Strangeness Production in pp, p-Pb and Pb-Pb Collisions at the LHC Energies Measured with ALICE

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The main goal of heavy-ion physics is to study the properties of the deconfined state of matter known as the Quark-Gluon Plasma (QGP) created in ultra-relativistic heavy-ion collisions. A systematic study of strangeness production is of fundamental importance for determining the thermal properties of the system created in such collisions. In the central barrel of the ALICE detector, K_s^0 , Λ , Ξ and Ω can be identified reconstructing their weak decay topology. It will be shown that the relative production (to pions) of strange particles follows a continuous increasing trend from low multiplicity pp to peripheral Pb-Pb collisions, above which a saturation is visible for central Pb-Pb collisions. This increasing trend is similar for pp and p-Pb collisions. Moreover, comparison of strange particle production in pp collisions at two different energies ($\sqrt{s} = 7$ TeV and 13 TeV) will be used to demonstrate that the observed trend in multiplicity is also energy independent.

Keywords: Hot Matter; QGP; Strangeness.

1. Introduction

Since the experimental observation^{1,2} of the predicted³ enhanced production of particles containing strange quark(s) in nucleus-nucleus with respect to (properly scaled) proton-proton collisions, the study of strangeness production has a central role in heavy-ion physics.

Measurements performed at the LHC energies in the last years suggest the presence of collective phenomena, typical of heavy-ion collisions, also in small systems such as pp and proton-lead (p-Pb) collisions. Examples are the observation of long-range angular correlations in pp⁴ and p-Pb collisions⁵.

In this paper the results on the strangeness production measurement will be shown and discussed in the context of collective phenomena and thermal production.

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Fig. 1. Λ/K_S^0 as a function of p_T in an high and a low-multiplicity class in pp (left), p-Pb (center) and Pb-Pb (right) collisions. The mean number of charged tracks ($\langle dN_{ch}/d\eta \rangle$) in each multiplicity/centrality class is reported for comparison between the three systems. Open boxes are total systematic uncertainties and shaded boxes represent the component which is uncorrelated for different multiplicity classes.

The Λ/K_S^0 ratio as a function of p_T and the multiplicity-differential strangeness production in the three colliding systems provided by the LHC and studied by ALICE will be presented.

2. Strange particle identification with the ALICE detector

The ALICE detector was designed to study heavy-ion physics at the LHC. At mid-rapidity, tracking and vertexing are performed using the Inner Tracking System (ITS), consisting of six layers of silicon detectors employing three different technologies, and the Time Projection Chamber (TPC), a large cylindrical drift detector. The two innermost layers of the ITS and the V0, a detector consisting of scintillation hodoscopes covering the forward pseudo-rapidity region on either side of the interaction point, are used for triggering. The V0 is also used to estimate the event centrality in Pb-Pb collisions as well as the event multiplicity in pp and p-Pb collisions. The ionisation energy deposited in the detector is proportional to the charged particle multiplicity in its acceptance. The event activity is estimated by measuring the sum of the signals in the two hodoscopes (V0M) for Pb-Pb and pp and the signal of the hodoscope placed on the Pb-going side for p-Pb collisions. A complete description of the ALICE sub-detectors can be found in ⁶.

The single-strange (K_S^0 and Λ) and multi-strange (Ξ and Ω) particles are reconstructed via their characteristic weak decay topologies with two or three charged hadrons in the final state, respectively. Tracks reconstructed by the TPC and the ITS are combined to select candidates satisfying a set of geometrical criteria. Particle identification is performed by a selection on the specific energy loss in the TPC for the daughter tracks. Particle yields as a function of p_T are determined, in various

multiplicity/centrality intervals, using an invariant mass analysis. Acceptance and efficiency corrections are calculated using dedicated Monte Carlo (MC) simulations. More details can be found in ^{7,8}.

During LHC Run-1 and the ongoing Run-2 periods, the ALICE Collaboration measured events in several colliding systems and at different colliding energies, namely: pp at $\sqrt{s} = 0.9, 2.76, 5.02, 7, 8.16$ and 13 TeV; p-Pb at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV; Pb-Pb at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV; Xe-Xe at $\sqrt{s_{NN}} = 5.44$ TeV.

3. Results

Ratios of particle yields, such as p/π or Λ/K_S^0 , are useful observables to investigate the role of production mechanisms in defining the spectral shape, at least in the intermediate- p_T region. It has been shown⁷ that predictions by theoretical models implementing hydrodynamics are in good agreement with data taken in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at low p_T , suggesting that the so-called "baryon anomaly" (an enhanced production of baryons at intermediate p_T with respect to mesons) observed in central Pb-Pb collisions may be solely a consequence of a strong radial flow. It has to be specified that models of parton recombination can also describe the data if radial flow effects are taken into account. The Λ/K_S^0 ratio has been measured in pp collisions at $\sqrt{s} = 7$ TeV (divided in ten V0M event multiplicity classes from highest (I) to lowest (X) multiplicity) and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and are shown in figure 1, compared to the measurement in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. In both systems the ratio behaves similarly to the Pb-Pb case with a depletion at low p_T and an enhancement at intermediate p_T going from low to high multiplicity. The magnitude of the effect is different across

Fig. 2. p_T -integrated K_S^0 , Λ , Ξ and Ω ratios to π for pp, p-Pb and Pb-Pb collisions as a function of event multiplicity density. The MC predictions of PYTHIA8 (solid line), DIPSY (dashed line) and EPOS LHC (dotted line) are shown. [Nature Physics 13 (2017) 535-539]

Fig. 3. Λ/K_S^0 and p/π ratios (left) and Ξ^*/Ξ ratio (right) as a function of average charged particle multiplicity in pp and p-Pb collisions. [Nature Physics 13 (2017) 535-539, Eur. Phys. J. C 77 (2017) 389]

the systems, but a quite smooth behavior is found if this ratio is studied in a given p_T bin as a function of the mean number of charged tracks at midrapidity. These similarities suggest presence of collectivity in small systems.

