Probing hadron formation at the LHC through the study of strange particles in different collision systems and energies with ALICE at the LHC

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Summary. — Strange hadrons constitute a unique tool for studying hadronization. While their production yield was first proposed as a clean signature of quark–gluon plasma [1] formation in heavy-ion collisions, at present the role of strangeness production in large and small collision systems is pivotal in understanding how a colored system evolves into the observed gas of mesons and baryons. This process started to be explored in more detail after the ALICE Collaboration made the groundbreaking observation that strange hadron yields increase with charged-particle multiplicity density, regardless of the collision system or the center-of-mass energy [7]. The data also shows that transverse momentum spectra in elementary interactions are affected by partonic collectivity even when only few particles are produced at midrapidity [14]. In this proceedings, a complete overview of the latest findings in the study of strange-hadron production at the LHC will be presented, with special emphasis on the discussion of present and future prospects of this field in view of the LHC Run 3 data taking campaign.

1. – Introduction

The high-energy heavy-ion collisions at the Large Hadron Collider (LHC) produce a state of matter known as a quark-gluon plasma (QGP) [2], which is characterized by extreme temperature and energy density. The QGP formed during the collision undergoes rapid expansion, behaving like a strongly-coupled liquid, and gradually cools until it reaches a temperature close to the phase transition point. At this critical temperature, the deconfined partons within the QGP recombine to form conventional, color-neutral matter. Strangeness production is regarded as a signal of quark-gluon plasma formation in nuclear collisions, because there are no strange valence quarks present in the initial state of the collision. Additionally, the sufficiently low mass of strange quarks allows them to be generated during the collision and participate in collective motion. The study of strange particle production allows the investigation of the properties of the partonic phase as well as the process of subsequent hadronization.

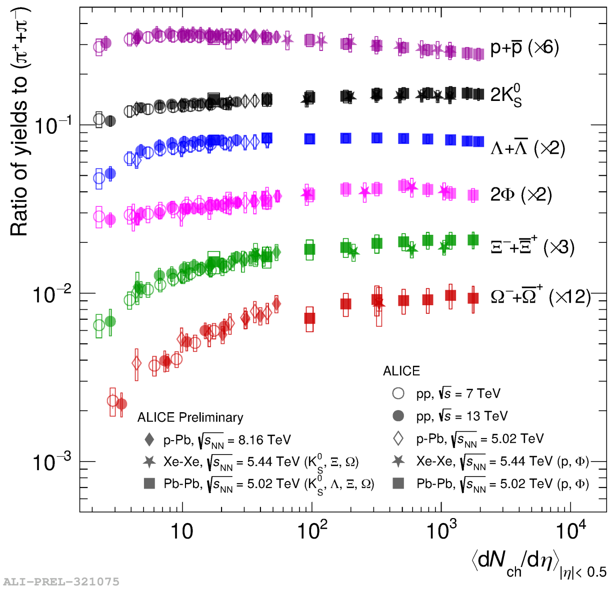

Fig. 1. – Ratio of hadron yields to pion yields as a function of charged-particle multiplicity density. The results for different collision systems and energies are shown by different symbols.

2. – Strangeness enhancement in different collision systems and energies

Strangeness enhancement had been observed at SPS [3], RHIC [4], and LHC [5] in large collision systems. The unprecedented observation of enhanced production of multi-strange hadrons in high-multiplicity pp collisions with the ALICE experiment [7], brought into prominence the importance of small systems and showed that strangeness enhancement is not an exclusive feature of heavy-ion collisions.The study of strangeness production from small to large collision systems is essential for understanding the origin of the strangeness enhancement phenomenon and constrains the particle production models. Figure 1 shows the ratio of particle yields to the corresponding charged-pion yield as a function of charged-particle multiplicity density, for different collision systems. It is clear that strange-baryon production depends on charged-particle multiplicity rather than on the initial collision system or center-of-mass energy. The ratio of strange to non-strange hadron yields increases with charged-particle multiplicity density and a smooth evolution across different collision systems and energies is seen. The strangeness production rates that are measured in high-multiplicity pp events are in remarkable agreement with those observed in Pb–Pb and Xe–Xe collisions, although a steeper increase in the yields for hadrons with a higher strangeness content is present.

