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

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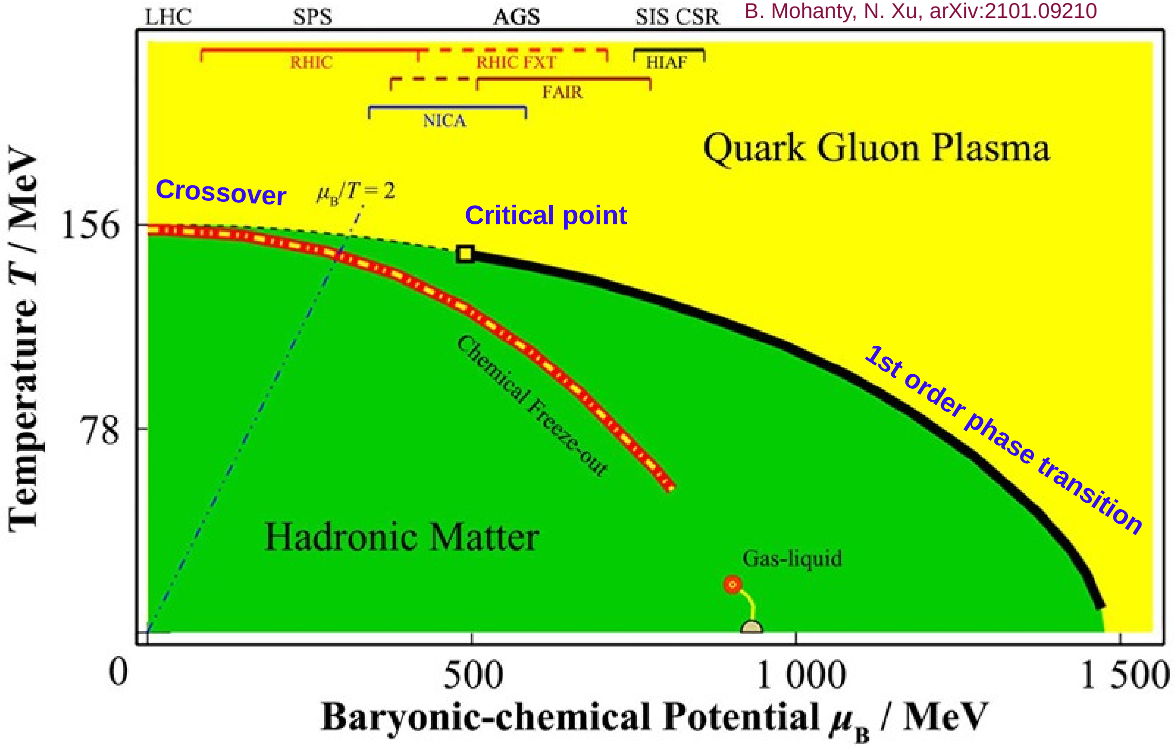
STAR

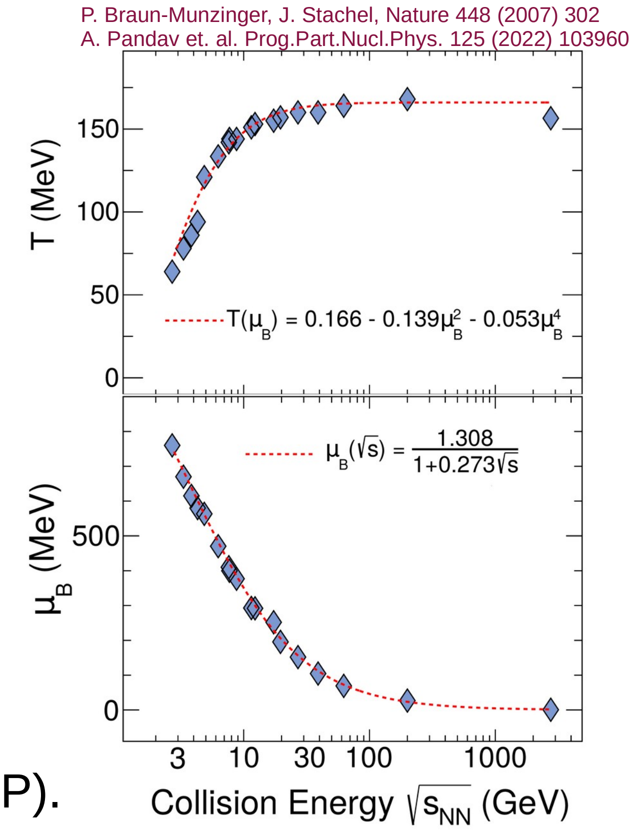
In part supported by

Outline :

