CUMULANTS OF NET-PROTON NUMBER FLUCTUATIONS FROM ALICE AT THE LHC*

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In the lattice QCD, the ratios of the various orders of quark number susceptibilities are used to determine freeze-out parameters and to locate the phase boundary. The cumulants of conserved charges fluctuations are directly related to the respective quark number susceptibilities. Therefore, the measurements of various order cumulants of conserved charges, such as the net-baryon number, can be used to determine the freeze-out parameters and to constrain the lattice QCD predictions. In this paper, we report on the first measurements of cumulants of net-proton number distributions up to the $4^{\rm th}$ order in Pb–Pb collisions with ALICE at the LHC. We also compare our results with RHIC measurements and hadron resonance gas model calculations.

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1. Introduction

One of the goals of heavy-ion collision experiments is to investigate the phase structure of the QCD matter. The QCD phase diagram can be studied in the temperature (T) and baryo-chemical potential ($\mu_{\rm B}$) plane to map the phase boundaries by varying the collision energy. Heavy-ion collision experiments at the LHC energies aim to study the QCD phase diagram at the chiral limit, where $\mu_{\rm B}$ is very small. According to the lattice QCD, the phase transition is a crossover at vanishing $\mu_{\rm B}$ [1]. In Ref. [2], it is suggested that the chiral crossover transition line will appear close to the freeze-out line. Therefore, the determination of freeze-out parameters is crucial to locate the phase boundary at the LHC energies. The freeze-out parameters are obtained by fitting identified particle yields and then

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comparing them with thermal statistical models like the Hadron Resonance Gas (HRG) model [3]. Recently, the chemical freeze-out temperature has been estimated as 156.5 ± 1.5 MeV at the LHC energies by the Statistical Hadronization Model using the ALICE particle yields [4]. On the other hand, the crossover temperature, T_{c}, estimated by the lattice QCD calculations is $155 \pm 1 \pm 8$ MeV [5]. It can be observed from the thermal model and lattice QCD calculations that the freeze-out temperature is close to the crossover temperature. Hence, additional measurements of the freeze-out temperature are needed to test lattice QCD predictions. Various theoretical works suggest that the study of fluctuations of conserved charges, such as net-charge, net-baryon (approximated by net-proton number), and net-strangeness in heavy-ion collision experiments are excellent tools for such a study [2, 6, 7].

In experiment, the n^{th} order of cumulants (C_n) of conserved charge distributions are measurable quantities, which are directly connected with quark number susceptibilities (χ_q^n) as $C_n = VT^3\chi_q^{(n)}$ [6]. The quark number susceptibilities are defined as

$$\chi_q^{(n)} = \frac{\partial^n \left[P(T,\mu)/T^4\right]}{\partial\left(\mu_q/T\right)^n} \,. \tag{1}$$

In Eq. (1), P is the pressure and V is the volume of the system. Direct measurement of the volume in the experiment is not possible. Hence, to get rid of the volume term, the freeze-out parameters are determined by taking the ratios of the various orders of cumulants [2, 6, 7].

In this work, the first experimental measurements of the cumulants of net-proton distributions up to 4^{th} order in minimum-bias Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV are reported. Additionally, the C_3/C_2 and C_4/C_2 results are compared with the Skellam expectations and RHIC Beam Energy Scan (BES) results.

2. Analysis details

The measurements are carried out using Pb–Pb collisions recorded at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV with the ALICE detector [8]. In total, 14×10^6 and 59×10^6 minimum-bias events are used for this analysis at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, respectively. The V0 detector, which covers the pseudorapidity ranges of $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C), is used for the trigger and centrality estimation. The collision centralities are defined using the V0 signal amplitudes [9]. The position of the reconstructed primary vertex along the beam axis is required to be within 10 cm of the center of the ALICE detector in order to ensure high-quality and uniform tracking performance at mid-rapidity. Tracks reconstructed using the Time Projection Chamber (TPC) within the transverse momentum (p_{T}) range

