Probing strangeness production in small systems through new multi-differential measurements with ALICE at the LHC

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Abstract. ALICE has observed that the relative fraction of strange hadrons grows strongly with multiplicity in small collision systems (proton-proton and proton-lead collisions) at LHC energies, in particular for multi-strange baryons. This implies that a proton-proton collision cannot be described as an incoherent sum of parton-parton collisions, an idea that has been central in most proton-proton generators, for example PYTHIA.

To accommodate the new ALICE results, models have to introduce significant final-state interactions. These final-state effects can have very different phenomenological origin. To be able to eventually discriminate experimentally between different final-state models, new experimental tools are required and in this paper different multi-differential observables will be tested with this goal in mind. Transverse Spherocity ($S_O$) is an observable that allows a topological selection of events that are "isotropic" (dominated by multiple soft processes) and "jetty" (where a single hard process is responsible for a significant part of the multiplicity). The underlying event activity is another observable that can be used to vary the amount of soft processes. It can be estimated by measuring the charged-particle multiplicity in the Transverse region ($R_T$).

Using these new observables, ALICE has obtained results for $\pi$, $K$, $\phi$, $p$, and $\Xi$ production at mid-rapidity ($|\eta| < 0.8$) as a function of event shape and underlying event activity in proton-proton collisions at $\sqrt{s_{NN}} = 13$ TeV. Finally, this contribution will report on how these new multi-differential measurements compare to predictions from PYTHIA and EPOS-LHC.

1. Introduction

Measurements in high-multiplicity proton-proton (pp) and proton-lead (p-Pb) collisions have revealed that small collision systems (i.e pp and p-Pb) exhibit some signatures that were previously considered unique features of heavy-ion collisions. Some of these signatures, such as an enhanced production of strange hadrons, or a collective expansion of the system, could be explained by the formation of a strongly interacting medium. However, it is difficult to argue for the presence of a strongly interacting medium in small-systems within current theoretical frameworks, because of the limits to the achievable lifetime and volume of the produced medium, as well as temperature/baryon density, see e.g [1] for discussions.

The observation of strangeness enhancement in small-systems at the Large Hadron Collider (LHC) indicates that pp collisions at these energies can no longer be seen as incoherent sums of parton-parton collisions, an idea that is central to most general-purpose, Quantum-Chromo Dynamics (QCD)-inspired Monte-Carlo event generators, such as PYTHIA [2]. EPOS-LHC is an event generator which forms a two-phase state consisting of a dense core of QGP, and a...
dilute corona (core–corona). The strangeness enhancement in EPOS-LHC is due to a change in the relative contribution of the corona (low strangeness production) and core (high strangeness production) with multiplicity. Strange-particle production constitutes a good probe to test if models such as PYTHIA or EPOS-LHC are better at describing hadronization in high-multiplicity small-system collisions.

This contribution presents new results from A Large Ion Collider Experiment (ALICE) on strangeness production in small systems. The data analyzed are from pp collisions at $\sqrt{s_{NN}} = 13$ TeV. The observables relate to the event topology and the activity of the underlying event; Transverse Spherocity $S_{O}^{p_{T}=1}$ and the self-normalized charged-particle density in the transverse region, $R_T$. New results from a third type of measurement, $\Xi$-h correlations, can be found here [3].

2. $\pi/K/p/\phi/\Xi$ Production as a Function of Unweighted Transverse Spherocity $S_{O}^{p_{T}=1}$

2.1. Method

The premise of the analysis, discussed in the following [4], is that the event topology in the azimuthal plane will reflect the main mode of particle production. Events dominated by a single hard scattering will have pronounced back-to-back jet structures, while events dominated by multiple soft scatterings will result in an isotropic topology, see Fig. 1 for an illustration. The unweighted transverse spherocity $S_{O}^{p_{T}=1}$ is used as an estimator to disentangle these two topological limits:

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

$S_{O}^{p_{T}=1}$ is calculated using charged particle tracks that have $p_{T} > 0.15$ GeV. Unlike the estimator discussed in [4], the transverse momentum ($p_{T}$) of each track is normalized to 1 ($p_{T} = 1$). This modification is required to minimize biases which affect neutral particle yields.

$N_{trks}$ is the sum of charged particles in a given event, and $\hat{n}$ is a unit vector that minimizes the function. The charged particle tracks are reconstructed using the ALICE Time-Projection Chamber (TPC), which is a gas detector that reconstructs charged particles, with a high efficiency and good momentum resolution, within the pseudorapidity interval $|\eta| < 0.8$.

