Physics Letters B 832 (2022) 137242

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Neutral to charged kaon yield fluctuations in Pb – Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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ARTICLE INFO

Article history:
Received 21 January 2022
Received in revised form 13 May 2022
Accepted 7 June 2022
Available online 9 June 2022
Editor: M. Doser

ABSTRACT

We present the first measurement of event-by-event fluctuations in the kaon sector in Pb – Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the LHC. The robust fluctuation correlator ν_{dyn} is used to evaluate the magnitude of fluctuations of the relative yields of neutral and charged kaons, as well as the relative yields of charged kaons, as a function of collision centrality and selected kinematic ranges. While the correlator $\nu_{dyn}[K^+, K^-]$ exhibits a scaling approximately in inverse proportion of the charged particle multiplicity, $\nu_{dyn}[K^0_S, K^\pm]$ features a significant deviation from such scaling. Within uncertainties, the value of $\nu_{dyn}[K^0_S, K^\pm]$ is independent of the selected transverse momentum interval, while it exhibits a pseudorapidity dependence. The results are compared with HIJING, AMPT and EPOS–LHC predictions, and are further discussed in the context of the possible production of disoriented chiral condensates in central Pb – Pb collisions.

The primary intent of high-energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and at the Large Hadron Collider (LHC) is the production and study of the state of matter in which quarks and gluons are deconfined. The matter formed in these collisions is characterised as a low-viscosity fluid, which undergoes a transition to the hadronic phase, after it expands and cools down [1]. The transition from the hadronic to the QGP phase involves a partial restoration of chiral symmetry and color deconfinement. Deconfinement of quarks and gluonic degrees of freedom, and the production of QGP were brought to light by measurements of jet quenching [2–6], quarkonium state suppression, and measurements of anisotropic flow [7–12]. Anomalous fluctuations of conserved charges were predicted to arise in the vicinity of the phase boundary and potential signals of the production of a deconfined phase [13–17].

Several studies of particle yield fluctuations have already been reported [18–21] but their interpretation is largely a matter of debate. More recently, the ALICE collaboration has also investigated fluctuations of net charge, net protons, as well as fluctuations of the relative yields of pions, kaons, and protons [22–24]. Measurements of such fluctuations are of interest, in particular, as they are nominally sensitive to QGP susceptibilities [25], the proximity of the hadron gas-QGP phase boundary, as well as, when considered at lower beam energy, the existence of a critical point [26,27] in the phase diagram of nuclear matter. Additionally, measurements of fluctuations are also of interest to probe the existence (or proximity) of the chiral phase transition, which should manifest itself by the production of anomalous fluctuations [17]. A specific manifestation of this transition from the chiral symmetric phase (high temperature) to a broken phase (low temperature) involves the production of disoriented chiral condensates (DCCs) [28], a region in isospin space where the chiral order parameter is misaligned from its vacuum orientation. Theoretical studies of the production and decay of DCCs are typically formulated in the context of the SU(2) symmetry. It is predicted that the production and decay of DCCs shall manifest through enhanced fluctuations of neutral and charged pion multiplicities [29,30]. The past searches in this sector have yielded no evidence for DCC production [31–33]. However, the production of distinct DCC domains might result in "isospin fluctuations" in the kaon sector, i.e., enhanced fluctuations of the relative yields of neutral and charged kaons which can be measured by means of the $\nu_{dyn}[K^0, K^c]$ [34–38]. Specifically, it was predicted that the production of DCC domains in A–A collisions might lead to an anomalous scaling of the net charge correlator ν_{dyn}, defined in the following, as a function of charged particle multiplicity [39]. A search of kaon isospin fluctuations at LHC energies is thus of significant interest. Given that kaons from DCC are expected to be produced at modest transverse momentum [40], the present study is restricted to measurements of $K^\pm$ and K^0_S at the lowest possible transverse momenta (p_T) aiming at checking whether data support some basic expectations from the DCC production.

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https://doi.org/10.1016/j.physletb.2022.137242

A measurement of dynamical neutral-to-charged kaon fluctuations, with $\nu_{\rm dyn}$, is also of interest in the broader context of two-particle correlations induced by the hadronization of the QGP, via e.g., quark coalescence, and the transport of produced hadrons, as well as the possibility that high mass resonances lead to the production of pairs of kaons. Examples of such resonance decays that contribute to the $\nu_{\rm dyn}$ correlator include $\phi(1020) \to {\rm K}^+ + {\rm K}^-$, $\phi_3(1850) \to {\rm K} + \overline{\rm K}^*$, $f_2(2300) \to \phi + \phi$, as well as several D-mesons states. As they decay in-flight, these high-mass states would induce pair correlations of charged and neutral kaons. The relative abundance of such states might be larger in central collisions because of higher initial temperature and density conditions. The relative yield of neutral and charged kaons, and their fluctuations, might then exhibit a centrality dependence as a result of feed-down contributions from such states. Additionally, given that the relative yield of neutral kaons and charged kaons in general is determined by the relative yields of strange, up, and down quarks (and their anti-particles) before hadronization, and given that the production of strangeness is both energy and collision centrality dependent, one might anticipate a change in the size of the fluctuations from peripheral to central heavy-ion collisions. Note, however, that the presence of kaons resulting from feed-down contributions, which, for central Pb – Pb collisions at LHC energy, amount to about 50 percent at the lowest momenta considered [41], reduces but does not eliminate the sensitivity of the method to the presence of strange DCCs or other processes inducing variations of the direct kaon production [39].

