Production of strange hadrons in jets and underlying events in pp and p–Pb collisions with ALICE

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Abstract
The production of strange ($K^0_S$, $\Lambda$) and multi-strange ($\Xi^\pm$ and $\Omega^\pm$) hadrons in jets and underlying events in pp and p–Pb collisions is studied with ALICE at the LHC. Transverse momentum ($p_T$) differential density distribution of particles produced in a jet is compared to that of inclusive particle production and that in underlying events. The particle yield ratios of $(\Lambda + \bar{\Lambda})/2K_S^0$ and $(\Xi^- + \Xi^+)/($\Lambda + \bar{\Lambda}$) as a function of $p_T$ are also investigated in jets and underlying events. The production of the multi-strange hadrons, $\Xi^\pm$ and $\Omega^\pm$, and the corresponding ratio in jets and underlying events are measured for the first time. The $p_T$-differential density distribution of hadrons associated with hard scattering decreases slower than that for inclusive production. The baryon-to-meson and baryon-to-baryon ratios measured in jets exhibit clear differences from values obtained from the inclusive spectra in the intermediate $p_T$ range. The $p_T$ distribution of strange hadrons produced in jets is also studied in pp collisions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 7$ TeV and in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The $p_T$ spectra of particle produced in jets are independent of collision systems and collision energies. No apparent collision energy and collision system dependence is observed for the particle yield ratios of $(\Lambda + \bar{\Lambda})/2K_S^0$ and $(\Xi^- + \Xi^+)/($\Lambda + \bar{\Lambda}$) associated with energetic jets. These new results are compared to PYTHIA 8 event generator. The $(\Lambda + \bar{\Lambda})/2K_S^0$ ratio are generally reproduced by the model, but large discrepancies between data and PYTHIA simulations are observed for $(\Xi^- + \Xi^+)/($\Lambda + \bar{\Lambda}$).

1. Introduction
The unprecedented energies available at the Large Hadron Collider (LHC) provide unique opportunities to investigate the properties of the quark-gluon plasma (QGP) [1–7]. Recent reports on the enhancement of (multi-)strange hadrons [8–12], double-ridge structure [13–17], non-zero $v_2$ coefficients [18–20], mass ordering in hadron $p_T$ spectra [21], and characteristic modifications of baryon-to-meson ratios [9, 10, 22, 23] suggest that collective phenomena are present at the LHC energies also in pp and p–Pb collisions. Those results indicate that the collective effects are not unique to heavy-ion collisions. However, several measurements show the absence of a nuclear effect on the jet production at mid-rapidity in pp and p–Pb collisions [24–32]. Therefore, it is of great interest to investigate the origin of the collectivity-driven features in small systems (pp and p–Pb).

The baryon-to-meson yield ratio, $p/\pi$ and $\Lambda/K_S^0$, as a function of $p_T$ exhibits an enhancement at intermediate $p_T$ (around 3 GeV/$c$) in high multiplicity small collision systems with respect to that in low multiplicity, which is qualitatively similar to that observed in Pb–Pb collisions [33]. The enhancement of baryon-to-meson ratios has been related to the interplay of radial flow and parton recombination. In addition to these effects one can expect that particle production in this region results from the hard fragmentation of partons in the high $p_T$ region. This is due to the steeply falling power-law spectrum characteristic for parton production. This so-called 'leading particle effect' was described in terms of a 'trigger bias' [34]. Studying the ratios of particles associated to jets allows to gain new insights into the origin of the baryon-to-meson ratio enhancement. The particles with a larger strangeness content are observed to be produced more abundantly for
high multiplicity in pp collisions [11, 35] and in p–Pb collisions [12, 21] with respect to their lower multiplicity collisions. The enhancements of both baryon-to-meson and strange-to-non-strange ratios suggest the existence of a common underlying mechanism determining the chemical composition of particles produced in these three collision systems. The particle production at LHC energies has both soft and hard-scattering origins. To understand the strange particle production mechanisms in small collision systems, separation of particle production in hard processes (hard scattering) from those of the underlying event (UE) is important.

