



# Event-by-Event Identified Particle Ratio Fluctuations in Pb-Pb Collisions with ALICE using the Identity Method

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## Abstract

The study of event-by-event fluctuations of identified hadrons may reveal the degrees of freedom of the strongly interacting matter created in heavy-ion collisions and the underlying dynamics of the system. The observable  $v_{dyn}$ , which is defined in terms of the moments of identified-particle multiplicity distributions, is used to quantify the magnitude of the dynamical fluctuations in event-by-event measurements of particle ratios. The ALICE detector at the LHC is well-suited for the study of  $v_{dyn}$ , due to its excellent particle identification capabilities. Particle identification based on the measurement of the specific ionisation energy loss,  $dE/dx$ , works well on a statistical basis but suffers from ambiguities when applied on an event-by-event level. A novel experimental technique called the "Identity Method" is used to overcome such limitations. The first results on identified particle ratio fluctuations in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV in ALICE as a function of centrality are presented. The ALICE results for the most peripheral events indicate an increasing correlation between pions and protons which is not reproduced by the HIJING and AMPT models. On the other hand, for the most central events the ALICE results agree with the extrapolations based on the data at lower energies from CERN-SPS and RHIC.

**Keywords:** Event-by-event fluctuations; Identified hadrons; QCD phase transition; Heavy-ion Collisions; LHC

## 1. Introduction

The theory of strong interaction, Quantum Chromodynamics (QCD), predicts that at sufficiently high energies nuclear matter transforms into a deconfined state where nucleons are no longer the basic constituents but rather quarks and gluons. The event-by-event fluctuations [1] of suitably chosen observables opens new possibilities to investigate the properties of the so called "QCD phase diagram".

In general, one can classify fluctuations into two parts. First, dynamical fluctuations which result from correlated particle production reflecting the underlying dynamics of the system. Second, statistical fluctuations induced by the measurement process itself due to the finite event multiplicity.

In case of independent particle production the multiplicity fluctuations follow a Poisson distribution. To quantify particle correlations the observable  $v_{dyn}$  was proposed in Ref. [2, 3]. It is defined as

$$v_{dyn}[A, B] = \frac{\langle N_A^2 \rangle}{\langle N_A \rangle^2} + \frac{\langle N_B^2 \rangle}{\langle N_B \rangle^2} - 2 \frac{\langle N_A N_B \rangle}{\langle N_A \rangle \langle N_B \rangle} - \left( \frac{1}{\langle N_A \rangle} + \frac{1}{\langle N_B \rangle} \right), \quad (1)$$

where  $N_A$  and  $N_B$  are the numbers of particle types A and B in a given event and  $\langle \dots \rangle$  denotes averaging over events. The quantity  $v_{dyn}$  vanishes when the multiplicity distributions of both particle types are Poissonian

and independent from each other. Since the negative terms in the formula of  $v_{dyn}$  contain a correlation term, negative values of  $v_{dyn}$  indicate the degree of correlation between particle species.

In this article, we present the measurements of  $v_{dyn}[\pi^+ + \pi^-, K^+ + K^-]$ ,  $v_{dyn}[\pi^+ + \pi^-, p + \bar{p}]$  and  $v_{dyn}[K^+ + K^-, p + \bar{p}]$  in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV in ALICE. The results are compared to the HIJING [4] and AMPT [5] models as well as to measurements at lower energies from CERN-SPS [6] and RHIC [7].

## 2. Analysis Details

The present analysis uses about 13 million minimum bias Pb-Pb events at  $\sqrt{s_{NN}} = 2.76$  TeV collected by the ALICE detector [8] during the 2010 LHC run. The subdetectors involved in the analysis were the Time Projection Chamber (TPC) for the tracking and particle identification and the Inner Tracking System (ITS) for the vertexing. Moreover, the two forward V0 detectors were used for the centrality estimation. Particle identification (PID) was based on the measurement of the specific ionisation energy loss,  $dE/dx$ , in the TPC gas. The charged particles reconstructed in the TPC in full azimuth and in the pseudo-rapidity range of  $|\eta| < 0.8$  were used in this analysis. The momentum range was restricted to  $0.2 < p < 1.5$  GeV/c in order to minimise the systematic uncertainties due to overlap of measured particle  $dE/dx$  distributions.

### 2.1. Identity Method

When the  $dE/dx$  distributions of different particle species are well separated, a unique particle identification is possible. However, this is not possible when the measured particle  $dE/dx$  distributions overlap.

