

## Relative Yield of Neutral and Charged Kaons in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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The first measurements of event-by-event correlated fluctuations of neutral and charged kaons are reported in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, which are proposed to be related to isospin fluctuations in the kaon sector. These dynamic fluctuations affect the mechanism of correlated productions of neutral and charged kaons in heavy ion collisions. In this work we have used the robust statistical observable,  $v_{\text{dyn}}$ , to study the dynamical fluctuations in the strangeness sector using charged and neutral kaons. A statistically significant signal of dynamical fluctuations are observed in the data which is underestimated by HIJING and AMPT model predictions, when moments of neutral and charged kaons are calculated as a function of centrality. We observed that  $K_S^0 - K^\pm$  fluctuations is not dominated by the correlation from particle decay like  $K^+ - K^-$ .

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## 1. Introduction

In high energy hadronic and nuclear collisions, a deconfined state of matter, the quark gluon plasma (QGP) is expected to be created, where quarks are massless. The chiral symmetry is restored in this phase. The system undergoes collective expansion and cools down to a state of matter where quarks have mass. This phase leads to the breaking of chiral symmetry. A possible consequence of the restoration and subsequent breaking of chiral symmetry may be the formation of Disoriented Chiral Condensates (DCC) [1, 2, 3, 4, 5], regions formed where the average chiral order parameter differs from its value in the vacuum. This can be described by the Lagrangian of the linear sigma model [2]. From the effective potential of the linear sigma model, it is clear that the region is in non-equilibrium. By radiating pions and kaons, the region equilibrates.

The formation of DCCs may produce a distinct signature in the kaon production relative to generic (normal) production [3, 6]. Under isospin symmetry, generic production yields an equal fraction of neutral and charged kaons. However, metastable DCC domains will favour the production of kaons with a particular isospin. If SU(3) symmetry is considered with massless quarks, the chiral order parameter can be described as  $\langle \sigma \rangle \sim \cos\theta \langle \bar{u}u + \bar{d}d \rangle + \sin\theta \langle \bar{s}s \rangle$ . Let us consider the probability distribution of the event wise ratio of the total number of neutral kaons to the total number of kaons produced in a single event. Let  $f_K$  be the fraction of neutral kaons over total kaons,

$$f_K = \frac{K^0 + \bar{K}^0}{K^0 + \bar{K}^0 + K^+ + K^-}. \quad (1.1)$$

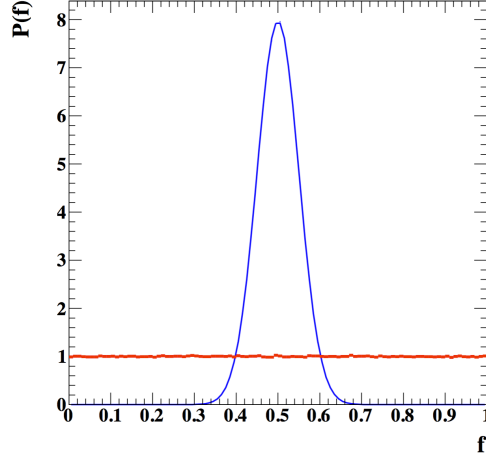
On general grounds, one expects because of isospin conservation in the strong interaction, that the production of all kaons species is equally probable. This mechanism leads to a binomial distribution of the neutral kaon fraction peaked at one-half, i.e.,  $\langle f_K \rangle = 0.5$ . If a DCC is formed, then the chiral field is misaligned with respect to the true vacuum direction. It realigns to the true vacuum direction, by radiating kaons. The probability distribution of the neutral kaon fraction taking into account the kaons from the DCC domain is very different from that of a generic case and was shown [3, 6] to be of the form

$$P(f_K) = 1, \quad 0 < f_K \leq 1. \quad (1.2)$$

The distribution  $P(f_K)$  for DCC (uniform) in Figure 1 is completely different from that for a generic distribution (binomial). The means,  $\langle f_k \rangle$ , of both distributions are the same, but the widths, characterised by the second moments, are quite different. A significant departure from the value 0.5 for  $f_K$  can then provide the cleanest evidence for the formation of a DCC. Gavin and Kapusta [7] proposed that the observable  $v_{\text{dyn}}$  [8] can be used to study isospin fluctuations in the strangeness (kaon) sector by virtue of the central limit theorem. It was also predicted, if collision centrality is varied, isospin fluctuation can appear as a change in magnitude of the dynamical isospin observable.