In this letter, we report measurements of event-by-event fluctuations of inclusive multiplicities of charged and neutral kaons based on the robust statistical observable, $\nu_{\rm dyn}$, defined as

$$\nu_{\rm dyn} = R_{\rm cc} + R_{00} - 2R_{\rm c0}, \tag{1}$$

where the indices c and 0 stand for charged and neutral kaons, respectively. The correlators R_{xy} are normalized factorial cumulants calculated according to

$$R_{xy} = \frac{\langle N_x(N_y - \delta_{xy})\rangle}{\langle N_x\rangle \langle N_y\rangle} - 1, \tag{2}$$

Here $\delta_{xy} = 1$ for x = y and 0 for $x \neq y$. The correlators R_{xy} and $\nu_{\rm dyn}$ vanish in the absence of pair correlations, i.e., for Poisson fluctuations, but deviate from zero in the presence of particle correlations. Their magnitudes are expected to approximately scale in inverse proportion of the charged particle multiplicity, $N_{\rm ch}$, produced in heavy-ion collisions and shall be insensitive to detection inefficiencies, and only weakly dependent on the acceptance of the measurement [38].

In order to reduce the challenge of measuring neutral kaon multiplicities on an event-by-event basis, the neutral kaon measurement is restricted to ${\rm K}^0_{\rm S}$ by means of their decay into a pair of π^+, π^- (69.2% branching ratio [42]) with a displaced vertex. The wide acceptance and high detection efficiency of charged pions enables event-by-event reconstruction of ${\rm K}^0_{\rm S}$ with high efficiency and small combinatorial background. It is thus possible to measure their multiplicity event-by-event and compute the first, $\langle N_{{\rm K}^0_{\rm S}}\rangle$, as well as second, $\langle N_{{\rm K}^0_{\rm S}}(N_{{\rm K}^0_{\rm S}} - 1)\rangle$ factorial moments. These constitute estimators to moments of neutral kaon (and anti-kaon) yields. Indeed, given neutral kaons have a 50% probability of being a ${\rm K}^0_{\rm S}$, with a binomial probability distribution, a measurement of the ratio $\langle N_{{\rm K}^0_{\rm S}}(N_{{\rm K}^0_{\rm S}} - 1)\rangle / \langle N_{{\rm K}^0_{\rm S}}\rangle^2$ is thus strictly equivalent to $\langle N_{{\rm K}^0}(N_{{\rm K}^0} - 1)\rangle / \langle N_{{\rm K}^0}\rangle^2$. Likewise, $\langle N_{{\rm K}^0_{\rm S}} N_{{\rm K}^{\rm c}}\rangle) / \langle N_{{\rm K}^0_{\rm S}}\rangle \langle N_{{\rm K}^{\rm c}}\rangle$ is equivalent to $\langle N_{{\rm K}^0} N_{{\rm K}^{\rm c}}\rangle) / \langle N_{{\rm K}^0}\rangle \langle N_{{\rm K}^{\rm c}}\rangle$. A measurement of $\nu_{\rm dyn}[N_{{\rm K}^0_{\rm S}}, N_{{\rm K}^{\rm c}}]$ thus provides a proper and unbiased proxy to that of $\nu_{\rm dyn}[N_{{\rm K}^0}, N_{{\rm K}^{\rm c}}]$ even without a measurement of ${\rm K}^0_{\rm L}$.

