Event-by-event fluctuation studies in the ALICE experiment

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Abstract. Event-by-event (E-by-E) fluctuations are considered to be one of the possible indications that a phase transition from ordinary hadronic matter to a plasma of quarks and gluons has occurred, as it is expected to happen in ultra-relativistic heavy-ion collisions. In this article, the results of a study concerning the observability of E-by-E fluctuations for the ALICE experiment at the LHC collider at CERN is presented. In particular, an estimate of the E-by-E statistical sensitivity in the measurement of the inverse slope parameter from the transverse momentum spectra of hadrons and of their particle ratios is discussed. The analysis relies on the excellent performance of ALICE in terms of particle identification.

1 Introduction

One of the main predictions of the lattice calculations of QCD (the theory of strong interactions) asserts that a phase transition from the ordinary hadronic matter to a deconfined state of quarks and gluons (the so-called quark-gluon plasma, QGP) should occur at very high temperature and energy density conditions. The nature of this phase transition (in other words the order of phase transition), and even whether this is more a crossover than a phase transition, and the existence of a (tri)critical end point are, however, topics still under discussion. Moreover, many parameters are involved, such as the value of the quark masses and that of the baryochemical potential \( \mu_B \).

The heavy-ion physics program of the large hadron collider (LHC) at CERN will concern \( \text{Pb} + \text{Pb} \) collisions at a centre-of-mass energy \( \sqrt{s_{NN}} = 5.5 \text{ TeV} \), allowing to investigate the unexplored regime of extreme energy densities \( \varepsilon = 15-40 \text{ GeV/fm}^3 \), and high temperatures \( \mu_B \ll T \), where no sharp boundary is expected to show up between the hadronic matter and the QGP. The nature and the time evolution of the hot and dense system created in a heavy-ion collision will carry on the fingerprints of the QGP phase transition, which nonetheless may vary even dramatically from one event to the other. For this reason, an analysis on an event-by-event (E-by-E) basis will offer the opportunity to study the QCD phase transition and to get insights into the QGP.

E-by-E fluctuations may originate from different sources. Apart from the statistical fluctuations due to the geometrical properties of the collision \([1–3]\), they may be related to the thermodynamics of the system (such as the temperature \([4,5]\)), to fluctuations of conserved quantities (such as the charge \([6,7]\)), to jets and minijets \([8,9]\), and also to more exotic phenomena (such as disoriented chiral condensate (DCC) formation \([10]\)).

ALICE (a large collider experiment) will be the experiment at the LHC dedicated to investigate the phase transition and the QGP in heavy-ion collisions. It will be able to perform event-by-event analyses thanks to the very high number of particles produced in each collision, and relying on its excellent particle identification capabilities. In this paper, the ALICE statistical sensitivity in measuring identified particle transverse momentum spectra and particle ratios \((K/\pi, p/\pi)\) will be presented. In Sect. 2, the Monte Carlo event sample used for the analysis will be described. Section 3 will deal with the ALICE particle identification capabilities, fundamental as far as particle \(p_T\) spectra and particle ratios are concerned. Sections 4 and 5 will present the results of the analyses on the \(p_T\) spectra for identified pions, kaons and protons, and for \(K/\pi, p/\pi\) ratios, respectively. Finally, in the last section, the summary and the conclusions will be provided.

2 Monte Carlo event sample

The Monte Carlo event sample used for this analysis consists of 300 \( \text{Pb} + \text{Pb} \) central collisions at \( \sqrt{s_{NN}} = 5.5 \text{ TeV} \) generated with the HIJING 1.36 Monte Carlo generator \([11–14]\). The impact parameter has been chosen to be in the range \(0 < b < 5 \text{ fm}\), corresponding to 10% of the total inelastic cross-section for \( \text{Pb} + \text{Pb} \) collisions at \( \sigma_{\text{inel}, \text{Pb} + \text{Pb}} = 8 \text{ barn}\). The magnetic field has been set to \( B = 0.5 \text{ T} \). The GEANT3 package \([15]\) has been used to track all the particles produced in the collision within the pseudorapidity range \(|\eta| < 8\), and to simulate the detector signals and responses. Vertex reconstruction, particle
3 Particle identification in ALICE

