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STRANGE AND MULTI-STRANGE PARTICLE PRODUCTION AT THE LHC ENERGIES WITH ALICE*

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Strange quark and particle production is studied at the LHC with unprecedented high beam energies in both heavy-ion and proton–proton collisions: on the one hand, strangeness is used for investigating chemical equilibration and bulk properties; on the other hand, strange particles contribute to probe different kinematical domains, from the one where collective phenomena are at play up to the region dominated by pQCD-calculable processes. We highlight the suitability of the ALICE experiment for this topic, presenting our latest measurements and comparing them to models.

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1. Introduction

Strange particles have been commonly used as probes of the quark-gluon plasma (QGP) by many experiments at the AGS, SPS and RHIC [1]. Several measurements of strangeness were expected with eagerness at the Large Hadron Collider (LHC) [2]. The ALICE experiment recorded high-statistics data in 2010 for both proton–proton and heavy-ion collisions [3] in order to tackle strange and multi-strange hadron production in detail.

Benefiting from the lowest material budget in the central rapidity region at the LHC, as well as from complementary particle identification techniques [4], ALICE can measure most of strange mesons and baryons, weakly decaying or resonances, over a large transverse momentum (p_{t}) range at the highest colliding energies. Instead of discussing extensively the wealth of results obtained less than a year after the first A–A collisions at the LHC,

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this contribution focuses on chosen highlights confirming the behaviours seen at lower energies and those for which heavy-ion and *pp* measurements are strikingly different.

In the next (second) section, we present strange hadron p_{t} spectra measured in *pp* collisions and draw comparisons with spectra from Monte Carlo generators. Although the description of some aspects of elementary hadronic collisions constitutes a challenge, especially for multi-strange baryons, these measurements set the baseline for Pb–Pb collisions. The third section is dedicated to strange baryon/meson ratio as a function of p_{t}, which is not only important for testing the validity of coalescence models for A–A collisions, but also helps to define the kinematical domain where pQCD-calculable processes dominate. The excitation function of the multi-strange baryon enhancement from SPS to LHC energies is discussed in the fourth section. In the fifth section, the suppression of strangeness spectra in central Pb–Pb collisions with respect to that in *pp* is put in context of the open-charm measurements.

2. Strange and multi-strange p_{t} spectra in *pp* collisions at 7 TeV

The design of the ALICE experiment was optimized for particle identification (PID), especially in the central barrel [2]. During the first two years of data taking, the complementarity of the detectors was exploited to obtain high precision p_{t} spectra in the soft physics regime for both *pp* and Pb–Pb collisions. In the case of strange hadrons, the identification methods included dE/dx loss in the Inner Tracking System and the Time Projection Chamber, Time-of-Flight measurements, as well as weak decay topology techniques and invariant mass analyses. Several of these methods were combined so that the production of strange hadrons including hyperons and resonances could be measured and compared to those from Monte Carlo generators [5, 6, 7].

Figure 1 shows the p_{t} spectra for charged kaons (left panel) and multi-strange baryons (right panel: Ξ^-, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$) normalized to inelastic *pp* events at $\sqrt{s} = 7\,\mathrm{TeV}$. Specific details of the analyses are reported in [5,6], where it is indicated that the Lévy–Tsallis functional form describes the shape of the p_{t} distributions fairly well, as illustrated for hyperons in the right panel. Consequently, fits with this function are used to extrapolate the measurements down to $p_{\mathrm{t}} = 0\,\mathrm{GeV}/c$ and to extract the global integrated yields for each species, as was done at $\sqrt{s} = 0.9\,\mathrm{TeV}$ [8, 9].

