Event-shape studies of strangeness production in $\sqrt{s}$ = 13 TeV proton–proton collisions with ALICE

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Abstract.
The ALICE Collaboration has observed that the ratio of strange to non-strange hadron yields increases strongly with multiplicity in small collision systems at LHC energies. The origin of this effect is still not fully understood. Models need to incorporate final-state interactions to accommodate the new ALICE results, and require new measurements to discriminate between the various phenomenological descriptions.
Two different ALICE studies, aiming to further elucidate the underlying mechanisms of strangeness production in high-multiplicity proton–proton (pp) collisions at $\sqrt{s}$ =13 TeV, are presented in this proceeding. First, the production of η and π^0 are studied as a function of multiplicity, combining several analysis techniques, allowing a measurement for the neutral meson production over a vast transverse momentum (p_{T}) range. This is followed by a measurement of π, K, ϕ, and Ξ as a function of the unweighed transverse spherocity $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$, an event-shape observable which allows us to explore particle production in azimuthal topologies dominated by either hard or soft QCD processes. The results are compared to predictions from PYTHIA and EPOS-LHC.

1 Introduction

The goal of this work is to further study the increased production of strange hadrons relative to π mesons observed in high-multiplicity proton–proton (pp) and proton-lead (p–Pb) collisions at the Large Hadron Collider (LHC). Previously thought to be a unique feature of heavy-ion collisions, it was one of the first proposed signatures of the formation of a quark–gluon plasma (QGP), a strongly interacting medium. Its discovery in smaller collision systems raises questions regarding the physical mechanism of strangeness production. This is compounded by the fact that several theoretical models are able to describe such an effect without modeling a QGP, and can instead reproduce the enhancement by introducing new phenomenological final-state interactions.

The onset of traditional QGP-like features in high-multiplicity small system collisions seems to be incongruent with the idea that proton–proton interactions can be modelled as an almost incoherent superposition of multiple parton–parton interactions (MPIs). PYTHIA 8.3 [1], a QCD-inspired Monte-Carlo (MC) theoretical model where hadronization occurs via “Lund strings", can describe the strangeness enhancement in high-multiplicity collisions by introducing “rope hadronization"; a phenomenological description where several Lund

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strings close in phase space overlap and form ropes, effectively increasing string tension and therefore the probability to produce heavier strange quarks.

In contrast, the event generator EPOS-LHC relies on a two-component description to model proton–proton collisions. In this picture, two different systems will form during the initial stages of a proton–proton interaction; a dense core dominated by soft, thermally equilibrated (QGP-like), and a dilute corona, dominated by traditional pp physics. Because the temperature of the core is expected to be close to the strange-quark mass, strangeness is favored to be produced in the core. Events with enhanced strangeness will have a relatively larger contribution from the core versus corona, and vice versa for suppressed strangeness production [2].

In these proceedings, two ALICE measurements performed in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV are presented. These results will further help to distinguish which models accurately predict the underlying hadronization processes in high-multiplicity small-systems. The first measurement is of the π^0 and η production as a function of multiplicity, to probe whether the neutral vector meson η, which has a strange–antistrange ($s\bar{s}$) component in the wave function, is enhanced in high-multiplicity events relative to π^0, which has no strangeness. The second study presents measurements on strange particle production as a function of the unweighted transverse spherocity $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$, aimed at investigating the dependence of the azimuthal event topology for high-multiplicity particle production.

2 π^0 and η production as a function of multiplicity at $\sqrt{s} = 13$ TeV

η and π^0 mesons are measured through the $X \rightarrow \gamma\gamma$ decay channel. The yield of both mesons are reconstructed by fitting a Gaussian function, convoluted with an exponential low-energy tail, to the invariant mass of photon pairs, $M_{\gamma\gamma}$, after subtracting the combinatorial background. The final yields are measured by performing the signal extraction procedure utilizing different ALICE sub-detector systems, for different p_{T} intervals. The measurements are then combined into a single multiplicity-dependent particle spectrum for each meson, over a broad p_{T} range. The primary identification techniques are:

- **Photo-Conversion Method (PCM)**: At low-to-intermediate p_{T} ranges, it is possible to reconstruct photons that have been converted in the detector material, for $|\eta| < 0.8$ with full azimuthal coverage. This is done by measuring the conversion products via electron identification and a secondary vertex finder.
- **Photon Spectrometer (PHOS)**: At intermediate p_{T}, photons are reconstructed using the PHOS electromagnetic calorimeter, located at the bottom of ALICE, covering $|\eta| < 0.12$, with 70° of azimuthal coverage.
- **Electromagnetic Calorimeter (EMC)**: The EMC is used to reconstruct photons at very high-p_{T}, located at $|\eta| < 0.67$, with 106° of azimuthal coverage.

