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 relative fraction of strange hadrons grows strongly with multiplicity in small collision systems at LHC energies, in particular for multi-strange baryons. The origin of this effect is still under debate, and models need significant final-state interactions to accommodate the new ALICE results, requiring new tools to discriminate experimentally between the various phenomenological ideas.
In these proceedings we present a multi-differential study of identified particle spectra with respect to the event multiplicity and two different event shape observables, the unweighted transverse spherocity $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$, and the self-normalized, transverse charged particle density, R_{T}, which allows us to explore particle production associated with hard and soft QCD processes. ALICE has measured π, K, ϕ, and Ξ production at mid-rapidity ($|\eta| < 0.8$) as a function of $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ and R_{T} in pp collisions at $\sqrt{s}$ = 13 TeV. This work reports on how these multi-differential measurements compare with predictions from PYTHIA and EPOS-LHC.

1 Introduction

Measurements in proton–proton (pp) and proton–lead (p–Pb) collisions at the Large Hadron Collider (LHC) have revealed that the relative production of strange hadrons is enhanced in high-multiplicity events, and the strength of the enhancement increases with the strange quark content. This phenomenon was historically believed to be a feature of heavy-ion collisions, interpreted as the formation of a strongly interacting medium, and its presence in pp collisions has led to new discussions regarding the physical interpretation of this signature, as several theoretical models are able to describe this enhancement by introducing various phenomenological final-state interactions.

In regard to QCD-inspired Monte-Carlo event generators, such as PYTHIA 8 [1], this observation seems to be contrary to the central assumption that pp collisions at these energies ($\sqrt{s}$ = 13 TeV) can be described as incoherent sums of parton–parton collisions. Such models require additional finale-state effects (color ropes, junctions, etc.) to describe the strangeness enhancement. In contrast, EPOS-LHC [2] is an event generator which forms a two-phase state (core-corona) consisting of a dense core of quark-gluon plasma (QGP) and a dilute corona. The strangeness enhancement in EPOS-LHC originates from a change in the relative contribution of the corona (low strangeness production) and core (high strangeness production) with multiplicity.

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New, multi-differential observables are needed in order to distinguish which of these models most accurately describes hadronization in high-multiplicity small-systems collisions; specifically to understand whether the final-state multiplicity is the driving force for the enhancement of strange hadrons, or if both the multiplicity and strangeness enhancement are driven by underlying phenomena that are currently not well understood. This contribution presents results from A Large Ion Collider Experiment (ALICE) on strange particle production as functions of the transverse spherocity, $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$, and the self-normalized charged-particle density in the transverse region, R_{T}, which relate to the event topology and the underlying event activity respectively.

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

Events can be categorized according to their azimuthal event topology. The unweighted transverse spherocity, $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$, is used to quantify the azimuthal distribution of tracks, and is defined as:

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

$S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ is measured using all tracks in each event, N_{trks}, and yields a value between 0 and 1. $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ is calculated using charged-particle tracks that have a transverse momentum p_{T} greater than 0.15 GeV, although in Eq. 1 the weight factor for p_{T} is set to 1 (hence "unweighted"). The $S_{\mathrm{O}}^{p_{\mathrm{T}}=1} \to 0$ limit represents azimuthal topologies with back-to-back jet structures mainly dominated by a single hard scattering, and the $S_{\mathrm{O}}^{p_{\mathrm{T}}=1} \to 1$ limit describes event shapes where particles are isotropically distributed due to multiple softer collisions. In these proceedings, the Jetty and Isotropic event samples are defined as the bottom and top 20% quantiles of the $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ distribution, respectively. The interpretation of the results relies on the premise that the azimuthal topology reflects the main mode of particle production.

The selected events are also required to be in the top 10% high-multiplicity quantile, estimated at mid-rapidity ($|\eta| < 0.8$), as well as having at least $N_{trks} \geq 10$, in order to maintain sensitivity to the event topology. There are also $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ studies performed where the multiplicity is measured at forward rapidity, which are discussed in further detail in Ref. [3]. π,K,p are identified via the specific energy loss $\mathrm{d}E/\mathrm{d}x$ and the time-of-flight (TOF). ϕ and Ξ yields are then extracted from invariant mass distributions of their identified decay daughters ($\phi \to \mathrm{K}^+\mathrm{K}^-$ and $\Xi^-[\Xi^+] \to \pi^-[\pi^+] + \Lambda[\bar{\Lambda}]$).