Adjusting Monte Carlo generators in *pp* (keeping in mind that *pp* interactions are useful as a reference to heavy-ion collisions) is a difficult task. The dedicated efforts of the authors must be acknowledged, especially for strangeness production [10]. In the years preceding the LHC start-up, these

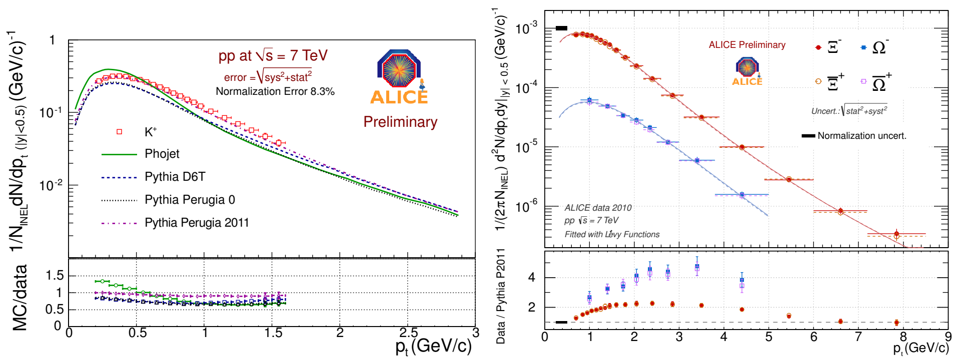

Fig. 1. Transverse momentum spectra for charged (positive) kaons (left panel) [5] and multi-strange baryons (Ξ^-, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$, right panel) [6] measured in the central rapidity region ($|y| < 0.5$) for pp inelastic events at $\sqrt{s} = 7$ TeV. Comparisons with PYTHIA 6.4 spectra are also shown.

models included phenomenological approaches such as multi-parton interactions or colour reconnections in the case of PYTHIA 6.4 [11]. These led to a general improvement for mesons, and PYTHIA Perugia 2011 gives a good description of kaons production in pp at $\sqrt{s} = 7$ TeV in particular [5]. It matches the spectra better than other PYTHIA tunes, although it is not perfect for multi-strange baryons: spectra are underestimated up to a factor of 2 and 5 for Ξ and Ω, respectively, in the intermediate $p_{\rm t}$ region. At high $p_{\rm t}$, the discrepancy seems to decrease for Ξ^- and $\overline{\Xi}^+$ when entering the fragmentation regime. More statistics is needed before trying to draw a similar conclusion for Ω^- and $\overline{\Omega}^+$. A further constraint is added when the spectra of baryonic resonances are compared to models [7].

3. Strange baryon over meson ratio as a function of $p_{\rm t}$

Many of the aforementioned discrepancies between PYTHIA and the $p_{\rm t}$ spectra measured for pp collisions at the LHC are pertinent to baryons. From the point of view of Lund's fragmentation the baryons are energetically more difficult to produce than mesons since baryon creation involves the formation of di-quark pairs instead of quark pairs. This is partly the reason why the observation at RHIC of a baryon/meson ratio close to unity in the intermediate $p_{\rm t}$ region (around $p_{\rm t} = 2.5$ GeV/c) for nucleus–nucleus collisions was unexpected [12]. This measurement suggested the presence of other hadronization mechanisms, including possible interplays between soft and hard processes. Quark coalescence, which could explain qualitatively such a behaviour in A–A, was invoked; in pp collisions, this hadronization scenario is unlikely due to the low phase space density in the final state. At the LHC, the follow-up was two-fold: *(i)* check if the unprecedented centre-of-mass energy would be insufficient for producing the same effect in *pp* collisions with the increased phase-space density; *(ii)* extract the centrality dependence of the ratio in heavy-ion collisions and then compare the LHC values to the RHIC ones. Preliminary measurements were presented in [13], here we only report the conclusions of the study.

The comparison of baryon and meson productions is illustrated by the $\Lambda/K^0_{\rm S}$ ratio in Fig. 2. The measurements are based on a topological identification method which offers the advantage of covering the relevant $p_{\rm t}$ range ($1 < p_{\rm t} < 6\,{\rm GeV}/c$). Feed-down corrections are performed so that the ALICE preliminary values and STAR results are directly comparable. For the *pp* colliding system, no difference can be seen from $\sqrt{s} = 0.2\,{\rm TeV}$ (by STAR), to 0.9 and 7 TeV (by ALICE): the maximum remains below unity independently of centre-of-mass energy. While the most peripheral Pb–Pb collisions exhibit a ratio similar to *pp*, the value increases with centrality up to 1.5 at $p_{\rm t} \simeq 3\,{\rm GeV}/c$ for the 0–5% top central collisions. The behaviour appears to be specific to A–A with both a centrality and an energy dependence, as shown in the right panel of Fig. 2.

