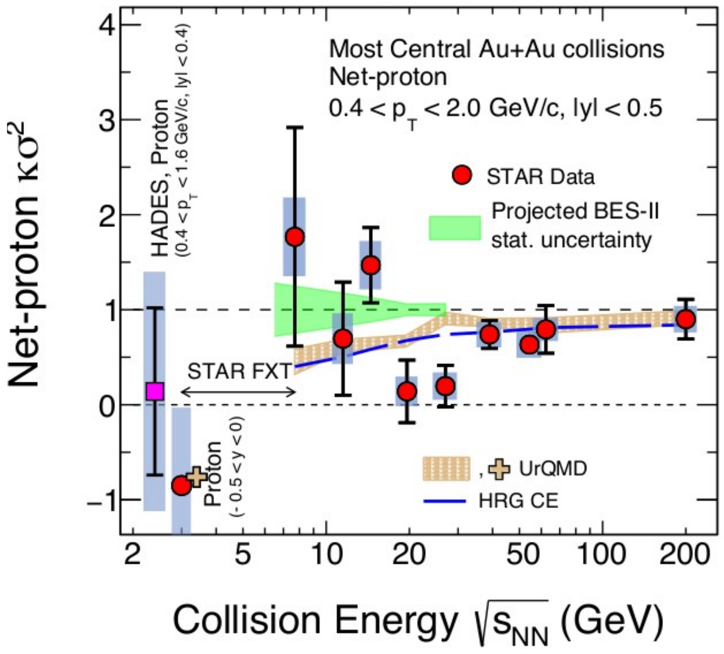
  Comparison with models

Gupta, Luo, Mohanty, Ritter, Xu, Science 332 (2011)
R.V. Gavai and S. Gupta, PLB696, 459(2011)
S. Ejiri, F. Karsch, K. Redlich, PLB633, 275(2006)

Result from BES-I and upgrades in BES-II

BES-I

STAR, PRL 126 (2021) 092301, PRL 128 (2022) 202303
HADES, PRC 102 (2020) 024914



- ✔ Fluctuation relative to Poisson baseline.
- ✔ Precision measurement needed at lower energies: **BES-II** $(7.7-27\,GeV)$
- ✔ To reach even lower energies $\left(\sqrt{s_{NN}}=3.0-7.7\,GeV\right)$: **FXT** program. Up to 3 GeV.

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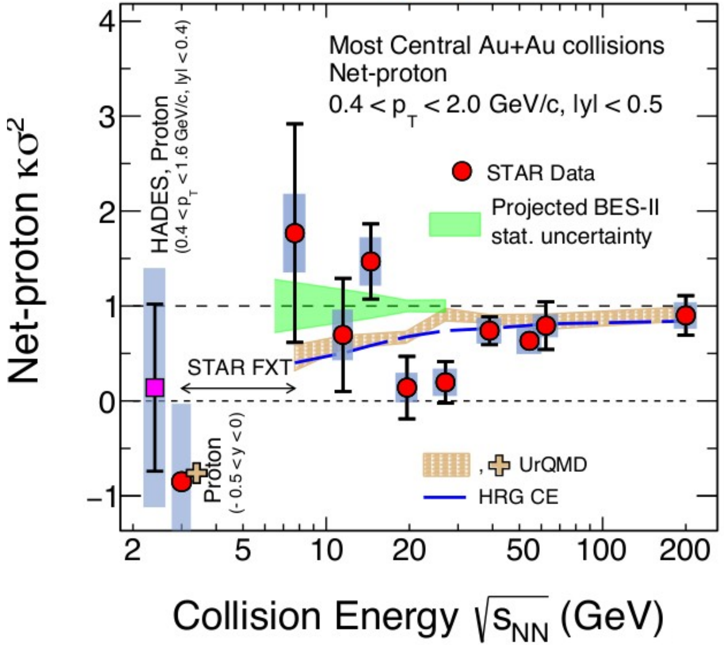

