

Results on strange hadron and resonance production in Pb–Pb collisions at the LHC with ALICE

Maria Nicassio^{1,a} for the ALICE Collaboration

¹Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

Abstract. Strange hadrons and resonances are among the most sensitive probes to investigate the characteristics of the system formed in high-energy heavy-ion collisions. The ALICE Collaboration has measured strange hadrons and meson resonances decaying into final states with charged particles. Results on the production of $K^*(892)^0$ and $\phi(1020)$ resonances, K_S^0 , Λ , Ξ^- and Ω^- and their anti-particles at mid-rapidity in $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb collisions are presented and compared with those at lower energy and in proton–proton interactions. Our current understanding will be discussed focussing on particle ratios, thermal model fits to particle yields, strangeness enhancement and baryon anomaly.

1 Introduction

In ultra-relativistic heavy-ion collisions, when a Quark-Gluon Plasma (QGP) is formed, the production of hadrons is strongly influenced by the occurrence of the deconfined state and differs from that in elementary collisions [1]. Studying strange particle production allows the evolution of the system to be characterized and its properties to be understood. Strange quarks are (thermally) created in the QGP phase of the interaction. After the partonic medium expansion and cooling, in the hadronic phase, hadrons and resonances are produced and hadron abundances fixed at the time of the chemical freeze-out. In this phase particles can still undergo elastic interactions until the kinetic freeze-out, when their momentum distributions are fixed. Strange baryons have a potentially lower hadronic scattering cross section than light hadrons and furthermore the multi-strange particles seem to freeze-out earlier, before most of the radial flow has developed [2, 3]. On the other hand, resonances can be regenerated in the hadronic medium and in addition, having a very short mean lifetime (45 fm/c and 4 fm/c for ϕ and K^{*0} , respectively), they can decay with their daughters being scattered, which may prevent their reconstruction. The two processes of regeneration and rescattering increase and decrease the signal and can lead to a modification of the measured yield compared to base line expectations in heavy-ion collisions. From particle yields and their ratios, the temperature at chemical freeze-out can be determined using thermal models [4]. From resonance yields the lifetime of the hadronic phase can be inferred [5].

2 Data sample and analysis

The results shown in the following are obtained with the Pb–Pb data at a centre-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV collected in 2010. Strange hadrons and resonances that decay into final states with charged particles only are reconstructed in ALICE. In this contribution the following main decays are covered: $K_S^0 \rightarrow \pi^- + \pi^+$, $\Lambda \rightarrow \pi^- + p$, $\phi(1020) \rightarrow K^- + K^+$ and $\Xi^- \rightarrow \pi^- + \Lambda$, $\Omega^- \rightarrow K^- + \Lambda$ and $K^*(892)^0 \rightarrow \pi^+ + K^-$ with their antiparticles. The detectors relevant to reconstruct these decays are the Inner Tracking System, made of six silicon layers with three different technologies, and the Time Projection Chamber [6], which also provides particle identification via the specific energy loss. For strange hadron decays, the topology is exploited (V-shaped decay topology for K_S^0 and Λ and cascade decay topology for the charged Ξ and Ω baryons) applying selection criteria on geometrical and kinematical variables when combining tracks [7, 8]. Resonances are reconstructed with all possible combinations of primary tracks from opposite-charged particles. In both cases particle identification of daughter tracks is used to reject false candidates. The remaining background is removed via an invariant mass analysis: in the hadron invariant mass distributions, it is fitted and subtracted, whereas for resonances event mixing and like-sign techniques are used to estimate it [9]. Correlated residual background however survives for resonances and is subtracted performing polynomial fits. The analysis is performed in momentum and centrality intervals. Transverse momentum spectra are obtained after correcting for branching ratios, detector acceptance and efficiency effects. Integrated yields are obtained integrating the measured spectra and using fit functions to extrapolate down to zero transverse momentum.