$S_{O}^{p_{T}=1}$ will vary by construction between values of 0 and 1, where the two limits will correspond to the two different topological limits: Events where $S_{O}^{p_{T}=1} \to 0$ will be dominated by a single back-to-back jet, whereas events where $S_{O}^{p_{T}=1} \to 1$ will be dominated by more isotropic particle production (absence of a preferred direction). The events in the bottom 20% quantile of the $S_{O}^{p_{T}=1}$ distribution will henceforth be referred to as “jetty” events (not in the strict sense of a jet-finding algorithm, but rather that the azimuthal topology is pencil-like), whereas the top 20% quantile is referred to as “isotropic” events.

In addition to the $S_{O}^{p_{T}=1}$ selection, a top 10% high-multiplicity (multiplicity classes I-III [4]) requirement is also imposed for event selection in order to maintain sensitivity to the event structure. Strangeness enhancement is a phenomenon observed in high-multiplicity pp collisions,
making this a region of specific interest. Furthermore, minimum-bias pp collisions mainly consist of collisions that produce few tracks, and it is not clear what a topology means in this case. For this reason, in addition to the top 10% multiplicity selection, events are also required to have at least $N_{trks} \geq 10$ to be considered (which is already the case for most of the top 10% events). The multiplicity is estimated using two different sub-detector systems in ALICE. The V0M scintillators measure the charged particle multiplicity at forward rapidity, in ranges of $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$. The multiplicity is also estimated at mid-rapidity ($|\eta| < 0.8$), using the ALICE Inner Tracking System (ITS), by measuring the number of short-track segments $N_{SPD}$, referred to as the CL1 multiplicity in the following, (as it is related to the CL1 trigger). The main difference between the two multiplicity estimators is that for V0M-based selections, the rapidity regions for multiplicity estimation and for the measurement of the particle spectra are different, whereas for CL1-based selections, the multiplicity and particle spectra are measured in the same rapidity region. Results from the CL1 is thus more sensitive to local fluctuations (auto-correlations, such as jets).

Particle Identification (PID) is used in order to measure the spectra of identified particle species in the different multiplicity and $S_{PT}^{O}=1$ regions. Pions, kaons and protons are identified from the specific energy loss $dE/dx$ measured by the TPC, together with the time-of-flight (TOF) information using the ALICE TOF detector. $\phi$ and $\Xi$ yields are extracted from invariant mass distributions of their identified decay daughters (after topological selections for the $\Xi$).

2.2. Results

Figure 2 presents the pion $\langle p_\perp \rangle$ as a function of the average pion yield in different multiplicity and spherocity bins. The figure illustrates how the multiplicity and spherocity selection biases the event samples. The V0M selected measurements maintain a similar $\langle p_\perp \rangle$ between the spherocity classes, but have large differences in $\langle dN_{\pi}/dy \rangle$.

In contrast, the $S_{PT}^{O}=1$ classes for the CL1 selected events are characterized by the $\langle p_\perp \rangle$ of the events, suggesting that $S_{PT}^{O}=1$ might be able to categorize events according to their hardness. The implicit multiplicity dependence of $S_{PT}^{O}=1$ is minimized when using a mid-rapidity multiplicity estimator, which is in agreement with findings from [3].

A similar effect as observed in Fig. 2 can also be seen in Fig. 3. The V0M ratios in the lower panel display a flat $p_\perp$-dependence for both spherocity classes, whereas a $p_\perp$ dependence can be observed for the CL1 triggered events. The particle ratios of $K/p/\phi/\Xi$-to-$\pi$, compared to equivalent PYTHIA and EPOS-LHC ratios, are shown in Figs. 4 to 7. It is observed that neither event generator can accurately predict the “single-ratios” in the upper panels. EPOS/PYTHIA tend to overestimate/underestimate the trends respectively.
Figure 3: The $\Xi$ spectra as a function of multiplicity and $S^O_{pT=1}$. The left (right) panel displays events where the multiplicity selection was done using the V0M (CL1) multiplicity estimator. Lower panels show the ratios to $S^O_{pT=1}$-integrated.

Figure 4: $\Xi$-to-$\pi$ ratio as a function of $p_T$ in bins of $S^O_{pT=1}$. The left (right) panel displays events where the multiplicity selection was done using the V0M (CL1) multiplicity estimator. Lower panels show the ratios to $S^O_{pT=1}$-integrated.

Both event generators are able to qualitatively describe the double-ratio (lower panels), which suggests that the simulations are able to describe the $S^O_{pT=1}$ selection but overestimate/underestimate the general enhancement of $K/p/\phi/\Xi$ production in high-multiplicity.
Figure 5: $p$-to-$\pi$ ratio as a function of $p_T$ in bins of $S_{O}^{p_T}=1$. The left (right) panel displays events where the multiplicity selection was done using the V0M (CL1) multiplicity estimator. Lower panels show the ratios to $S_{O}^{p_T=1}$-integrated.

events. The double-ratios highlight an overall relative enhancement of K and $\Xi$ hadrons compared to pions in “isotropic” events, and a suppression in “jetty” events. This suggests that the enhancement of strange hadrons in high-multiplicity pp collisions is driven by soft processes rather than hard processes.

