

New insights into strange-quark hadronization measuring multiple (multi-)strange hadron production in small collision systems with ALICE

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Abstract. Among the most important results from the Run-1 and Run-2 of the LHC is the observation of an enhanced production of (multi-)strange to non-strange hadron yields, gradually rising from low-multiplicity to high-multiplicity pp and p–Pb collisions, reaching values close to those measured in peripheral Pb–Pb collisions [1]. The observed behaviour cannot be quantitatively reproduced by any of the available QCD-inspired MC generators. In this contribution an extension of this study is presented: the measurement of the K_S^0 , Λ , Ξ^- and Ω^- (together with antiparticles) multiplicity distributions in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of the charged-particle multiplicity, together with the average probability for the multiplets production, extending the study of strangeness production beyond its average. This novel method, based on counting the number of strange particles event-by-event, represents a new test bench for production mechanisms, probing events with a large imbalance between strange and non-strange content.

1 Introduction

Among several probes of the quark–gluon plasma (QGP) formation, the so-called *Strangeness Enhancement* (SE) was one of the first proposed [2] and observed experimentally [3]. In addition to confirm the SE at the highest center-of-mass energy [4–6], the ALICE Collaboration carried out a comprehensive study of strange hadron production (relative to charged pions) as a function of the charged-particle multiplicity at midrapidity [1]. The main finding is that strangeness increases progressively with multiplicity in a compatible way across different collision systems and center-of-mass energies [1, 7, 8]. The invariance of the SE pattern on the colliding system suggests that the mechanisms at play in high-multiplicity pp interactions could be the same as those involved in particle formation in Pb–Pb collisions. Moreover the enhancement, previously unexpected in pp interactions, is proportional to the strangeness content in the hadron being the highest for the Ω^- baryon. However, the observed behaviour cannot be quantitatively reproduced by any of the available QCD-inspired models, suggesting that further developments are needed to obtain a complete microscopic understanding of strangeness production.

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2 Measurement of (multi-)strange particle multiplicity distribution

To obtain more information about the strangeness production mechanism, the (multi-)strange particle multiplicity distribution, $P(n_S)$, has been measured in pp collisions at $\sqrt{s} = 5.02$ TeV using a new technique based on counting the number of strange particles on an event-by-event basis. The signal extraction has been performed by developing a procedure based on signal/background weights obtained from the data after the application of selective cuts on topological features of the weak decay and performing particle identification of the daughters. As a first step, a fit to the 1-dimensional invariant mass spectrum given by the sum of a function for the signal (double-sided Crystal Ball [9]) and one for the background (polynomial of order 1 for all particles, except for Ω^- for which a polynomial of order 2 was chosen) was performed in different p_T and multiplicity bins. In this way, for each invariant mass and p_T range, it is possible to define a probability that the candidate is signal as the ratio between the value of the signal function and the total one, or background as the ratio between the value of the background function and the total one. After this first step, all events are re-spell-checked to apply the procedure to all the N candidates per event. Event by event, each candidate is considered, associating the probability for it to be signal or background (from the previous step). Then, all the products of the different probabilities associated to each candidate are computed and grouped according to the total signal yield. Consequently, it is possible to obtain that all candidates are signal, all are background, or all the intermediate situations, having for each event with N candidates a full raw probability spectrum spanning from 0 to N . Summing the result obtained for each event, it is possible to measure the spectra for each multiplicity class. In the Λ and $\bar{\Lambda}$ analysis, a feed-down correction is performed removing from the total candidates yield the fraction of Λ ($\bar{\Lambda}$) coming from the decay of Ξ^- (Ξ^+) and Ξ^0 . The correction for the detector response was obtained by performing a uni-dimensional Bayesian unfolding procedure [10] using a MC simulation that includes realistic strange particle p_T distributions and detector conditions. The probability of producing n K_S^0 event is reported on the left in Fig. 1 for several multiplicity classes (including INEL > 0 ¹) showcasing that events with up to 7 K_S^0 can be observed. The same procedure has been applied to obtain the (multi-)strange particle (antiparticle) multiplicity distribution for Λ ($\bar{\Lambda}$), Ξ^- (Ξ^+) and Ω^- (Ω^+) measuring up to 5, 4 and 2 particles/event respectively and observing that, as expected at the LHC energies, the production of particles and antiparticles is the same from the highest to the lowest multiplicity class. It is worth noting that the measurement of the probability of producing n particles of a given species per event represents a unique opportunity to test the connection between charged and strange particle multiplicity production all the way to very extreme situations, e.g. spanning from events with 7 K_S^0 at low average charged-particle multiplicity – where $\langle dN/d\eta \rangle_{|\eta| < 0.5} \sim 3$, with potentially large fluctuations – to events with 0 K_S^0 high multiplicity – where $\langle dN/d\eta \rangle_{|\eta| < 0.5} \sim 20$.