The results presented in this letter are based on 1.3×10^7 minimum bias (MB) Pb – Pb collisions at center-of-mass energy per nucleon pair, $\sqrt{s_{\rm NN}}$ = 2.76 TeV collected during the 2010 LHC heavy-ion run with the ALICE detector. The reported correlation functions are measured for charged particles reconstructed within the Inner Tracking System (ITS) [43] and the Time Projection Chamber (TPC) [44]. The TPC consists of a 5 m long gas volume contained in a cylindrical electric field cage oriented along the beam axis, which is housed within a large solenoidal magnet designed and operated to produce a uniform longitudinal magnetic field of 0.5 T. Signals from charged particles produced in the TPC gas are readout at both end caps. The ITS is comprised of three subsystems, each consisting of two cylindrical layers of silicon detectors designed to match the acceptance of the TPC and provide high position resolution. Together, the TPC and ITS provide charged particle track reconstruction and momentum determination with full coverage in azimuth over the pseudorapidity range $|\eta| < 0.8$ and with good reconstruction efficiency for charged particles with $p_{\rm T} > 0.2$ GeV/c. Two forward scintillator systems, known as V0A and V0C, covering the pseudorapidity ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively, are additionally used for triggering and event classification purposes. Detailed descriptions of the ALICE detector components and their respective performances are given in Refs. [45,46]. The MB interaction trigger required at least two out of the following three conditions: i) two pixel chips hit in the outer layer of the silicon pixel detectors ii) a signal in V0A iii) a signal in V0C. The hit multiplicity in the V0 detectors is additionally used to estimate the collision centrality reported in seven classes corresponding to 0–5% (most central), 5–10%, 10–15%, 15–20%, 20–40%, 40–60%, and 60–80% (most peripheral) of the hadronic Pb – Pb cross section [47]. The approximate position along the beam line of the primary vertex ($z_{\rm vtx}$) of each collision is first determined based on hits recorded in the two inner layers of the ITS detector. Reconstructed charged particle tracks in the ITS and TPC are finally propagated to the primary vertex to achieve optimal position resolution. In the context of this analysis, the vertex is required to be in the range $|z_{\rm vtx}| \leq 10$ cm of the nominal interaction point in order to ensure a uniform detector acceptance and minimize variations of the efficiency across the fiducial volume of the experiment. In addition, the standard track quality selections were used to ensure that only well-reconstructed tracks were taken in the analysis. All selected tracks of each event are processed to identify pions and kaons with the techniques described below. Event-by-event combinations of two oppositely charged pions are formed to reconstruct topological ${\rm K}^0_{\rm S}$ candidates. Standard ALICE topological criteria, also detailed below, are then used to identify and select ${\rm K}^0_{\rm S}$ candidates. Charged and neutral kaons are counted, event-by-event, to calculate the moments $\langle N_c\rangle$, $\langle N_0\rangle$, $\langle N_c(N_c - 1)\rangle$, $\langle N_0(N_0 - 1)\rangle$ and $\langle N_c N_0\rangle$, in each collision centrality class. The corrections for particle losses are obtained event-by-event by dividing single and pair yields by the detection efficiency and products of efficiencies, respectively. Transverse momentum and pseudorapidity dependent efficiencies were evaluated from GEANT simulations (discussed below) of the particle detection performance with the HIJING model. The moments are finally combined to calculate $\nu_{\rm dyn}$ values in each class according to Eq. (1).

Charged particle identification (PID) is performed in the pseudorapidity range $|\eta| < 0.5$ using the $n\sigma$ method based on their energy loss (dE/dx) and their time of flight, measured in the TPC and TOF detectors, respectively [45,46]. A selection resulting in a PID with a high purity is crucial in order to minimize biases in measurements of $\nu_{\rm dyn}$. Kaons are selected from TPC dE/dx with $|n\sigma| < 2$ in the ranges $0.2 < p < 0.39$ GeV/c and $0.47 < p < 0.5$ GeV/c, and $-0.5 < n\sigma < 2$ in the range $0.39 < p < 0.47$ GeV/c to reduce contamination from electrons. Both TPC and TOF signals, with $|n\sigma| < 2$, are used in the range $0.5 < p < 1.5$ GeV/c. Further-

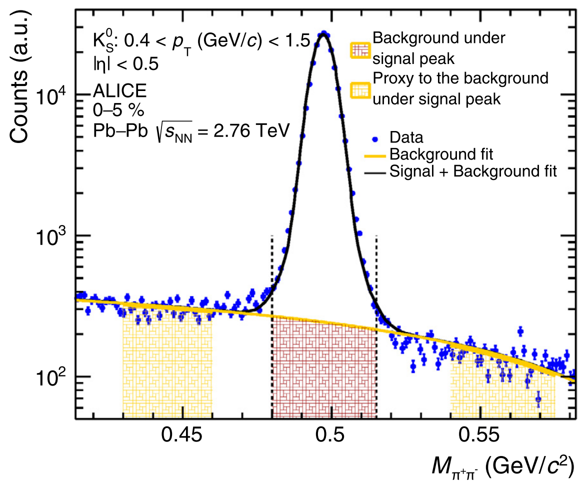

Fig. 1. Invariant mass distribution of $\pi^+ + \pi^-$ pairs measured in central (0–5%) Pb – Pb collisions. The yellow and black solid lines show a second order polynomial fit of the combinatorial background and a Gaussian+second order polynomial fit to the invariant mass spectrum, respectively. The vertical dash lines delineate the mass range used for the determination of neutral-kaon yields. Given the red-brown area, which corresponds to combinatorial background, cannot be properly assessed event by event, the average of the yellow areas is used as proxy, event-by-event, to estimate the true combinatorial yield represented by the red-brown area.