^ae-mail: m.nicassio@gsi.de

3 Thermal model fit of particle yields

Abundances of hadrons made up of light quarks (u, d, s) are fitted in the statistical hadronization model [4]. This model is based on the assumption of a hadron gas in equilibrium, formed at the chemical freeze-out after a phase transition from a partonic medium at local thermal equilibrium. The model has a small set of parameters: T, μ_B, V that are the temperature at chemical freeze-out, the baryo-chemical potential and the fireball volume, respectively. The main model elements are the partition function which contains the contributions of most hadrons and resonances and the baryon number, strangeness and charge conservation laws. To describe high-energy central A–A collisions, it is formulated in the adequate grand canonical ensemble formalism: since many particles are produced per event, strangeness is conserved globally and distributed over the whole volume of the fireball. For lower-energy or peripheral high-energy A–A collisions or in high-energy elementary collisions where the initial conditions required for deconfinement are not necessarily established, the formulation of the statistical model in the canonical ensemble is needed with respect to strangeness conservation, that must be implemented locally because the number of produced particles is low. The exact conservation of quantum numbers, that is the canonical approach, reduces strongly the phase-space available for particle production, thus reducing their yields.

The model has been successful in describing yields in elementary and central heavy-ion collisions at low energies up to RHIC energies [10]. In figure 1 the yields for mesons, baryons and resonances measured in the 20% most central collisions are shown. Predictions obtained extrapolating from RHIC data are shown as a blue line ($T = 164$ MeV): they significantly overestimate the proton and Λ yields. A similar result is obtained fitting the data excluding protons and antiprotons with a good agreement with the data. The fit of the yields including all particles except resonances (dotted lines) gives a lower temperature ($T = 152$ MeV) but significantly underpredicts multi-strange baryons. Resonances are not included in the fit since the regeneration and rescattering processes can produce a variation which is not accounted for in the model. A similar disagreement is already present at RHIC top energy [11] and can indicate an anomaly in the proton yield, caused by annihilation of $p\bar{p}$ pairs between chemical and kinetic freeze-out. This hypothesis is supported by model calculations [12, 13]. However annihilation should also affect strange baryons, even though slightly, as data suggest.

Recently, particle yields measured by the ALICE Collaboration in different centrality intervals have been fitted with a chemical non-equilibrium implementation of the model [14]. In this implementation the phase space occupancy factors $\gamma_{s,q}$, which are additional non-equilibrium parameters introduced in some models to account for non-thermal production, are used. This approach relies on a sudden hadronization which occurs from a cool QGP ($T \approx 140$ MeV) in thermal equilibrium, so that there is no significant modification of the quark abundances and they remain close to the chemical equilibrium values.

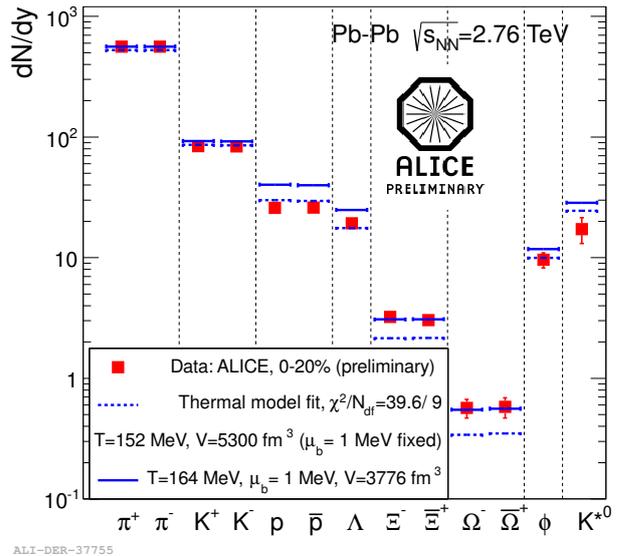


Figure 1. Particle yields measured in the 0-20% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (red symbols) with the prediction of the thermal model from RHIC extrapolation (blue line) and the fit performed excluding resonances (dotted blue line).

4 Strangeness enhancement

An enhanced production of strange particles in ultra-relativistic heavy-ion collisions with respect to the production in elementary collisions was proposed in 1982 as a signature of the QGP formation [15] with two main arguments: in a deconfined system of quarks and gluons $s\bar{s}$ pairs are more easily produced than strange–antistrange hadron pairs in a hadron gas and the time to reach thermal equilibrium is also much longer in the latter case, exceeding the system lifetime. The comparison was first made at the SPS between Pb–Pb, p–A collisions and later at RHIC between Au–Au (and Cu–Cu) collisions and pp collisions [16]. The ratio of the yields of strange baryons to the same yields in elementary collisions, both normalized to the number of participating nucleons, was defined as enhancement. If the production scales with the number of participating nucleons the enhancement has to be unity. As shown in figure 2, this ratio grows with the number of participants, it shows a hierarchy based on the strangeness content of the particle and, comparing ALICE results to SPS and RHIC results, it decrease as energy increases. The original idea does not explain all the features observed experimentally and has gone through further developments. The statistical model within the canonical formulation of strangeness conservation qualitatively predicts the experimental observation, the trend with energy and the increasing magnitude with the strangeness content of the particle. In the right panel of figure 2, where the ratio of Ξ/π yields is shown for central heavy-ion and pp collisions as a function of the centre-of-mass energy, it can be observed that the hyperon-to-pion yield ratio does not change with energy in central heavy-ion collisions but the pp one does increase. This increase can be interpreted as the decrease

