PROCEEDINGS OF SCIENCE

Looking for collective origin of strangeness enhancement in small collision systems with ALICE at the LHC

Ishaan Ahuja[a,*] **on behalf of the ALICE Collaboration**

[a] *Faculty of Science, P.J. Šafárik University, Košice, Slovak Republic*

E-mail: ishaan.ahuja@cern.ch

The main goal of the ALICE experiment is to study the physics of strongly interacting matter, including the properties of the quark–gluon plasma (QGP). The increase in relative production of strange hadrons with respect to non-strange hadrons as a function of multiplicity is historically considered as one of the signatures of QGP formation during the evolution of the system created in heavy-ion collisions. Recent measurements performed in high-multiplicity proton–proton (pp) and proton–lead (p–Pb) collisions have shown features that are reminiscent of those observed in lead–lead (Pb–Pb) collisions. The microscopic origin of this phenomenon is still not fully understood: whether it is related to soft particle production or to hard scattering events, such as jets? To separate strange hadrons produced in jets from those produced in soft processes, the angular correlation between high-p_{T} charged particles and strange hadrons has been exploited. The near-side jet yield and the out-of-jet yield of $\mathrm{K^0_S}$, Ξ, Λ and ϕ have been studied as a function of the multiplicity of charged particles produced in pp collisions at $\sqrt{s}$ = 5.02 TeV and 13 TeV and p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. New results suggest that out-of-jet processes are the dominant contributor to strange particle production.

Hard Probes 2023
26-31 March 2023
Aschaffenburg, Germany

*Speaker

https://pos.sissa.it/

PoS(HardProbes2023)122

1. Introduction

Strangeness enhancement is considered as one of the first proposed key signatures [1] for the formation of the quark–gluon plasma (QGP), a strongly interacting quantum chromodynamics state of nuclear matter with deconfined quarks and gluons. In ultrarelativistic heavy-ion collisions with sufficiently high temperatures and energy densities where QGP formation is anticipated, an enhanced production of strange hadrons with respect to small systems (like pp or p–Pb collisions) is observed [2–4], with an emphasis on relative yield of multi-strange baryons to non-strange hadrons being more pronounced. In smaller collision systems such as proton–proton (pp) and proton–lead (p–Pb), strangeness enhancement can be described as an increasing ratio of strange hadron yields over pion yields as a function of charged particle multiplicity. Multiplicity dependent studies performed at the ALICE experiment at the LHC have demonstrated a smooth evolution of this ratio across multiple collision systems with different collision energies. The increase is more prominent in multi-strange particles, indicating that the enhancement scales with particle strangeness content [5].

2. Identifying strange hadrons with ALICE

The ALICE experiment employs a topological reconstruction technique in the central rapidity region to identify weakly-decaying strange hadrons through their decay topologies into charged particles: $\Lambda \rightarrow \mathrm{p}\,\pi^-$, $\mathrm{K^0_S} \rightarrow \pi^+\pi^-$, and cascade decay channel for $\Xi^- \rightarrow \Lambda\,\pi^- \rightarrow \mathrm{p}\,\pi^-\pi^-$, along with their charge conjugates. The reconstructed decay particles are filtered through a set of kinematic and geometric selection criteria to ensure the daughter track characteristics comply with the expected decay topologies and to reduce combinatorial background. The strange hadrons of interest are subsequently identified through invariant-mass technique. For relatively short-lived resonance $\phi \rightarrow \mathrm{K^+\,K^-}$ where topological selections are not required, signal extraction can be performed based solely on invariant-mass technique.

The experimental setup consists of a central barrel covering $|\eta| < 0.9$ over the full azimuthal angle (φ), focusing on vertex reconstruction, tracking, and charged particle identification, accompanied by dedicated forward detectors. Key subdetectors for identifying strange hadrons include the six-layered silicon-based Inner Tracking System (ITS) [6] and an inert gas filled Time Projection Chamber (TPC) [7], which are used in particle identification, tracking, momentum measurement and particle trajectory evolution, enabling particle track reconstruction in 3D space. The Time-Of-Flight detector (TOF) [8], in conjunction with the ITS, is utilized to reject out-of-bunch pileup. The V0 detector [9] comprises of two sets of scintillator arrays on each side of the interaction point, spanning the pseudorapidity ranges $2.8 < |\eta| < 5.1$ (V0A) and $-3.7 < |\eta| < -1.7$ (V0C). By measuring the number of clusters in the two innermost layers of the ITS (Silicon Pixel Detector) and the signal amplitude in the V0's scintillator arrays, charged particle multiplicity can be estimated for mid- and forward pseudorapidities. A detailed description and performance of the ALICE detector can be found in Ref. [10].

