New insights into strangeness production in pp collisions with ALICE at the LHC

Francesca Ercolessi[a,b,*]

[a] *Dipartimento di Fisica e Astronomia, University of Bologna, Italy*
[b] *INFN Sezione di Bologna, Italy*

E-mail: francesca.ercolessi@cern.ch

The observed increase of (multi-)strange hadron yields relative to non-strange hadron yields with the charged-particle multiplicity measured in pp collisions is reminiscent of the heavy-ion phenomenology but still remains to be understood. ALICE is addressing this open question exploiting different multi-differential techniques. In pp collisions the emission of leading baryons at very forward rapidity reduces the initial effective energy available for particle production with respect to the full center-of-mass energy. The production of Ξ multi-strange baryons is studied as a function of the particle multiplicity measured at midrapidity and of the very forward energy detected by ALICE Zero Degree Calorimeters. To study the relative contribution to strange hadron production from hard and soft QCD processes, the angular correlation between high-momentum charged particles and strange hadrons is studied. The toward- and transverse-to-leading yield of $\mathrm{K^0_s}$ and $\Xi^{\pm}$ are measured as a function of the charged particle multiplicity. The results of these measurements are compared to expectations from state-of-the-art phenomenological models implemented in commonly used Monte Carlo event generators.

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[*] Speaker

1. Introduction

Strangeness enhancement, i.e. the enhanced production of strange hadrons in heavy-ion collisions relative to that in minimum-bias pp collisions, was historically considered one of the first signatures of quark-gluon plasma formation [1]. This phenomenon was observed for the first time at SPS [2], then at RHIC [3] and later at the LHC [4] at increasing collision energies. At the LHC, the ALICE experiment also observed that small systems, such as p–Pb and pp collisions, show striking similarities with A–A collisions when multiplicity dependent studies are performed. The ratio of strange particle yields to pion yields was found to increase with the charged particle multiplicity produced in the event, evolving smoothly across different collision systems and energies. The results were compared to different model predictions, such as a statistical hadronization description using the canonical suppression approach [6], rope hadronization models including colour reconnection effects [7] and two-component (core-corona) models [8]. However, the effect cannot be satisfactorily reproduced by any of the available models and further experimental studies are needed to obtain a complete microscopic understanding of strangeness production in hadronic collisions.

2. Strangeness reconstruction with ALICE

The ALICE experiment identifies strange hadrons via the topological reconstruction of their weak decays in the central rapidity region, using a set of geometrical and kinematic selections applied to the reconstructed candidates to identify specific decay topologies. The experimental apparatus is composed of a central barrel, which covers $|\eta| < 0.9$ and is devoted to vertex reconstruction, tracking and charged particle identification, complemented by specialised forward detectors. The main detectors involved in strange hadron identification are the six-layer high resolution Inner Tracking System (ITS) [9, 10] and the large volume Time Projection Chamber (TPC) [11]. In addition, the Time-Of-Flight detector (TOF) [12] is exploited in combination with the ITS to suppress the out-of-bunch pileup. The sample of pp collisions is divided into percentile classes based on the signal amplitude measured by the V0 detector [13] and on the number of clusters measured by the two innermost layers of the ITS, the Silicon Pixel Detectors (SPD). The V0 detector is composed of two sets of plastic scintillators covering the pseudorapidity regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ and it is also used for triggering purposes. The energy carried by leading baryons, which are emitted at very forward rapidities, is measured through the Zero-Degree Calorimeters (ZDC). This detector is composed of two sets of hadronic calorimeters, one for protons (ZP, $6.5 < |\eta| < 7.4$) and one for neutrons (ZN, $|\eta| > 8.8$) on each side of the interaction point. A detailed description of the ALICE apparatus and its performance can be found in Ref. [14].

3. Strangeness correlation with effective energy

The charged-particle multiplicity in pp collisions is strongly correlated with the initial energy which was available for particle production (effective energy). In pp collisions the emission of leading baryons in the very forward pseudorapidity region reduces the effective energy with respect to the full $\sqrt{s}$ [15]. ALICE is able to measure the energy of very forward emitted baryons through the Zero Degree Calorimeters, providing an observable which is anti-correlated with the initial effective energy. Strange hadron production can be studied as a function of the final particle multiplicity produced at midrapidity and of the very forward energy detected by the ZDC, providing insights into the correlation of strangeness production with the earlier stages of the collision. In this analysis, events are classified using double-differential percentile selections based on the information from the SPD and V0 detectors. Strange hadron yields are measured as a function of midrapidity multiplicity and ZDC energy in event classes:

- with constrained SPD clusters and different V0 signals: selecting events which are characterized on average by the same multiplicity produced at midrapidity;
- with constrained V0 signals and different SPD clusters: selecting events which are characterized on average by ZDC energy measurements fixed in a small range.