3 Multiple strange hadron production yields and yield ratios

From the measurement of $P(n_S)$ and using Eq. 1, it is possible to calculate the average probability $\langle Y_{n\text{-part}} \rangle$ for the production of n particles per event. On the right side of Fig. 1, the average production yield of 1, 2, 3, 4 and 5 K_S^0 a function of the charged-particle multiplicity at midrapidity are reported respectively as black, red, blue, magenta and green markers. The increase with multiplicity is more than linear for the production of multiple strange hadrons

¹INEL > 0 is an event class in which at least one reconstructed silicon pixel detectors tracklet is produced in the pseudorapidity interval $|\eta| < 1$ with respect to the beam, corresponding to about 75% of the total inelastic cross-section.

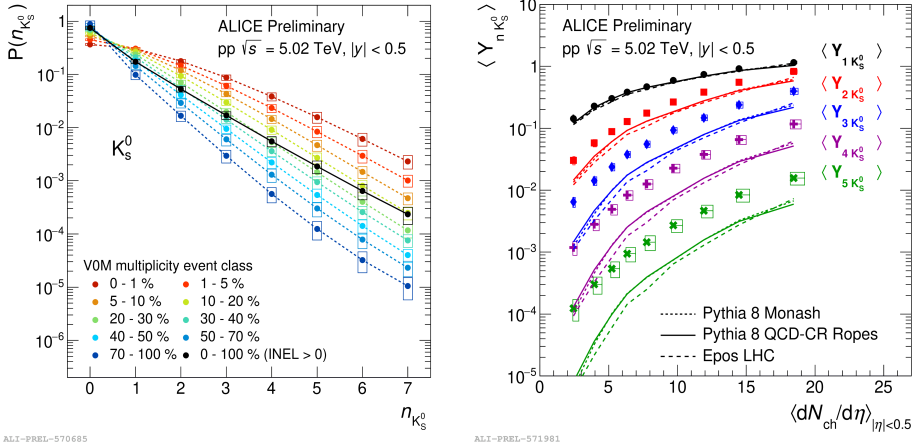


Figure 1: *Left*: K_S^0 particle multiplicity distribution for several multiplicity classes. The distribution obtained for INEL > 0 has been reported in black and lines are drawn to guide the eye. *Right*: Multiple strange hadron production yields for K_S^0 a function of the charged-particle multiplicity with model comparison. Model predictions obtained considering Pythia 8 Monash, Pythia 8 QCD-CR Ropes and Epos LHC are shown as dotted, continuous and dashed lines respectively.

and comparing the results with Pythia 8 Monash [11], Pythia 8 (QCD-CR) Ropes [12] and Epos LHC [13], one can see that the agreement worsens as the number of particles per event increases.

$$\langle Y_{n-part} \rangle = \sum_{i=0}^{\infty} \frac{i!}{n!(i-n)!} P_{i-part}. \quad (1)$$