$0.4 < p_{\rm T} < 1.0$ GeV/c and pseudorapidity range of $|\eta| < 0.8$ are used for this analysis. The tracks resembling a secondary decay topology are rejected. Additionally, a $p_{\rm T}$-dependent distance of closest approach (DCA) condition is imposed to minimize the contribution from secondaries and weak decays. The specific ionization energy-loss ($\mathrm{d}E/\mathrm{d}x$) information of a track in the TPC volume is used for the identification of (anti-)protons. A condition of $|n\sigma| < 2.5$ around the expected mean values of $\mathrm{d}E/\mathrm{d}x$ for (anti-)proton is applied. The contamination due to particle misidentification for $p_{\rm T}$ up to 0.85 GeV/c is negligible, and for $0.85 < p_{\rm T} < 1.0$ GeV/c is around 10%, which is taken into account in the systematic uncertainties. A $p_{\rm T}$-dependent efficiency correction method proposed in Ref. [10] is used to correct the raw cumulant results of the net-proton distribution. HIJING events processed through the ALICE geometry and tracking framework are used for estimating the $p_{\rm T}$-dependent proton (p) and anti-proton ($\bar{p}$) reconstruction efficiencies [11]. Within the mentioned kinematic range, the reconstruction efficiency of p and $\bar{p}$ are approximately of 65% and 60%, respectively. The cumulants are presented after centrality bin-width correction [12]. The statistical uncertainties are estimated using the subsample method with 30 subsamples. The systematic uncertainties are estimated by varying the track and V_z selection criteria. Furthermore, the results are compared with Skellam expectations as baseline. Skellam distributions are used in Hadron Resonance gas model calculations [6, 13].

3. Results and discussion

Figures 1 and 2 illustrate the centrality dependence of the cumulants of net-proton distributions in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. It can be observed from Figs. 1 and 2 that the C_2 and C_4 of net-proton distributions are decreasing from central to peripheral events. However, C_3 of net-protons does not show such a strong centrality dependence. The cumulant results of net-proton distributions for both energies are similar within the uncertainties.

Figure 3 shows the collision centrality dependence of C_3/C_2 and C_4/C_2 of net-proton distributions in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The results are compared with the Skellam expectations, which are represented by the dotted lines in Fig. 3. It can be seen that the values of C_3/C_2 are consistent with the Skellam expectations for both energies in all centrality bins within the uncertainties. In central and semi-central events, the values of C_4/C_2 for net-proton distributions agree with the Skellam expectations. However, some significant deviations from the Skellam line are observed in peripheral events, which will be investigated in the future.

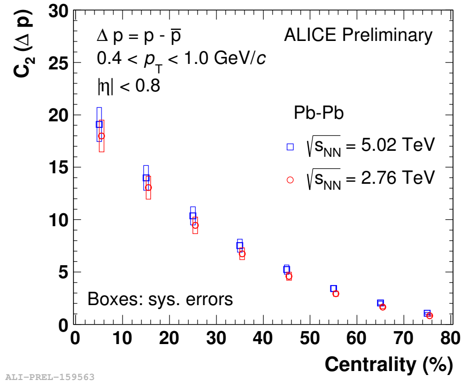

Fig. 1. Centrality dependence of C_2 of net-proton distributions in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The statistical uncertainties are within the marker size. The boxes represent the systematic uncertainties.

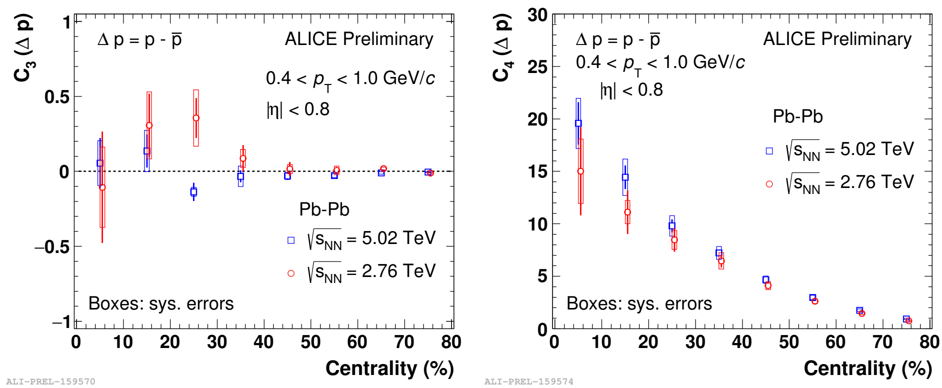

Fig. 2. (Color online) (From left to right) Centrality dependence of C_3 and C_4 of net-proton distributions in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The vertical lines and boxes represent the statistical and systematic uncertainties, respectively.