3. – Baryon-to-meson ratio

Ratio of the p_{T}-integrated yields of Λ and $\mathrm{K}^0_{\mathrm{s}}$ is pivotal in the understanding of strangeness-enhancement origin. Both $\mathrm{K}^0_{\mathrm{s}}$ and Λ are singly strange, so any strangeness enhancement should cancel out in their ratio. Figure 2 shows the baryon-to-meson ratio as a function of p_{T} for different collision systems. The behavior of the ratio below 1 GeV/c is similar across various centrality classes and collision systems and can be understood in

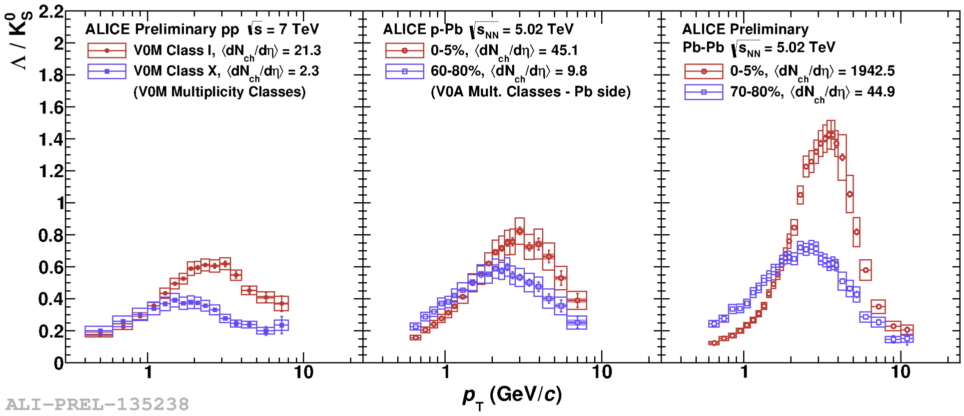

Fig. 2. – Λ over K^0_s corrected spectra versus p_T for different collision systems and centrality classes [6].

terms of hydrodynamical models [12]. At at intermediate p_T, the interplay of radial flow and quark recombination creates a pronounced maximum, the so called baryon anomaly. The position of the maximum evolves with collision centrality and can be described by recombination models [10], [11]. One question that arises from these results is whether this effect is connected to hard or soft processes such as jet fragmentation or production of particles in the bulk. For this reason, baryon-to-meson ratio was studied in and out of jets, see Fig. 3. Surprisingly, the enhancement in the ratio is dominated by out-of-jets processes, leading to conclusion that the baryon anomaly arises from the bulk.

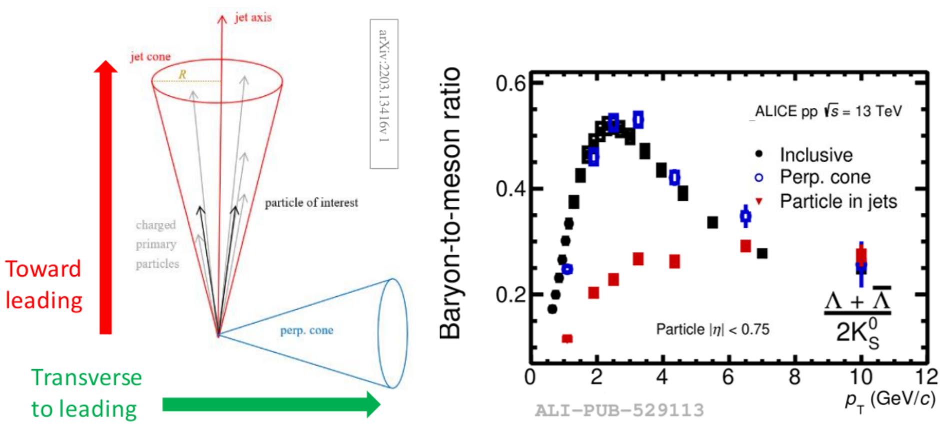

Fig. 3. – Left: Illustration of a jet cone and a perpendicular cone [8]. Right: Baryon to meson ratio as a function of transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV. The results of in-jet particles (red triangles) are compared with that of inclusive (black closed circles) and out-of-jet (blue open circles) particles. The reconstructed jets are leading charged-particle-track anti-k_t jets with $R = 0.4$. Statistical uncertainties are represented by vertical error bars and systematic uncertainties by boxes.