more, kaon tracks are selected based on their distance of closest approach (DCA) to the collision primary vertex in order to select primary tracks and suppress contamination from secondary particles and processes. Only tracks with DCAs smaller than 3.2 cm and 2.4 cm along and transverse to the beam direction, respectively, are included in the analysis. These selection cuts lead to charged kaon contamination ranging from 1.0% (TPC) to 1.4% (TPC+TOF) in peripheral collisions, and 2.7% (TPC) to 4.4% (TPC+TOF) in 5% most central collisions.

Neutral kaons, K^0_S, are reconstructed and selected within $0.4 < p_T < 1.5$ GeV/c and $|\eta| < 0.5$ based on their weak decay $K^0_S \to \pi^+ + \pi^-$ topology and an invariant mass selection criterion, $0.480 < M_{\pi^+\pi^-} < 0.515$ GeV/c^2 with their decay-product tracks within the acceptance window $|\eta| < 0.8$. Standard ALICE topological cuts [48] are used towards the selection of K^0_S candidates formed from π^+ and π^- tracks identified with the TPC and TOF detectors with $p_T > 0.2$ GeV/c. The maximum DCA of neutral kaons is set to 0.1 cm in all directions. The required $n\sigma$ values for the pions were $|n\sigma| < 2$ in both TPC and TOF detectors for $0.2 < p < 1.5$ GeV/c. These selection criteria yield a combinatorial $\pi^+ + \pi^-$ pair contamination ranging from 1.3% in peripheral collisions to 4.0% in 5% most central collisions, shown as a red-brown area in Fig. 1.

Event-by-event fluctuations of the combinatorial background artificially increase the factorial moment $\langle N_0(N_0-1)\rangle$ and may bias $\langle N_0 N_c\rangle$. A correction for such contamination is accomplished by additionally measuring correlators involving moments of the number of background pion pairs, N_b, in side band mass ranges $0.430 < M < 0.460$ GeV/c^2 and $0.540 < M < 0.575$ GeV/c^2 used as proxies of the number of background pairs in the nominal mass range $0.480 < M < 0.515$ GeV/c^2, shown in Fig. 1, as yellow and red-brown areas. The background suppressed correlators R_{00} and R_{c0} are thus calculated according to

$$R_{00} = (1 - f_{ab})^{-2}\left[R_{aa} - 2 f_{ab} R_{ab} + f_{ab}^2 R_{bb}\right], \quad (3)$$

$$R_{c0} = (1 - f_{ab})^{-1}\left[R_{ac} - f_{ab} R_{bc}\right], \quad (4)$$

where the labels a, b, and c represent pairs in the nominal mass range, pairs observed in either side bands, and pairs of charged kaons, respectively. The fraction $f_{ab} = \langle N_b\rangle / \langle N_a\rangle$ is determined for each collision centrality bin as the average number of background pairs in the range $0.480 < M < 0.515$ GeV/c^2 estimated from a polynomial fit to the background, as illustrated in Fig. 1. Corrections for combinatorial contamination based on Eqs. (3), (4) range from 4.7% in peripheral to 2.5% in central collisions. Additionally, given the number of charged and neutral kaons grows monotonically with collision centrality, values of $\nu_{dyn}[K^0_S, K^\pm]$ are corrected for finite centrality bin widths. The bin width correction is calculated by considering the weighted average of ν_{dyn} evaluated in 1% intervals of collision centrality across the reported bin widths [49]. These corrections range from 3.9% in peripheral to 2.1% in central collisions.

Statistical uncertainties are evaluated with the event subsampling method using 10 subsamples [24,50]. The systematic uncertainties include contributions from secondary particles, as well as from the p_T dependence of the tracking efficiency which is not perfectly canceled in the determination of the normalized cumulants R_{xy}. The event and track selection criteria were varied, and a statistical test [51] was used to identify significant sources of systematic uncertainties. The largest sources of systematic uncertainties include: (i) the effect of varying the minimum or maximum decay length (< 4%), (ii) variations of the $K^\pm$ purity when changing the sigma selection criteria (< 4%), (iii) variations during the data taking period of the $K^\pm$ and K^0_S yields (< 3%), and (iv) variations of R_{00} when correcting for combinatorial background using different fiducial invariant mass ranges and side bands (< 2%). Additional uncertainties arise when varying the range of accepted primary vertices (< 4%). Adding all sources in quadrature, systematic uncertainties are estimated to be smaller than 13%, independently of collision centrality.

