PROCEEDINGS OF SCIENCE

Recent Highlights from the STAR Experiment

Rutik Manikandhan[a,*] **for the STAR collaboration**

[a] *University of Houston,*
4302 University Dr, Texas, U.S.A,

E-mail: manikandhan.rutik@gmail.com

We summarize the latest correlation and fluctuation measurements derived from the RHIC Beam Energy Scan-II (BES-II) data, collected by the STAR experiment. We will focus on the recent results of higher-order net-proton cumulants ($C_1 - C_4$) in the energy range of 7.7 to 27 GeV Au+Au collisions. Furthermore, we will present measurements of transverse momentum correlations of charged particles, particularly focusing on 2-particle correlators and their dependency on centrality in 3.0 and 3.2 GeV Au+Au collisions.

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1. Introduction

The study of event-by-event correlations and fluctuations in global quantities can provide insight into the properties of the hot and dense matter created in Au+Au collisions at ultra relativistic collision energies [1] [2]. The event-by-event fluctuations of conserved quantities such as net charge, net-baryon number, and net strangeness are predicted to depend on the non-equilibrium correlation length, ξ, and thus serve as indicators of critical behavior [3] [4].
Correlations of transverse momentum, p_t, have been proposed as a measure of thermalization [5] [6] and as a probe for the critical point of quantum chromodynamics (QCD) [7] [8]. Studying these observables and quantifying their deviations from baselines of uncorrelated emissions could elucidate the possible existence of the critical point.

In these proceedings, we present the results of proton cumulant measurements $(C_1 - C_4)$ and factorial measurements $(\kappa_1 - \kappa_4)$ along with their ratios from Beam Energy Scan-II (BES-II) collider energies at $\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.6, 17.3, 19.6 and 27 GeV and preliminary results of the 2-particle transverse momentum correlators from the BES-II Fixed-Target (FXT) energies at $\sqrt{s_{NN}}$ = 3.0 and 3.2 GeV and how they probe the QCD phase digram for the existence of a critical point.

2. Analysis Method

Experimentally measured proton multiplicity distributions are described by the central moments, i.e., $\langle(\delta N)^2\rangle$, $\langle(\delta N)^3\rangle$, $\langle(\delta N)^3\rangle$ etc... The symbol $\langle ...\rangle$ indicates the average for all events, N is the multiplicity of protons in a given event, and $\delta N = N - \langle N\rangle$ is the deviation. The relations between the cumulants C_n and the central moments are defined as:

$$\begin{aligned} \text{Mean:} \quad & M = \langle N\rangle = C_1 \\ \text{Variance:} \quad & \sigma^2 = \langle(\delta N)^2\rangle = C_2 \\ \text{Skewness:} \quad & S = \langle(\delta N)^3\rangle/\sigma^3 = C_3/C_2^{3/2} \\ \text{Kurtosis:} \quad & \kappa = \langle(\delta N)^4\rangle/\sigma^4 - 3 = C_4/C_2^2 \end{aligned}$$

The ratios of the cumulants are often used to reduce volume dependence: $C_2/C_1 = \sigma^2/M$, $C_3/C_2 = S\sigma$, and $C_4/C_2 = \kappa\sigma^2$. An additional advantage is that the ratios of these cumulants can be readily compared with theoretical calculations of susceptibility ratios for, e.g. $\sigma^2/M = \chi_2/\chi_1$, $S\sigma = \chi_3/\chi_2$, and $\kappa\sigma^2 = \chi_4/\chi_2$. In case there are no intrinsic correlations among the measured particles, all ratios of the cumulants are unity, thus Poisson statistics is a trivial baseline for experimentally measured cumulant ratios [9] [10].

All of the shown measurements have been corrected for pile-up, detector efficiency and centrality bin width effects which have been discussed in detail in [11], [12], [13] and references therein.