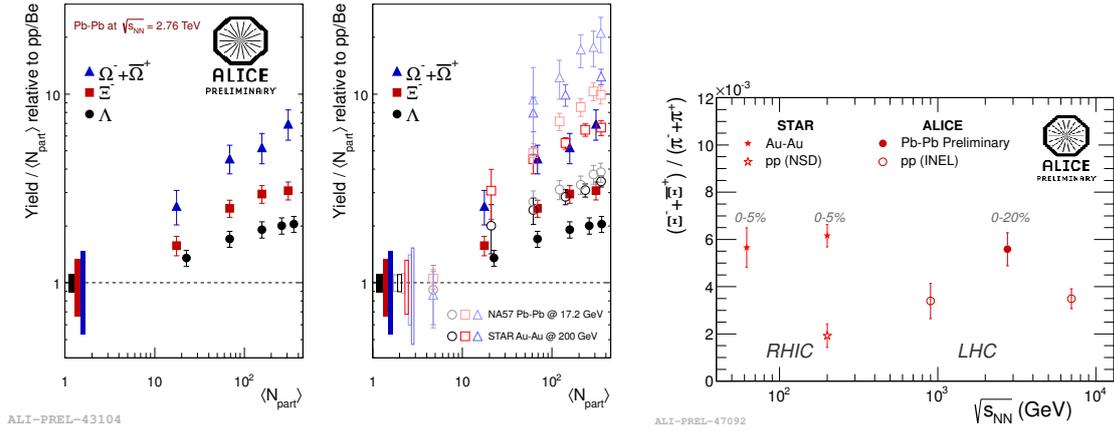


Figure 2. Left panels: strangeness enhancement of baryons as a function of the mean number of participants measured by ALICE in Pb–Pb collisions (full symbols) with respect to pp collisions compared to that measured at lower energies (hollow symbols) by NA57 and STAR in Pb–Pb (normalized to p–Be) and Au–Au (normalized to pp) collisions respectively. The boxes on the dotted lines represent the systematic uncertainties on the pp and p–Be reference ($\langle N_{\text{part}} \rangle = 2$ and 2.5 respectively). The hollow symbols at $\langle N_{\text{part}} \rangle = 4.75$ are WA97 measurements in p–Pb collisions normalized to p–Be collisions. For ALICE data the reference is calculated interpolating data as described in [8]. Right panel: hyperon-to-pion ratio as a function of the centre-of-mass energy for heavy-ion (full symbols) and pp (hollow symbols) collisions for ALICE and STAR data.

of canonical suppression in elementary collisions as the centre-of-mass energy increases and explains the trend of the enhancements with energy. As for the centrality dependence, the experimental results are both due to the lifting of strangeness suppression in central heavy-ion collisions, in agreement with the grand canonical description of the thermal model, and a result of the charged multiplicity increase with centrality [17]. More detailed experimental studies and theoretical understanding are needed to explain all the features of the lifting of strangeness suppression observed so far in a consistent picture, such as the centrality dependence, which is not well reproduced with the thermal model, the magnitude, which is not correctly predicted, and the dependence on the size of the colliding system.