## 2. Fluctuation Observable: $v_{\text{dyn}}$

The robust statistical observable  $v_{\text{dyn}}$  is useful for the study of fluctuations, because the identification techniques for charged and neutral kaons feature different efficiencies. Neutral kaons  $K^0$



**Figure 1:** Probability distributions of the fraction of neutral kaons for generic and DCC productions.

and  $\bar{K}^0$  are observed as  $K_L^0$  and  $K_S^0$ . We use the multiplicity of  $K_S^0$  as the neutral kaons as  $K_L^0$  is difficult to observe due to its long lifetime. These are detected by the decay  $K_S^0 \rightarrow \pi^+ \pi^-$  (69.2%BR). The correlation between  $K_S^0$  and  $K^\pm (= K^+ + K^-)$  yield is quantified by measurement of the relative isospin covariance

$$R_{c0} = \frac{\langle N_c N_0 \rangle}{\langle N_c \rangle \langle N_0 \rangle} - 1, \quad (2.1)$$

where  $N_0$  and  $N_c$  are the number of  $K_S^0$  and  $K^\pm$  respectively. We take  $N_0 = N_{K_S^0}$  and  $N_c = N_{K^+} + N_{K^-}$  for kaons. The charged ( $R_{cc}$ ) and neutral variance ( $R_{00}$ ) terms can be written as

$$R_{cc} = \frac{\langle N_c(N_c - 1) \rangle}{\langle N_c \rangle^2} - 1 \quad (2.2)$$

$$R_{00} = \frac{\langle N_0(N_0 - 1) \rangle}{\langle N_0 \rangle^2} - 1. \quad (2.3)$$

These observables are robust against detection efficiency. To study isospin fluctuations in the kaon sector, the isospin observable can be defined as

$$v_{\text{dyn}} = R_{cc} + R_{00} - 2R_{c0} \quad (2.4)$$

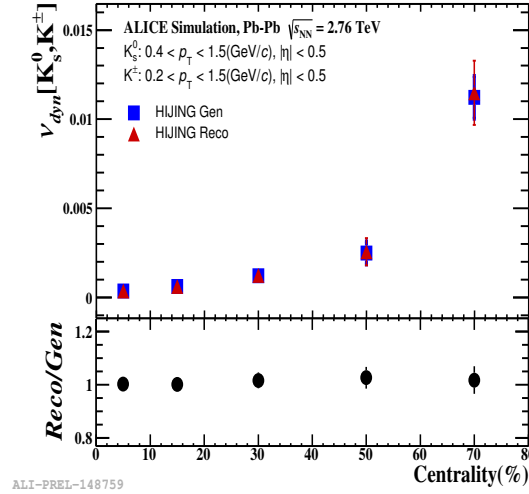
The first two terms essentially measure the fluctuations of, respectively, charged and neutral particles. The third term measures the strength of charged-neutral kaon correlation. For purely statistical fluctuations, in the limit of very large multiplicity, these individual terms would become unity. However, for finite multiplicity, these terms can deviate from unity even if there are no dynamical fluctuations. So it is difficult to reach a conclusion based on the measurements of the individual terms. However, when all three terms are added to form  $v_{\text{dyn}}$ , by construction, the finite multiplicity statistical fluctuations are eliminated. Therefore,  $v_{\text{dyn}}$  becomes zero for purely statistical fluctuations and non-zero only in the presence of dynamical fluctuations or correlations [9]. In this analysis we use  $v_{\text{dyn}}$  to study the hidden fluctuation among strange particles, because:

1. the observable is robust against detection efficiency.

2. it measures the relative strength of charge-charge, neutral-neutral and charge-neutral correlations
3. it serves as an indicator of any anomaly in the production of kaon fluctuation which might signal the existence of kaon DCCs

### 3. Analysis Details

The measurement is based on ALICE data from Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV acquired during Run 1 in 2010. 13 M minimum bias events are selected for data analysis. Two Monte-Carlo (MC) event generators, HIJING and AMPT are considered to study the sensitivity of  $v_{\text{dyn}}$  to different particle production dynamics. In this work, 3 M HIJING events are used. We have considered 3 different tunes of the AMPT event generators, (i) string melting ON, rescattering OFF (39 M), (ii) string melting OFF, rescattering ON (53 M), (iii) string melting ON, rescattering ON (38.94 M).



**Figure 2:** Top:  $v_{\text{dyn}}$  vs centrality for HIJING model calculations for  $K_S^0 K^\pm$ . Bottom: The ratio of reconstructed to generated values of  $v_{\text{dyn}}$  as a function of centrality.

This analysis is based on minimum bias (MB) events. The MB trigger was based on a combination of information of the hits from SPD and two sides of V0 detectors. The collision centrality was determined using the V0 multiplicity. We have considered various centralities for this analysis: 0–10%, 10–20%, 20–40%, 40–60% and 60–80%. Charged kaons ( $K^\pm$ ) are selected based on the signals measured from the combined information of TPC and TOF detectors. The  $K^\pm$  are selected in the kinematic ranges:  $|\eta| < 0.5$  and  $0.2 < p_T < 1.5$  GeV/c. The measurement of neutral kaons is carried out based on the weak decay  $K_S^0 \rightarrow \pi^+ + \pi^-$ . These decays are identified from the decay topology of V0 particle and the invariant mass of  $K_S^0$ . The decay vertex of  $K_S^0$  is reconstructed and calculated from pairs of detected  $\pi^+ \pi^-$  tracks. Standard ALICE topological cuts are used to obtain the neutral kaons. Neutral kaons with a transverse momentum within  $0.4 < p_T < 1.5$  GeV/c measured in the pseudo-rapidity range  $|\eta| < 0.5$  are selected with a invariant mass cut  $0.48$  GeV/c<sup>2</sup>

$\langle M_{\text{inv}}(\pi^+\pi^-) \rangle < 0.515 \text{ GeV}/c^2$ . Similar cuts are used in MC models to select charged and neutral kaons.