Figure 1 shows the self-normalized Ξ yields per charged particle as a function of the self-normalized charged-particle multiplicity at midrapidity and of the self-normalized forward energy detected by the ZDC. The V0 standalone selection (black diamonds) shows that strange hadron production increases with the particle multiplicity produced in the event (left), but also decreases at increasing energy emitted in the forward region (right). However also when events with fixed midrapidity multiplicity are considered (coloured circles) the Ξ yield per charged particle shows an increasing trend (left), universally scaling with ZDC energy among different event classes (right). A good qualitative agreement with data is achieved with the Pythia Monash tune including Color Ropes hadronization models, in which multiparton interactions can produce overlapping strings acting together coherently to form a rope, which hadronizes with a higher string tension [16, 17].

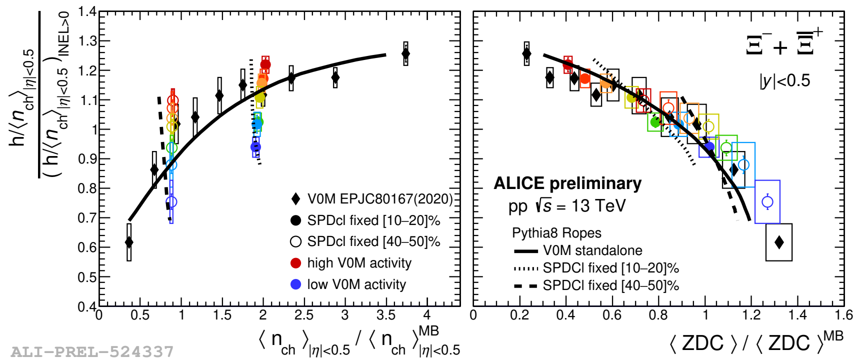

Figure 1: Self-normalized Ξ yields per charged particle as a function of the particle multiplicity produced at midrapidity (left) and of the very forward energy detected by the ZDC (right). The V0 standalone selection is shown in black diamonds, coloured circles show the double differential analysis where SPD clusters (SPDcl) are fixed and the V0 estimator is varied. Pythia Color Ropes predictions are shown with lines.

The results obtained when events with constrained ZDC energy are considered are shown in Figure 2 (coloured squares). The increase with multiplicity of the self-normalized Ξ yields per charged particle is strongly reduced when the ZDC energy is constrained (left). Within the small range where the forward energy is fixed the points show again a universal trend with ZDC energy (right). Also in this case a good qualitative agreement with data is achieved with the Pythia Color Ropes tune. The results show that strange hadron production in pp collision is correlated with the initial effective energy.

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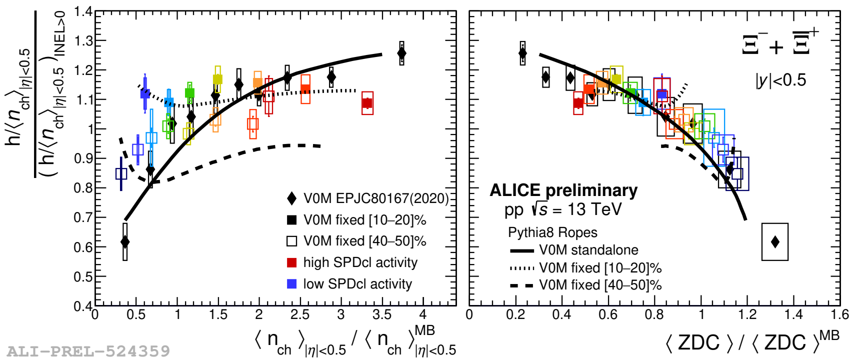
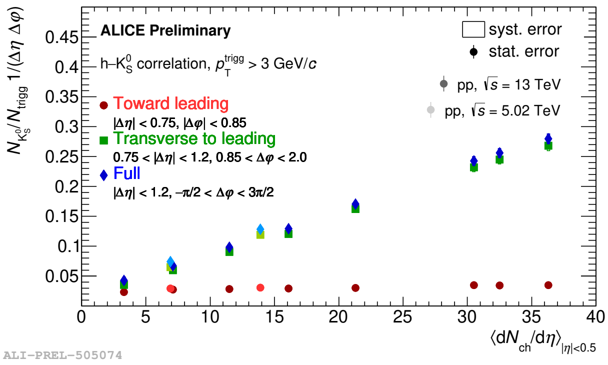


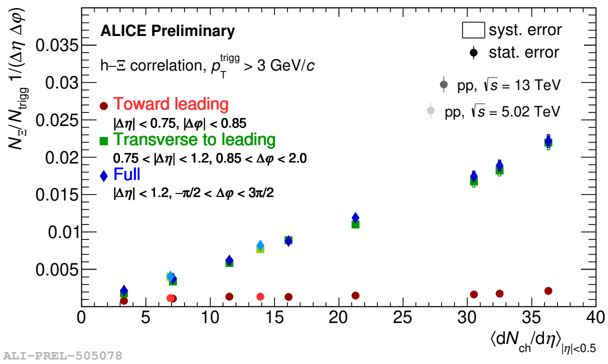
Figure 2: Self-normalized Ξ yields per charged particle as a function of the particle multiplicity produced at midrapidity (left) and of the very forward energy detected by the ZDC (right). The V0 standalone selection is shown in black diamonds, coloured squares show the double differential analysis where the V0 estimator is fixed and SPD clusters (SPDcl) are varied. Pythia Color Ropes predictions are shown with lines.