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

Introduction- QCD phase diagram





- **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

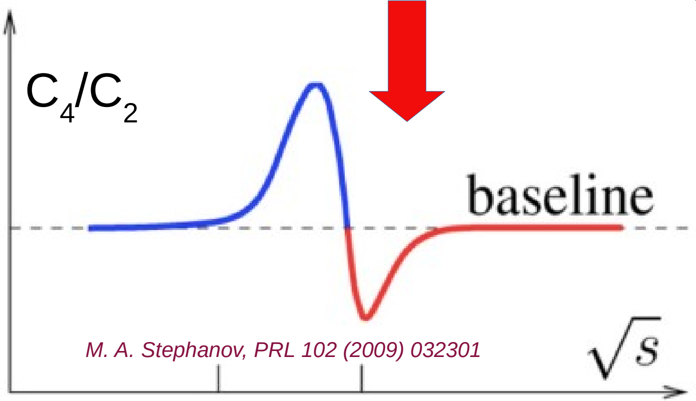
✿ Higher order cumulants of (net-) proton multiplicity distribution

Cumulants	Factorial Cumulants
$C_1 = \langle N \rangle$	$\kappa_1 = C_1$
$C_2 = \langle (\delta N)^2 \rangle$ $here, \delta N = N - \langle N \rangle$	$\kappa_2 = -C_1 + C_2$
$C_3 = \langle (\delta N)^3 \rangle$	$\kappa_3 = 2C_1 - 3C_2 + C_3$
$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$	$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$

Skewness: Asymmetry   **Kurtosis**: Peakedness

✿ **Theory expectation:**
Presence of critical point -> non-monotonic collision energy dependence of C_4/C_2

✿ **Related to correlation length:** $C_2 \sim \xi^2$ $C_4 \sim \xi^7$
finite size/time effects reduce ξ
Higher order -> More sensitive