The strangeness enhancement is known as one of the proposed signatures for the QGP formation in relativistic heavy-ion collisions. Rafelski and Müller's expectation, first proposed in 1982³, is that QGP formation should lead to a higher abundance of strangeness per participating nucleon than a simple hadron gas. Even though its interpretation is still discussed and nowadays generally not considered as a signature of QGP formation, this phenomenon has been actually observed at SPS¹, RHIC² and LHC⁸. It has been found to increase with centrality and with the strangeness content of the particle, and decrease as the centre-of-mass energy increases. Statistical hadronization models (SHM) based on a grand-canonical approach have been demonstrated to be able to predict particle yield ratios in heavy-ion collisions over a large energy range⁹. In this description, the energy dependence of strangeness enhancement has been understood as the consequence of a suppression of strangeness production due to the reduced phase-space volume in reference pp collisions (canonical suppression)¹⁰.

A modern way to look at this phenomenon is to show the ratio to pions of the yield as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta| < 0.5}$. In figure 2, this ratio is provided for K_S^0 , Λ , Ξ and Ω for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV and pp at $\sqrt{s} = 7$ TeV collisions. In Pb-Pb the ratios follow a rather constant behaviour. In pp and p-Pb collisions, the ratios Ξ/π and Ω/π increase from low to high multiplicity events to values consistent with those measured in peripheral Pb-Pb collisions. Comparison of hyperon-to-pion ratios as a function of pion multiplicity to the trends predicted by SHM indicates that the behaviour is qualitatively consistent with the lifting of canonical suppression with increasing multiplicity¹¹.

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Fig. 4. Ratios of baryons (p, Λ , Ξ , Ω) to pions, normalised to the corresponding ratio in the 0-100% multiplicity class as a function of the average charged particle multiplicity in pp and p-Pb collisions. [Nature Physics 13 (2017) 535-539]

Fig. 5. p_T -integrated K_s^0 , Λ , Ξ and Ω yield for pp collisions at $\sqrt{s} = 7$ TeV (blue) and 13 TeV (red) as a function of event multiplicity density. The MC predictions of PYTHIA6 (dashed line), PYTHIA8 (dotted line) and EPOS LHC (solid line) are shown.

The strong increase of yield ratio to pion observed for Ξ and Ω in pp and p-Pb collisions might be due to mass, baryon/meson nature or strangeness content of the particle. In figure 3 (left panel) the flat trend as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ of the p_T -integrated baryon-to-meson ratio having equal number of strange quark (Λ/K_s^0)

or not having any strange quark (p/π) rules out the hypothesis of the baryon/meson nature of the particle. A similar behaviour with multiplicity is observed in p-Pb collisions for the resonant state of Ξ in the Ξ^{*0}/Ξ ratio, dismissing a role of the mass (figure 3, right panel). Figure 4 shows the hadron-to-pion ratios in pp and p-Pb collisions as a function of multiplicity normalised to the multiplicity-integrated ratio in pp, corresponding to the INEL>0 event class. This plot clarifies that the relative increase of strange and multi-strange baryon yield follows a clear hierarchy with the strangeness content of the particle. As shown in figure 2, the MC event generators based on QCD-inspired models DIPSY and EPOS LHC qualitatively describe the relative increase, but fail to predict quantitatively its magnitude, while PYTHIA8 does not show any strangeness enhancement.

Data taken during the ongoing LHC Run-2 with pp collisions at $\sqrt{s} = 13$ TeV can help to disentangle multiplicity and energy dependence of particle production, having in mind that $\langle dN_{ch}/d\eta \rangle$ increases by 20% from 7 to 13 TeV. In figure 5 the p_T -integrated yield as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ for K_s^0 , Λ , Ξ and Ω are shown. The two distributions lie on the same line, implying that the event activity drives the particle production irrespective of the collision energy. In the same figure MC predictions are superimposed to data: EPOS LHC reproduces only qualitatively the trend with multiplicity while PYTHIA fails to describe the data.

4. Conclusion

It has been shown that features of strange hadron production typically observed in Pb-Pb collisions are present also in pp and p-Pb collisions. While these features are usually interpreted as due to collectivity in Pb-Pb collisions, their origin in smaller systems is still to be fully understood. The hyperon-to-pion ratios have been observed to smoothly evolve from low multiplicity pp collisions to most central Pb-Pb collisions. Such a multiplicity dependence is not satisfactorily explained by QCD-inspired models and has a qualitative explanation in the statistical hadronization models as the gradual removal of the canonical suppression. Further insights will come from the study of very high multiplicity pp events, that will tell us if strangeness production in pp collisions will continue to increase with multiplicity or show a tendency to saturate.

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