Modeling of Charged-Neutral Kaon Fluctuations as a Signature of DCC Production in A–A Collisions

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Anomalous event-by-event fluctuations of the relative yields of neutral (K^0) and charged kaon (K^±) have been predicted to yield a signature for the formation of Disoriented Chiral Condensate (DCC) in relativistic heavy-ion collisions. In this work, we model the production and decay of DCCs in the context of heavy-ion collisions at the Large Hadron Collider, and estimate the sensitivity of many small DCCs suggested the study of isospin fluctuations in the kaon sector using the \( \nu_{\text{dyn}} \) variable. This exploration was motivated, in part, by an extension of the two flavor idealization of the linear sigma model to a three flavor model based on SU(3) symmetry. In this model, fluctuations of strange quarks are coupled to those of up and down quarks and the chiral condensate is determined by a \( u - d - s \) scalar field. As DCC domains relax, they radiate pions, kaons, and

I. INTRODUCTION

Ultra-relativistic heavy-ion collisions at Large Hadron Collider (LHC) energies produce matter consisting of quarks and gluons in a de-confined state. This matter expands and cools through the critical temperature thereby forming hadrons. Within the hot and dense plasma of quarks and gluons, one expects the production of regions where the chiral symmetry is nearly restored. Restoration of chiral symmetry and its subsequent relaxation towards the normal vacuum is additionally posited to yield transient regions where the value of the chiral order parameter differs from that of the surrounding medium. These regions are called Disoriented Chiral Condensate (DCC). Theoretical studies of the production and decay of DCCs were formulated in the context of the SU(2) linear sigma model, more than two decades ago. It was predicted that the production and decay of DCCs shall manifest through enhancement of electromagnetic processes and anomalous distributions of neutral and charged pion multiplicities.

To date, experimental studies of chiral symmetry restoration and searches for the production of DCCs were based on the two-flavor linear sigma model and involved measurements of pion production and their fluctuations. Unfortunately, these measurements were largely inconclusive. More recently, however, observation of a significant enhancement of the production of \( \Omega \) and \( \Omega^- \) baryons in 17 A GeV in Pb–Pb collisions measured at the CERN SPS provided new insight. It is conceivable that DCC domains also affect the strange particle production. Strange DCC production might then explain the observed enhancement of \( \Omega \) observed at the SPS. This implies that the evolution of the chiral condensate could feature a substantial strangeness component. Relaxation to vacuum of the DCC could thus produce kaon isospin fluctuations. One of the first theoretical works to address the observable consequence of kaon fluctuations in the presence of many small DCCs is the study of isospin fluctuations in the kaon sector using the \( \nu_{\text{dyn}} \) variable. This exploration was motivated, in part, by an extension of the two flavor idealization of the linear sigma model to a three flavor model based on SU(3) symmetry. In this model, fluctuations of strange quarks are coupled to those of up and down quarks and the chiral condensate is determined by a \( u - d - s \) scalar field. As DCC domains relax, they radiate pions, kaons, and
\(\eta\) mesons. At low beam energy, the linear sigma model simulations indicate that pion fluctuations should dominate three flavor DCC behaviour given the fraction of energy imparted to kaon fluctuations is very small due to its larger mass. However, this may not be true for collisions at LHC energies where the kaon mass is small relative to the energy available towards particle production. Strangeness might indeed play an important role in the decay of DCCs once the temperature exceeds the mass of the strange quark. The rapid and oscillatory relaxation of order parameters would lead to an enhanced production and field fluctuations of kaons, albeit to a lesser degree than pions [8]. DCC production might thus induce anomalous fluctuations of the kaon total isospin measurable in the form of charged vs. neutral kaon yields fluctuations. A search for charged vs. neutral kaon yield fluctuations at LHC energies is thus of significant interest.

Experimental observations of DCC signals depend on various factors such as the probability of occurrence of DCC in a collision, the number of DCC domains produced in an event, the size of the domains and the number of particles emitted from these domains, as well as the interaction of these particles with the rest of the collision system [11]. Uncertainties about these conditions make the detection of DCC signals quite challenging experimentally. It is thus appropriate to first study kaon yield fluctuations in systems that do not feature DCC detection quite challenging experimentally. Therefore, it is appropriate to first study kaon yield fluctuations in systems that do not feature DCC signals quite challenging experimentally. It is thus appropriate to first study kaon yield fluctuations in systems that do not feature DCC detection quite challenging experimentally. It is thus appropriate to first study kaon yield fluctuations in systems that do not feature DCC detection quite challenging experimentally. It is thus appropriate to first study kaon yield fluctuations in systems that do not feature DCC detection quite challenging experimentally.