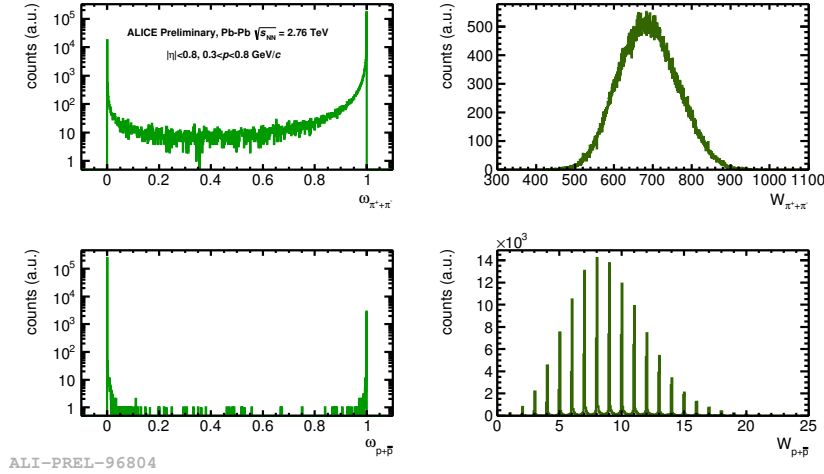


Fig. 1:  $\omega$  and  $W$  distributions for pions and protons within the momentum range of  $0.3 < p < 0.8$  GeV/c.

The so called "Identity Method" [9] proposes a solution to this misidentification problem. The method follows a probabilistic approach using the inclusive  $dE/dx$  distributions measured in the TPC, and determines the moments of the multiplicity distributions by an unfolding procedure. It requires two basic experimentally measurable event-by-event quantities,  $\omega$  and  $W$ , which are defined as

$$\omega_j(x) = \frac{\rho_j(x)}{\rho(x)} \longrightarrow \omega_j \in [0, 1], \quad W_j \equiv \sum_{i=1}^{N(n)} \omega_j(x_i), \quad (2)$$

where  $x$  stands for the  $dE/dx$  of a given track,  $\rho_j(x)$  is the  $dE/dx$  distribution of particle  $j$ ,  $\rho(x)$  is the inclusive  $dE/dx$  distribution within a given event and  $N(n)$  is the number of tracks within the  $n$ th event. In other words,  $\omega_j$  is a Bayesian probability measure of being particle type  $j$  for a given track. Thus, in case of perfect identification one expects  $\langle W_i \rangle = \langle N_i \rangle$ , while this does not hold in case of misidentification.

The moments of the  $W$  distributions  $\langle W_i \dots W_j \rangle$  can be easily constructed directly from experimental data. The identity method provides the real moments  $\langle N_i \dots N_j \rangle$  of the particle multiplicity distributions by means of an unfolding procedure using the moments of these  $W$  distributions. Examples for distributions of  $\omega$  and  $W$  in Pb-Pb data are shown in Fig. 1. Details of the derivation can be found in Ref. [10, 11].

## 2.2. Particle Identification (PID)

The identity method exploits the fits of inclusive  $dE/dx$  distributions for the calculation of  $\omega$ . Since the overlap regions in the  $dE/dx$  distributions are also allowed, one needs very good fits of inclusive  $dE/dx$  spectra over the full momentum range covered in the analysis. Therefore, a good understanding of the detector response of the TPC is required. To this end, clean particle samples, which were retrieved from V0 decay particles (pions from  $K_S^0$  decays, protons from  $\Lambda$  decays and electrons from photon conversions), were used. Fig. 2 left panel shows the determination of the detector response for pions, where a generalised Gauss function was used for a better description of the response shape. The detector response functions obtained in this way were later used as the fit functions in the inclusive  $dE/dx$  spectra fits as shown in Fig. 2 right panel.

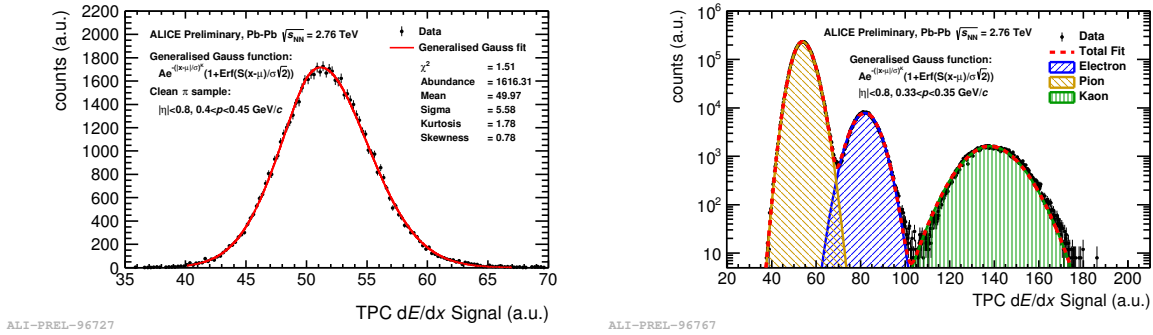


Fig. 2: Left:  $dE/dx$  distribution of a clean pion sample retrieved from the decay of  $K_S^0$ . A generalised Gauss function was used for the fit. Right:  $dE/dx$  distributions of pions, kaons and electrons within the momentum interval of  $0.33 < p < 0.35$  GeV/c.

