Strangeness production in ALICE

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Abstract. The ALICE experiment at the LHC has measured the production of strange and multi-strange hadrons both in Pb–Pb and pp collisions at unprecedented beam energies. Transverse momentum spectra at mid-rapidity for \( K^0_S \) mesons, \( \Lambda \), \( \Xi^- \) and \( \Omega^- \) baryons and their anti-particles in Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV are presented in different centrality intervals. Particles are reconstructed via their weak decay topologies into charged particles only over a wide momentum range, exploiting the tracking and particle identification capabilities of the ALICE detector. The corresponding production yields are compared with those observed in pp collisions and lower energy heavy-ion reactions. In particular, results on baryon-to-meson ratio, strangeness enhancements, elliptic flow and nuclear modification factors are discussed. The comparison of strange particle spectra in pp collisions at \( \sqrt{s} = 7 \) TeV with PYTHIA Perugia-2011 predictions is also presented.

1. Introduction
Measuring strange and multi-strange particle production in relativistic heavy-ion interactions is a unique tool to investigate the properties of the hot and dense matter created in the collision, as there is no net strangeness content in the initially colliding nuclei. In particular, an enhanced production of strange particles in A–A compared to pp interactions was one of the earliest proposed signature of a deconfined Quark-Gluon Plasma (QGP) [1, 2].

Measurements in pp collisions serve not only as baseline for those in heavy-ion reactions but also as a valuable handle on the different production mechanisms at play. The low material budget in the central rapidity region and the complementary particle identification techniques allow ALICE to measure strange particle spectra over a wide transverse momentum (\( p_T \)) range: from low to medium \( p_T \left( < 6 \text{ GeV}/c \right) \) where soft interactions are expected to be the main source of particle production, to the high \( p_T \) region where pQCD-calculable processes dominate.

Following a brief description of the ALICE detector and the analysis techniques used to reconstruct the strange particle decays (section 2), the strange hadron \( p_T \) spectra measured in pp collisions at \( \sqrt{s} = 7 \) TeV are presented in section 3 and compared with predictions from Monte Carlo generators. The fourth section deals with the main results in Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV: baryon to meson ratios as a function of \( p_T \) for different centrality intervals and compared to pp results, strangeness enhancements as a function of \( \langle N_{\text{part}} \rangle \) and their excitation function from SPS to LHC, strange particle elliptic flow and nuclear modification factors.

2. Strange decay reconstruction with the ALICE detector
The ALICE detector was designed to study heavy-ion physics at the LHC. It consists of a central barrel with a large solenoid providing a 0.5 T field for tracking and particle identification, plus a
dimuon spectrometer equipped with its own dipole magnet giving a 0.7 T field, and other forward detectors for triggering and centrality selection. Tracking and vertexing are performed using the Inner Tracking System (ITS), consisting of six layers of silicon detectors, and the Time Projection Chamber (TPC). The two innermost layers of the ITS and the VZERO detector (scintillation hodoscopes placed on either side of the interaction region) are used for triggering. The VZERO also provides the centrality determination in Pb–Pb collisions. A complete description of the ALICE sub-detectors can be found in [3].

Results presented in this contribution are based on a sample of about $130 \times 10^6$ pp collisions at $\sqrt{s} = 7$ TeV and about $30 \times 10^6$ Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, both collected in 2010. Strange hadrons are measured through the reconstruction of their weak decays into charged particles only. $K^0_S$, $\Lambda$ and $\bar{\Lambda}$ candidates are found by combining two charged tracks into V-shaped decays (V0 topology), while for multi-strange baryons, a selected V0 ($\Lambda$ candidate) is further combined with a third track (bachelor candidate). Candidates are required to satisfy topological and kinematic restrictions. In addition, each of the daughter tracks is checked for compatibility with the pion, kaon or proton hypotheses using their energy loss in the TPC. Further details on the candidate selection and signal extraction procedure can be found in [4, 5]. A correction factor, which includes both detector acceptance and reconstruction efficiency, is determined for each particle species as a function of $p_T$, using PYTHIA [6] and HIJING [7] for pp and Pb–Pb respectively. To reduce the required event statistics, enriched events with additional injected particles have been used for Pb–Pb and for multi-strange baryons in pp.