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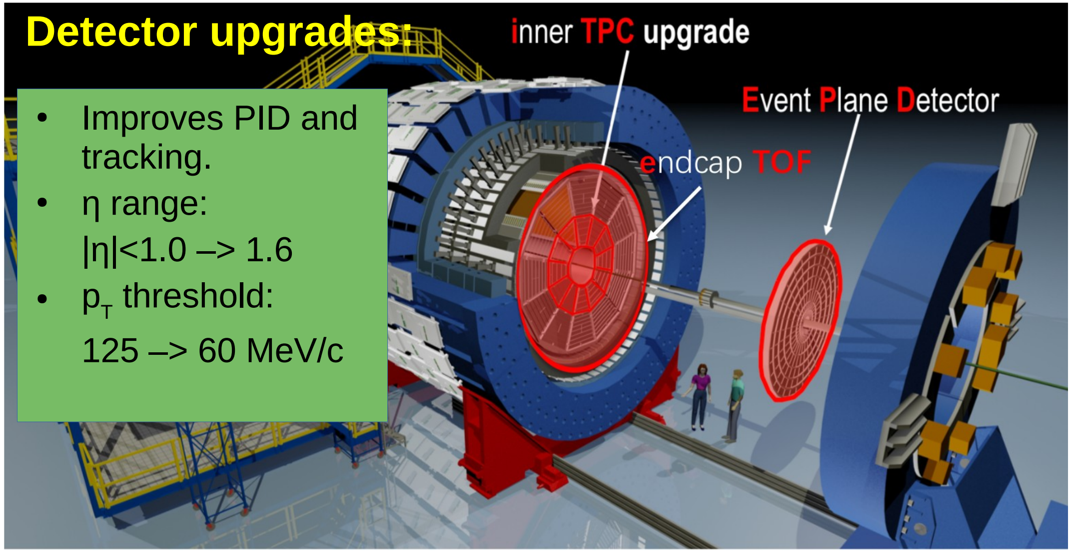
Upgrades in BES-II

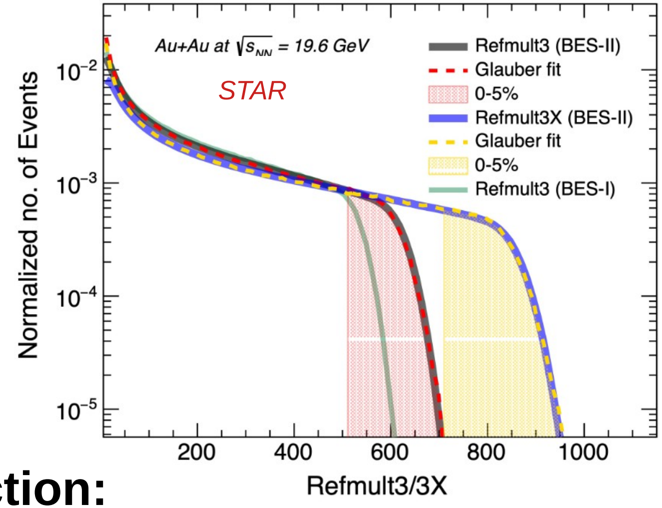


Improvement in statistics:

$\sqrt{s_{NN}}\,(GeV)$	7.7	9.2	11.5	14.5	17.3	19.6	27
$\mu_B\,(MeV)$	420	372	316	262	230	206	156
Events BES-I (10^6)	3	-	7	20	-	15	30
Events BES-II (10^6)	45	78	110	178	116	270	220

Centrality, PID & net-proton distribution

✿ Centrality:



1. RefMult3: Charge particles excluding protons/ anti protons within **|η|<1.0**

2. RefMult3X: Charge particles excluding protons/ anti protons within **|η|<1.6**

3. Centrality resolution:

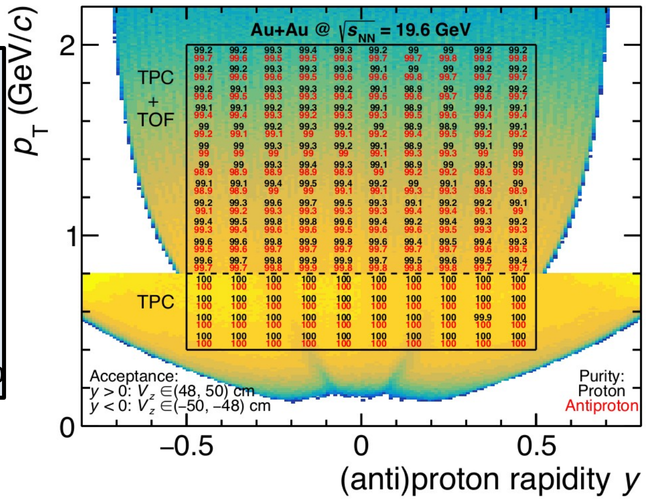
RefMult3X (BES-II) > RefMult3 (BES-II) > RefMult3 (BES-I)