Figure 6: K-to-$\pi$ ratio as a function of $p_T$ in bins of $S_{O}^{p_T}=1$. The left (right) panel displays events where the multiplicity selection was done using the V0M (CL1) multiplicity estimator. Lower panels show the ratios to $S_{O}^{p_T=1}$-integrated.
Figure 7: $\phi$-to-$\pi$ ratio as a function of $p_T$ in bins of $S_{\text{ch}}^{p_T=1}$. The left (right) panel displays events where the multiplicity selection was done using the V0M (CL1) multiplicity estimator. Lower panels show the ratios to $S_{\text{ch}}^{p_T=1}$-integrated.

The $p$-to-$\pi$ V0M ratios in Fig. 5 highlight that the baryon-to-meson enhancement at intermediate $p_T$ (usually attributed to radial flow [6]) is larger in isotropic events, which suggests that these events indeed have more flow, as we expect if a strongly-interacting medium is present. In contrast, the CL1 $p$-to-$\pi$ ratios seem to suggest a strict enhancement/suppression of proton production in the different event types, similar to effects observed in measurements of the jet-$p_T$ evolution [7].

The $\phi$-to-$\pi$ ratio (Fig. 7) indicates that $\phi$ particle production has no significant dependence between “jetty” or “isotropic” events. Furthermore, the dependence on V0M and CL1 multiplicity slicing appears to be the same.

### 3. $\pi/K/p/\phi/\Xi$ Production as a Function of $R_T$

#### 3.1. Method

The purpose of this measurement is to estimate the production of hard probes relative to the underlying event. Analyzed events are required to have a leading trigger particle of $p_T \geq 5.0$ GeV, to ensure that at least one hard scattering took place in the event. The event is sectioned into three different azimuthal regions, relative to the leading track, as seen in the left panel of Fig 8. Letting $\phi_L$ define the azimuthal angle of the leading particle, the three regions are defined as containing charged particle tracks within relative differences of azimuthal angle:

- **Toward:** $|\phi - \phi_L| \leq \frac{\pi}{3}$
- **Away:** $\frac{2\pi}{3} \leq |\phi - \phi_L| \leq 2\pi$
- **Transverse:** $\frac{\pi}{3} < |\phi - \phi_L| < \frac{2\pi}{3}$

Particle production in the Toward region will be dominated by jet fragmentation, as well as soft collisions due to the underlying event. The Away-side region (often) captures the back-scattered jet, and particle production in this region is also dominated by a combination of jet
Figure 8: Left panel illustrates the three different azimuthal regions relative to the leading track \[9\]. Right panel showcases the average charged-particle production in the different regions as a function of the $p_T$ of the leading track \[10\].

fragmentation and the underlying event. The Transverse region is perpendicular to the leading track, and by definition, is almost a pure sample of the underlying event (although with possible contamination from initial-and final-state radiation). This can also be observed in the right panel of Fig. 8. For trigger particles with $p_T \geq 5.0$ GeV, the charged-particle production in the Transverse region is largely independent of the trigger particle $p_T$, indicating that the underlying event has the same properties so that one can integrate over the trigger $p_T$.

The particle yield of $\pi/K/p/\phi/\Xi$ is measured in the azimuthal regions as a function of the self-normalized transverse charged particle density $R_T$. If $N_T$ is defined as the number of charged particles reconstructed in the Transverse region, $R_T$ is defined as shown in Eq. 2. $R_T$ is used to control the underlying event relative to the hard scattering \[8\], where events in the limit of $R_T \to 0$ approaches “$e^+e^-$” physics (only consisting of a single hard scattering), and $R_T \to \infty$ approaches “AA”-like physics, where events are dominated by multiple soft collisions.