Thanks to the measurement of multiple strange hadron production yields, one can explore several yield ratios to investigate the relative probability for a specific number of s -quarks to hadronize into different types of final hadrons. Firstly, yield ratios with a perfect strangeness balance ($\Delta S = 0$) as a function of the charged-particle multiplicity were considered, starting from the ratio between $n \Lambda$ and $n K_S^0$. This is reported in the left side of Fig. 2, where an increasing pattern is observed when looking at multiple strange particle production, indicating that when the strangeness remains constant, the likelihood to obtain a baryon and not a meson rises with multiplicity. However, to better understand whether the observed increase is related to the production of the baryon itself or to the difference in mass, type or number of light quarks involved, other multiple strange yield ratios with perfect strangeness balance were considered. Figure 2 (right) shows the yield ratios between m baryons and $n K_S^0$, where a decreasing trend is observed when a larger number of light quarks are involved in the denominator. This is consistent with the idea that at high multiplicity it is simpler to pair s with u and d quarks, which are present in large abundance. Contrarily, in low multiplicity situations the surplus of s -quarks (fixed at 2 or 4 for the reported ratios) increases the probability of forming a multi-strange baryon. Looking at the model comparison, both Pythia 8 QCD-CR Ropes and Epos LHC can reproduce qualitatively the increasing or decreasing trends with multiplicity, but Epos LHC tends to underestimate the magnitude. Looking more closely, all trends are rather well reproduced by Pythia 8 QCD-CR Ropes suggesting that the strange quark production rate remains a puzzle, but once s

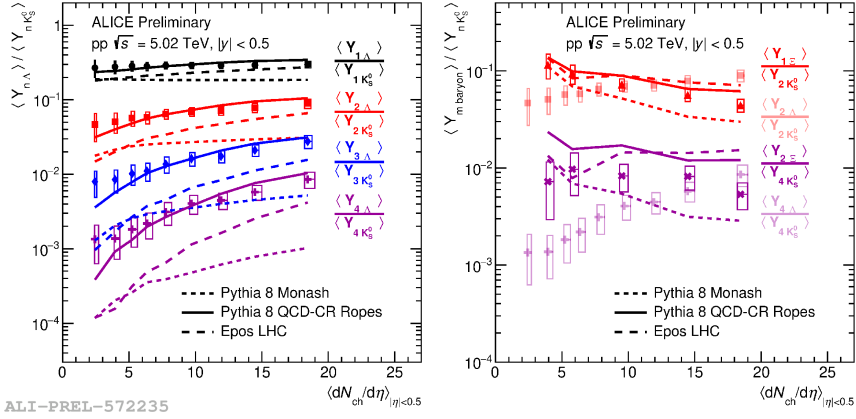


Figure 2: *Left.* Ratio $\langle Y_{n\Lambda} \rangle / \langle Y_{nK_S^0} \rangle$ as a function of the charged-particle multiplicity. *Right.* Ratio $\langle Y_{mbaryons} \rangle / \langle Y_{nK_S^0} \rangle$ as a function of the charged-particle multiplicity. In both plots there is a comparison to models: Pythia 8 Monash (dotted line), Pythia 8 QCD-CR Ropes (continuous line) and Epos LHC (dashed line).

is created the model of re-connection with light quarks catches the trends observed in the data.

In summary, the multiplicity distribution of (multi-)strange particles provides a valuable benchmark for testing production models in events with significant imbalances between charged and strange particle multiplicities. By analyzing $P(n_S)$ distributions, strange hadron yields and their ratios, balanced by strangeness, can be calculated as a function of charged-particle multiplicity. Notably, the ratio $\langle Y_{n\Lambda} \rangle / \langle Y_{nK_S^0} \rangle$ increases with multiplicity for $n > 1$, suggesting that factors beyond strangeness imbalance influence yield ratios. Conversely, ratios involving multi-strange baryons decline with multiplicity, implying that neither mass nor baryon number are directly tied to yield enhancement. These observed trends align with a basic quark coalescence model, and ongoing work with extreme strangeness differences (up to five) will allow to study the strangeness production at its extremes.

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