Heavy-ion collisions simulated with the HIJING v2.0 [52] and AMPT v2.21 [53] Monte Carlo (MC) event generators, including the propagation of the produced particles through the detectors using GEANT3 [54], are used to validate the correction method. To that end, the reconstructed values of ν_{dyn} obtained from full MC simulations are processed as data, then the fully corrected ν_{dyn} values are compared to those obtained at generator level, i.e., from simulations without detector effects. The agreement between the reconstructed and generator level values of ν_{dyn} are found to be within 1%. Generator level MC simulations performed with the AMPT and EPOS–LHC [55] models are additionally used to obtain basic theoretical expectations for the magnitude of charged to neutral kaon yield fluctuations. AMPT events produced with the options of string melting on (SON) and rescattering off (ROFF), string melting off (SOFF) and rescattering on (RON), and SON and RON are considered. Furthermore, EPOS–LHC events are analyzed at generator level for Pb – Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. All sets of simulated data are analyzed with selection parameters and conditions identical to those used in the analysis of the experimental data. Additionally, the robustness of the analysis was tested by performing a closure test. To that end, values of $\nu_{dyn}[K^0_S, K^\pm]$ obtained with HIJING simulated events at both the detector and generator levels are compared, and verified that values of ν_{dyn} obtained with full simulations of the detector performance and data reconstruction (detector level) are in excellent agreement with those obtained with generator level data sets.

The top panel of Fig. 2 (a) presents $\nu_{dyn}[K^0_S, K^\pm]$ (red solid circles) as a function of the Pb–Pb collision centrality. The largest ν_{dyn} is observed in the most peripheral collisions and monotonically decreases for more central collisions. Such a behavior is qualitatively well described by HIJING, AMPT and EPOS–LHC calculations, but these models underestimate the magnitude of $\nu_{dyn}[K^0_S, K^\pm]$ by an approximate factor of two in peripheral collisions and by an order of magnitude in most central collisions. The magnitude of $\nu_{dyn}[K^0_S, K^\pm]$ is expected to approximately scale in inverse proportion to the number of sources of correlated particles, N_s, for a

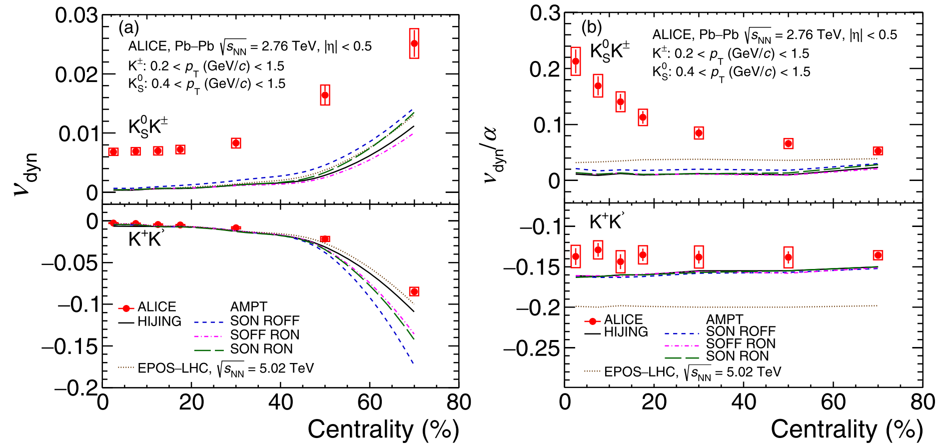

Fig. 2. (a) Measured values of $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]$ (top) and $\nu_{\rm dyn}[{\rm K^+},{\rm K^-}]$ (bottom) compared with HIJING and AMPT model calculations of these observables at generator level. (b) Values of $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]$ (top) and $\nu_{\rm dyn}[{\rm K^+},{\rm K^-}]$ (bottom) scaled by $\alpha \equiv (\langle {\rm K^0_S}\rangle^{-1} + \langle {\rm K^\pm}\rangle^{-1})$. Statistical and systematic uncertainties are represented as vertical bar and boxes, respectively.

collision system involving independent nucleon–nucleon collisions and no scattering of produced particles. This scaling is explored in the top panel of Fig. 2(b) which displays the centrality dependence of $\nu_{\rm dyn}$ scaled by the factor $\alpha \equiv (\langle {\rm K^0_S}\rangle^{-1} + \langle {\rm K^\pm}\rangle^{-1})$. This factor is known to be approximately proportional to $N_{\rm s}$ [56]. Scaled values predicted by the models are found to be essentially invariant with collision centrality. HIJING, in particular, exhibits nearly constant values of $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]/\alpha$ as a function of collision centrality, whereas AMPT calculations with SON and ROFF options display a very modest collision centrality dependence, hardly visible in Fig. 2(b). The measured data, by contrast, feature a strong variation with decreasing centrality. In particular, $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]/\alpha$ rises from $\approx 0.053 \pm 0.005({\rm stat}) \pm 0.007({\rm sys})$ in the 60–80% collision centrality range to $0.213 \pm 0.021({\rm stat}) \pm 0.025({\rm sys})$ in 5% most central collisions and thus one then concludes the expected $1/N_{\rm s}$ scaling of $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]$ is strongly violated.