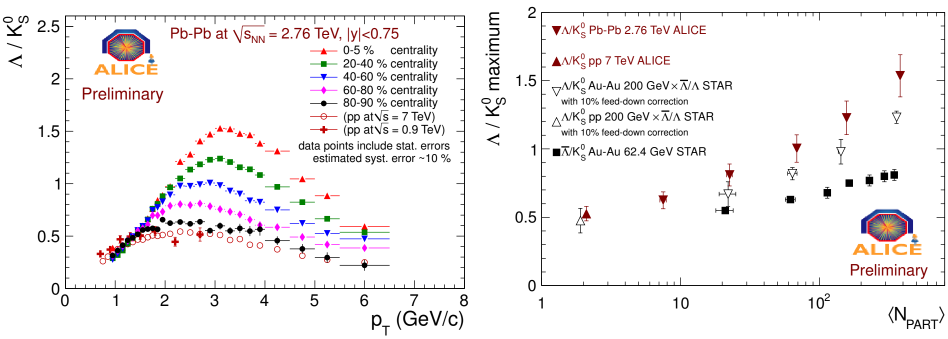

Fig. 2. Centrality dependence of the baryon over meson ratio as a function of $p_{\rm t}$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76\,{\rm TeV}$, illustrated with $\Lambda/K^0_{\rm S}$ and compared with minimum bias *pp* collisions at $\sqrt{s} = 0.9$ and 7 TeV (left panel). Maximum value of the $\Lambda/K^0_{\rm S}$ ratio as a function of the mean number of participating nucleons ($\langle N_{\rm part}\rangle$) for different colliding systems and energies (right panel). Figures are taken from [13]. Feed-down corrections are applied. Because the net-baryon free region is not yet achieved in central rapidities of RHIC collisions, the $\overline{\Lambda}/K^0_{\rm S}$ is used for comparison (the $\Lambda/K^0_{\rm S}$ is scaled with $\overline{\Lambda}/\Lambda$ when appropriate).

4. Excitation function of multi-strange baryon enhancement from SPS to LHC energies

An enhanced production of strange hadrons was suggested 30 years ago as an indication that the state of matter produced in ultra-relativistic nucleus–nucleus collisions is different from a hadron gas created at the same energy in nucleon–nucleon collisions [14]. Indeed, the large yields found in heavy-ion collisions at the SPS [15, 16] and RHIC [17], especially for multi-strange baryons, could hardly be understood as coming from a hadronic phase: instead they would require a fast equilibration and a large correlation volume [18]. The observed effect matches one of the earliest predictions made for the QGP formation, as it was reiterated at this conference (dedicated discussions can be found in [19] and references therein).

Figure 3 summarizes the enhancement factors obtained for different hyperon species as a function of the mean number of nucleons participating in the collision for WA97/NA57 at the SPS [15, 16], STAR at RHIC [17] and ALICE at the LHC [20]. The corresponding colliding energies are $\sqrt{s_{NN}} = 17.2\,\mathrm{GeV}$, $200\,\mathrm{GeV}$ and 2.76 TeV, respectively. The measurements were performed using topological identification techniques, common to all experiments and essentially the same as was described in Sect. 2 for pp events. It must be noted that NA57 results are normalized to pBe yields. The associated enhancements are calculated for pPb and different centrality classes for Pb–Pb, translated to a mean number of participating nucleons. No enhancement is seen for pPb contrarily to Pb–Pb. The STAR and ALICE yields for Au–Au and Pb–Pb, respectively, were also extracted as a function of centrality and translated to a mean number of participants, then normalized to pp collisions (in the case of ALICE, the pp yields are interpolated between $\sqrt{s} = 0.9\,\mathrm{TeV}$ and $7\,\mathrm{TeV}$). Details on the signal extraction and efficiency corrections at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ with the ALICE experiment can be found in [20].