In this proceeding, the production of strange and multi-strange hadrons in jets and UE in pp and p–Pb collisions will be investigated with ALICE at LHC. The production of strange particles is studied separately within the jet and the UE region which separates the contribution associated with hard and soft processes. The hard process is tagged by selecting a reconstructed charged-particle jets with transverse momentum $p_{T,\text{jet}}>10$ GeV/$c$ using the anti-$k_T$ algorithm [36] with a resolution parameter $R=0.4$. Particle production in UE is estimated in the perpendicular cone (PC) to the jet axis with a radius $R_{\text{cone}}=0.4$. The inclusive production of hadrons in minimum bias events is compared to that in jets and in underlying events. The ratio of $(\Lambda + \bar{\Lambda})/2K^0_S$ and $(\Xi^- + \Xi^+)/2K^0_S$ as functions of particle transverse momentum is presented in charged-particle jets and UE. The result is compared to the PYTHIA 8 simulations with the color rope model [37–39]. The $(\Xi^- + \Xi^+)/2K^0_S$ and $(\Omega^- + \Omega^+)/2K^0_S$ ratios, which carry the information about multi-strange particles, are also investigated by the PYTHIA 8 simulation.

2. Experimental setup and analysis strategy

The data samples used in this analysis were recorded by the ALICE detector [40, 41] during LHC pp run in 2010 (\sqrt{s} = 7 TeV), 2015 (\sqrt{s} = 13 TeV) and in p–Pb runs in 2013 (\sqrt{s_{\text{NN}}}= 5.02 TeV). A detailed description of the ALICE apparatus and its performance can be found in [42, 43]. This analysis relies on the central tracking system and the forward V0 detector [44] in ALICE. The Inner Tracking System (ITS) [45] covering pseudorapidity of $|\eta|<0.9$ is used to measure the charged particle and to provide measurement of the primary interaction vertex (PV). The Time Projection Chamber (TPC) [46], also one of the central barrel detectors, is the main detector used for charged particle measurement and covers the pseudo rapidity range $|\eta|<0.9$. The TPC provides in addition information about particle type obtained through measurements of $dE/dx$. The two forward scintillator arrays V0A (covering pseudo-rapidity range of $2.8<\eta<5.1$), and V0C ($-3.7<\eta<-1.7$) combined with ITS are employed for providing the event trigger information.

The strange particles $K^0_S, \Lambda, \bar{\Lambda}$, and $\Xi^\pm$ are reconstructed at mid-pseudorapidity ($|\eta|<0.75$) via their specific weak decay topology. The following charged decay channels are used [47]:

$$K^0_S \rightarrow \pi^+ + \pi^- \quad \text{B.R.} = (69.20 \pm 0.05)\%,$$
$$\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^- (\pi^+) \quad \text{B.R.} = (63.9 \pm 0.5)\%,$$
$$\Xi^- (\Xi^+) \rightarrow \Lambda(\bar{\Lambda}) + \pi^- (\pi^+) \quad \text{B.R.} = (99.887 \pm 0.035)\%.$$

The proton and pion tracks are identified in the TPC via their measured energy deposition [43]. The identification method of the $V^0$ ($K^0_S$ and $\Lambda(\bar{\Lambda})$ which decays into two oppositely charged daughter particles) and $\Xi^\pm$ candidate is the same as in earlier ALICE publication [8, 22, 48–51]. The signal extraction is performed as a function of $p_T$. In each $p_T$ interval, an invariant mass histogram is filled with the corresponding counts. The raw yield (signal number) of strange hadrons in each $p_T$ intervals is extracted by bin counting method [50].

Charged-particle jets are reconstructed with the anti-$k_T$ algorithm [36] in the FastJet package [52], with a resolution parameter $R = 0.4$. The charged particle tracks, which are used as input for jet reconstruction, are selected in $|\eta|<0.9$ (TPC acceptance). The transverse momentum ($p_T$) of tracks should be larger than 0.15 GeV/$c$. Pseudorapidity of the charged-particle jet is constrained to $|\eta|<0.35$ (0.75–0.4). These conditions ensure that the jet cone is fully overlapping with the acceptances of both charged-particle tracks and strange particles ($|\eta|<0.75$). The transverse-momentum density of the background ($\rho_{\text{bkg}}$) originating from the UE and/or pile-up, contributes to the jet energy reconstructed by the jet finder. The background density ($\rho_{\text{bkg}}$) determined by the $k_T$ algorithm [53, 54] in pp collisions is negligible and not subtracted. In p–Pb collisions, an estimator adequate for the more sparse environment than Pb–Pb collisions is employed by scaling $\rho_{\text{bkg}}$ with an additional factor to account for event regions without particles [55]. A transverse momentum cut on the charged-particle jets, $p_{T,\text{jet}}^\text{ch} > 10$ GeV/$c$, is applied to tag the hard scattering processes [36].