✿ Proton selection:

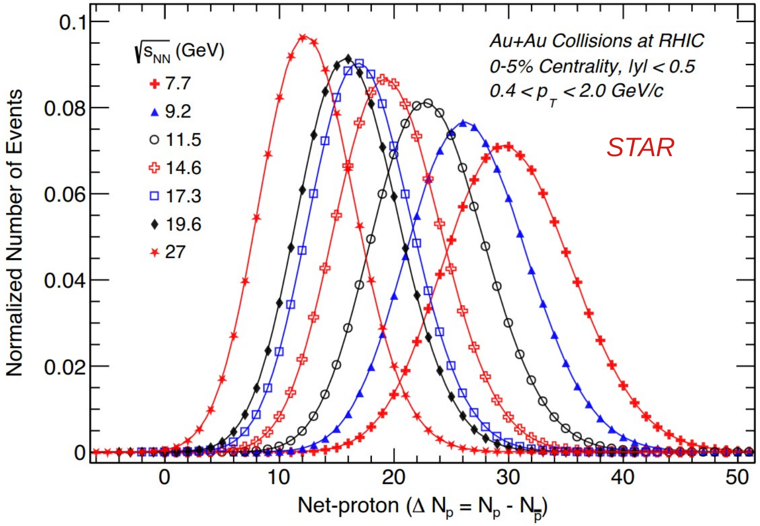
1. TPC and TOF used.

2. kinematic range: $0.4 < p_T$ (GeV/c) <2.0 and $|y| < 0.5$

3. purity for proton and anti proton > 99%



✿ Net-proton distribution: Efficiency uncorrected



Precision of measurements

Percentage statistical and systematic error in net-proton cumulant ratios in 0-5% centrality

$\sqrt{s_{NN}}$	7.7 GeV		19.6 GeV	
	% stat. err	% sys. err	% stat. err	% sys. err
C_2/C_1	0.1%	0.3%	0.06%	0.3%
C_3/C_2	2.1%	1.3%	0.7%	1%
C_4/C_2	61%	29%	22%	11%

Systematic uncertainty estimation: by varying criteria for track selection, particle identification (PID) and reconstruction efficiencies.

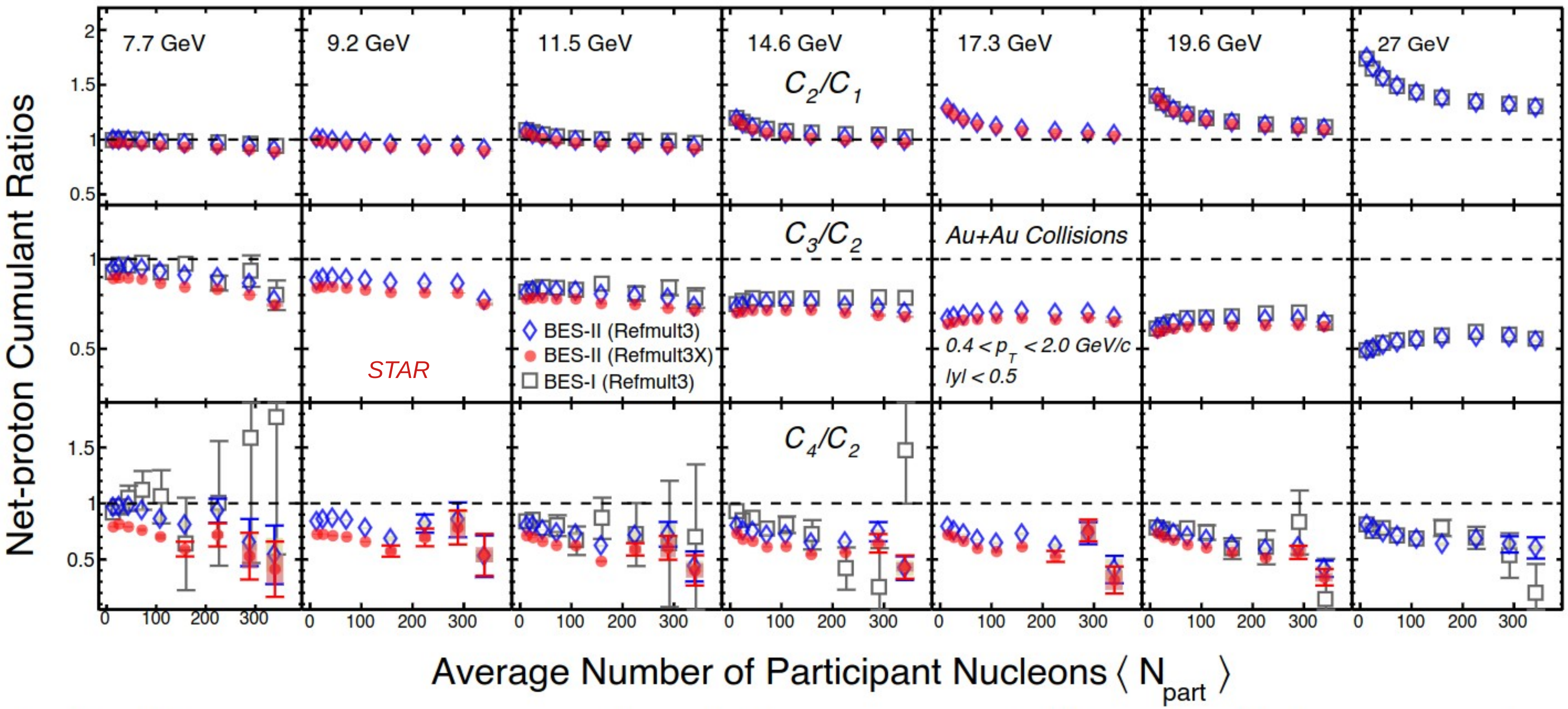
Reduction factor in uncertainties in 0-5% C_4/C_2: BES-II vs BES-I