3. Studying strange hadron production in hard and soft processes

In hadronic collisions, particle production mechanisms can be categorised into either hard or soft processes depending on the momentum transfer involved. Hard scattering processes involve high momentum transfer from an energetic parton resulting in a narrow, collimated spray of hadrons retaining a significant amount of the initial beam momentum, called a "jet". The charged hadron with the highest transverse momentum (p_{T}) in the event is called the jet-leading particle, or the "trigger" particle, which also acts as a proxy for the jet axis and defines the near-side jet region. Alternatively, soft processes involving particle production governed by bulk properties of the medium are characterised by low momentum transfer and can be studied in the transverse to leading or out-of-jet regions. Understanding the relative contribution of hard and soft processes to strangeness production in small collision systems is of particular interest and can be studied using techniques such as full-jet reconstruction and/or two-particle angular correlations. Recent ALICE results presented in these proceedings utilize the angular correlation method to distinguish strange hadrons (ϕ, Λ, $\mathrm{K}^0_{\mathrm{S}}$, $\Xi^{\pm}$) produced in hard processes (e.g., jets) from soft processes (out-of-jet).

3.1 Two-particle angular correlations

Studying strange hadron production using the method of two-particle angular correlations [11] with respect to jet axis in the ($\Delta\varphi$, $\Delta\eta$) plane involves selecting the trigger particle and identifying strange hadrons of interest in the event. The analyses presented here impose kinematic selection criteria for the trigger particles: $p_{\mathrm{T}} > 3\,\mathrm{GeV}/c$ ($\mathrm{K}^0_{\mathrm{S}}$, $\Xi^{\pm}$) and $4 < p_{\mathrm{T}} < 8\,\mathrm{GeV}/c$ (ϕ, Λ). From the same event, strange hadrons of interest with smaller transverse momenta (p_{T}) than the trigger particle are labeled as "associated" particles. The angular correlations can be constructed using the angular differences ($\Delta\varphi$, $\Delta\eta$) between the trigger and the associated particles. The angular distribution is divided into three regions: towards leading (near-side jet), transverse to leading (out-of-jet or underlying event), and full inclusive region, covering the entire angular correlation plane. For each region, per-trigger yield of associated particles is computed from the 2D correlation distribution and corrected for factors such as trigger and associated particles' reconstruction efficiencies, pair detector acceptance, and contamination from non-primary particles.

4. Results

To study the contribution of hard and soft processes in strangeness enhancement observed in small collision systems, results accumulated from different collision systems and energies for multiple strange hadrons are presented. $\mathrm{h}-\mathrm{K}^0_{\mathrm{S}}$ and $\mathrm{h}-\Xi$ correlations for minimum bias pp collisions at $\sqrt{s}$ = 5.02 TeV and high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV are analysed. Findings from similar studies performed for $\mathrm{h}-\Lambda$ and $\mathrm{h}-\phi$ correlations in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV are shown.

Figure 1 illustrates the p_{T} spectra of $\mathrm{K}^0_{\mathrm{S}}$ and Ξ in pp collisions at $\sqrt{s}$ = 5.02 TeV and 13 TeV. As anticipated, the near-side jet spectra are harder than the out-of-jet spectra, signifying different production mechanisms, with the former pertaining to hard particle production. The full spectra follow the shape of the out-of-jet spectra, indicating a higher relative contribution of the latter.