## 3. Results

The results on particle ratio fluctuations are presented in terms of  $v_{dyn}$ , which is constructed from the moments of the  $W_j$  distributions (Eq. 1, 2). We have verified with a Monte Carlo simulation that the finite reconstruction efficiency affects the results for  $v_{dyn}$  by less than 10%, which was added to the systematic uncertainties. The other two main contributions to the systematic uncertainties are from the inclusive  $dE/dx$  spectra fits (15%) and the cut on the maximum distance of the reconstructed vertex to the nominal interaction point along the beam axis (5%). Fig. 3 shows results for  $v_{dyn}[\pi^+ + \pi^-, K^+ + K^-]$ ,  $v_{dyn}[\pi^+ + \pi^-, p + \bar{p}]$  and  $v_{dyn}[K^+ + K^-, p + \bar{p}]$  divided by the charged-particle multiplicity density at mid-rapidity,  $dN_{ch}/d\eta$ , as a function of the collision centrality, also expressed in terms of  $dN_{ch}/d\eta$  [12]. The results are compared to calculations with the HIJING [4] and AMPT [5] event generators. In this representation, the HIJING results are almost independent of centrality, reflecting that HIJING is based on a superposition of independent p-p collisions. AMPT, which includes initial state fluctuations and collectivity, shows a weak centrality dependence. Both models exceed the data with the exception of  $v_{dyn}[\pi^+ + \pi^-, K^+ + K^-]$ , where AMPT is in reasonable agreement with the data.

The ALICE results for the most central Pb-Pb collisions are compared to NA49 [6] and STAR [7] data in Fig. 4. It should be noted here that the detector acceptances, momentum ranges and primary particle selection criteria are slightly different. The ALICE data indicate positive results for  $v_{dyn}$  in all three cases and are consistent with Poissonian expectation within  $2\sigma$ .

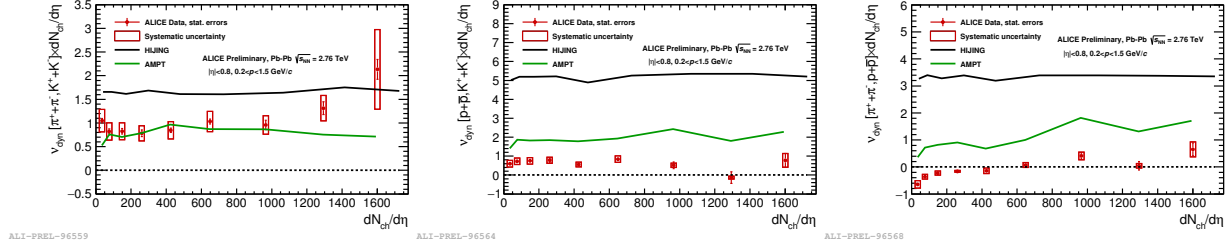


Fig. 3: ALICE results for  $v_{dyn}$  scaled by  $dN_{ch}/d\eta$ . Black and green solid lines show HIJING [4] and AMPT [5] model calculations, respectively.

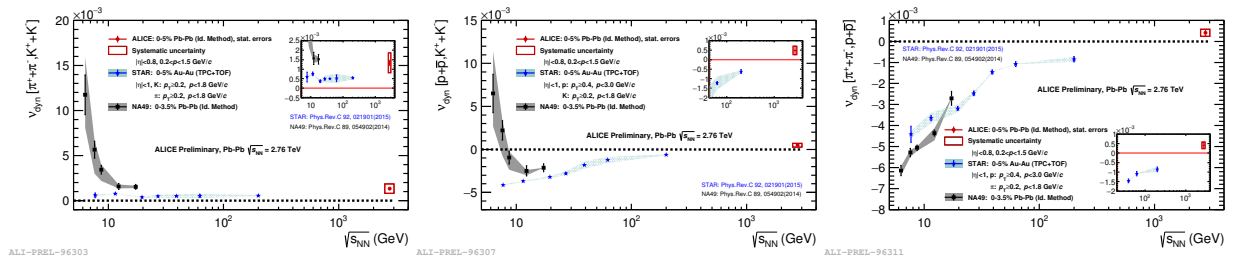


Fig. 4: Energy dependence of  $v_{dyn}$ . ALICE results are shown as red solid circles. Results from the Identity method for central Pb-Pb collisions from NA49 [6] are shown with black solid squares. Stars represent results from STAR [7] in central Au-Au collisions.

#### 4. Conclusions

In summary, dynamical fluctuations of identified particle ratios were measured as function of centrality in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV with ALICE. The identity method, which is planned to be used in further event-by-event analyses in ALICE, was applied to ALICE data successfully for the first time. The results for  $v_{dyn}[K^+ + K^-, p + \bar{p}]$  and  $v_{dyn}[\pi^+ + \pi^-, K^+ + K^-]$  are in qualitative agreement with models. However, the negative values of  $v_{dyn}[\pi^+ + \pi^-, p + \bar{p}]$  observed in most peripheral collisions, which indicate a correlation between pions and protons, are not reproduced by the models. In all three cases, ALICE results in the most central events indicate positive results consistent with Poissonian expectation within  $2\sigma$  which agree with the extrapolations based on the data at lower energies from CERN-SPS and RHIC. As a next step, a more differential analysis of  $v_{dyn}$  in terms of rapidity,  $p_T$ , and charge sign dependence as well as a study in p-p collisions is presently being prepared.

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