Within the context of the SU(3) linear sigma model, DCC domains relax by radiating pions, kaons, and \(\eta\) mesons. The relaxation of these disoriented domains is predicted to produce widely fluctuating neutral pion and kaon yields relative to those of charged pions and kaons in a given fiducial acceptance. These fluctuations may be characterized in terms of a neutral pion fraction \(f_\pi\) and a neutral kaon fraction \(f_K\). The neutral pion fraction is defined as
\[
\eta = \frac{N_{\pi^0}}{(N_{\pi^-} + N_{\pi^0} + N_{\pi^+})}
\]
where, \(N_{\pi^0}, N_{\pi^+},\) and \(N_{\pi^-}\) represent the yields of neutral, positively charged, and negatively charged pions measured within the fiducial acceptance, respectively. The neutral kaon fraction is defined as
\[
\eta = \frac{N_K}{N_{K^0} + N_{K^0} + N_{K^+} + N_{K^-}}
\]
where \(N_{K^0}, N_{K^0}, N_{K^+},\) and \(N_{K^-}\) represent the yields of neutral kaon, neutral-anti-kaon, positively charged kaons, and negatively charged kaons measured within the fiducial acceptance, respectively. For any given DCC, the neutral pion fraction \(f_\pi\) is predicted to fluctuate according to the probability density [1]
\[
P(f_\pi) = \frac{1}{2\sqrt{f_\pi}}
\]
whereas the neutral kaon fraction \(f_K\) shall be maximally fluctuating with a probability density [10]:
\[
P(f_K) = 1.
\]
It should be noted that these probability densities deviate significantly from those expected from “normal hadronic matter” involving clusters or res-
onance decays, that yield fluctuations of \( f_\pi \) and \( f_K \) determined by multinomial distributions with averages \( 1/3 \) and \( 1/2 \), respectively. Several experimental difficulties arise, however, towards measurement of these fractions. First, measurements of particle yields are impaired by particle losses determined by the limited detection efficiencies of the experimental device, the reconstruction techniques, and identification protocols used in any given analysis. This leads to binomial sampling and a broadening of the variance of measured multiplicities. Second, the pion and kaon yields may fluctuate for a number of reasons having little to do with the relative yields of produced charged and neutral kaons (anti-kaons) mix as multiplicities. Second, the pion and kaon yields may need a fluctuation observable that is sensitive to the existence and production of DCCs. One expects fluctuations of their relative values may be evaluated with the \( \nu_{\text{dyn}}(n_c, n_0) \) observable defined as

\[
\nu_{\text{dyn}}(\alpha, \beta) = R_{\alpha\alpha} + R_{\beta\beta} - 2R_{\alpha\beta},
\]

where the correlators \( R_{\alpha\beta} \) are calculated according to

\[
R_{\alpha\beta} = \frac{\langle n_{\alpha}(n_0 - \delta_{\alpha\beta}) \rangle}{\langle n_0 \rangle} - 1, \quad (4)
\]

with \( \delta_{\alpha\beta} = 1 \) for \( \alpha = \beta \) and \( \delta_{\alpha\beta} = 0 \) otherwise. It is straightforward to verify that the correlators \( R_{\alpha\beta} \) are robust against experimental efficiencies \( \mathcal{E} \), i.e., they are equal to the values of these correlators obtained based on the true (produced) multiplicities \( N_c = N_{K^+} + N_{K^-} \) and \( N_0 = N_{K^0} \). Corrections for contamination and admixtures of combinatorial backgrounds are possible by measuring their correlators \( R_{\alpha\beta} \) explicitly.

The magnitude of \( \nu_{\text{dyn}}(n_c, n_0) \) is determined by the relative strength of charged and neutral kaon correlations: \( R_{cc} \) measures the strength of charged kaon correlations, \( R_{00} \) measures the strength of neutral kaon correlations, and \( R_{c0} \) is sensitive to charged-neutral kaon correlations. Together, the three terms measure the strength of fluctuations of the difference of the number of charged and neutral kaons \( N_c - N_0 \). Thus, \( \nu_{\text{dyn}}(n_c, n_0) \) is thus sensitive to fluctuations of the neutral fraction \( f_K \). Given it automatically accounts and corrects physical and experimental effects causing particle losses, it then constitutes a practical observable for a measurement of neutral vs. charged kaon yield fluctuations.

Note that the individual terms \( R_{\alpha\beta} \) shall vanish in the absence of pair correlations, i.e., for Poissonian particle production, and their magnitude is expected to approximately scale in inverse proportion of the total multiplicity of heavy-ion collisions [6].