5 Baryon anomaly

It was first observed at RHIC that the production of baryons becomes similar to that of mesons in central heavy-ion collisions at intermediate transverse momentum ($3 < p_T < 5$ GeV/c) when comparing proton and pion yields and, in the strange sector, Λ and K_S^0 yields. In figure 3 (left panel) the ratio of strange baryon to meson yields, Λ/K_S^0 ratio, as a function of p_T is shown for several centrality classes and compared to the same ratio in pp collisions: the production ratio is similar in peripheral A–A and pp collisions and increases from the most peripheral classes to the most central. The peak shifts towards higher p_T and becomes higher going from the most peripheral to the most central collisions (right panel of figure 3). A possible explanation is the recombination of quarks as an additional hadronization mechanism in presence of a deconfined medium at intermediate p_T . The recombination mechanism is implemented in models based on quark coalescence [20], which should not be at work in pp collisions

due to the low phase space density in the final state. Such models were successful in describing RHIC data. A redistribution of the produced baryons at higher momentum due to radial flow is also conceivable and is consistent with the shift of the maximum towards higher p_T as centrality increases. However, the interplay of effects which are dominant in the low, mid and high momentum regions has to be considered in models of hadronization in heavy-ion collisions. A good description of the behaviour in centrality classes and over the whole p_T range is obtained with the EPOS hadronic interaction model [19], as it can be seen in figure 3 (left panel). In this model particle production from a hadron–hadron interaction has three main sources: a soft and a hard part and the contribution of the remnants of the two hadrons. It also includes nuclear effect and hydrodynamics.

6 Resonance to non-resonance ratios

The two competing processes of regeneration and rescattering could affect the measured yields of resonances. Their relative strength can be inferred from resonant to non-resonant particle yield ratios and comparing them to thermal model predictions. The ratio of resonances to negatively-charged kaons is shown in figure 4 for A–A and pp interactions: no significant variation is seen for the ϕ , while for the K^{*0} the ratio is lower in A–A than in pp collision, as already observed at RHIC. As shown in figure 5, the ratio does not depend on centrality for the ϕ , whereas shows a decrease with centrality for the K^{*0} .

These results, which show suppression in A–A central collision compared to pp and A–A peripheral collisions for the K^{*0} and not for the ϕ , are compatible with the predominance of the rescattering over regeneration, given that ϕ has ten times longer lifetime than the K^{*0} . In addition

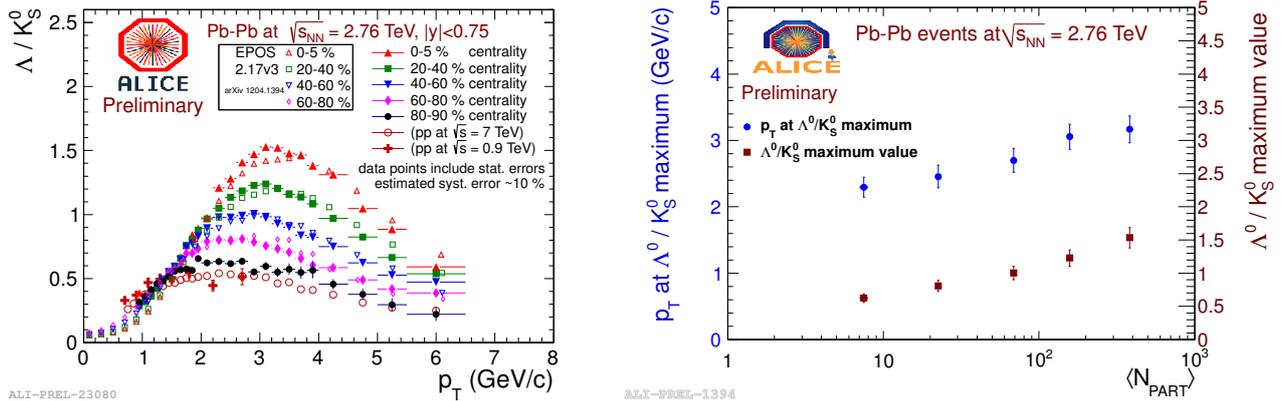


Figure 3. Left panel: baryon-to-meson yield ratio for Λ and K_S^0 as a function of p_T for several centrality intervals in Pb–Pb collisions and for pp collisions at two energies. Pb–Pb data are compared to the prediction of the EPOS model. Right panel: properties of the maximum of the Λ/K_S^0 ratio. The height (red symbols) and the position in p_T (blue symbols) are shown as a function of centrality.

there is a fair agreement for the ϕ/K ratio with the thermal model prediction and not for the K^{*0}/K ratio, which is clearly overpredicted. The absence of centrality dependence of the ϕ/K ratio also disfavors ϕ production via kaon coalescence, predicted in hadron transport models, such as RQMD and UrQMD [21], as the dominant production mechanism for mesons. In these models the ratio is larger for more central collisions.