This enhancement increases with centrality, and gets systematically larger with the strangeness content of the hyperon: the maximum value is ~ 20 for $\Omega^- + \overline{\Omega}^+$ in the most central collisions recorded by NA57. Focusing on the excitation function from $\sqrt{s_{NN}} = 17.2\,\mathrm{GeV}$ to $2.76\,\mathrm{TeV}$, the relative enhancements seem to decrease with increasing energy, as has been observed at the SPS and then between the SPS and RHIC, even with the uncertainties on the normalization (depicted as rectangles at the bottom left of Fig. 3). It must be stressed that the absolute production of hyperons in heavy-ion collisions increases with energy from the SPS to the LHC. However, the increase of the yields for the systems (pBe or pp) used as reference, appears to be slightly faster, suggesting that the normalized heavy-ion yields could saturate.

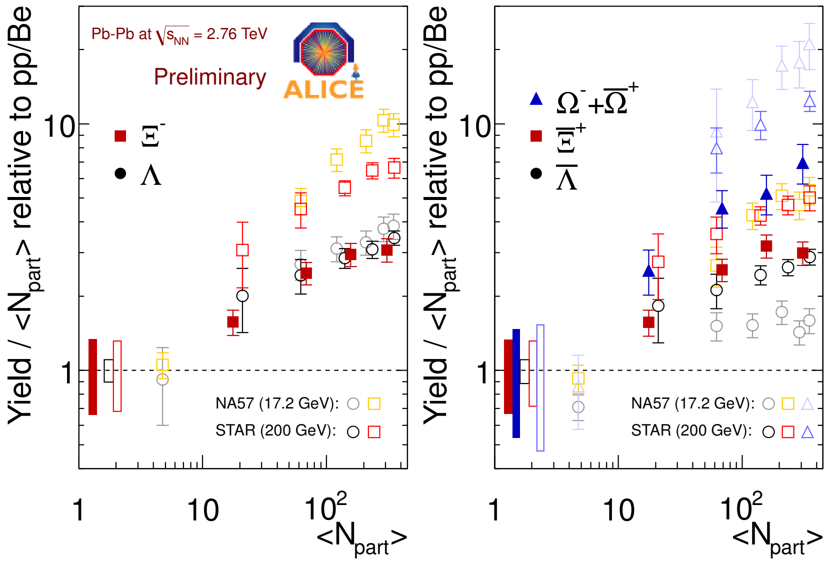

Fig. 3. Enhancement for hyperon Pb–Pb yields measured at central rapidity ($|y| < 0.5$) with ALICE, normalized to $\langle N_{\rm part}\rangle$ and using minimum bias *pp* values as reference. The left (right) panel shows baryons which can (not) include valence quarks from the incoming nucleons. The ALICE results are compared to SPS and RHIC data [20]. The quadratic sum of statistical and systematics uncertainties are represented with vertical errors on data points. Uncertainties on the *pp* references (or *p*Be for the SPS data) are noted with rectangles on the left hand of the dotted line located at unity.

5. Strangeness suppression at high $p_{\rm t}$

A spectacular difference between nucleus–nucleus and *pp* collisions was observed for the first time at RHIC: the hadron production at large $p_{\rm t}$ for central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV is a factor ~ 4 suppressed when compared to expectations from a geometrical superposition of nucleon–nucleon collisions [21, 22]. It was promptly interpreted as resulting from the energy loss suffered by partons produced in hard parton-scattering when traversing the hot and dense matter created in ultra-relativistic heavy-ion collisions. The RHIC observations were confirmed by the first Pb–Pb collisions at the LHC with single-particle nuclear modification factor R_{AA} as a function of $p_{\rm t}$ [23].

The aim now is to characterize further the medium properties using the high statistics available at the LHC and to check whether there is any obvious dependence on the kind of parton probing the QCD medium. The suppression is studied as a function of the event centrality in order to extract more information about the density of the medium; it is observed that *(i)* the amount of suppression increases with increasing centrality; *(ii)* for all centralities, the R_{AA} exhibits a minimum at $p_{\rm t} = 6$–$7\,{\rm GeV}/c$, then *(iii)* it increases slowly up to $\sim 30\,{\rm GeV}/c$ [24]. A larger energy loss is also found when comparing the ALICE results to the ones at RHIC: for the most central (0–5%) collisions, the R_{AA} measured at the LHC is smaller than that at RHIC, confirming the expectation that the density of the medium created in the collision increases with the centre-of-mass energy.