III. HIJING AND AMPT MODEL PREDICTIONS

We carried out calculations of \( \nu_{\text{dyn}}(n_c, n_0) \) for Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV simulated with the HIJING and AMPT event generators to establish an approximate baseline for the magnitude of charge vs. neutral kaon fluctuations to be expected in the absence of strange DCC production. A total of 3 Million HIJING events were generated whereas, 39, 53, and 39 Million events were produced with AMPT using options (1) string-melting on (SON) and re-scattering off (ROFF), (2) string-melting off (SOFF) and re-scattering on (RON), and (3) string melting on and re-scattering on, respectively. No momentum smearing or par-
ticle losses were used in the simulations and \( K^0_S \) were not decayed. Events were partitioned into five centrality classes based on the fractional cross-section (number of events) studied as a function of the total charged particle multiplicity observed in the pseudo-rapidity range \( 2.8 \leq \eta \leq 5.1 \) and \(-3.7 \leq \eta \leq -1.7 \). Events were then analyzed at generator level, in each centrality class, by selecting \( K^\pm \) and \( K^0_S \) in the transverse momentum range \( 0.2 < p_T < 1.5 \) GeV/c and the pseudo-rapidity range \( |\eta| < 0.5 \) to mimic the conditions of an ongoing ALICE analysis [14]. The number of charged, \( N_c \), and neutral, \( N_0 \), kaons were counted event-by-event and used to compute event-ensemble averages \( \langle N_c \rangle \) and \( \langle N_0 \rangle \), and second factorial moments \( \langle N_c(N_c-1) \rangle, \langle N_0(N_0-1) \rangle \), and \( \langle N_cN_0 \rangle \). In turn, these were combined to compute the correlators \( R_{cc}, R_{c0}, R_{c0}, \) and \( \nu_{\text{dyn}}(N_c,N_0) \) according to Eq. 4, in each centrality class.

The HIJING and AMPT generators do not include DCC production but otherwise feature many of the physical processes required to model heavy-ion collisions. They thus provide us a rough baseline set of values of \( \nu_{\text{dyn}} \) to be expected in the absence of DCC formation. We explore in the next section how the production of DCC may then modify these basic expectations. Additionally note that given HIJING does not feature flow-like collectivity, one should expect its predictions of \( \nu_{\text{dyn}} \) to exhibit a simple \( 1/N \) scaling with collision centrality. It shall then provide us with a basic reference to study the evolution of \( \nu_{\text{dyn}} \) with collision centrality and possible departure from this scaling associated with the production of DCC in mid-central to central-collisions.

Figure 1 shows a graph of \( \nu_{\text{dyn}} \) vs. centrality class obtained with HIJING and the three AMPT dynamical modes. In all four cases shown, values of \( \nu_{\text{dyn}} \) exhibit a monotonic increase from 0-10%, corresponding to most central collisions, to 70%, corresponding to the most peripheral collisions studied in this analysis. Additionally, small differences in magnitude are observed, at any given centrality, between the three AMPT dynamical modes considered. However, their trend with collision centrality remain similar. This indicates that \( \nu_{\text{dyn}} \) is indeed sensitive to final state interactions that modify the yield of produced \( K^\pm \) and \( K^0_S \) as well as their correlations in Pb–Pb collisions, even if these effects are small.

In order to account for the dilution of the \( R_2 \) correlators with increasing particle multiplicity (and number of sources), we scale values of \( \nu_{\text{dyn}} \), in Fig. 1 (b), by the geometric mean, \( \sqrt{N_{K^\pm}N_{K^0}} \), of the numbers of \( K^\pm \) and \( K^0_S \) produced in the fiducial acceptance of the measurement. As expected, scaled values calculated with HIJING and AMPT/RON are essentially invariant with collision centrality, whereas scaled values calculated with AMPT/SON/ROFF exhibit a weak collision centrality dependence, owing to the production of higher mass states in most central collisions. Overall, both HIJING and AMPT produce nearly invariant values of \( \nu_{\text{dyn}} \sqrt{N_{K^\pm}N_{K^0}} \) showing that the expected \( 1/N \) dilution is approximately verified.

It is interesting to compare calculations of \( \nu_{\text{dyn}}(N_c,N_0) \), discussed above, with predictions for \( \nu_{\text{dyn}}(N_+,N_-) \) computed with the same models and also shown in Fig. 1 (a). Conservation laws, namely electric charge and strangeness conservation, restrict the level of fluctuations possible in the production of charged kaons. The cumulant \( R_{++} \) is larger than either of \( R_{++} \) and \( \nu_{\text{dyn}}(N_+,N_-) \) is consequently negative at all collision centralities. By contrast, charge conservation does not limit the fluctuations of the relative yields of \( K^\pm \) and \( K^0 \) and \( \nu_{\text{dyn}}(N_c,N_0) \) takes positive values at all centralities. Note, however, that the magnitude of \( \nu_{\text{dyn}}(N_+,N_-) \) influences in part the value of \( \nu_{\text{dyn}}(N_c,N_0) \), given

\[
R_{cc} = f^2R_{++} + (1-f)^2R_{--} + 2f(1-f)R_{+-} = \frac{1}{4}(2R_{++} + 2R_{--} - \nu_{\text{dyn}}(N_+,N_-)), \tag{5}
\]

where \( f = \langle N_+ \rangle/\langle (N_+) + (N_-) \rangle \) and in the second line, we assumed \( f = 0.5 \), which is approximately valid at LHC energy. Finally, note that values of \( \nu_{\text{dyn}}(K^+,K^-) \) scaled by the number of charged kaons are also invariant with collision centrality, while AMPT/SON/ROFF displays a modest collision centrality dependence.