In the central rapidity region $-0.9 < \eta < 0.9$, inside the L3 magnet (which provides the experiment with a weak solenoidal magnetic field $B = 0.2$–$0.5$ T), ALICE will be endowed with subdetectors aimed at the tracking and the identification of the particles produced in the collisions. Going outwards from the centre of the experiment, the innermost detector is the ITS (inner tracking system), which is a silicon detector mainly aimed at the reconstruction of the primary and the secondary vertices. Then, next to the ITS, the ALICE main tracking device, the TPC (time projection chamber), will be installed, characterized by a momentum resolution $\sigma(p)/p < 2.5\%$ up to 10 GeV/c. Both the ITS and the TPC will be able to perform particle identification for charged hadrons via $dE/dx$ measurements in the low momentum region ($p \lesssim 1$ GeV/c). After the TPC, the transition radiation detector (TRD), will concentrate mainly on the identification of high momentum electrons ($p > 1$ GeV/c) in the central region, playing also an important role in the ALICE particle tracking. At 3.7 m from the centre of the experiment, the time of flight (TOF) detector will be devoted to charged hadron identification in the intermediate momentum range ($0.5 \lesssim p \lesssim 4$ GeV/c). The central region will be also equipped with two small-area detectors: the HMPID (high momentum particle identification detector), a RICH detector which will carry out charged hadron identification in the high momentum range (up to $p \sim 3$–$5$ GeV/c), and the PHOS (photons spectrometer), a crystal calorimeter for the detection of electromagnetic particles. At large rapidity values, ALICE will be endowed with other detectors, namely the muon spectrometer, the zero degree calorimeter (ZDC), the photon multiplicity detector (PMD), the forward multiplicity detector (FMD) and the V0 and T0 detectors (for more details see [17]).

The event-by-event fluctuation studies reported in the following rely on the excellent capabilities of the ALICE experiment in terms of particle identification (PID). As a matter of fact, the ALICE experiment will be able to identify charged particles in a wide momentum range, from $\sim 0.1$ GeV/c up to a few GeV/c (and even more, up to a few tens of GeV/c, thanks to the TPC $dE/dx$ measurements in the relativistic region [16]). This will be possible taking advantage of the particle identification capabilities of the various detectors, each playing a role in this sense in some narrower momentum range, complementary to the others. Besides, when some tracks are reconstructed simultaneously by different detectors, then a dedicated particle identification procedure can be applied, in order to combine all the available PID information.

For the analysis presented hereafter, the concern has been turned on the PID capabilities of the central tracking detectors ITS and TPC, and of the time of flight detector. The ITS, TPC and TOF enter the common Bayesian approach framework adopted by every ALICE detector performing PID. This kind of approach allows to combine PID information of different nature, coming from different detectors, at the same time, with the advantage of being completely automatic. Moreover, it combines signals distributed according to quite different probability density functions. For more details on ALICE particle identification, see [16].

In particular, for the present study, the PID algorithm combines the signals from ITS, TPC and TOF making a logic “or” of them (ITS||TPC||TOF). This means that to each particle an identity is assigned provided that at least one of the three detectors has been able to perform particle identification on it. The main advantage of this choice is an increase in the number of useful tracks for the E-by-E analysis, even if at the expense of a higher contamination in the cases when only one PID signal is available.

Figure 1 shows the results of the combined PID algorithm when applied to the event sample, in terms of efficiency $\varepsilon_{PID}^id$ and contamination $C_{PID}^id$ defined as:

$$
\varepsilon_{PID}^id = \frac{N_{tid}^i}{N^i}, \quad C_{PID}^id = \frac{N_{wt}^i}{N_{tid}^i + N_{wt}^i}, \quad (1)
$$

$N^i$ being the number of particles of type $i$ ($i = \pi, K, p$) reconstructed by the central tracking, $N_{tid}^i$ the number

\begin{table}[h]
\centering
\caption{Mean number of charged (both negative and positive) primaries per event generated in the pseudorapidity range $-0.9 < \eta < 0.9$, with transverse momentum $0 < p_T < 4$ GeV/c. The values refer to the sample of 300 HIJING central Pb+Pb events used for the results presented in this article}
\begin{tabular}{|c|c|}
\hline
Particle species & Number of primaries \\
\hline
\pi & 7690 \\
K & 745 \\
p & 385 \\
\hline
\end{tabular}
\end{table}

1 A particle is defined here as primary if its generated production vertex is less than 1 \(\mu\text{m}\) from the generated interaction vertex.