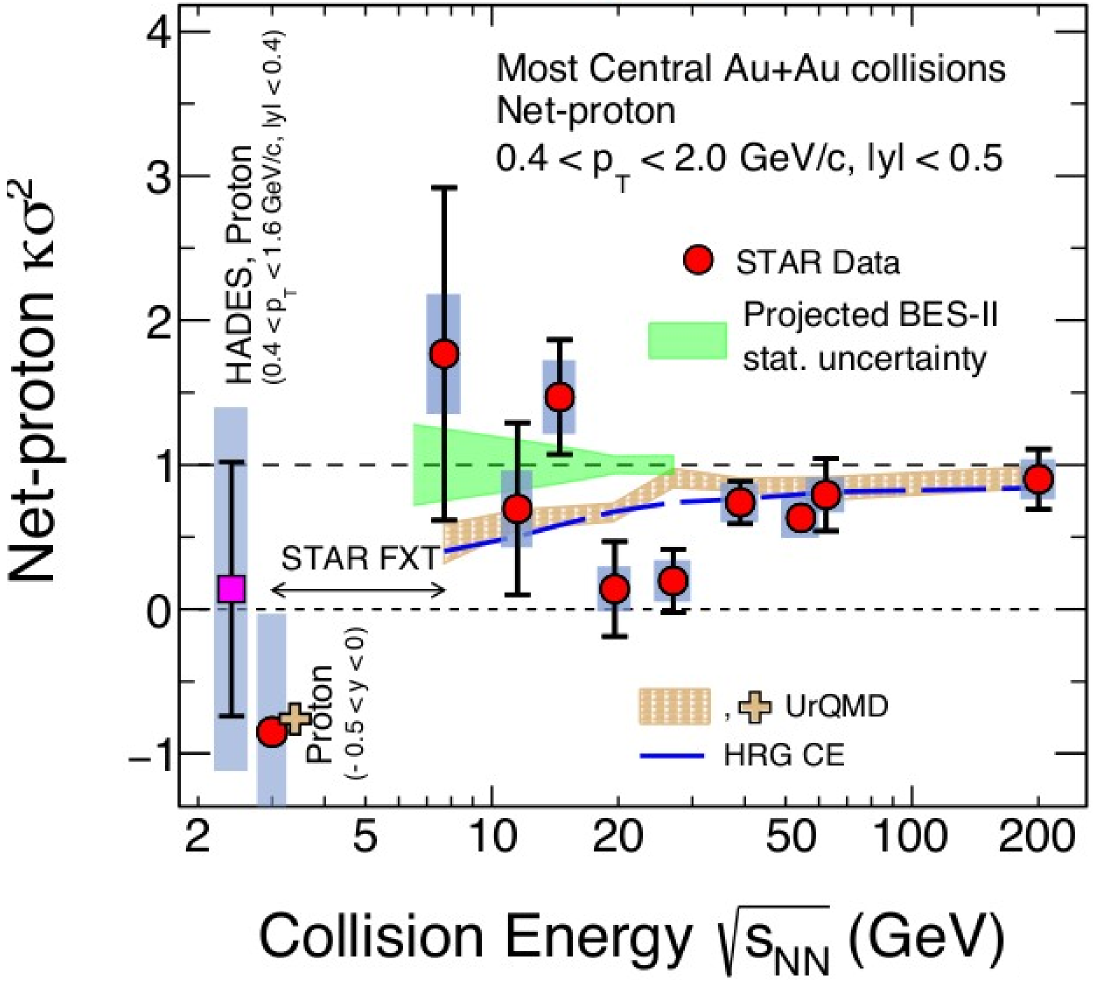


✿ **Related to Susceptibility:**
Comparison with models

$$\frac{C_4}{C_2} = \kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}}$$

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



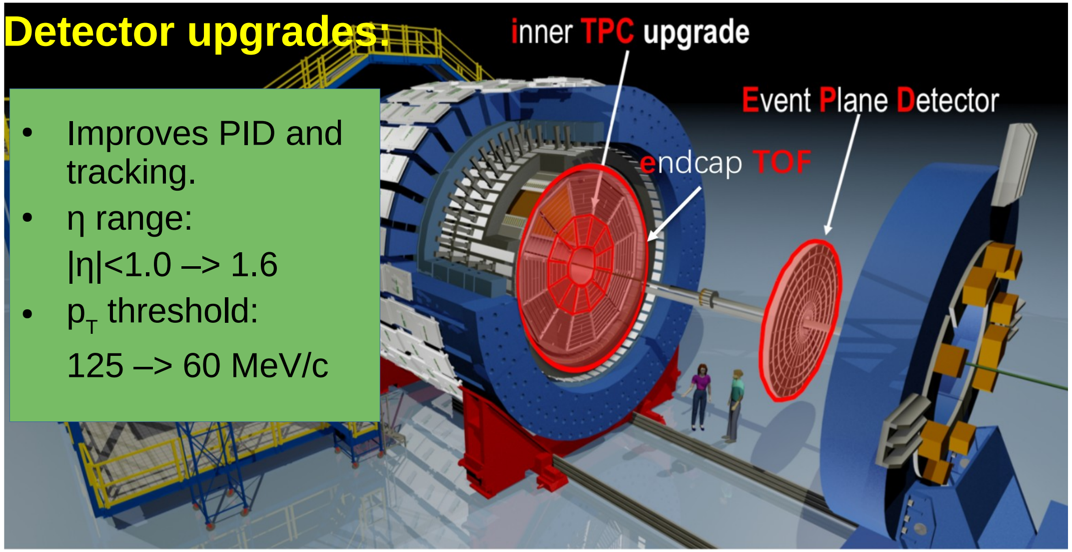
STAR, PRL 126 (2021) 092301, PRL 128 (2022) 202303
HADES, PRC 102 (2020) 024914

- **Phase I of Beam Energy Scan Program (BES-I).**
- **Interesting trend observed.**
- **Fluctuation relative to poisson baseline.**
- **Limited by statistics at lower energies.**
- **BES-II needed for precision measurement.**
- **To reach lower collision energies with FXT program.**

BES-II Program

✿ Upgrades in BES-II:

Detector upgrades:



- Improves PID and tracking.
- η range: $|\eta|<1.0 \rightarrow 1.6$
- p_T threshold: 125 –> 60 MeV/c

Improvement in statistics:

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

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 result			12	3.0 (3.85)	260 + 2000	750