#### 4. Results

Once we obtain the number of  $K^\pm$  and  $K_S^0$  in each centrality with specific acceptance, average numbers of singles and pairs can be calculated. Values of  $v_{\text{dyn}}$  are then determined for each centrality bin. The values of  $v_{\text{dyn}}$  for both HIJING generated and reconstructed level are obtained and shown in the Top panel of Figure 2, as a function of centrality. Reconstructed HIJING events are obtained by passing generated HIJING events through a GEANT3 description of the ALICE detector. The values are bin width corrected. The values of  $v_{\text{dyn}}$  for both HIJING generated and reconstructed are steeply rising and are positive, when measured as a function of collision centrality. The values in each centrality bin are in agreement with each other. The statistical uncertainty on the values of  $v_{\text{dyn}}$  for HIJING MCs are calculated the sub-sampling method. The Bottom panel of Figure 2 depicts the ratio of reconstructed to generated values of  $v_{\text{dyn}}$  as a function of centrality. The ratios are within few percents of unity in all centrality bins. The error on the ratio is calculated using the binomial error propagation method. The measurement of  $v_{\text{dyn}}$  in HIJING MC is unaffected by the detector efficiencies.

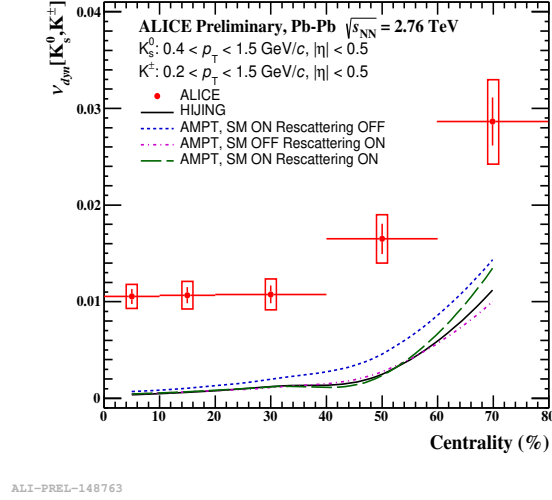
The ALICE data for  $v_{\text{dyn}}[K_S^0, K^\pm]$  are compared to MC model predictions in Figure 3. All values are corrected for centrality bin width. Statistical errors were evaluated using the sub-sampling method.

Measured  $v_{\text{dyn}}$  values are positive and significantly larger than those obtained with the model calculations. The trend is different in data compared to model predictions. The  $v_{\text{dyn}}[K_S^0, K^\pm]$  values are flat in central to mid-central events (0–40%) and rise towards peripheral collisions (40–80%). The covariance term of  $v_{\text{dyn}}$  becomes positive in charge-neutral correlations and cross correlations are weak in data. We observe a violation of  $1/n$  scaling in data, where “ $n$ ” is the number of sources. Both models predict  $1/n$  scaling. The two models fail to describe the behaviour of data. The anomalous behaviour in data indicates possible isospin fluctuation in the kaon sector.

We observe that the  $v_{\text{dyn}}$  values for AMPT except for string melting (SM) ON, rescattering OFF (blue lines) are in agreement with HIJING in each centrality bin. The values are a little bit higher for SM ON, rescattering OFF, compared to other cases. The hadronic rescattering includes decay of resonance particles, when it is OFF resonance decay ceases. This might influence the decrease in the number of produced particles and increase the value of  $v_{\text{dyn}}$ . A weaker correlation is expected from the production of large strange DCCs as shown in a simple phenomenological model of kaon DCC production [10].

#### 5. Conclusions

The first measurement of isospin fluctuations in the kaon sector in Pb-Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$  has been performed. Neutral-charge kaon correlation in the data shows anomalous behaviour ( $1/n$  scaling is violated), when studied as a function of collision centrality. This violation might indicate possible isospin fluctuation in the kaon sector. HIJING and AMPT, fail to describe



**Figure 3:**  $v_{\text{dyn}}$  vs centrality for ALICE data, HIJING and AMPT model calculations for  $K_S^0 K^\pm$ .

the behaviour of data. The  $v_{\text{dyn}}$  values for data are larger compared to models in each centrality. The AMPT results suggest that  $v_{\text{dyn}}$  is sensitive to the production dynamics.

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