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## Feasibility studies of conserved charge fluctuations in Au-Au collisions with CBM

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### Abstract

We present the CBM physics performance study for measurements of the higher order cumulants of the net-proton multiplicity distributions. These observables are proxy for net-baryon fluctuations and are commonly used to study the phase structure of QCD phase diagram. The simulation is done for  $Au + Au$  collision at beam kinetic energy  $E_{lab} = 10$  AGeV. The cumulants of net-proton distributions have been calculated at midrapidity ( $|\Delta y| = 1$ ) for the transverse momentum range  $0.2 < p_T < 2.0$  GeV/c. The centrality dependence of cumulants of net-proton upto order four is presented. The efficiency and detector effects are corrected using unfolding techniques. This work shows that the higher order cumulants of net-proton can be measured using the CBM detector.

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### 1. Introduction

Substantial theoretical as well as experimental efforts world-wide have been devoted to investigate properties of matter under extreme conditions. According to the Lattice Quantum Chromodynamics (LQCD) calculation there should be a smooth crossover transition between hadronic phase and quark-gluon plasma (QGP) at high temperature  $T$  and zero baryon chemical potential  $\mu_B$  [1]. On the other hand, various QCD based models [2] predict a first-order phase transition at low  $T$  and high  $\mu_B$ . Hence, there must be a critical point (CP) at high  $T$  and non-zero  $\mu_B$  where the first-order phase transition line ends. Several heavy-ion collision experimental program world-wide have been devoted to the investigation of QCD matter over a wide range of  $T$  and  $\mu_B$ . Heavy ion collision experiments at the Large Hadron Collider (LHC), CERN and Relativistic Heavy Ion Collider (RHIC) at BNL are presently investigating QCD matter at high  $T$  and small  $\mu_B$  region of the phase diagram. To search the QCD CP a Beam Energy Scan (BES) program [3] is ongoing at RHIC. A similar energy and system size scan by the NA61/SHINE [4] collaboration at CERN SPS is also in progress. The HADES experiment [5] at GSI, Darmstadt is investigating a medium at the very large  $\mu_B$ . In future, the Nuclotron-based Ion Collider Facility (NICA) at JINR, Dubna and the Compressed Baryonic Matter (CBM) experiment [6] at the Facility for Antiproton and Ion Research (FAIR) at GSI will also study nuclear matter at large  $\mu_B$  region of the phase diagram. The CBM experiment at SIS100 synchrotron will offer the opportunity to study the nuclear matter with very high precision data at the center of mass energy range  $\sqrt{s_{NN}} = 2.7 - 4.9$  GeV for  $Au + Au$  collisions [6].

Fluctuations and correlations of conserved charges are believed to be important observables to search of the phase transition and the CP of the QCD phase diagram. Here conserved charges are those which are conserved in strong interaction like baryon number, strangeness number or electric charge. Experimentally, net-charge  $N_q = N_q^+ - N_q^-$  multiplicity distribution is measured in a finite acceptance on an event-by-event basis. The  $n^{\text{th}}$  order central moment of the distribution is defined as  $\langle(\delta N_q)^n\rangle = \langle(N_q - \langle N_q \rangle)^n\rangle$ , where  $\langle N_q \rangle$  is the mean value of the distribution. The higher order moments  $\langle(\delta N_q)^3\rangle$ ,  $\langle(\delta N_q)^4\rangle$  are expected to be sensitive to the matter properties in the vicinity of the CP [7]. To characterize a distribution, cumulants are used. Cumulants are related to the central moments by the following relations:

$$C_1 = \langle N_q \rangle, \quad C_2 = \langle(\delta N_q)^2\rangle, \quad C_3 = \langle(\delta N_q)^3\rangle, \quad \text{and} \quad C_4 = \langle(\delta N_q)^4\rangle - 3\langle(\delta N_q)^2\rangle^2. \quad (1)$$

The cumulants upto order four are studied in the present work. Cumulants are connected to the theoretically calculable susceptibilities of the conserved charges by the relation  $C_n = VT^3\chi_q^n$  [8, 9], where  $\chi_q^n$ ,  $V$  and  $T$  are the  $n^{\text{th}}$  order susceptibility, volume and temperature of the system, respectively.