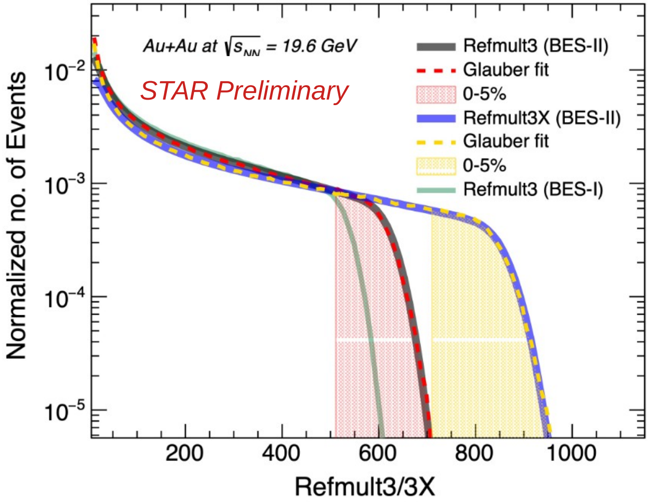
$$3 \leqslant \sqrt{s_{NN}}(GeV) \leqslant 200 \longrightarrow 750 \geqslant \mu_B(MeV) \geqslant 25$$

(widest μ_B coverage to date)

- ☑ Two new collider energy: 9.2 & 17.3 GeV.
- ☑ In BES-II, about 10 – 18 times increase in statistics for Au + Au collision.

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:

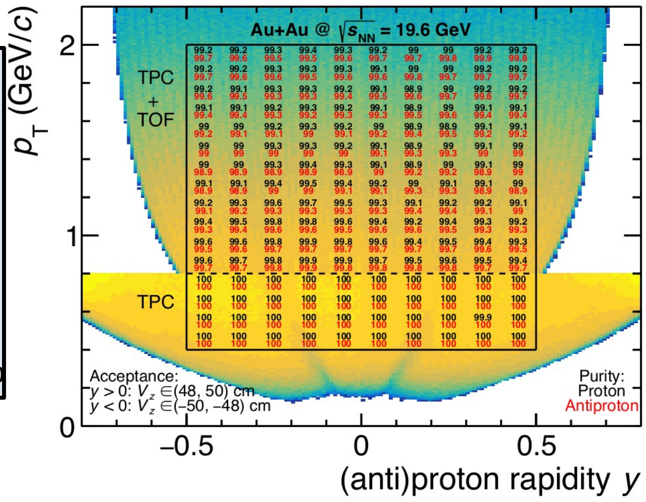
RefMult3X (BES-II) > RefMult3 (BES-II) > RefMult3 (BES-I)

✿ PID:

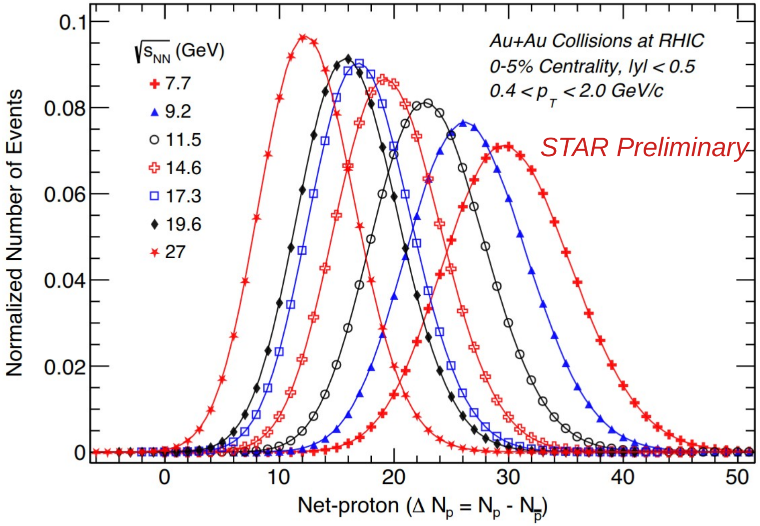
1. TPC and TOF used.