3. Results in pp collisions

The transverse momentum spectra for $K^0_S$, $\Lambda$ and $\bar{\Lambda}$ in pp collisions at $\sqrt{s} = 7$ TeV are shown in Fig. 1. The $\bar{\Lambda}/\Lambda$ ratio is compatible with unity over the measured $p_T$ range. The integrated production yields are obtained by fitting the spectra with the Tsallis function: the fraction in the unmeasured region is about 15% for $\Lambda$ and negligible for $K^0_S$.

![Figure 1](https://example.com/figure1.png)

Figure 1. Transverse momentum spectra for $\Lambda$, $\bar{\Lambda}$ and $K^0_S$ (symbols) in pp collisions at $\sqrt{s} = 7$ TeV, compared to PYTHIA Perugia-2011 predictions (lines).

The spectra have been compared with predictions from PYTHIA Perugia-2011 [8, 9], which provides the best description for the multi-strange baryons [5] and has been tuned to the
measured charged particle multiplicity in pp collisions at $\sqrt{s} = 7$ TeV. The agreement is rather good in the high $p_T$ region ($> 6$ GeV/$c$), while in the soft part PYTHIA underestimates the spectra by approximately 20% for $K_S^0$ and more than a factor of two for $\Lambda$.

A larger disagreement between PYTHIA Perugia-2011 and data can be seen in the left panel of Fig. 2 for the multi-strange baryon spectra. While being the best available tune, PYTHIA Perugia-2011 underestimates up to a factor of 2 and 5 the $\Xi$ and $\Omega$ spectra respectively, in the intermediate $p_T$ region. At high $p_T$ the discrepancy decreases for $\Xi^-$ and $\Xi^+$ when entering the fragmentation regime, while no conclusion can be draw for $\Omega^-$ and $\Omega^+$ with the available statistics. In the right panel of Fig. 2, the multi-strange baryon yields and $\langle p_T \rangle$ are shown for ALICE data at $\sqrt{s} = 0.9$ TeV and 7 TeV [4, 5] and STAR at $\sqrt{s} = 0.2$ TeV [10]; it can be seen that PYTHIA Perugia-2011 roughly reproduces the energy dependence.

4. Results in Pb–Pb collisions

A broad range of measurements has been obtained in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Strange and multi-strange hadron spectra have been measured in different centrality intervals according to the fraction of the total inelastic cross-section. The definition of the event centrality is based on the sum of the amplitudes measured in the VZERO detectors, as described in [11].

4.1. Strange baryon to meson ratio

An enhanced baryon to meson ratio in the intermediate $p_T$ region (around 2.5 GeV/$c$) was first observed in $\sqrt{s_{NN}} = 130$ and 200 GeV Au–Au collisions at RHIC [12]. The result of these measurements cannot be explained within the fragmentation model, where baryons are energetically more difficult to be produced than mesons. Alternative hadronization mechanisms have been invoked, such as quark coalescence: this could explain qualitatively the results in A–A but unlikely be at work in pp due to the low phase space density in the final state.

Results from the ALICE measurements are illustrated in Fig. 3. The left panel shows the $\Lambda/K_S^0$ ratio as a function of $p_T$ for several centrality classes in Pb–Pb collisions at
\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) and for minimum bias pp collisions at \( \sqrt{s} = 0.9 \) and 7 TeV. While in pp the ratio stays about the same at different energies (also compared to RHIC data), a strong centrality dependence is observed in Pb–Pb: the value increases with centrality up to its maximum of about 1.5 at \( p_T \sim 3 \text{ GeV}/c \) for the most central events. The behaviour appears to be specific to A–A collisions and is reproduced by the EPOS model [13]. The maximum value of the \( \Lambda/K_S^0 \) ratio as a function of \( \langle N_{\text{part}} \rangle \) is shown in the right panel of Fig. 3 to increase with centrality and with the centre-of-mass energy of the colliding system.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Left: Centrality dependence of \( \Lambda/K_S^0 \) as a function of \( p_T \) in Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), compared with minimum bias pp collisions at \( \sqrt{s} = 0.9 \) and 7 TeV. Right: Maximum value of the \( \Lambda/K_S^0 \) ratio as a function of the average number of participating nucleons \( \langle N_{\text{part}} \rangle \), for different collision systems and energies.