The strategy of obtaining strange hadrons in charged-particle jets, follows that presented in [56]. The distance of particle to the jet axis on the $\eta - \varphi$ plane is defined as:

$$R(\text{par, jet}) = \sqrt{(\eta_{\text{jet}} - \eta_{\text{par}})^2 + (\varphi_{\text{jet}} - \varphi_{\text{par}})^2}.$$

When the distance of particle to jet axis $R(\text{par, jet})$ is less than the jet cone size $R_{\text{cone}} = 0.4$, the particle is considered inside the jet cone (JC). The remaining contribution from the underlying event (UE) in the JC...
selection, which refers to the particle not associated with jet fragmentation, is estimated in the perpendicular cone (PC) to the jet axis with radius $R_{PC} = 0.4$. The systematic uncertainty due to the UE subtraction is estimated by using two methods:

- **Outside cone (OC):** particles are reconstructed outside the jet cone of the reconstructed jet in the event, i.e. $R_{par, jet} > R_{cone}$.

- **Non-jet events (NJ):** particles found in events without any jet with $p_T > 5$ GeV/$c$

To obtain the corrected spectra, the acceptance and efficiency factors as a function of $p_T$ have to be computed. The acceptance and efficiency of each particle are obtained from Monte Carlo simulated data. Due to differences in the experimental acceptance for particles associated with jets and the UE, efficiencies of particles are estimated separately for each case [56].

The per event $p_T$-differential density $d\rho/dp_T$ of strange particles is defined as:

$$\frac{d\rho}{dp_T} = \frac{1}{N_{\text{event}}} \times \frac{1}{\langle \text{Area} \rangle} \times \frac{dN}{dp_T},$$

where $N_{\text{event}}$ is the number of events, $\langle \text{Area} \rangle$ is the acceptance area in pseudorapidity and azimuthal angle ($\Delta\eta \times \Delta\varphi$), and $dN/dp_T$ is the strange particle yield in each $p_T$ bin. This density is evaluated for particles in the jet cone (JC) and UE. The density of particles coming from jet fragmentation (JE) is calculated by

$$\frac{d\rho_{JE}}{dp_T} = \frac{d\rho_{IC}}{dp_T} - \frac{d\rho_{UE}}{dp_T}.$$

### 3. Results

The results of $K_S^0$, $\Lambda$, $\Xi^+$, and $\Omega^+$ spectra and the corresponding baryon-to-meson and baryon-to-baryon ratios in pp collisions at $\sqrt{s} = 7$ TeV, $\sqrt{s} = 13$ TeV and in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are presented in this section.

#### 3.1. Strange particle production

The fully corrected $p_T$-differential densities of $K_S^0$, $\Lambda$ and $\Xi^+ + \Xi^+$ obtained with various selections in pp collisions at $\sqrt{s} = 13$ TeV are shown in figure 1. The inclusive particle spectra are shown in the black solid circles. The particle spectra in charged-particle jets (labeled as 'JE') and in the underlying event (labeled as 'UE') are presented with red and blue solid squares, respectively. As expected, the density distributions in JE, which are corresponding to jet fragmentation, are considerably higher than that in UE. The spectra of UE particles rapidly decreases with $p_T$, reaching values of about one order of magnitude lower than that with the JE particles for $p_T$ exceeding 4 GeV/$c$. This is consistent with the expectation that the high-$p_T$ particles originate from jet fragmentation. The density distributions of the inclusive particles obtained in minimum-bias events are also compared with that of the JE and UE particles in figure 1. Due to trigger bias, particle density in UE containing at least one jet with $p_{T, jet}^{ch} > 10$ GeV/$c$ is higher than that of inclusive particles obtained in minimum-bias events.

Figure 2 shows the comparison of the $p_T$-differential density of $K_S^0$ (left) and $\Lambda$ (right) produced in charged-particle jets in pp collisions at $\sqrt{s} = 7$ TeV and in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, respectively [56]. As we know, the multiplicity and collision system dependence of inclusive $p_T$–differential spectra of $K_S^0$, $\Lambda$, $\Xi$, and $\Omega$ are observed [12, 21, 57]. However, the results shown in figure 2 indicate a weak dependence of collision system and system energy of the $p_T$-differential particle density in jets.