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 cumulants in 0-5% centrality

$\sqrt{s_{NN}}$	7.7 GeV		19.6 GeV	
	% stat. error	% sys. error	% stat. error	% sys. error
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%

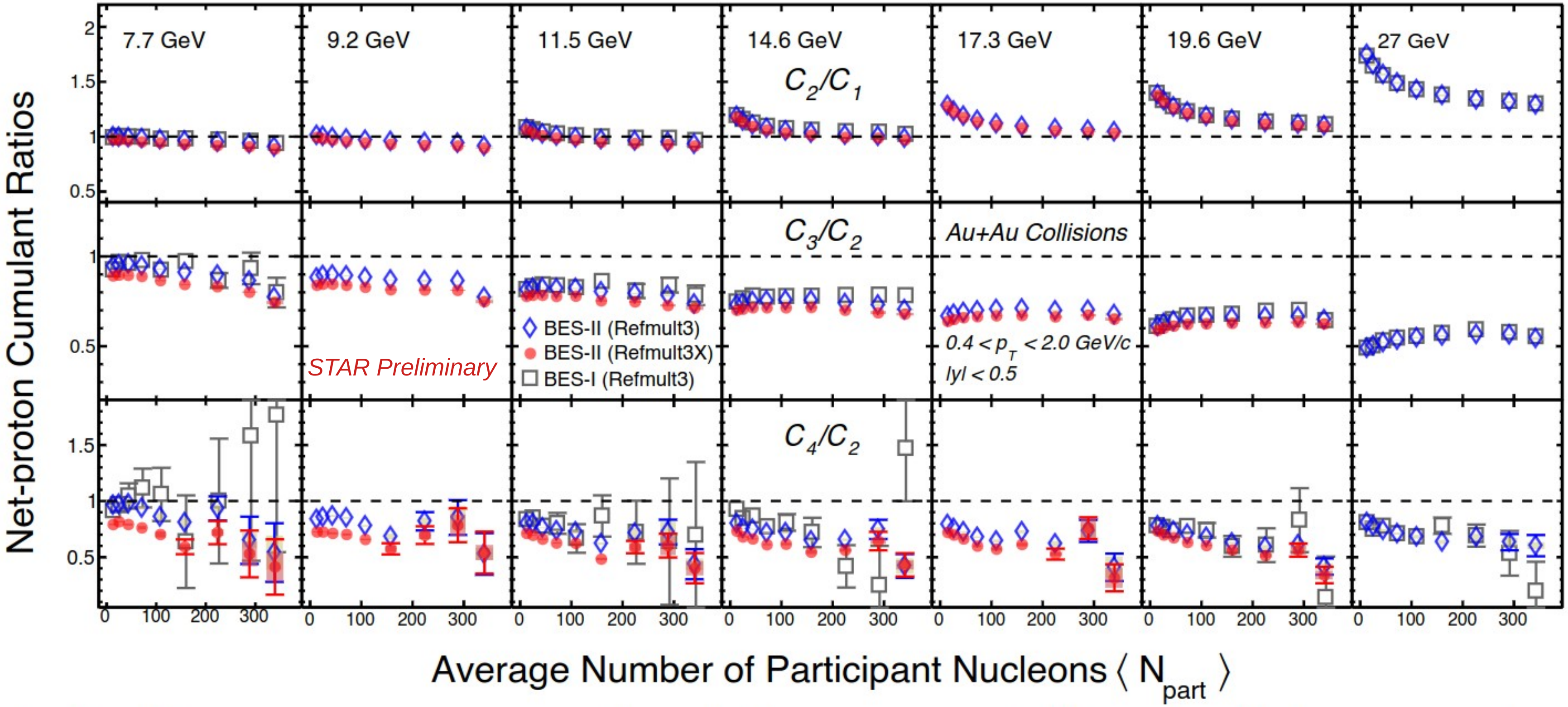
Reduction factor in uncertainties in 0-5% C_4/C_2: BES-II vs BES-I