### 4.2. Strangeness enhancements

The enhancement of strange and multi-strange particle production in heavy-ion collisions compared to pp was one of the earliest proposed signatures for the QGP [1, 2]. In the original studies, it was argued that in a deconfined state, the system of free quarks and gluons would quickly find chemical equilibrium describable in terms of a grand canonical ensemble, implying a considerable increase in strange quark phase space occupancy compared to the observed strangeness production levels in pp interactions. Indeed, both at SPS [15, 16] and RHIC [17] the large production yields observed in A–A, especially for multi-strange baryons, could hardly be understood as coming from a hadronic phase and would require instead a faster equilibration.

The strangeness enhancements are defined as ratios of the strange particle yields measured in Pb–Pb collisions, normalized to the mean number of participant nucleons \( \langle N_{\text{part}} \rangle \), to the corresponding quantities in pp interactions at the same energy. The ALICE results for \( \Lambda (|S|=1) \), \( \Xi^- (|S|=2) \) and \( \Omega^- + \Omega^+ (|S|=3) \) are shown in the left panel of Fig. 4 as a function of \( \langle N_{\text{part}} \rangle \). The pp reference values were obtained by interpolating ALICE data at two energies \( \langle \sqrt{s} = 0.9 \) and 7 TeV [5, 14] for \( \Lambda \) and \( \Xi^- \), and STAR data at 200 GeV [10] and ALICE data at 7 TeV for \( \Omega^- + \Omega^+ \). The enhancements are larger than unity for all the particles and increase with \( \langle N_{\text{part}} \rangle \). They also increase with the strangeness content of the particle, showing the hierarchy already observed at lower energies and consistent with the picture of enhanced \( s\bar{s} \) pair production in a hot and dense partonic medium. In the right panel of Fig. 4 the ALICE results are compared with lower energy measurements performed at SPS and RHIC: the enhancements are seen to decrease with increasing centre-of-mass energy, continuing the same trend first established at the SPS and then confirmed going from SPS to RHIC energies. However, since the hyperon to pion ratios have been shown to be constant with centrality and the charged particle multiplicity does not
scale with \( \langle N_{\text{part}} \rangle \), further studies are currently ongoing to quantify the specific enhancements of strange particles out of the general relative increase of multiplicity at mid-rapidity.

![Graph showing strangeness enhancements](image)

**Figure 4.** Left: Strangeness enhancements for \( \Lambda \), \( \Xi^- \) and \( \Omega^- + \bar{\Omega}^+ \) as a function of the mean number of participants \( \langle N_{\text{part}} \rangle \). Boxes on the dashed line at unity indicate statistical and systematic uncertainties on the pp reference. Right: Comparison with lower energy measurements at SPS and RHIC (hollow symbols).

### 4.3. Strange particle elliptic flow

The elliptic flow \( (v_2) \) coefficient is connected to one of the most informative observables for understanding the dynamics of the heavy-ion collisions and the properties of the created hot and dense matter [18]. Since collectivity is cumulative throughout the evolution of the collision, both partonic and hadronic stages should contribute to the observed transverse flow. To estimate the relative contributions to the elliptic flow from early deconfined partonic interactions and later hadronic rescatterings in the system evolution, measurements of the \( v_2 \) for strange and particularly multi-strange particles are crucial due to their small hadronic cross-section.