PoS(HardProbes2023)122

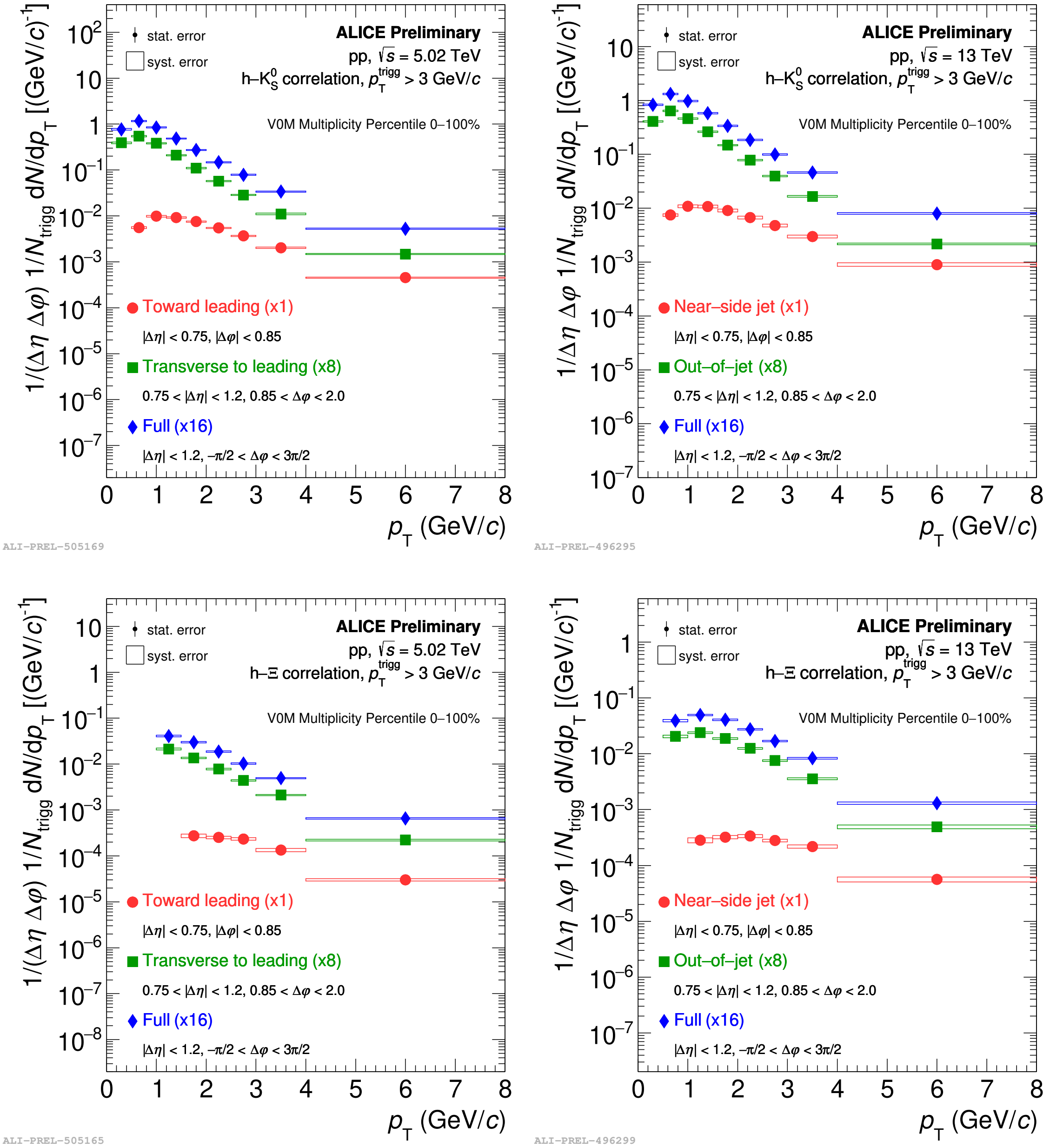

Figure 1: Toward leading (near-side jet), transverse-to-leading (out-of-jet) and full (inclusive) transverse momentum (p_{T}) spectra of $\mathrm{K^0_S}$ (top) and Ξ (bottom) for pp collisions at $\sqrt{s}$ = 5.02 TeV (left) and $\sqrt{s}$ = 13 TeV (right). The statistical uncertainties are represented by the error bars and the total systematic uncertainty by the empty boxes.

The p_{T} integrated yields for $\mathrm{K^0_S}$ and Ξ can be obtained by summing the bin contents and using an average integral of four fit functions — Levy-Tsallis, Boltzmann, Fermi-Dirac and m_T scaling — in low-p_{T} and high-p_{T} intervals, where the yield cannot be measured and extrapolation is required [12]. The $\mathrm{K^0_S}$ and Ξ yields per trigger particle as a function of charged-particle multiplicity (Fig. 2) reveal a stronger multiplicity dependence in the transverse to leading and full region as compared to the near-side jet region. The relative increase in per-trigger yield in the transverse to leading (out-of-jet) region in comparison to toward leading (near-side jet) region suggests that the relative contribution of soft processes increases with multiplicity, while hard processes (near-side jet yield) rise with a comparatively smaller slope with $\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$.