IV. DCC MODEL SIMULATIONS

We simulate the production of DCCs with a simple phenomenological model to gain insight into the correlation strength measurable with \( \nu_{\text{dyn}} \) in the presence of condensates decaying into neutral and charged kaons. The DCC simulator is designed to match the pion and kaon multiplicity production observed experimentally and involves “normal” and DCC particle generation components. The former produces charged and neutral particles based on a binomial distribution, whereas the DCC particle production is determined by Eqs. 1 2 for pions and kaons, respectively. Events can be
set to consist of DCC matter entirely or a mix of normal and DCC matter by used of a parameter $f_{\text{DCC}}$ which controls the number of particles produced within the binomial and DCC components. The average fraction of particles consisting of kaons is determined by a user selected parameter $f_{K}$ set at simulation startup. However, the kaon to pion yield ratio is allowed to fluctuate according to a binomial distribution determined by this fraction and the total multiplicity. This multiplicity is randomly chosen according to a PDF that approximately replicates the charged particle multiplicity reported by the ALICE collaboration in 0-10% collision centrality, scaled by a factor of 3/2 to account for neutral particle production. The number of $K^0_S$s in the DCC and normal parts of an event are randomly generated according to a binomial distribution with a mean probability of 0.5 based on the number of neutral kaons in either parts.

We explore the impact of DCC production by varying the size and number of DCC in generated events. Figure 2 displays the fractions of neutral pions (top panel) and kaons (bottom panel) obtained in generated events with selected values of the DCC fraction $f_{\text{DCC}}$. We consider few distinct particle production scenarios: **Scenario 1**: All generated events are assumed to contain one DCC domain but the size of the domains is varied by changing the fraction of (a) pions and (b) kaons they produce relative to the full system. As shown in Fig. 3, $\nu_{\text{dyn}}$ increases monotonically with the DCC size and reaches very large magnitudes for events containing large DCC domains. The rise of $\nu_{\text{dyn}}$ at small event multiplicity is due to a decline of the cross-term $R_{c0}$ relative to $R_{00}$ and $R_{cc}$.

**Scenario 2**: The DCC size is kept fixed and accounts for 100 percent of the event size but the probability of occurrence of DCCs is varied. The magnitude of $\nu_{\text{dyn}}$ rises with the fraction of events containing a DCC, called $p_{\text{DCC}}$, as illustrated in Fig. 4. Sizeable $\nu_{\text{dyn}}$ magnitudes and deviations from binomial expectation values occur for probabilities as small as $p_{\text{DCC}} = 0.01$. **Scenario 3**: We use HIJING events as a baseline for the description of pion and kaon production and their event-by-event fluctuations. DCC-like fluctuations are introduced by randomizing the charge of kaons produced by HIJING. Figure 5 displays the collision centrality evolution of $\nu_{\text{dyn}}$ obtained when progressively increasing the fraction of events containing a single (large) strange DCC. As already discussed in Sec. 3 the magnitude $\nu_{\text{dyn}}$ exhibits an approximate $1/N$ behaviour with increasing event multiplicity $N$, shown as a purple line in Fig. 5.
The event-by-event fluctuations of neutral and charged kaons were studied using the $v_{\text{dyn}}$ observable in Monte Carlo models (HIJING and AMPT) in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for various collision centralities. The estimates from these models are relevant to the ongoing experimental search of DCC-like signals in heavy ion collisions at LHC and RHIC as these models do not include the dynamics of DCC physics. A simple phenomenological model was developed to implement the DCC-type events and study the sensitivity of the $v_{\text{dyn}}$ observable to the fraction of DCC events as well as the size of DCC domains. The value of $v_{\text{dyn}}$ increases with a rising fraction of DCC-like events in the sample for a given multiplicity class. The variation of $v_{\text{dyn}}$ was also studied as a function of multiplicity for different size of DCC domains. Both studies indicate that $v_{\text{dyn}}$ is very sensitive to the presence of DCC-like events in heavy-ion collisions.

VI. ACKNOWLEDGEMENTS

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FIG. 5. (a): $v_{\text{dyn}}$ for $K_0^+ - K^+$ as a function of centrality, (b): $v_{\text{dyn}}$ scaled with kaon multiplicity as a function of centrality, and (c): $v_{\text{dyn}}$ scaled with charged particle multiplicity as a function of centrality, for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

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