In order to interpret the dependence of $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]$ on collision centrality and identify the origin of the $1/N_{\rm s}$ scaling violation, we study the collision centrality dependence of the components $R_{\rm cc}$, $R_{\rm c0}$, and R_{00} relative to those obtained with HIJING. Correlators computed with HIJING have a nearly perfect $1/N_{\rm s}$ scaling as a function of collision centrality. This means they can be used as "no-scaling-violation" baselines to investigate the collision centrality dependence of the evolution of the measured $R_{\rm cc}$, $R_{\rm c0}$, and R_{00} correlators with collision centrality. Fig. 3 presents ratios of measured correlators to those obtained with HIJING as a function of collision centrality. The ratio $R_{00}/R_{00}^{\rm HIJING}$ exhibits the largest deviation from unity but is otherwise independent, within uncertainties, of collision centrality. This term thus essentially features the $1/N_{\rm s}$ scaling expected from a system consisting of a number of independent sources, albeit with a magnitude larger by about 15% than that expected from HIJING. By contrast, the ratio $R_{\rm cc}/R_{\rm cc}^{\rm HIJING}$ is closest to unity but features a modest collision centrality dependence. This modest dependence, discussed further below, is not the main cause of the observed scaling violation of $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]$ with collision centrality. Indeed, it is found that the ratio $R_{\rm c0}/R_{\rm c0}^{\rm HIJING}$ manifests a more significant collision centrality dependence. The ratio is of the order of unity in the 60–80% collision centrality range with a deviation from unity consistent, more or less, with that observed for the ratio $R_{\rm cc}/R_{\rm cc}^{\rm HIJING}$ across all centralities. HIJING thus appears to provide a reasonable approximation of the measured correlation strength of neutral to charged kaons in peripheral collisions. However, the deviation of the measured $R_{\rm c0}$ from HIJING predictions increases monotonically from peripheral to central Pb–Pb collisions, with the largest deviation observed for

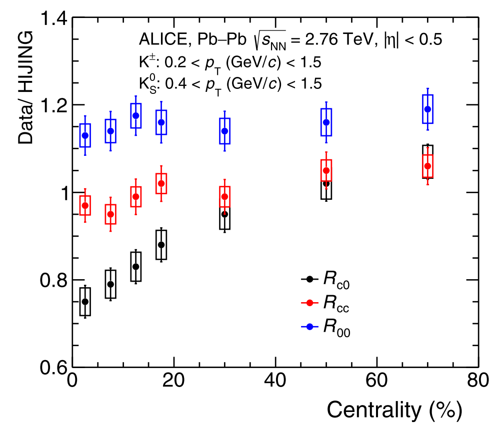

Fig. 3. Ratio (Data/HIJING) of individual terms of $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]$ as a function of collision centrality. Statistical and systematic uncertainties are represented as vertical bar and boxes, respectively.

the 0–5% Pb–Pb collisions. We then conclude that it is the $R_{\rm c0}$ term that most affect the collision centrality dependence and scaling violation of $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]$. Interestingly, it happens to be the term most sensitive to variations in the make up of kaons: combining a strange quark (s) with anti-up ($\bar{u}$) and anti-down quark ($\bar{d}$), one obtains $\rm K^-$ and $\rm K^0$, respectively (similarly, combining $\bar{s}$ to u and d quarks, one obtains $\rm K^+$ and $\rm K^0$). Fluctuations in the relative number of neutral and charged kaons, measured by the $R_{\rm c0}$ term, are thus sensitive to fluctuations in the relative local abundances of u ($\bar{u}$) and d ($\bar{d}$) quarks. The observed scaling violation of $R_{\rm c0}$ with collision centrality thus suggests the relative abundances of $\bar{u}$ and $\bar{d}$ (as well as u and d) available for the makeup of kaons might be evolving with collision centrality.