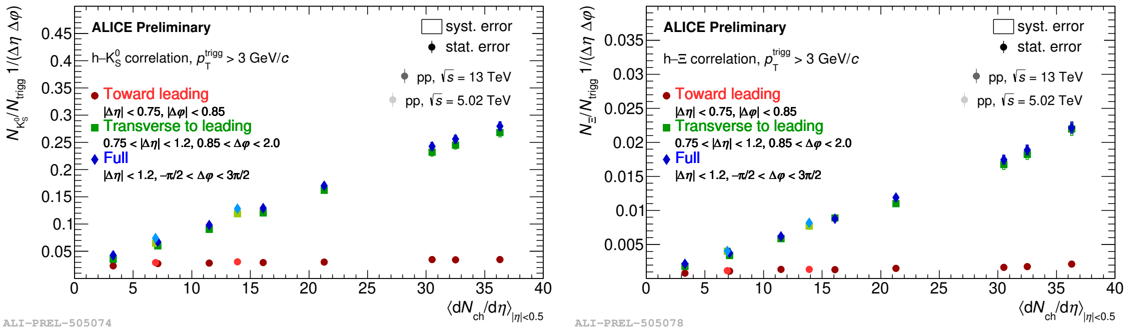

Figure 2: K^0_S (left) and Ξ (right) yields (integrated over full $p_{T,\,assoc}$) per trigger particle and per unit $\Delta\varphi\Delta\eta$ as a function of charged particle multiplicity at midrapidity $\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$. The statistical uncertainties are represented by the error bars and the total systematic uncertainty by the empty boxes.

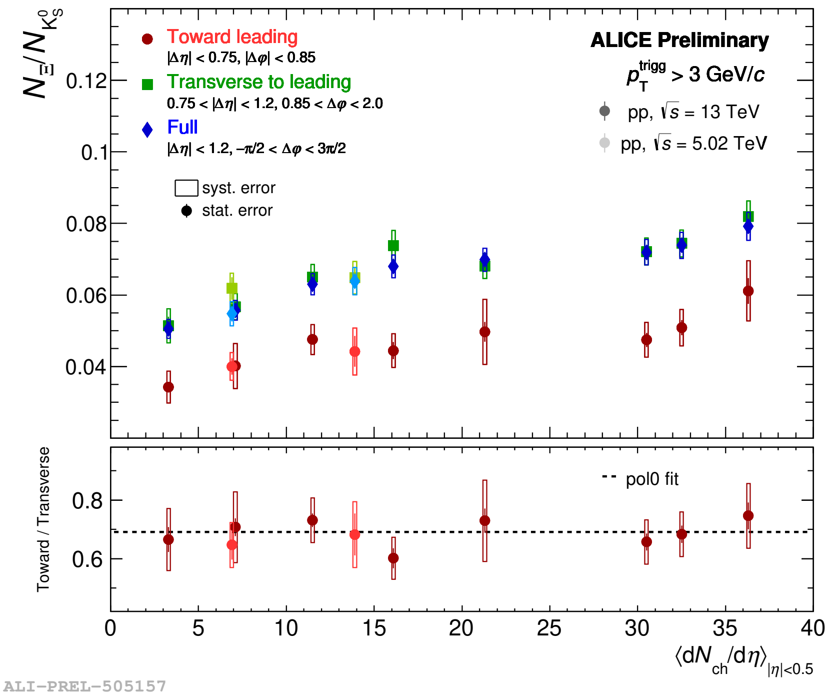

Figure 3: Ξ/K^0_S yield ratio (integrated over full $p_{T,\,assoc}$) as a function of charged particle multiplicity at midrapidity $\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$. The statistical uncertainties are represented by the error bars and the total systematic uncertainty by the empty boxes.

To study the strangeness enhancement effect, Ξ/K^0_S integrated yield ratio as a function of charged particle multiplicity (Fig. 3) is examined. The full yield ratio increases with multiplicity due to the larger strangeness content of Ξ ($|S| = 2$) with respect to K^0_S ($|S| = 1$). The rise in out-of-jet and near-side jet regions seem compatible albeit the near-side ratio exhibiting larger uncertainties.

The near-side jet ratio being smaller represents dominant contribution to the full yield ratio arising from out-of-jet processes. None of the results suggest any dependence on centre-of-mass energy.

In case of p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, similar trends in strangeness enhancement can be observed (Fig. 4). For $2 < p_{\mathrm{T,\,assoc}} < 4$ GeV/c, it can be seen that the yield ratios in total, out-of-jet (underlying event), away-side jet and near-side jet region increase as a function of multiplicity, although higher values in the underlying event region indicate a dominant contribution to the total yield ratio coming from soft particle production mechanisms.