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

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

Results

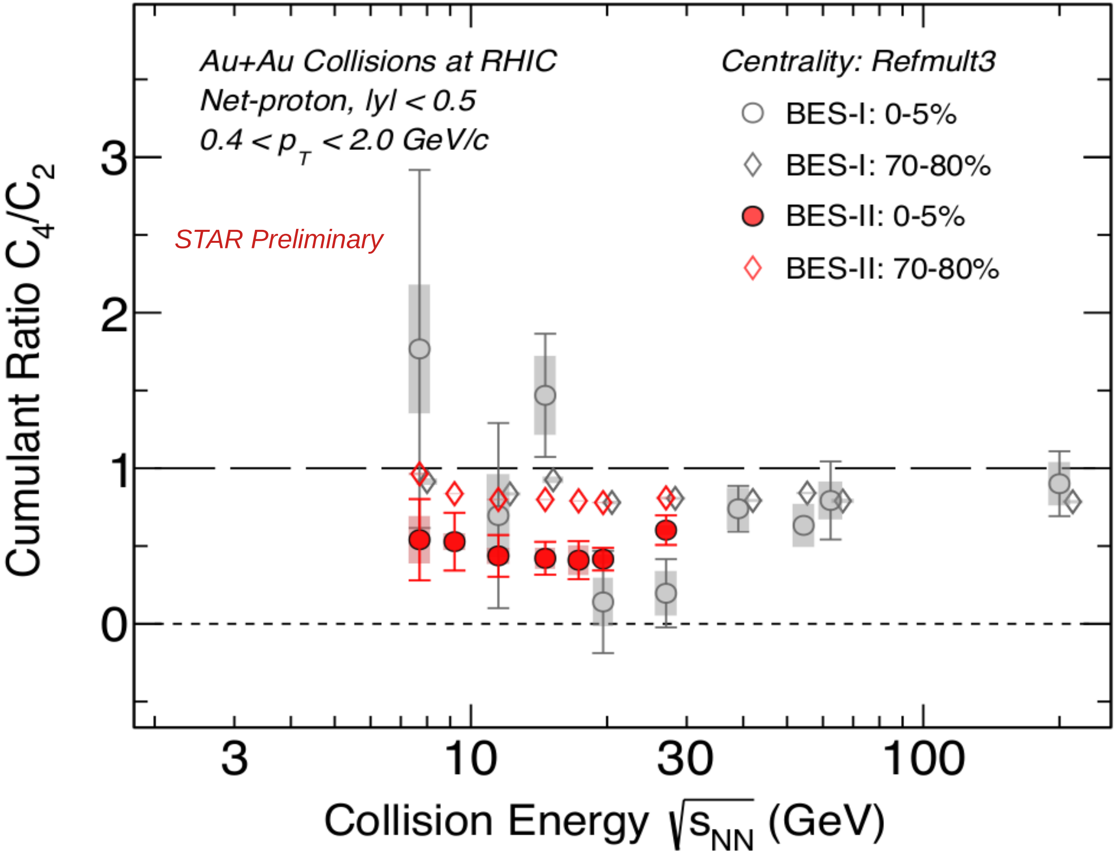
Centrality dependence: net-proton cumulant ratios