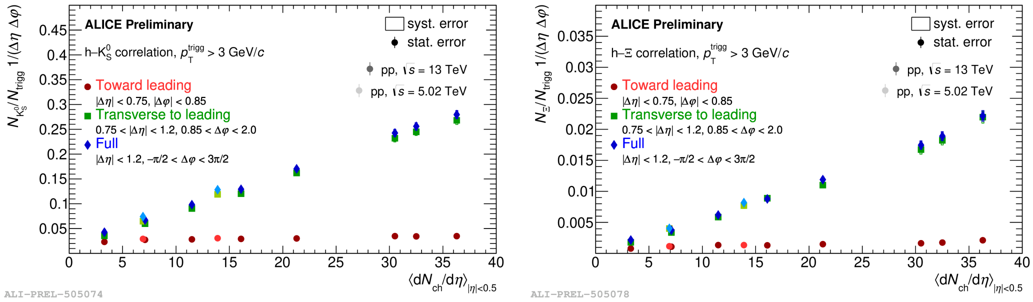

Fig. 4. – Ratio of K^0_s (left) and $\Xi^{\pm}$ (right) yields to unidentified-charged-trigger-particle yields as a function of charged-particle multiplicity density. The results for in-jet particles (red points) are compared with those of inclusive (blue points) and out-of-jet (green points) particles. Statistical uncertainties are represented by vertical error bars and systematic uncertainties by boxes.

4. – Strangeness in and out of jets

In order to understand the contribution of soft and hard processes to strangeness production, $\Xi^{\pm}$ yields and K^0_s yields over the yields of unidentified charged particles with $p_T > 3$ GeV/c have been measured both in jet cone and the perpendicular-to-jet cone processes. Figure 4 illustrates the particle yields as a function of multiplicity in small systems. It is observed that the inclusive and out-of-jet yields increase with multiplicity, while the in jets yields show no dependence on particle production at midrapidity, for both $\Xi^{\pm}$ and K^0_s. It is thus seen that the enhanced production of strange and multistrange hadrons emerges mostly from the underlying events, which is consistent with the above results.

5. – The upgraded ALICE

The important observations that are discussed in this proceedings will be further investigated with the upgraded ALICE detector [13] in Run 3, where ALICE plans to significantly increase the integrated luminosity of pp and Pb–Pb data. This will allow us to further increase the bias on charged-particle multiplicity in the pp sample. Figure 5 shows the new silicon vertex detector ITS2, whose first layer is closer to the interaction point w.r.t. the ITS in Run 2, the new FIT detector, and the upgraded TPC readout based on GEM foils. These new detectors make it possible to improve pointing resolution, increase readout rate, and suppress background. Multi-differential analysis is taking place in order to show whether there is a unified picture of particle production and QCD mechanisms from small (pp, p–Pb) to large (Pb–Pb) systems, or to reveal new mechanisms that are important in heavy-ion collision.

6. – Conclusions

Strange-hadron yields increase with charged-particle multiplicity density, regardless of the collision system or the energy regime at the LHC. Several features observed in large collision systems, which are attributed to the formation of the QGP, are also observed in the small systems. Small collision systems for instance exhibit baryon-to-meson enhancement, which has been explained in Pb–Pb collisions as the interplay of radial flow and

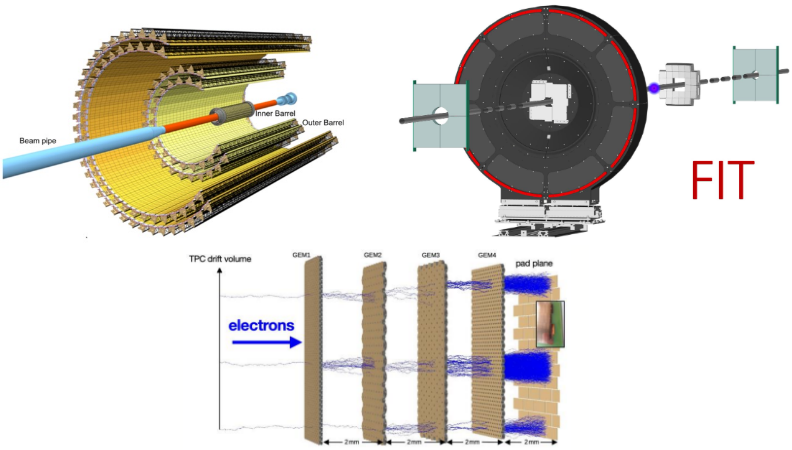

Fig. 5. – The upgraded ALICE. Top Left: New Inner Tracking System (ITS). Top right: New Fast Interaction trigger (FIT). Bottom: Upgrade of the Time Projection Chamber (TPC) readout which is based on GEM foils.

parton recombination at intermediate p_{T}. Its absence within the jet cone demonstrates that these effects are indeed limited to soft particle production processes. Additionally, in contrast to what is observed in the underlying event, there is no significant event-multiplicity dependence for strange particle production in jets. Large data samples collected in Run 3 are expected to reveal whether the strangeness production in pp collisions with extreme multiplicity saturates at the thermal equilibrium yields that are reached in Pb–Pb collisions or whether it continues to increase. This will allow us to finally understand the mechanisms responsible for hadronisation in small and large systems [15].

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