7 Summary and conclusions

Some of the main results on strangeness production in Pb–Pb collisions obtained by the ALICE Collaboration have been presented and compared to the observations at lower energies and in pp collisions. These results are valuable in the interpretation of the effects and characteristics related to particle production, not only specifically in the strangeness sector, though further investigation is still needed both on the theoretical and the experimental side. Tensions are observed when fitting particle yields in the equilibrium statistical hadronization model. This opens the question whether a common freeze-out picture is still valid at the LHC and this feature is (in fact) already present at lower energy. It can also point to an issue with proton yields that can be better investigated with further precision measurements, including correlations among baryons and anti-baryons to study annihilation. It can even be a hint of non-equilibrium of the hadron gas. Therefore more investigation is required for hadrons which exhibit challenges to the model, such as protons and multi-strange baryons. The pattern of the strangeness enhancement, established at lower energies, is confirmed at the LHC. The observed effect can be better quantified with strange to non-strange yield ratios to disentangle the contributions convoluted in the usual definition of enhancements, i.e. canonical suppression in elementary collisions, the lifting of suppression in heavy-ion collisions and the growth of charged multiplicity with centrality. More studies can also help to understand the features observed at lower energy in different colliding systems. The so-called baryon anomaly has

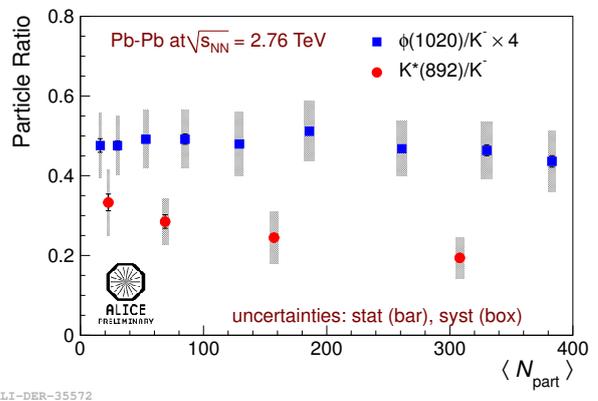


Figure 5. Resonance to non-resonance yield ratios as a function of centrality for ϕ and K^{*0}

to be further investigated as well, and our data are important to test models of particle hadronization and transport in order to identify the origin of the increased production of baryons compared to mesons at intermediate p_T . Possible explanations are a redistribution due to flow and the interplay of quark recombination and fragmentation. Further studies are also ongoing for resonances to understand the role played by rescattering and regeneration in the observed abundances.

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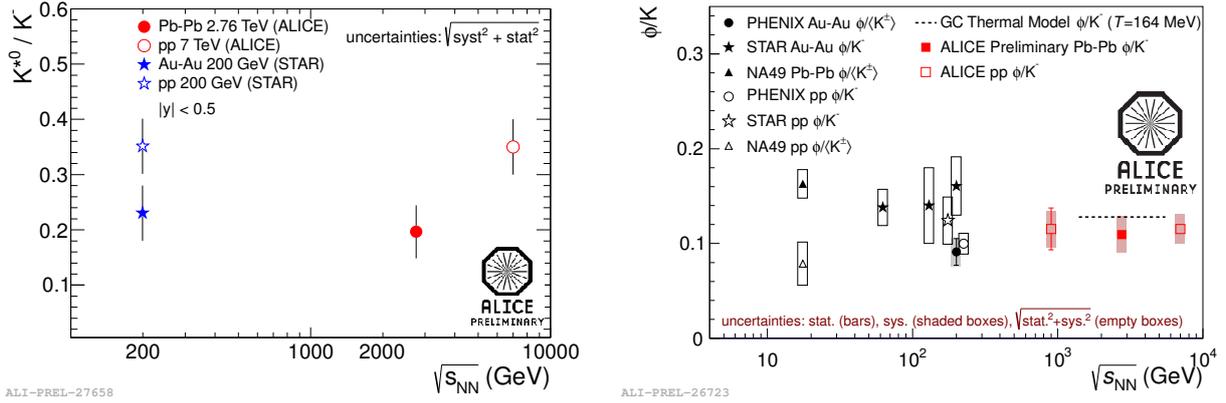


Figure 4. Resonance to non-resonance yield ratios for K^{*0} (left panel) and ϕ (right panel) as a function of the centre-of-mass energy for pp and A–A collisions. The thermal model prediction for LHC energies ($T=164$ MeV) is also shown for the ϕ/K ratio.

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