- ☑ 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

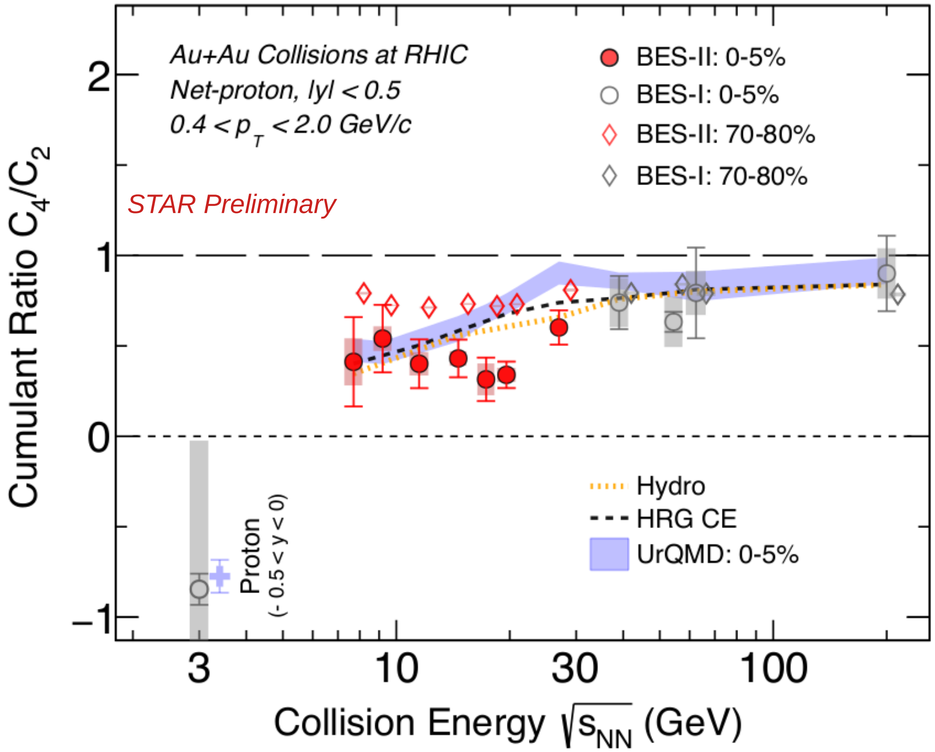


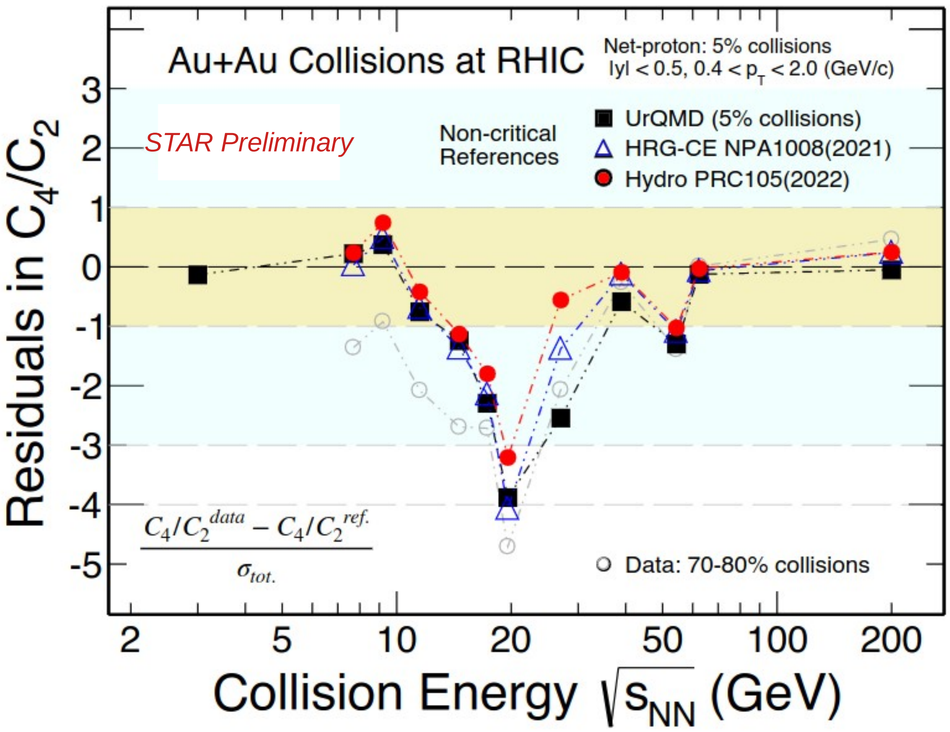
Deviation between BES-I and BES-II:

$\sqrt{s_{NN}}$ (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.