(p_t) correlations are characterized by the two-particle correlation function defined as the covariance:

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$$\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle = \frac{1}{N_{events}} \sum_{k=1}^{N_{events}} \frac{C_k}{N_k(N_k - 1)} \tag{1}$$

where

$$C_k = \sum_{i=1}^{N_k} \sum_{j=1, j\neq i}^{N_k} (p_{t,i} - \langle\langle p_t \rangle\rangle)(p_{t,j} - \langle\langle p_t \rangle\rangle) \tag{2}$$

N_{events} is the number of events, N_k is the number of tracks in the k^{th} event, and $p_{t,i}$ is the transverse momentum of the i^{th} track in the given event. The event averaged p_t is defined as:

$$\langle\langle p_t \rangle\rangle = \frac{\sum_{k=1}^{N_{events}} \langle p_t \rangle_k}{N_{events}} \tag{3}$$

where $\langle p_t \rangle_k$ is the average p_t of the k^{th} event defined as:

$$\langle p_t \rangle_k = \frac{\sum_{i=1}^{N_k} p_{t,i}}{N_k} \tag{4}$$

To characterize, two-particle p_t correlations, we present the relative dynamical correlation, $\sqrt{\langle \Delta p_{t,i} \Delta p_{t,j} \rangle} / \langle\langle p_t \rangle\rangle$. It represents the magnitude of the dynamic fluctuations of the average transverse momentum in units of $\langle\langle p_t \rangle\rangle$. This scaling cancels out detector efficiency effects [14] and flow effects [5] making it an ideal probe for critical point searches.

3. Results and Discussion

The results shown here for the proton cumulants are within a common kinematic acceptance across all energies. The Time-Projection Chamber (TPC) and Time-Of-Flight detectors have been used for identifying the protons and the anti-protons. The TPC identifies the low p_T ($0.4 < p_T < 0.8$ GeV/c) protons and anti-protons with high purity and the TOF identifies particles at higher p_T ($0.8 < p_T < 2.0$ GeV/c) [12] within a rapidity window ($|y| < 0.5$) as shown in Fig. 1 a).

The STAR detector had major upgrades done for BES-II, which allowed measurements of charged particles at wider pseudorapidity acceptances ($|\eta| < 1.6$). This allowed for a new centrality definition, namely RefMult3X and due to larger multiplicity within the acceptance we have better centrality resolution.

The STAR detector has recorded data in the Fixed-Target mode as well, this allowed data taking at even lower energies, all the way down to $\sqrt{s_{NN}} = 3.0$ GeV. For the analysis of (p_T) correlations, all charged particles in an acceptance of p_T ($0.20 < p_T < 2.0$ GeV/c) and η_{cm} ($|\eta_{cm}| < 0.5$), where $\eta_{cm} = \eta_{lab} - \eta_{mid}$ (black box in Fig.1 b)) are analyzed and compared as a function of collision energy.

Fig.2 shows how the net-proton cumulants ($C_2/C_1, C_3/C_2, C_4/C_2$) depend on centrality with two different centrality definitions for BES-II and these measurements are compared to previous BES-I measurements [13].

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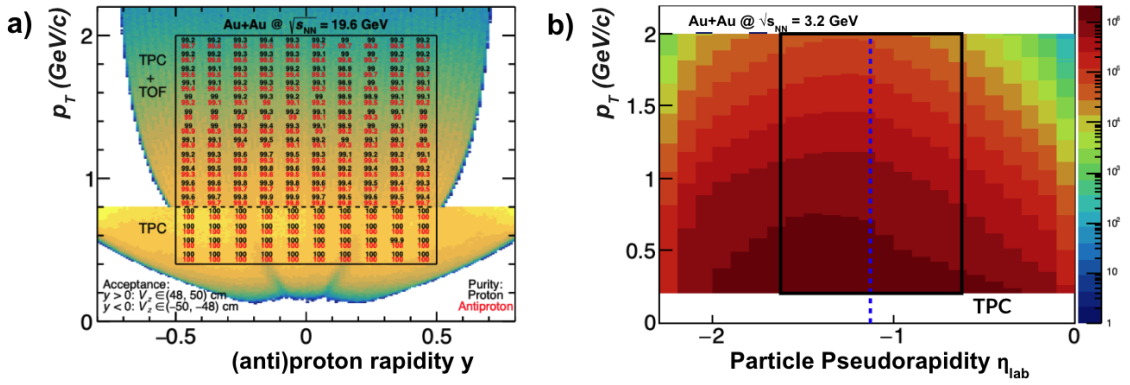

Figure 1: (Anti)Proton acceptance along with purity at $\sqrt{s_{NN}}$ = 19.6 GeV and charged particle acceptance at $\sqrt{s_{NN}}$ = 3.2 GeV, the dashed blue line is mid-pseudorapidity at $\sqrt{s_{NN}}$ = 3.2 GeV.