## 2. Analysis detail

In this performance study, net-proton (which are used as a proxy of net-baryon) fluctuation for  $Au + Au$  collision at the beam kinetic energy  $E_{lab} = 10$  AGeV have been calculated. Simulations have been performed within the CbmRoot framework. Five million minimum bias events generated by UrQMD model [10] are transported through the CBM detector setup using GEANT3 Monte-Carlo. The list of CBM detector subsystems simulated for this study includes: Micro Vertex Detector (MVD), Silicon Tracking System (STS), Ring Imaging Cherenkov Detector (RICH), Transition Radiation Detector (TRD) and Time-of-Flight Detector (TOF). The lab pseudorapidity range covered by CBM detector system is  $1.5 < \eta < 3.8$ . The MVD gives the collision vertex of the event and the STS provides the momentum information of the charged particle tracks.

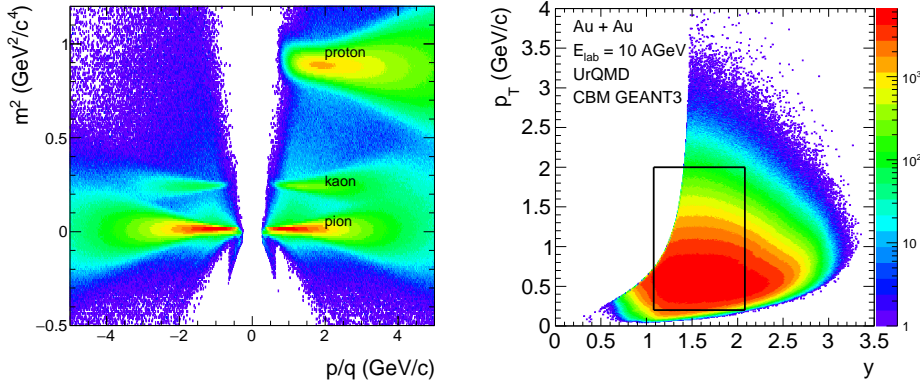


Fig. 1. (Left) Distribution of  $m^2$  as measured by the TOF detector as a function of  $p/q$ . (Right)  $p_T$  vs  $y$  distribution of protons and anti-protons in  $Au + Au$  collisions at  $E_{lab} = 10$  AGeV. Box indicates the region of analysis of net-proton cumulants.

### 2.1. Particle identification

For the purpose of particle identification, TOF detector has been used. The TOF detector provides flight time ( $t$ ) of a particle inside the detector. By knowing the length of the track ( $L$ ), we can calculate velocity ( $\beta = v/c = L/tc$ ,  $c$  is the velocity of light in vacuum), which depends on mass ( $m$ ) and the momentum ( $p$ ) of the particle. Hence one can calculate the relation of  $m^2$  with  $p$  using  $m^2 = p^2(1/\beta^2 - 1)$ . Left panel of Fig. 1 shows distribution of  $m^2$  and  $p/q$ , where  $q$  is the charge of the particle. For positive values of  $p/q$  one can see three well separated bands which corresponds to  $\pi^+$ ,  $K^+$  and proton, respectively. Anti-particles have a negative value of  $p/q$ . At the CBM energies significantly smaller number of anti-protons compared to that

of protons is expected. Tracks with  $m^2$  between 0.6 and 1.2 GeV<sup>2</sup>/c<sup>4</sup> are identified as protons or anti-protons with purity more than 96%. This figure shows that clean proton identification is possible and hence one can study the net-proton (proxy for net-baryon) higher order moments using CBM detector.

## 2.2. Centrality estimation

The collision centrality is determined using the reconstructed charged particle multiplicity measured with STS. The charged particles are selected using  $m^2$  less than 0.4 GeV<sup>2</sup>/c<sup>4</sup> which exclude the protons and anti-protons for multiplicity measurements and avoids self correlation effects. The analysis is done in nine centrality bins 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70% and 70-80%. Centrality bin 0-5% corresponds to most central whereas 70-80% corresponds to the most peripheral collision events.

## 3. Results

In this work we calculate cumulants up to the order of four net-proton ( $\Delta N = N_p - N_{\bar{p}}$ ) multiplicity distribution. The protons and anti-protons are counted within the transverse momentum range  $0.2 < p_T < 2.0$  GeV/c and unit rapidity ( $|\Delta y| = 1$ ) window at mid-rapidity relative to the beam rapidity  $y_{beam} = 1.58$ . The  $y - p_T$  acceptance for protons and anti-protons selection in  $Au + Au$  collision at  $E_{lab} = 10$  AGeV is shown in right panel of Fig. 1. Efficiency of protons and anti-protons detection in different collision centrality varies between 62 % to 46 %. Figure 2 shows the reconstructed event-by-event (without efficiency correction) net-proton multiplicity distributions for different centrality classes. The finite width of a centrality class may