#### 3.2. Baryon-to-meson and baryon-to-baryon ratios

The $(\Lambda + \bar{\Lambda})/2K_S^0$ ratios with different selection criteria as the function of $p_T$ in pp collisions at $\sqrt{s} = 13$ TeV are presented in figure 3. The result suggests that the inclusive and the UE ratios manifest an enhancement at $p_T$ around 2 – 3 GeV/$c$. The ratios of JE particles are significantly lower than the inclusive and UE case at low and intermediate $p_T$. The $(\Lambda + \bar{\Lambda})/2K_S^0$ ratio in charged-particle jets is approximately independent on $p_T$ in the region beyond 3 GeV/$c$, especially without a maximum at intermediate $p_T$. This suggests that the enhancement of the baryon-to-meson ratio at intermediate $p_T$ is not driven by the jet fragmentation. In addition, the ratio of inclusive particles becomes consistent with that of JE particles for $p_T > 6$ GeV/$c$ as the high-$p_T$ particles originate from jet fragmentation. In figure 3, the $(\Lambda + \bar{\Lambda})/2K_S^0$ ratios are compared with the PYTHIA 8 color rope simulation [37]. It is shown that the PYTHIA 8 can generally describe the trend both for inclusive and JE.
The $(\Lambda + \overline{\Lambda})/2K^0_S$ ratio in charged-particle jets in pp collisions at $\sqrt{s} = 13$ TeV is compared to that in pp collisions at $\sqrt{s} = 7$ TeV and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in figure 4 [56]. The $(\Lambda + \overline{\Lambda})/2K^0_S$ ratio in pp collisions at $\sqrt{s} = 7$ TeV is lower than that in other two cases, but the deviation is less than 2σ. This should be investigated further with larger statistics. Currently, no visible dependence on the collision system and collision energy is observed for $(\Lambda + \overline{\Lambda})/2K^0_S$ ratio produced by jets.
The \((\Xi^- + \Xi^+) / (\Lambda + \bar{\Lambda})\) ratio in different selections is also investigated in figure 5. In this case, the numerator contains one more strange quark than the denominator. Similar to the \((\Lambda + \bar{\Lambda}) / 2K^0\) ratio shown in figure 3, the \((\Xi^- + \Xi^+) / (\Lambda + \bar{\Lambda})\) ratios from UE are consistent with that from the inclusive measurement. The ratio of inclusive and UE particles increases with \(p_T\) till around 4 GeV/\(c\). However, in the measured \(p_T\) acceptance, the ratio of UE particles is almost independent of \(p_T\). This implies the production mechanism of \(\Xi\), as multi-strange particle, in jets may be different with that in the UE. The results are compared with the PYTHIA 8 simulations in figure 5. There are large discrepancies between data and PYTHIA 8 simulations. The result in PYTHIA 8 simulation is largely underestimating the inclusive \((\Xi^- + \Xi^+) / (\Lambda + \bar{\Lambda})\) ratio. The ratio of UE particles given by PYTHIA 8 soft QCD increases dramatically with \(p_T\). On the contrary, the ratio of UE particles given by hard QCD is more reasonable. It is likely that in the PYTHIA 8 with soft QCD the \(ss\)-diquark string production rate is much higher than that within the jet fragmentation found in data.

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The multi-strange baryon-to-meson ratios, \((\Xi^- + \Xi^+) / 2K^0\) and \((\Omega^- + \bar{\Omega}^+) / 2K^0\), which carry the information about multi-strange particles, are also investigated by PYTHIA 8 simulation, shown in figure 6. It can be seen that PYTHIA with the soft QCD mode predicts similar strong increase as observed above. In summary, our measurement thus provides important constraints on the production mechanisms of particles, especially for those in multi-strange sector.
4. Summary

In summary, the production of $K_S^0$, $\Lambda$, $\Xi$ and $\Omega$ is measured separately for particles associated with hard scatterings and the UE in pp and p–Pb collisions. The baryon-to-meson and baryon-to-baryon ratios in pp collisions at $\sqrt{s} = 13$ TeV are compared with PYTHIA 8 simulations. The $(\Lambda + \bar{\Lambda})/2K_S^0$ ratio can generally be reproduced by the model, but large discrepancies between data and PYTHIA simulations are observed for the $(\Xi^- + \Xi^+)/\Lambda$ ratio. The $p_T$-differential density of particles in jets is almost independent on collision systems and collision energies. The baryon-to-meson and baryon-to-baryon ratios in jets are systematically lower than the inclusive measurement and independent of the particle $p_T$. The baryon-to-meson ratio enhancement has been linked to the interplay of radial flow and parton recombination at intermediate $p_T$. However, this enhancement is not seen within the jet, which indicates that these effects are indeed limited to the soft particle production processes.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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