Furthermore, the results are compared with the net-proton cumulants measured in Au–Au collisions in the BES by the STAR experiment at RHIC. The results reported by STAR are measured at the mid-rapidity ($|y| < 0.5$) within the p_T range of $0.4 < p_T < 0.8$ GeV/c [14]. Figure 4 shows the beam-energy-dependent results for C_3/C_2 and C_4/C_2 for the most central collision events. Within the relatively small kinematic window, the beam-energy-dependent results show that from RHIC to the LHC the ratios of cumulants, *i.e.*, C_3/C_2 and C_4/C_2 in central events, approach the Skellam expectations. Although current results are measured in a different kinematic range ($0.4 < p_T < 1.0$ GeV/c, $-0.8 < \eta < 0.8$), the RHIC kinematic ranges have negligible effect to this measurement.

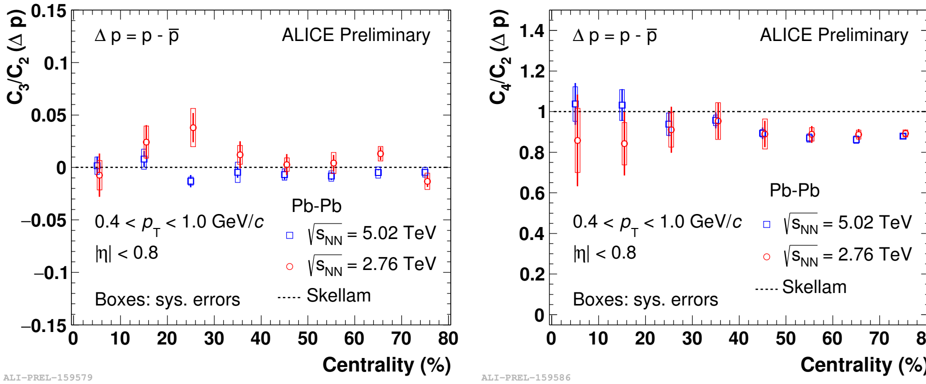

Fig. 3. Centrality dependence of C_3/C_2 and C_4/C_2 of net-proton distributions in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The vertical lines and boxes represents the statistical and systematic uncertainties, respectively.

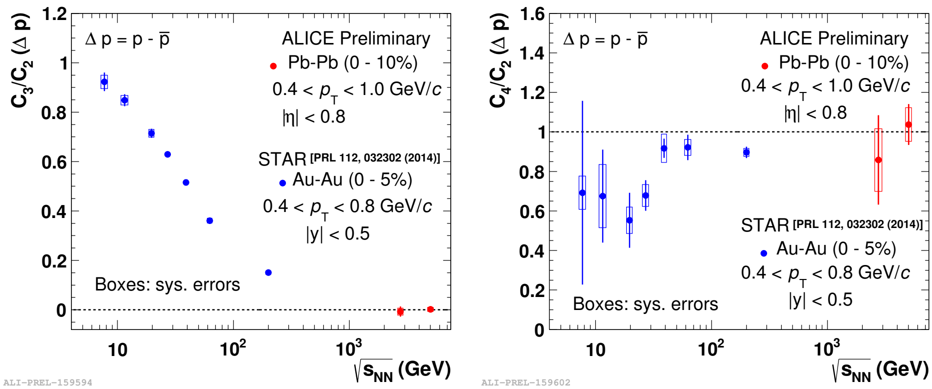

Fig. 4. Energy dependence of C_3/C_2 and C_4/C_2 of net-proton distributions for the most central collision events. The vertical lines and boxes represents the statistical and systematic uncertainties, respectively.

4. Summary and outlook

In this report, the first measurements of C_2, C_3, C_4, and the ratios C_3/C_2 and C_4/C_2 of net-proton distributions in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV as a function of centrality are discussed. The cumulant results are similar for both the collision energies within the uncertainties. Within the current kinematic range, the ratios of the cumulants are found to be consistent with the Skellam expectations within the uncertainties. It is observed that from RHIC to the LHC, the ratio approaches the Skellam expectations. More data in the upcoming Pb–Pb run at 5.02 TeV will help to constrain the freeze-out parameters. The measurement of higher order cumulants of net-proton distributions in a wider kinematic window using the Identity Method is ongoing [15]. Moreover, the study of the effect of volume fluctuations and conservation laws is underway. The measurement of higher order cumulants of net-charge and net-kaon distributions is also a subject of future study.

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