$$R_T = \frac{N_T}{\langle N_T \rangle} \quad (2)$$

3.2. Results

The particle ratios of $K/p/\phi/\Xi$-to-$\pi$ as a function of $R_T$ in the Toward and Transverse regions are presented in Figs. 9 to 12. The $p$-to-$\pi$ ratio in Fig. 9 displays a similar dependence on the event activity ($R_T$) as observed in multiplicity-dependent pp studies \[6\]. This effect is enhanced in the Transverse region. Notably, the high-$R_T$ $p$-to-$\pi$ ratio in the Toward region approaches the $p$-to-$\pi$ values in the Transverse region. This effect is also observed in the $\Xi$-to-$\pi$ ratio in Fig. 10. Furthermore, there is a large difference between the two $R_T$ bins that is only present in the Toward region. This indicates that the relative $\Xi$-to-$\pi$ production is proportional to $R_T$. The difference seen in the Toward region between the two $R_T$ limits indicate that the relative $\Xi$-to-$\pi$ rate is different in jet-fragmentation and underlying-event production, suggesting that the enhancement of strange-hadron production at increased multiplicity originates from the underlying event.
Figure 9: p-to-π ratio as a function of $p_T$ in bins of $R_T$. Left panel displays the p-to-π ratio of particles extracted from the Toward region. Right panel displays the p-to-π ratio extracted from the Transverse region. Lines (dashed and solid) represent equivalent EPOS-LHC and PYTHIA comparisons respectively. Lower panels show the ratios to the integrated $R_T$ selection.

Figure 10: Ξ-to-π ratio as a function of $p_T$ in bins of $R_T$. Left panel displays the p-to-π ratio of particles extracted from the Toward region. Right panel displays the p-to-π ratio extracted from the Transverse region. Lines (dashed and solid) represent equivalent EPOS-LHC and PYTHIA comparisons respectively. Lower panels show the ratios to the integrated $R_T$ selection.

The $\phi$-to-π and K-to-π ratios displayed in Figs. 11 to 12 largely resemble the same kind of phenomena observed in the previously shown baryon ratios. Notably, there is a very large modification of $\phi$ meson yield in the Toward region for events with large underlying event activity. Together with the Ξ-to-π results, this observation strengthens the suggestion that
Figure 11: K-to-π ratio as a function of $p_T$ in bins of $R_T$. Left panel displays the K-to-π ratio of particles extracted from the Toward region. Right panel displays the K-to-π ratio extracted from the Transverse region. Lines (dashed and solid) represent equivalent EPOS-LHC and PYTHIA comparisons respectively. Lower panels show the ratios to the integrated $R_T$ selection.

Figure 12: $\phi$-to-π ratio as a function of $p_T$ in bins of $R_T$. Left panel displays the $\phi$-to-π ratio of particles extracted from the Toward region. Right panel displays the $\phi$-to-π ratio extracted from the Transverse region. Lines (dashed and solid) represent equivalent EPOS-LHC and PYTHIA comparisons respectively. Lower panels show the ratios to the integrated $R_T$ selection. Note that the lower $R_T$-limit is different for this particle species, arising from complications in the yield extraction for low-$R_T$ events.

Strange particle production is enhanced in the underlying event. Furthermore, while both of the models are able to qualitatively predict the relative production
of kaons and protons, they are not able to accurately account for the $R_T$-dependent phenomena observed for $\phi$ and $\Xi$ hadrons. While PYTHIA manages to describe low-$R_T$ trends in the Toward region, it is currently not capable of describing the increase of relative $\phi$ and $\Xi$ production observed as the underlying event increases, both in the single and double ratios. However, EPOS-LHC is able to model the qualitative increase of $\Xi$ and $\phi$ production as a function of $R_T$ (although slightly overestimating/underestimating the increase of the single-ratio for $\Xi$ and $\phi$ production respectively).

4. Conclusions
This work has showcased two new measurements from ALICE that aim to achieve a better understanding of light-flavor hadronization in small systems. It has been demonstrated that $S_O^{p_T=1}$ is able to disentangle events based on their azimuthal topology and overall hardness. Therefore, $S_O^{p_T=1}$ can be used as a proxy to probe particle production in events that are either dominated by hard or soft processes. It has also been shown that $S_O^{p_T=1}$ can be used as a tool to disentangle biases from local fluctuations that arise when measurements and multiplicity estimations occur in the same rapidity region. Furthermore, the observations presented in Figs. 4 - 7 suggest that the enhancement of $K$ and $\Xi$ hadrons seen in high-multiplicity small-system collisions are primarily driven by dynamics that arise from events with isotropic topologies. The $\phi$ meson displays no modifications dependent on $S_O^{p_T=1}$.

The measurements of relative $p/K/\phi/\Xi$ production relative to $\pi$ as a function of $R_T$ also support some of the indications seen in the $S_O^{p_T=1}$ measurements. The two estimators are indirectly linked, as the underlying event is produced through multiple soft isotropic interactions. Events with a large underlying event will thus on average tend to have an isotropic azimuthal event topology. As seen in Fig. 9 and Fig. 12, the relative production of strange hadrons in the Toward region is greatly enhanced alongside the underlying event activity. Furthermore, the relative production of all $\Xi$ and $\phi$ hadrons to $\pi$ in the Toward region, in high-$R_T$ events, tends to saturate toward the equivalent distributions for the Transverse region. This further suggests that the enhancement of strange hadron production with multiplicity is mainly driven by the underlying event.

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