The strength of charged kaon correlations is examined in closer detail by plotting measured values of $\nu_{\rm dyn}[{\rm K^+},{\rm K^-}]$ and predictions by AMPT, HIJING and EPOS–LHC for this observable as a function of collision centrality in the bottom panel of Fig. 2 (a), and values scaled by α in Fig. 2 (b). The deviations of measured $\nu_{\rm dyn}[{\rm K^+},{\rm K^-}]$ from model predictions are smaller than those for $\nu_{\rm dyn}[{\rm K^0_S},{\rm K^\pm}]$ but measured $\nu_{\rm dyn}[{\rm K^+},{\rm K^-}]$ values lie systematically above those obtained from the models. Although HIJING, AMPT and EPOS–LHC do not perfectly capture the magnitude and collision dependence of $\nu_{\rm dyn}[{\rm K^+},{\rm K^-}]$, they nonetheless provide a relatively accurate description of the role of charge conservation, for charged kaons, in Pb – Pb collisions. Additionally note that scaled values $\nu_{\rm dyn}[{\rm K^+},{\rm K^-}]/\alpha$ are invariant, within uncertainties, with col-

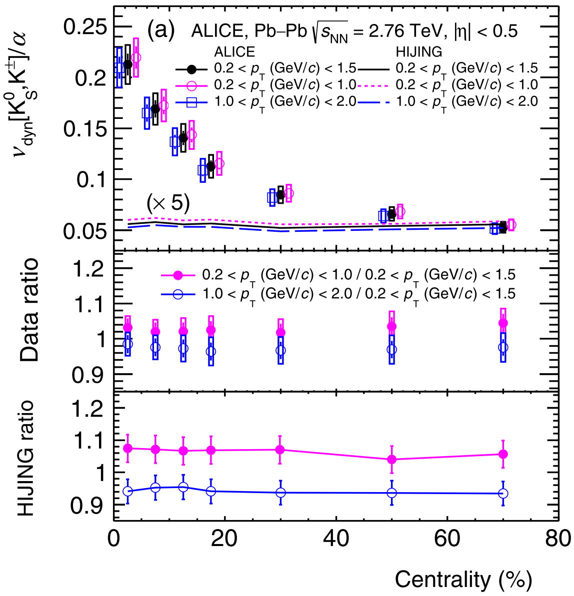

Fig. 4. (a) top: measured and HIJING (generator level) predicted values of $\nu_{dyn}[K^0_S, K^\pm]$ scaled by α as a function of collision centrality for various transverse momentum interval of charged kaons. HIJING predicted scaled values are multiplied by a factor of 5 to approximately match the measured values in most peripheral collisions; middle: ratio of data for various transverse momentum interval as a function of centrality; bottom: ratio of HIJING for various transverse momentum interval as a function of centrality.

lision centrality, much like values obtained with the three models. Scaling violations of $\nu_{dyn}[K^+, K^-]$ with collision centrality, if any, are not observable within the uncertainties of this measurement and stand in sharp contrast to the large scaling violation of $\nu_{dyn}[K^0_S, K^\pm]$ shown in the top panel of Fig. 2(b). One can then conclude that the large centrality dependence of $\nu_{dyn}[K^0_S, K^\pm]$ does not originate from anomalous charge correlations.

The observed strong decrease of $R_{c0}/R_{c0}^{\rm HIJING}$ in central collisions indicates that the level of correlations between neutral and charged kaons is weakening in this range relative to that predicted by HIJING. A weaker correlation is expected from the production of large strange DCCs, as shown in Fig. 5 of Ref. [39] presenting a simple phenomenological model of kaon DCC production. The observed dependence of $\nu_{dyn}[K^0_S, K^\pm]$ on collision centrality is consistent with expectations based on a simple DCC model. However, significant contributions from other final state effects in central collisions might also dilute the correlation developed in initial stages.

Nominally, the production of strange DCCs should manifest itself by the emission of relatively low-p_T kaons in the rest frame of the DCC [37]. Even though there is no quantitative prediction in the literature, the radial acceleration [57,58] known to occur in relativistic A–A collisions may affect the DCCs and the particles they produce. Therefore, the strength of the $\nu_{dyn}[K^0_S, K^\pm]$ correlator is studied in different ranges of transverse momentum.