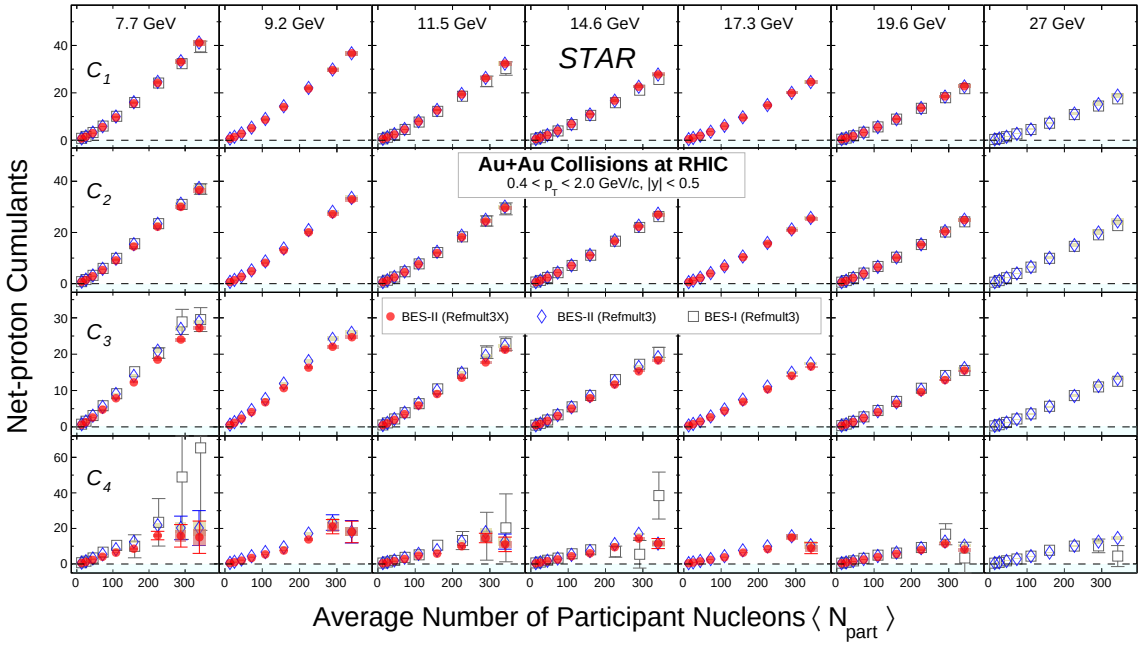

Figure 2: Cumulants of net-proton multiplicity distribution from $\sqrt{s_{NN}}$ = 7.7 27 GeV as a function of collision centrality ($<N_{part}>$) in Au+Au collisions at STAR-RHIC. Results from BES-II with RefMult3X (RefMult3) used for centrality definition are shown as red (blue) markers, while those from BES-I [13] (RefMult3) are shown as open squares. The bars and bands on the data points from BES-II represent statistical and systematic uncertainties, respectively. Total uncertainties are shown for BES-I data points as bars on data points.

The results are consistent with previous BES-I measurements. The cumulant ratios have a smooth variation across centrality and collision energy, and higher centrality resolution is observed to improve the ratios.

The collision energy dependence of net-proton (C_4/C_2) in $0-5\%$ centrality class is shown in Fig.3. Compared to various non-CP model calculations [15],[16],[17] and data in 70-80% peripheral collisions, the net-proton C_4/C_2 measurement in 0-5% collisions shows a minimum around $\sqrt{s_{NN}}$

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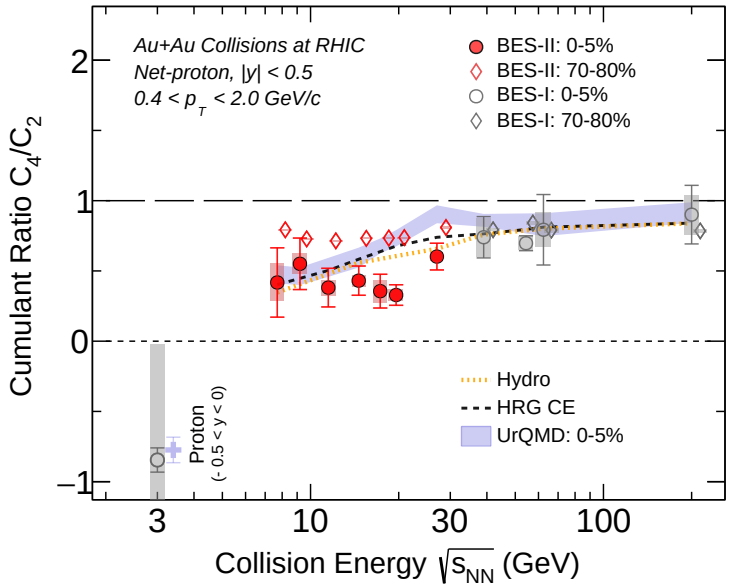