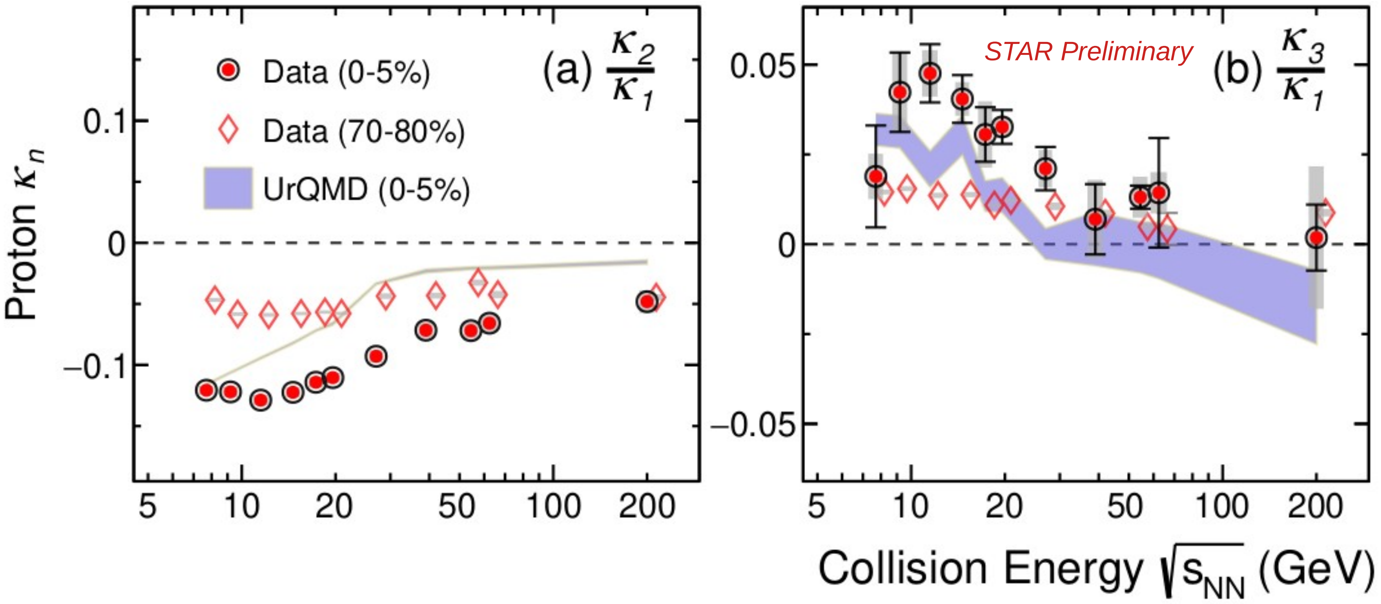
Quantification of deviation





- **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).

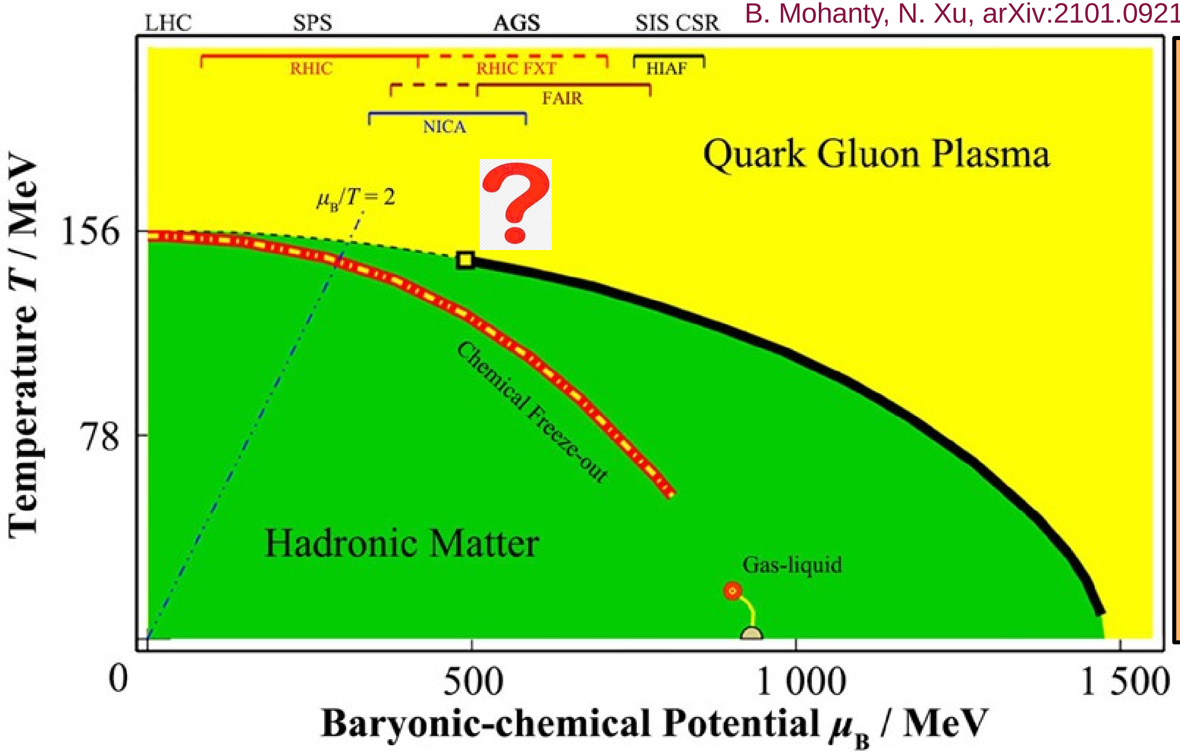
Energy dependence: proton factorial cumulant ratios



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

Summary

B. Mohanty, N. Xu, arXiv:2101.09210



- **Precision measurements** from BES-II collider energies $(\sqrt{s_{NN}})$ 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
- **Comparison to theory calculations with critical point needed** to draw conclusion regarding existence of 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.

Acknowledgement:

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- We thank DAE and DST for funding the project.