The collision centrality evolution of the scaled values of $\nu_{dyn}[K^0_S, K^\pm]$ is shown in Fig. 4 for selected p_T ranges. The ν_{dyn}/α scaling violation is observed in both the higher and lower selected p_T ranges. Contrary to what one expects from DCC production, within uncertainties, the scaled correlation strength does not show a significant enhancement at low p_T. As shown in the bottom panel of Fig. 4, HIJING also predicts larger correlation strengths in the lower p_T range. Additionally, Fig. 5 presents the dependence of $\nu_{dyn}[K^0_S, K^\pm]$, in panel (a), and $\nu_{dyn}[K^0_S, K^\pm]/\alpha$, in panel (b), on the width of the pseudorapidity acceptance, $\Delta\eta$, for 0–5% and 5–10% Pb – Pb collision centrality ranges. In panel (a), the data exhibit a monotonic decrease of $\nu_{dyn}[K^0_S, K^\pm]$ with increasing $\Delta\eta$, which reflects the finite correlation width of all three integral correlator terms R_{xy}, whereas in panel (b), scaled values of $\nu_{dyn}[K^0_S, K^\pm]$ exhibit a monotonically decreasing trend with decreasing $\Delta\eta$ acceptance that stems largely from the decrease of the integrated yield of kaons with shrinking $\Delta\eta$ acceptance. DCCs are expected to produce relatively low p_T particles [29,36] and should thus be characterized by relatively narrow correlation functions in momentum space. Radial acceleration associated with the collision system expansion shall further narrow the correlation dependence on $\Delta\eta$. We note, however, that the peak widths, $\sigma_{\Delta\eta}$, observed in data are not significantly smaller than those obtained with the HIJING calculations. Qualitatively, one would expect radial flow to further reduce the $\sigma_{\Delta\eta}$ difference among low-p_T kaons produced by the decay of strange DCCs. Unfortunately, the absence of a prediction of the effect of radial flow on DCCs and given that the observed widths are only slightly smaller than those estimated with HIJING, the measured data thus do not make a compelling case for the production of strange DCCs in Pb – Pb collisions at the TeV scale.

In this letter, we presented measurements of event-by-event fluctuations of the relative yield of the neutral and charged kaons in Pb – Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV based on the ν_{dyn} observable. The centrality dependence of ν_{dyn} is observed to violate the $1/N_s$ multiplicity scaling expected from a system of N independent sources, but this effect is not reproduced by HIJING, AMPT, and EPOS–LHC models. Close examination of the three terms of ν_{dyn} reveals that the strength of correlations among charged kaons features a collision centrality dependence close to that expected with these three models. The R_{c0} cross-term, however, is found to weaken considerably, in most central collisions, relative to a naive $1/N_s$ expectation. This indicates correlations between charged and neutral kaons are significantly suppressed in central collisions. Given the fact that at this time it is unknown if other processes could mimic the signature of kaon production via DCCs and that the expected momentum dependence is not observed in the data, the reported measurement does not support the case for strange DCC production in heavy-ion collisions at LHC energies. Further measurements of differential correlations in $\Delta\eta$ vs. $\Delta\phi$ and higher factorial moments are of interest, as they could provide information on the momentum correlation length and the typical size of correlated kaon sources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ALICE reports was provided by European Organization for Nuclear Research.

Acknowledgement

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Österreichische Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e

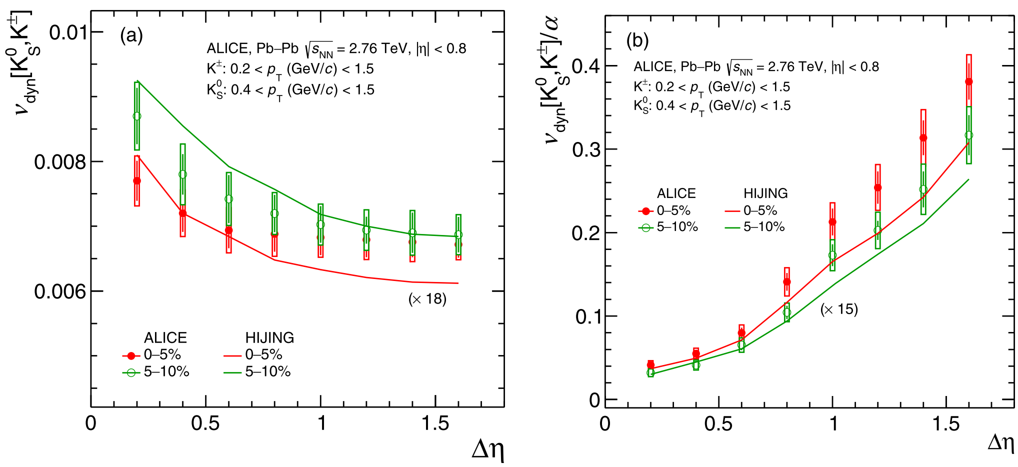

Fig. 5. (a) Measured values of $\nu_{dyn}[K^0_S, K^{\pm}]$ plotted as a function of the width of the acceptance $\Delta\eta$ in the 0–5% and 5–10% collision centrality ranges are compared HIJING (generator level) calculations scaled by a factor of 18. (b) Values of $\nu_{dyn}[K^0_S, K^{\pm}]$ shown in panel (a) are scaled by α. HIJING values are scaled by a factor of 15 for easier comparison with the data. The statistical and systematic uncertainties are represented as bar and boxes, respectively.

Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Ministry of Education of China (MOEC), Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the Villum Fonden and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Énergie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy, Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Sciences, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Académico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Education and Science, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics, Ministry of Research and Innovation and Institute of Atomic Physics and University Politehnica of Bucharest, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSDTA) and Office of the Higher Education Commission under NRU project of Thailand, Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

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