Figure 3: Collision energy dependence of net-proton C_4/C_2 in 0-5% and 70-80% centrality classes. Theoretical calculations from a hydrodynamical model [15] (Hydro, orange dashed line), thermal model with canonical treatment for baryon charge [16] (HRG CE, black dashed line), transport model [17] (UrQMD, violet band) are also presented.

= 19.6 GeV for significance of deviation at ~ 2–5 σ.

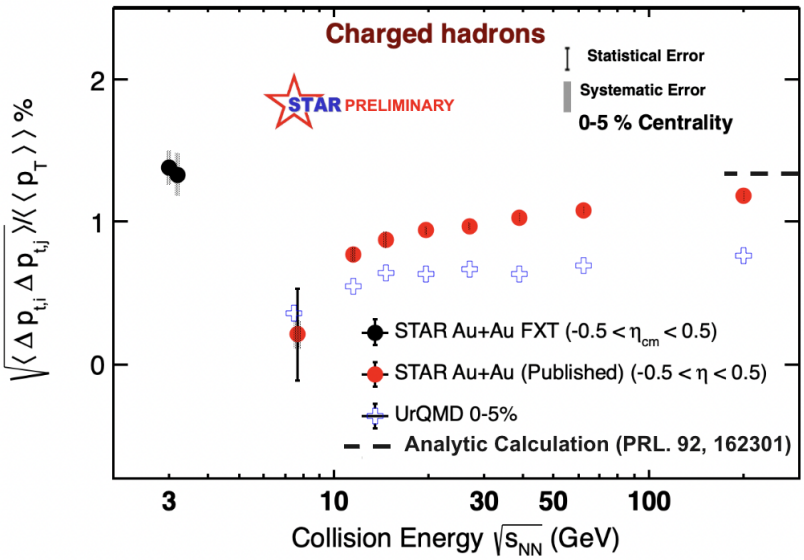

Figure 4: Collision energy dependence of $\sqrt{\langle \Delta p_{t,i} \Delta p_{t,j} \rangle}/\langle \langle p_t \rangle \rangle$ in 0-5% centrality class. Theoretical calculations from transport model [17] (UrQMD,blue markers) and analytic method [5] (dashed line) are shown

The collision energy dependence of the 2-particle (p_T) correlator in most central collisions is shown in Fig.4, a breaking of monotonicity is observed in the high-baryon density region. This non-

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monotonous dependence on collision energy could possibly be described due to critical phenomena and the correlation length changing as a function of collision energy [5].

The dashed line shown in Fig. 4 is a theoretical calculation [5] for the expected baseline if the system is thermalized and correlation length remains constant.

We see that the transport code calculations [17] always deviate from our measurements at the collider energies but qualitatively capture the trend.

4. Conclusion

In these proceedings, BES-II measurements of net proton cumulants at $\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.6, 17.3, 19.6 and 27 GeV and preliminary results of the 2-particle transverse momentum correlators from the BES-II Fixed-Target (FXT) energies at $\sqrt{s_{NN}}$ = 3.0 and 3.2 GeV are presented. The net-proton cumulants are discussed as a function of centrality and collision energies, they are compared to the previous measurements from BES-I and to various non-CP models to quantify any kind of critical behavior. The net-proton C_4/C_2 measurement in 0-5% collisions shows a minimum around $\sqrt{s_{NN}}$ = 19.6 GeV for significance of deviation at $\sim$ 2–5 σ. The (p_T) correlations exhibit a non-monotonic dependence on collision energy in central collisions, potentially signaling critical phenomena. Ongoing studies aim to explore additional energy ranges in this regime and establish theoretical baselines to better quantify any observed deviations.
These highlights underscore the importance of additional measurements from STAR's fixed-target (FXT) energy program to confirm the existence and pinpoint the location of the critical point on the QCD phase diagram.

5. Acknowledgements

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