2.1 Results

The K-to-π, ϕ-to-π and Ξ-to-π ratios as a function of $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ are all presented in Fig. 1. EPOS-LHC is able to qualitatively describe the K-to-π trend, but neither EPOS-LHC nor PYTHIA is able to describe the ϕ-to-π and Ξ-to-π ratios as a function of $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$. However, both EPOS-LHC and PYTHIA are able to qualitatively describe the double-ratios (lower panels), which suggests that the simulations capture most of the $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$ selection but overestimate/underestimate the general enhancement of strange particle production in high-multiplicity events.

Both the K/π and Ξ/π ratios highlight an overall relative enhancement of K and Ξ hadrons compared to pions in Isotropic events, and a suppression in Jetty events. This suggests that strangeness enhancement in high-multiplicity pp collisions is driven by the multiple softer collisions found in isotropic topologies, rather than hard processes. The ϕ-to-π ratio suggests that the ϕ meson production is mostly insensitive to $S_{\mathrm{O}}^{p_{\mathrm{T}}=1}$, which differentiates it from other strange particle species.

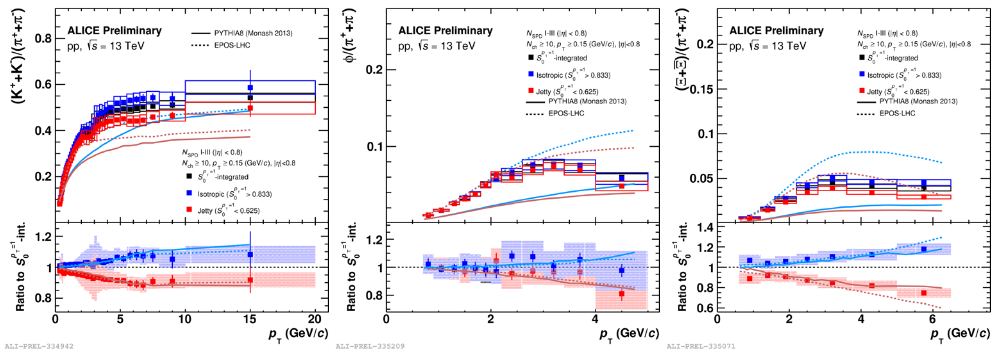

Figure 1: K-to-π (left), ϕ-to-π (middle) and Ξ-to-π (right) ratios as a function of $p_{\rm T}$ in bins of $S_{\rm O}^{p_{\rm T}=1}$, for Jetty (red), Isotropic (blue), and $S_{\rm O}^{p_{\rm T}=1}$-integrated (black) events. Lower panels show the ratios to $S_{\rm O}^{p_{\rm T}=1}$-integrated. The results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

3 Particle production as a function of $R_{\rm T}$

The purpose of the $R_{\rm T}$ analysis is to estimate the strange particle production as a function of the size of the underlying event (UE), relative to a hard probe. The events are cut into different azimuthal segments relative to the azimuthal angle $\varphi_{\rm L}$ of the leading track (which has a $p_{\rm T} \geq 5$ GeV/c requirement to ensure that a hard scattering occurs).

The "Toward" region is located around the leading track, where $|\varphi - \varphi_L| \leq \frac{\pi}{3}$. The particle production in this region is dominated by jet fragmentation due to the hard scattering, in addition to the soft collisions in the UE. The "Transverse" regions are located perpendicular to the leading particle, where $\frac{\pi}{3} < |\varphi - \varphi_L| < \frac{2\pi}{3}$, and the particle production in these regions will almost be a pure sample of the UE (with possible local fluctuations due to initial-and final state radiation).

$R_{\rm T}$ is defined as the self-normalized charged particle density in the transverse region, $R_{\rm T} = N_{\rm tracks}^{\rm Transverse} / \left\langle N_{\rm tracks}^{\rm Transverse} \right\rangle$. With $R_{\rm T}$, one is able to control the size of the UE relative to the hard scattering. Events with $R_{\rm T} < 1.0$ have a smaller-than-average UE, and vice versa for $R_{\rm T} > 1.0$. Particle momentum spectra are then measured in different $R_{\rm T}$ classes in order to estimate the impact of the UE on strange particle production.