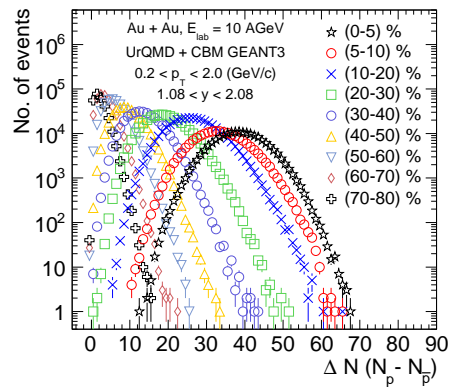


Fig. 2. Distributions of net-proton multiplicities in different centrality bins.

cause volume fluctuations within this class. The cumulants need to be corrected for such effects [11]. The centrality bin width corrected cumulants are calculated as  $C_n = w_r C_{n,r}$  where  $C_{n,r}$  and  $w_r$  are respectively cumulant and the fraction of event in  $r^{th}$  multiplicity bin i.e.  $w_r = n_r / \sum_r n_r$ . The  $n_r$  is the number of events and cumulant in  $r^{th}$  multiplicity bin.

The measured cumulants are also affected by the reconstruction efficiencies of the proton and anti-protons. We have corrected for this and other detector effects using the method of unfolding [12]. For this purpose we use the RooUnfoldBayes algorithm which is based on the Bayes theorem. The measured and true number of particles are related by the relation  $y = R \cdot x$ , where  $y$  and  $x$  are the measured and true distribution and  $R$  is a response matrix. We have divided the simulated data set in two halves where first half is used to reconstruct the response matrix and the second half of the data set is used for the analysis. The response matrix is used to get the true number of protons and anti-protons from the information of measured (reconstructed) protons and anti-protons.

Centrality dependence of cumulants of net-proton multiplicity distribution up to the order of four have been shown in Fig. 3. The solid squares correspond to the centrality bin width corrected cumulants calculated from reconstructed net-proton distributions whereas open circles show the generated net-proton

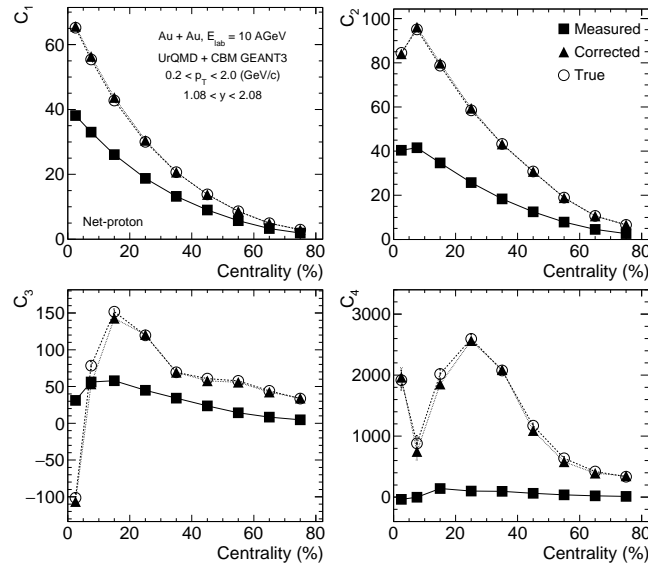


Fig. 3. The centrality dependence of cumulants of net-proton distributions up to order four.

cumulants. The solid triangles show the cumulants obtained after the application of unfolding procedure. Within statistical uncertainties unfolding method is able to reproduce the true value of the cumulants. The volume of the produced QCD matter (or the number of participants) decrease from central to peripheral collisions. Hence, decrease of cumulants from central to peripheral collisions are expected, which is indeed observed except for few centrality bins ( $C_2$  in 0-5 %,  $C_3$  in 0-5 % and 5-10 %,  $C_4$  in 0-5 %, 5-10 % and 10-20 %). The error bars shown on the data point are statistical only which are estimated using delta theorem approach [13].

In summary, we have performed the physics performance study of net-proton fluctuations for CBM detector setup. It demonstrates the feasibility of doing higher moments measurements of net-proton distributions using CBM detector. In future we plan to analyse cumulants up to order six with large statistics and other energies of SIS100. Similar analysis is also ongoing for the net-charge and will be done for net-kaon and mixed cumulants.

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