In radiative energy loss models, gluons are expected to loose more energy than quarks when traversing the hot QCD matter. With the fraction of hadrons from gluon jets increasing with the colliding energy, it is also possible that the more pronounced suppression seen at the LHC with respect to RHIC originates from a stronger contribution of gluons.

Figure 4 also addresses the parton dependence of energy loss from the flavour point of view [25]. On the left panel, it can be seen that the suppressions of $K^0_{\rm S}$ and Λ are similar to that of unidentified charged hadrons for $p_{\rm t} > 6\,{\rm GeV}/c$ in the most central (0–5%) Pb–Pb collisions. This is also the case between $K^0_{\rm S}$ and charged hadrons at lower transverse momenta, however, the R_{AA} of Λ is significantly higher and should be related to alternative hadronization mechanisms as discussed in Sec. 3. A stronger constraint is

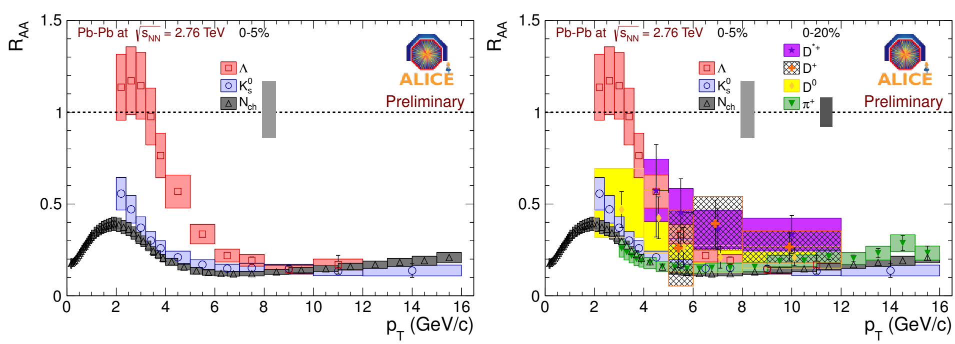

Fig. 4. The nuclear modification factors R_{AA} as a function of $p_{\rm t}$ for $K^0_{\rm S}$ (circles) and Λ (squares) in central (0–5%) Pb–Pb collisions (left panel) together with $N_{\rm ch}$, the unidentified charged hadrons (triangles) at $\sqrt{s_{NN}} = 2.76\,{\rm TeV}$. Vertical errors are statistical whereas the boxes correspond to systematics. The uncertainty due to the calculation of the mean number of binary collisions ($\langle N_{\rm bin}\rangle$) is given by the grey boxes on the dotted line located at unity [25]. The nuclear modification factors for charmed mesons are superimposed on the right panel for comparison together with charged pions (using a larger 0–20% centrality bin was necessary because of statistics).

added to energy loss models when complementing the picture (right panel of Fig. 4) with charmed mesons. Within uncertainties, and taking into account that a wider centrality had to be used because of statistics, no strong difference between light and heavy flavour is observed [26].

6. Summary

We present the results of several studies illustrating how strangeness production can help the investigation of the properties of the strongly interacting matter created at the LHC in heavy-ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Measurements are based on the high-statistics data recorded in 2010 with ALICE. After setting the *pp* baseline with strange hadron p_{t} spectra, the Λ/K^0_{S} ratio as a function of p_{t} is discussed in the context of similar measurements at lower $\sqrt{s_{NN}}$. The A–A ratio seems to be energy-dependent contrarily to the one in *pp*. Then the excitation function of hyperons enhancements from SPS to LHC energies is described: the relative enhancements seem to decrease with increasing energy, confirming the trend observed at the SPS and then between the SPS and RHIC. Finally, we report that no strong difference between light and heavy flavour is observed within uncertainties in central Pb–Pb collisions for the nuclear modification factor.

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