Fig. 5 shows the \( K^0_S \), \( \Lambda \) and \( \phi \) \( v_2 \) as a function of \( p_T \) for 10-20\% (left panel) and 40-50\% (right panel) centrality Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), compared with charged pions, kaons and protons. At low \( p_T \) (< 2.5 GeV/c), a clear mass ordering of the \( v_2 \) is observed, i.e. lower \( v_2 \) for heavier hadrons than that for lighter ones. The relative mass-splitting of \( v_2 \) also increases with centrality: this can be explained by a stronger radial flow effect for more central collisions. In Fig. 6 the measurements for multi-strange baryons confirm the mass ordering at low \( p_T \), which is also reproduced by calculations from the VISH2+1 viscous hydrodynamic model [19].

### 4.4. Strange particle nuclear modification factors

One of the most striking differences between the A–A and pp collisions first observed at RHIC was the suppression of the hadron production at high \( p_T \) in central Au–Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) when compared to expectations from a geometrical superposition of nucleon-nucleon interactions [20, 21]. The effect, confirmed by the charged-particle nuclear modification
Figure 5. $p_T$ differential $v_2$ for $K_S^0$, $\Lambda$ and $\phi$ compared with charged pions, kaons and protons, measured for 10-20% (left) and 40-50% (right) centrality Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Figure 6. $p_T$ differential $v_2$ for identified particles in 20-40% centrality Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, compared to VISH2+1 viscous hydrodynamic model calculations.
probably related to the baryon enhancement at intermediate transverse momenta and then to alternative hadronization mechanisms. Higher $R_{AA}$ values and even reduced differences are seen for more peripheral events, as shown in the right panel of Fig. 7.

![Graph showing nuclear modification factors for K\(_0^s\), Λ and charged particles as a function of $p_T$ in 0-5\% (left) and 60-80\% (right) centrality Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.](image)

**Figure 7.** Nuclear modification factors for K\(_0^s\), Λ and charged particles as a function of $p_T$ in 0-5\% (left) and 60-80\% (right) centrality Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

### 5. Conclusions

ALICE measurements confirm that particles containing $s$-quarks are a valuable tool for the investigation of the strongly interacting matter created in Pb–Pb collisions at the LHC energy. Results on baryon anomaly, strangeness enhancements, elliptic flow and high $p_T$ suppression have been presented and discussed. In addition, strange and multi-strange hadron spectra measured in pp collisions have been shown to play a relevant role not only as a baseline for the Pb–Pb measurements but also as constrain to the Monte Carlo generator models.

### References

[1] J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982).
[2] P. Koch, B. Müller and J. Rafelski, Phys. Rep. 142, 167 (1986).
[3] K. Aamodt et al., JINST 3, S08002 (2008).
[4] K. Aamodt et al., Eur. Phys. J. C 71, 1594 (2011).
[5] B. Abelev et al., Phys. Lett. B 712, 309 (2012).
[6] T. Sjostrand, S. Mrenna and P.Z. Skands, JHEP 05, 026 (2006).
[7] X.-N. Wang and M. Gyulassy, Phys. Rev. D 44, 3501 (1991).
[8] P.Z. Skands, Phys. Rev. D 82, 074018 (2010).
[9] R. Skands, arXiv:1010.3558v1, (2010).
[10] B. I. Abelev et al., Phys. Rev. C 75, 064901 (2007).
[11] K. Aamodt et al., Phys. Rev. Lett. 106, 032301 (2011).
[12] M.A.C. Lamont et al., Eur. Phys. J. C 49, 35 (2007).
[13] K. Werner et al., arXiv:1204.1394v1, (2012).
[14] K. Aamodt et al., Eur. Phys. J. C 71, 1594 (2011).
[15] F. Antinori et al., J. Phys. G 32, 427 (2006).
[16] F. Antinori et al., J. Phys. G 37, 045105 (2010).
[17] B. I. Abelev et al., Phys. Rev. C 77, 044908 (2008).
[18] R. Snellings, New J. Phys. 13, 055008 (2011).
[19] U.W. Heinz, C. Shen and H. Song, AIP Conf. Proc. 1441, 766 (2012).
[20] K. Adcox et al., Phys. Rev. Lett. 88, 022301 (2002).
[21] C. Adler et al., Phys. Rev. Lett. 89, 202301 (2002).
[22] K. Aamodt et al., Phys. Lett. B 696, 30 (2011).