The multiplicity estimation is performed by measuring the deposited charge in the forward V0A and V0C detectors. By taking the mean signal of both detectors (V0M), a multiplicity distribution is created. The multiplicity selection is based on percentiles of the V0M signal.

2.1 Results

The multiplicity-differential η/π^0 ratio as a function of p_{T} is shown in the left panel of Fig. 1. The ratio suggests that there is little to no multiplicity modification of η production relative to π^0, across the entire p_{T} range. All presented multiplicity classes are consistent with the minimum bias (0–100%) baseline, even for the top 0–0.01% high-multiplicity events.

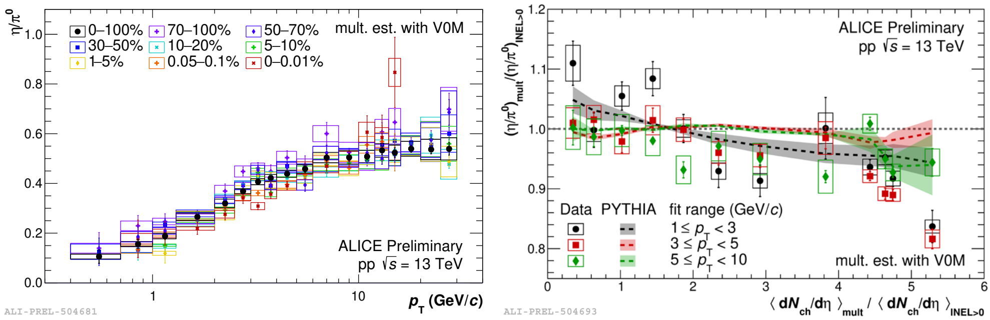

Figure 1: (left): The η/π^0 ratio as a function of p_{T}, in different multiplicity intervals. (right): The double-ratio (DR) between the multiplicity-dependent and minimum-bias η/π^0 ratios, as a function of the self-normalized, average charged-particle density at midrapidity, in three different p_{T} intervals. The results are compared to predictions from PYTHIA8 Monash (dashed lines). Statistical/systematic uncertainties are represented by lines/boxes, respectively.

Further insight can be gained by studying the double ratio (DR), which is a ratio between the multiplicity dependent and minimum-bias η/π^0 ratios. This allows us to study a possible multiplicity modification with high precision. The DR is presented as a function of multiplicity, for three different p_{T} ranges, in the right panel of Fig. 1. The multiplicity selection is the same as presented in the single ratio (left panel), but is expressed in terms of the equivalent self-normalised charged-particle density at midrapidity. These results suggest a small suppression of η production as a function of multiplicity, with a slight enhancement at low multiplicities in the lowest p_{T} range. PYTHIA 8 captures the ordering between three different p_{T} intervals, but is not able to quantitatively describe the trends presented in the data, especially the suppression of η/π^0 at high-multiplicity. Further studies are required to allow for a more quantitative comparison.

3 Particle production as a function of spherocity $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$

The azimuthal topology of the event can give insight into the very early stages of the collision, and which type of physics drives particle production. This topology can be estimated using the unweighted transverse spherocity, $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$, defined as

$$S_{\mathrm{O}}^{p_{\mathrm{T}}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\hat{p_{\mathrm{T},i}} \times \hat{n}|}{N_{\mathrm{trks}}} \right), \tag{1}$$

where $\hat{p_{\mathrm{T},i}}$ and $\hat{n}$ are unit vectors. $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ is calculated using all charged tracks, N_{trks}, with $p_{\mathrm{T}} > 0.15$ GeV/c. $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ can be used as an estimator of the event topology, characterized by two different limits. $S_{\mathrm{O}}^{p_{\mathrm{T}}=1} \to 1$ represents events with isotropic topologies, where particle production is expected to be driven by several soft processes. In contrast, events where $S_{\mathrm{O}}^{p_{\mathrm{T}}=1} \to 0$ are likely to be dominated by hard physics processes, with either back-to-back or single-cone jet-like structures.