3.1 Results

As seen in Fig. 2, the strange hadron yields in the Toward region show a significant dependence on $R_{\rm T}$. This indicates not only that the relative strange particle production rate is proportional to $R_{\rm T}$, but also that the relative strange particle production rate due to jet-fragmentation is fundamentally different from the same production rate in the UE. Furthermore, the relative yields in the high-$R_{\rm T}$ events in the Toward region approach the values of the (K, ϕ, Ξ)-to-π ratios found in the Transverse Region, although the $R_{\rm T}$ dependence in the Transverse region seems to be diminished. Notably, there is a very large modification of ϕ and Ξ hadron yields in the Toward region for events with large underlying event activity, with respect to the $R_{\rm T}$-integrated spectra. This implies that at high-$R_{\rm T}$, the contribution from the hard scattering is relatively small to the contribution from the UE, suggesting that the enhancement of strange hadrons at high-multiplicity pp collisions originates from the UE.

Contrasting the two models, both EPOS-LHC and PYTHIA qualitatively describe the K-to-π ratio, but neither is able to accurately predict the enhancement of ϕ and Ξ hadrons in high-$R_{\rm T}$ events. EPOS-LHC qualitatively reproduces the general trends going from low-

R_T to high-R_T, but seems to underestimate and overestimate the ϕ and Ξ high-R_T curves, respectively. On the other hand, while PYTHIA is able to describe the low-R_T trends in the Toward region, it is currently not capable of describing the enhancement found in the high-R_T events.

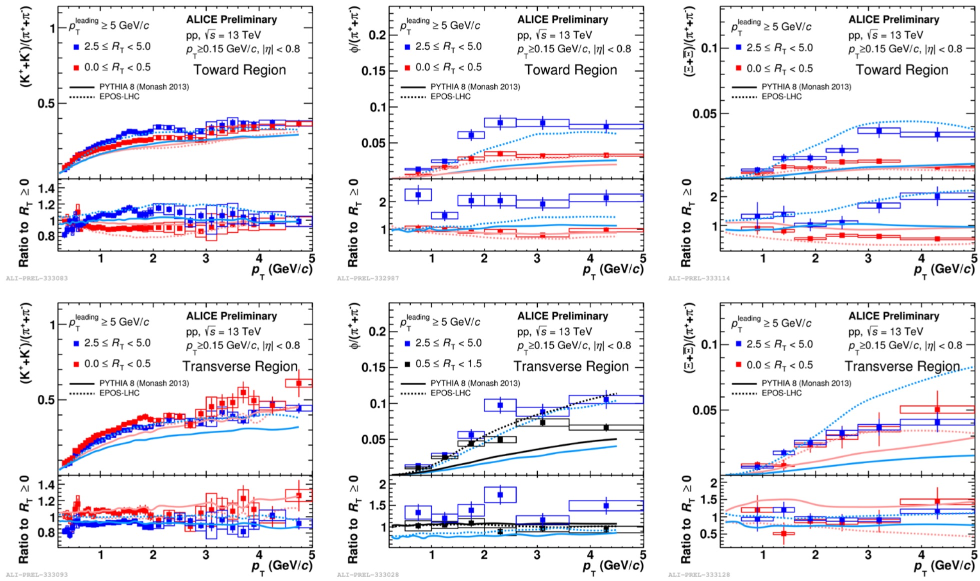

Figure 2: K-to-π (left), ϕ-to-π (middle) and Ξ-to-π (right) ratios as a function of p_T in bins of low-R_T (red, black) and high-R_T (blue) events. The upper/lower rows showcases the Toward and Transverse regions, respectively. The lower panels in each plot show the ratios to R_T-integrated. The results are compared to predictions from PYTHIA8-Monash (solid lines) and EPOS-LHC (dashed lines).

4 Conclusion

Using $S_O^{p_T=1}$, one is able to disentangle event topologies based on the azimuthal distribution of particles. Observations shown in Fig. 1 indicate that the enhancement of strange hadrons in high-multiplicity pp collisions is primarily driven by dynamics that arise from events with isotropic topologies. Likewise, Fig. 2 highlights how the R_T results support this indication. They suggest that the rate of strangeness production is proportional to the size of the UE, as the UE is produced through softer isotropic interactions. Moreover, they indicate that the rate of strangeness production in the UE outweighs the production due to jet-fragmentation. The measurements of R_T and $S_O^{p_T=1}$ suggest that strangeness enhancement in high-multiplicity pp collisions is driven by several soft collisions.

The role of the ϕ contrasting the two observables is striking to the author: the ϕ is insensitive to the $S_O^{p_T=1}$ measurement, unlike the K and Ξ, which have non-zero net strangeness. However, the R_T measurement shows a significant ϕ modification, alongside other strange particles. Narrower event criteria are being examined to gain further insight into this effect.

References

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