7.7 GeV		19.6 GeV	
stat. err	sys.err	stat. err	sys. err
4.7	3.2	4.5	4

Precision measurement.
Better quality of data.
Better statistical precision.
Better control on systematics.

Results

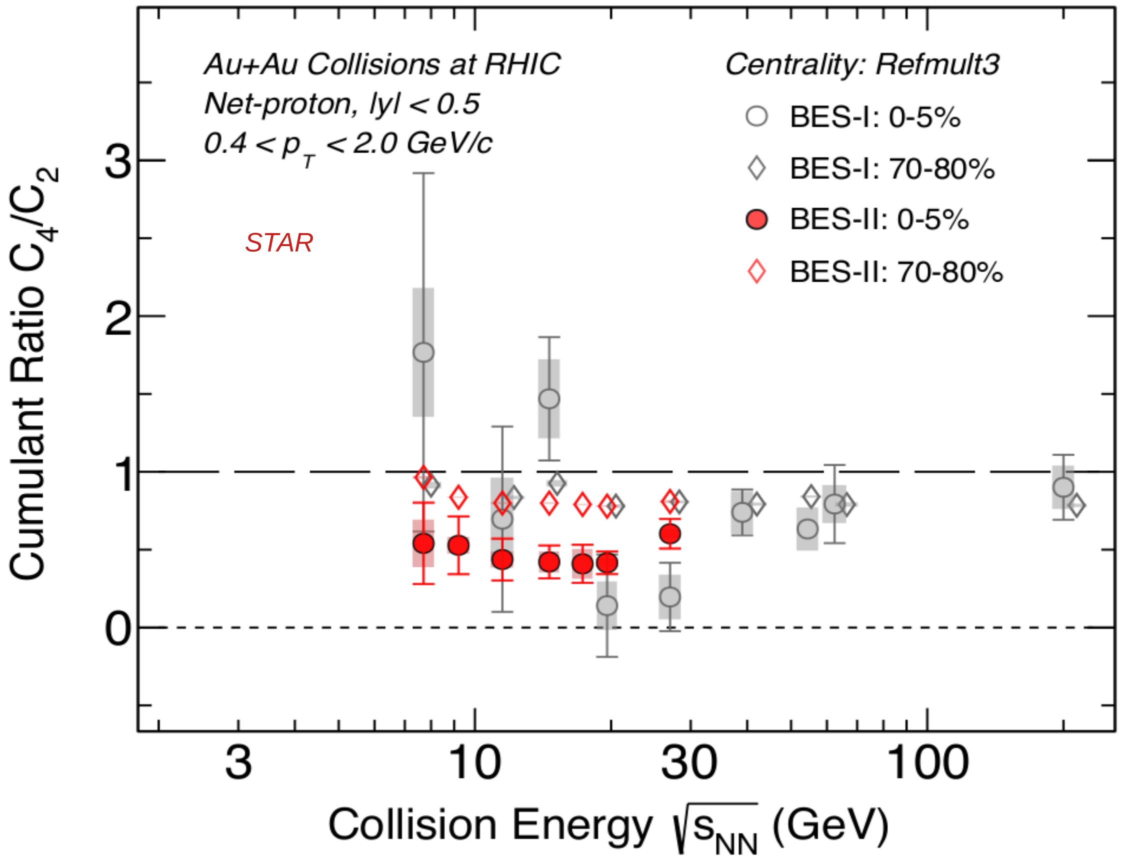
Centrality dependence: net-proton cumulant ratios