In these proceedings, high-multiplicity events within the top 10% of the multiplicity distribution are analyzed (requiring also $N_{\mathrm{trks}} > 10$, to ensure that $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ is topologically meaningful), in conjunction with the 20% top and bottom percentiles of the $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ distribution denoted as Isotropic and Jetty events, respectively. The $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ study utilizes a midrapidity ($|\eta| < 0.8$) multiplicity estimation to minimize the implicit multiplicity dependence of $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$

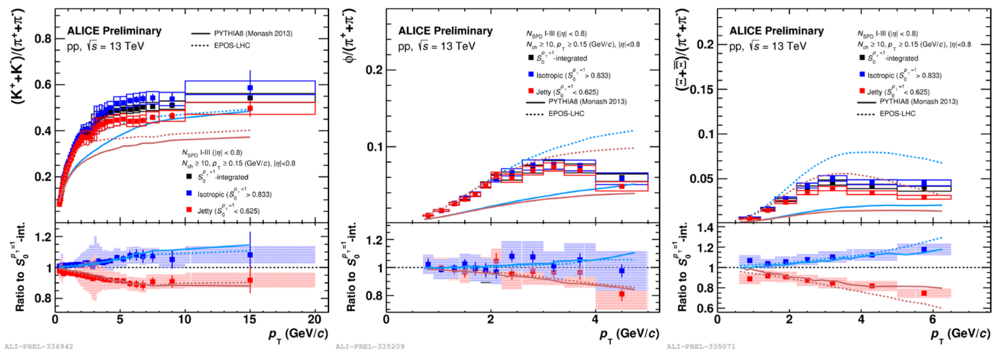

Figure 2: K-to-π (left), ϕ-to-π (middle), and Ξ-to-π (right) ratios as a function of $p_{\rm T}$ in bins of $S_{\rm O}^{p_{\rm T}=1}$, for Jetty (red), Isotropic (blue), and $S_{\rm O}^{p_{\rm T}=1}$-integrated (black) events. Lower panels show the ratios to $S_{\rm O}^{p_{\rm T}=1}$-integrated. The results are compared to predictions from PYTHIA8-Monash (solid lines) and EPOS-LHC (dashed lines).

(events with higher multiplicities will on average be more isotropic), and gain sensitivity to variations in the hardness of the event, see Ref. [3] for more details.

$\pi^{\pm}$ and $K^{\pm}$ are identified via the specific energy loss dE/dx measured by the TPC, and the time-of-flight (TOF). ϕ meson Ξ baryon yields are reconstructed by calculating the invariant mass of the identified decay daughters, through the decay channels $\phi \to K^+K^-$ and $\Xi^-[\Xi^+] \to \pi^-[\pi^+] + \Lambda[\bar{\Lambda}]$.

3.1 Results

The $p_{\rm T}$-differential particle ratios for K-to-π, ϕ-to-π, and Ξ-to-π are presented in Fig. 2, where the DR w.r.t the $S_{\rm O}^{p_{\rm T}=1}$-integrated high-multiplicity class are displayed in the lower panels. The K/π and Ξ/π ratios suggest an increased production of K and Ξ in isotropic events, but a suppression in Jetty events. This indicates that strange particle production in high-multiplicity collisions favors isotropic topologies, generally driven by multiple softer collisions, instead of di-jet topologies which are driven by hard processes. The ϕ-to-π highlights that the ϕ meson does not behave like a strange particle w.r.t $S_{\rm O}^{p_{\rm T}=1}$, as both Isotropic and Jetty productions of ϕ are consistent with the high-multiplicity average.

The EPOS-LHC and PYTHIA 8 models are able to qualitatively describe the behavior exhibited in the DR, predicting the interplay between $S_{\rm O}^{p_{\rm T}=1}$ and high-multiplicity production. However, neither EPOS-LHC nor PYTHIA 8 are able to capture the trends observed in the single ratios. PYTHIA 8 is largely overestimating the yield of pions relative to the production of K, ϕ, and Ξ. While EPOS-LHC overpredicts the high-$p_{\rm T}$ production of ϕ and Ξ, it underestimates the amount of kaons produced relative to what is observed in the data.

4 Summary

These proceedings have highlighted two studies that aim to give further insight into the hadronization processes in high-multiplicity pp collisions. First, the η/π^0 was presented, whereby combining analyses across several ALICE detector systems, the ratio could be measured over an unprecedented $p_{\rm T}$ range. It was shown that there is little multiplicity-dependence in the single η/π^0 ratio. However, the double ratio to minimum-bias indicated a small overall suppression of η production at extremely high multiplicities.

Furthermore, utilizing the unweighted transverse spherocity $S_{\rm O}^{p_{\rm T}=1}$ to categorize events based on the azimuthal event topology, it was shown that strange particle production is enhanced in isotropic topologies, which are often dominated by multiple soft processes. Remarkably, the ϕ-to-π ratio suggests that ϕ production is insensitive to the azimuthal topology in high-multiplicity events, and in the context of $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ behaves like a non-strange particle.

References

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[3] A. Nassirpour et al, *J.Phys.Conf.Ser.* **1602** (2020) 1, 012007