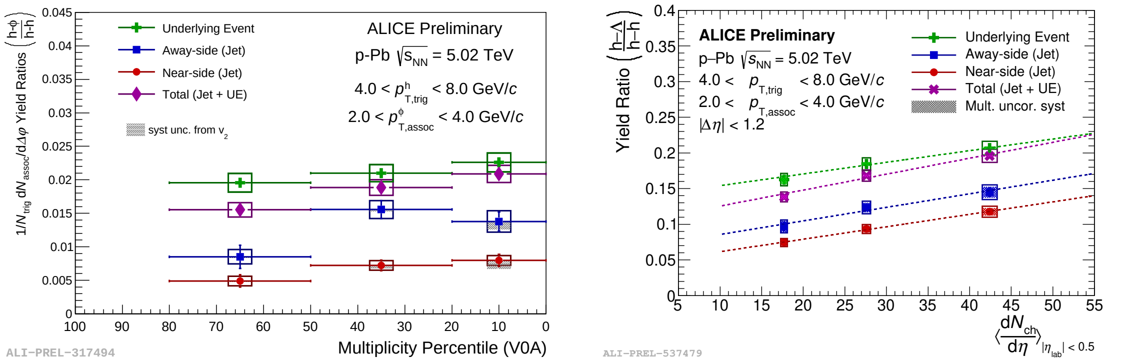

Figure 4: Pair-wise per-trigger yield ratios for $\frac{\mathrm{h}-\phi}{\mathrm{h}-\mathrm{h}}$ (left) and $\frac{\mathrm{h}-\Lambda}{\mathrm{h}-\mathrm{h}}$ (right) correlated pairs as a function of charged particle multiplicity at midrapidity $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle_{|\eta|<0.5}$ in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. The statistical uncertainties are represented by the error bars and the total systematic uncertainty by the empty boxes. The dotted straight-line fits (right) were taken considering only the systematic errors that are uncorrelated with multiplicity, shown as shaded boxes.

5. Conclusions

The ALICE Collaboration has conducted comprehensive studies of the production of strange hadrons in various hadronic collision systems, revealing a remarkable smooth trend that correlates with increasing multiplicity from pp to heavy-ion collisions. Ongoing analyses and investigations to understand the origins of strangeness production and strangeness enhancement in hard and soft processes are of particular interest, and the results presented here shed some light on these particle production mechanisms in small collision systems.

Utilising the method of two particle correlations, it can be observed that strange hadrons in jets have different production mechanism than those outside the jet cone, based on the harder transverse momentum spectra for in-jet particles. Initial collision energy dependence has not been observed for strangeness enhancement in any region, however dependence on charged particle multiplicity is noticed. The per-trigger yield ratios demonstrate this multiplicity dependent enhancement, which is compatible for in-jet and out-of-jet regions. However, all observed cases point to a larger contribution from out-of-jet regions in comparison to in-jet region, indicating soft processes dominate over hard scattering processes in strange particle production.

Further studies based on dataset from Run 3 of the LHC are anticipated to provide more extensive and detailed outcomes thanks to a significantly larger sample of high-multiplicity pp collisions.

References

[1] J. Rafelski and B. Müller, *Strangeness Production in the Quark-Gluon Plasma*, *Phys. Rev. Lett.* **48** (1982) 1066.

[2] WA97 Collaboration, *Strangeness enhancement at mid-rapidity in Pb Pb collisions at 158-A-GeV/c*, *Phys. Lett. B* **449** (1999) 401.

[3] STAR Collaboration, *Enhanced strange baryon production in Au+Au collisions compared to* $p + p$ *at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. C* **77** (2008) 044908.

[4] B. Abelev et al., *Multi-strange baryon production at mid-rapidity in Pb–Pb collisions at* $\sqrt{s_{\mathrm{NN}}} = 2.76$ *TeV*, *Physics Letters B* **728** (2014) 216.

[5] ALICE Collaboration, *Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions*, *Nature Physics* **13** (2017) 535 [1606.07424].

[6] ALICE Collaboration, *Technical Design Report for the Upgrade of the ALICE Inner Tracking System*, *Journal of Physics G: Nuclear and Particle Physics* **41** (2014) 087002.

[7] J. Alme et al., *The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **622** (2010) 316.

[8] ALICE Collaboration, *Performance of the ALICE Time-Of-Flight detector at the LHC*, *JINST* **14** (2019) C06023 [1806.03825].

[9] ALICE Collaboration, *Performance of the ALICE VZERO system*, *JINST* **8** (2013) P10016 [1306.3130].

[10] ALICE Collaboration, *Performance of the ALICE experiment at the CERN LHC*, *International Journal of Modern Physics A* **29** (2014) 1430044.

[11] ALICE Collaboration, *Long-range angular correlations on the near and away side in p-Pb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV*, *Phys. Lett. B* **719** (2013) 29 [1212.2001].

[12] C. De Martin, *Understanding the production mechanisms of particles with strangeness in pp collisions with the ALICE experiment at the LHC*, Ph.D. thesis, Università degli Studi di Trieste, 2022.