4. Strangeness in- and out-of jets

The processes which take part in particle production in hadronic collisions can be classified into hard and soft ones according to the momentum transfer at play. The relative contribution of hard and soft processes to strangeness production in pp is still an open question and can be studied through different techniques involving full-jet reconstruction and/or two-particle correlations. The ALICE results presented in these proceedings exploit the angular correlation method to separate $\mathrm{K^0_S}$ and Ξ hadrons produced in hard processes, such as jets, from those produced out-of-jet. This technique is based on the observation that particles produced in the near-side jet region are characterised by a small angular separation from the trigger particle of the jet, which is identified as the particle with the highest transverse momentum in the event and $p_{\mathrm{T}} > 3$ GeV/c [18]. The angular distribution between the trigger particle and the associated strange hadron is studied in the $(\Delta\eta, \Delta\phi)$ plane, which is divided into three regions: a transverse-to-leading region, proxy for the out-of-jet production, a toward-to-leading region, proxy for the near-side-jet production, and a full inclusive region, which covers the entire angular correlation plane. The near-side-jet contribution is obtained subtracting the out-of-jet yield from the full yield in the toward-to-leading angular region. The $\mathrm{K^0_S}$ and Ξ yields per trigger particle and per unit of $\Delta\eta\Delta\phi$ are displayed in Figure 3 as a function of the charged-particle multiplicity produced at midrapidity. The yields in the full and transverse-to-leading regions increase with the charged particle multiplicity, while the toward-to-leading region yields show a weak multiplicity dependence. Comparing the results obtained in pp collisions at $\sqrt{s}$ = 13 TeV and $\sqrt{s}$ = 5 TeV, no energy dependence is observed. These results suggest that out-of-jet processes are the dominant contribution to strange particle production in pp collisions.
The ratio of Ξ yields over $\mathrm{K^0_S}$ yields as a function of midrapidity multiplicity is shown in Figure 4. The full and transverse-to-leading yield ratios are found to increase with multiplicity, in agreement with the expected strangeness enhancement hierarchy with the hadron strangeness content. The toward-to-leading yield ratio shows an increasing trend with multiplicity as well within the uncertainties, but is found to be lower with respect to full and out-of-jet ratios. The toward- and transverse-to-leading ratios are found to increase with increasing multiplicity with proportional slopes.



(a)



(b)

Figure 3: K^0_S (a) and Ξ (b) yields per trigger particle and per unit of $\Delta\eta\Delta\phi$ in the full, toward- and transverse-to-leading azimuthal regions. The yields are reported as a function of the midrapidity multiplicity.

5. Conclusion

The ALICE Collaboration has provided a comprehensive set of results on the production of strange hadrons in hadronic collisions, which show a striking smooth trend with increasing multiplicity from pp to heavy-ion systems. The mechanisms responsible for these observations are still to be fully understood and ALICE is addressing this open question through multi-differential analyses which study strange hadron production in small systems. By studying the correlation of strange hadron production with midrapidity multiplicity and very forward energy in multi-differential classes, ALICE showed that strangeness production is correlated with the earlier stages of the collision (effective energy). By separating the contribution of soft and hard processes through two-particle correlation techniques, ALICE observed that out-of-jet processes are the dominant contribution to strange hadron production. The Run 3 of LHC will provide a sample of high-multiplicity pp collisions larger by more than three orders of magnitude with respect to that of Run 2, which will allow the upgraded ALICE experiment to make more comprehensive studies on strangeness production. Among them, the very high number of accessible Ω baryons in the Run 3 sample will allow ALICE to study also the production of these hadrons in-jet and out-of-jet over a large multiplicity range.

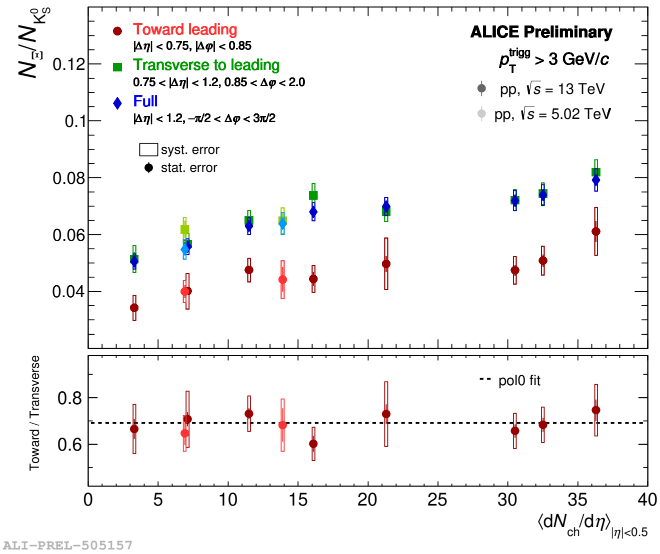


Figure 4: Ratio between Ξ and K^0_S full, toward- and transverse-to-leading yields as a function of charged particle multiplicity at midrapidity.

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