- ☑ Efficiency corrected (detector efficiency & PID efficiency) cumulants
- ☑ Statistical error using bootstrap method

- ✿ Smooth variation of cumulant ratios over centrality and collision energy $\left(\sqrt{s_{NN}}\right)$
- ✿ Higher centrality resolution: lower ratios (especially mid central collisions)
  RefMult3X (BES-II) > RefMul3 (BES-II) > RefMult3 (BES-I)
- ✿ Weak effect of centrality resolution: **for 0-5% centrality**

C_4/C_2 energy dependence: BES-I vs BES-II

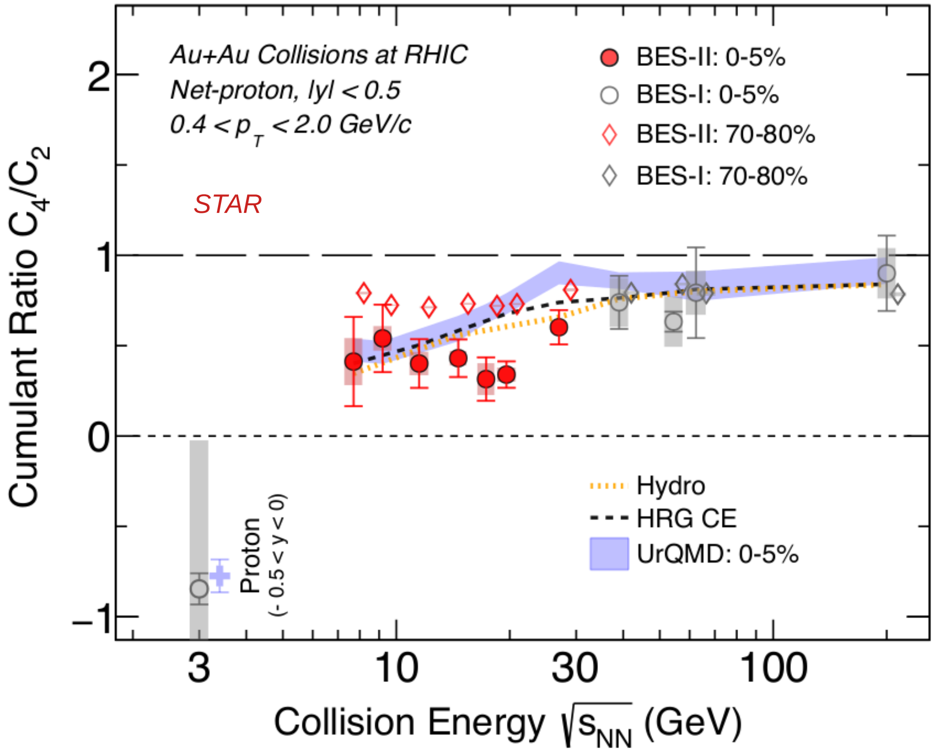


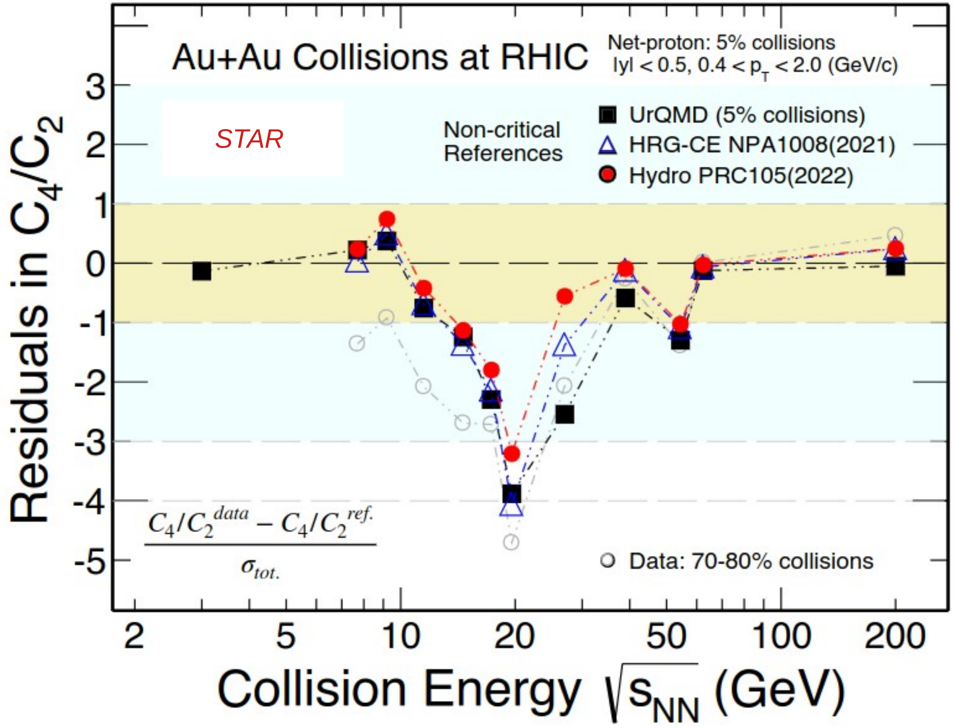
Deviation between BES-I and BES-II:

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

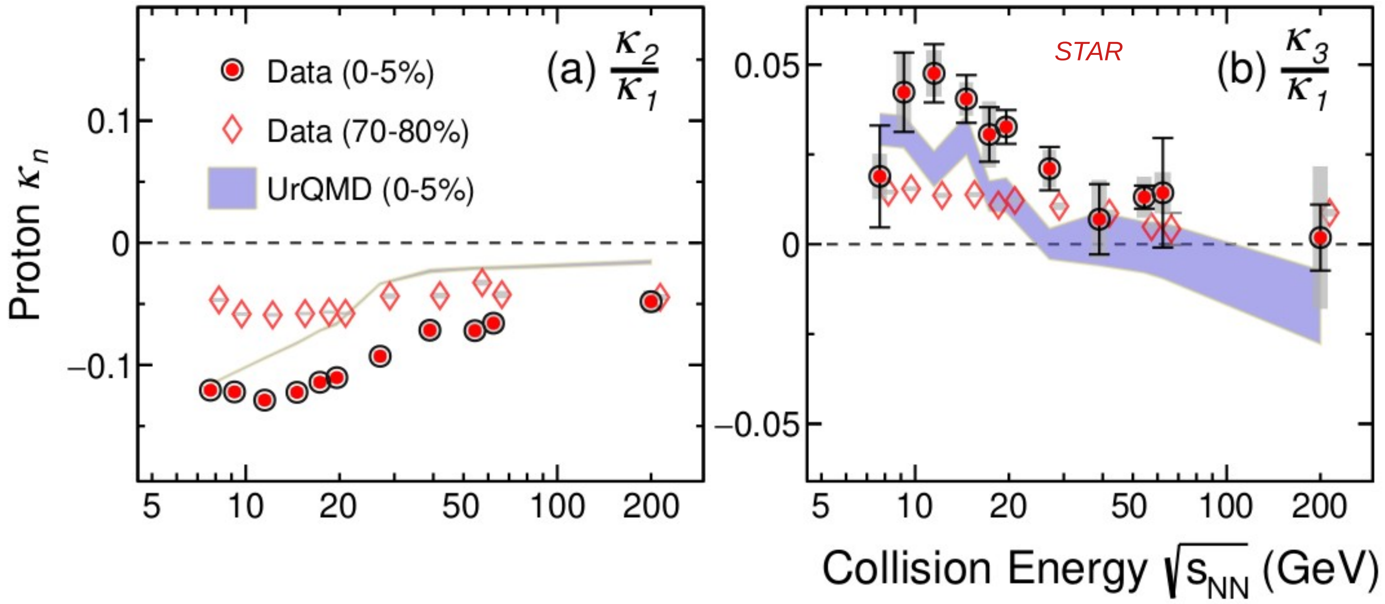
Quantification of deviation





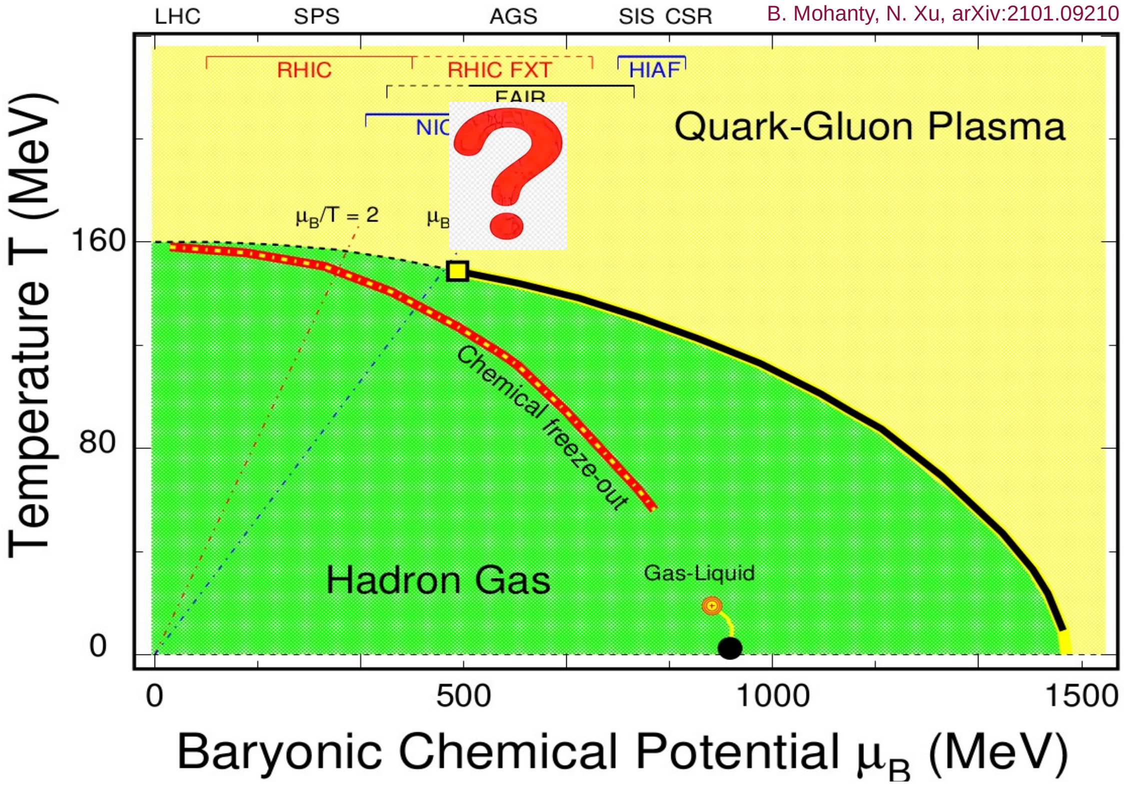
- **Non-CP Models:** Hydro, HRG-CE, UrQMD (All models include baryon number conservation).
- **C_4/C_2 shows minimum around ~20 GeV** comparing to non-CP models, 70-80% data.
- **Maximum deviation: 3.2 – 4.7σ** at 20 GeV (1.3 – 2σ at BES-I).

Energy dependence: proton factorial cumulant ratios



- Deviate from poisson baseline at 0.
- Peripheral results (70-80%) closer to 0.
- UrQMD does not fully describe the data.

Summary



- **Precision measurements** from BES-II collider energies $\left(\sqrt{s_{NN}}\right)$ 7.7 – 27 GeV.
- **Better statistical precision**, better centrality resolution, better control on systematics.
- **Maximum deviation** for 0-5% C_4/C_2 w.r.t various non-CP models and 70-80% data is observed at $\sqrt{s_{NN}} = 20\,GeV$ **(μ_B ~ 206 MeV)** at a level of 3.2 – 4.7σ
- Information of high moment of protons at larger baryon density or lower collision energy is needed in order to pin down the possible existence of the QCD critical point.

Outlook:

- Similar studies for Au+Au collision at fixed target (FXT) energies are being carried out.
- Studies of higher order fluctuation (C_5, C_6, κ_5, κ_6)
- p_T & y dependence study.