

# Probing the hadronic phase with resonances of different lifetimes in Pb-Pb collisions with ALICE

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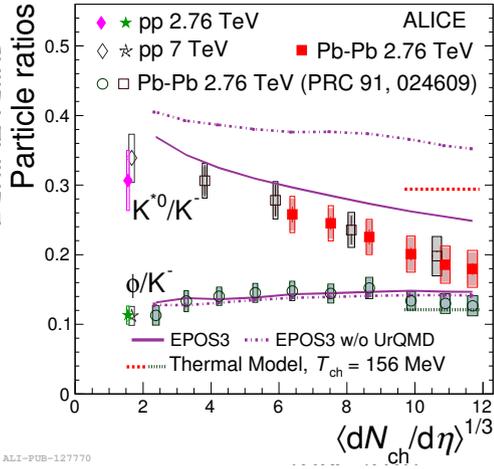
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**Abstract.** The ALICE experiment has measured the production of a rich set of hadronic resonances, such as  $\rho(770)^0$ ,  $K^*(892)^0$ ,  $\phi(1020)$ ,  $\Sigma^\pm(1385)$ ,  $\Lambda(1520)$  and  $\Xi^{*0}$  in pp, p-Pb and Pb-Pb collisions at various energies at the LHC. A comprehensive overview and the latest results are presented in this paper. Special focus is given to the role of hadronic resonances for the study of final-state effects in high-energy collisions. In particular, the measurement of resonance production in heavy-ion collisions has the capability to provide insight into the existence of a prolonged hadronic phase after hadronisation. The observation of the suppression of the production of  $\Lambda(1520)$  resonance in central Pb-Pb collisions at  $\sqrt{s_{NN}}=2.76$  TeV adds further support to the existence of such a dense hadronic phase, as already evidenced by the ratios  $K^*(892)^0/K$  and  $\rho(770)^0/\pi$ .

## 1 Introduction

Lattice QCD calculations performed with 2 + 1 flavors of quarks predict that at high enough temperature ( $T_c \sim 154 \pm 9$  MeV) and energy density ( $> 1$  GeV/fm<sup>3</sup>), nuclear matter undergoes a phase transition to a deconfined state of quarks and gluons known as the Quark-Gluon Plasma (QGP) [1]. These critical conditions are experimentally achieved by colliding heavy ions at ultra-relativistic energies [2, 3]. In such collisions, a fireball of very hot and dense partonic matter is formed and persists for a very short time (few fm/c). The QGP matter cools down and transitions back to confined hadronic matter, which subsequently undergoes chemical and kinetic freeze-out. Due to their lifetimes shorter or comparable to the lifetime of the fireball ( $\sim 10$  fm/c [4]), hadronic resonance are good probes to investigate the properties of the hadronic medium existing in between the chemical and kinetic freeze-out. Resonances are produced at hadronisation and can decay inside the hadronic medium. If the hadronic phase lasts long enough, the decay daughters of very short-lived resonances experience its full evolution and suffer rescattering via elastic collisions in the dense hadronic medium, which could modify their correlations and hence the experimentally measured resonance yields. As a consequence, the reconstructible resonance yield is lower than the original yield. Alternatively, depending upon the density and duration of the hadronic medium, hadrons might interact pseudoelastically to form resonances, which can increase the resonance yield. The competing effects of rescattering and regeneration on the final reconstructible resonance yields is dependent on the time scale between chemical and kinetic freeze-out, the relevant hadronic interaction cross sections and the resonance

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**Figure 1.** The  $p_T$ -integrated ratios of  $K^*(892)^0/K^-$  and  $\phi(1020)/K^-$  as a function of  $\langle dN_{ch}/d\eta \rangle^{1/3}$  measured at mid-rapidity in pp collisions at  $\sqrt{s} = 2.76$  TeV and 7 TeV and Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV [8]. The statistical, total systematics and centrality uncorrelated systematic uncertainties are represented by the bars, empty boxes and shaded boxes, respectively. The expectations from a SHM calculation with a chemical freeze-out temperature of 156 MeV for the most central collisions and EPOS3 calculations are shown.

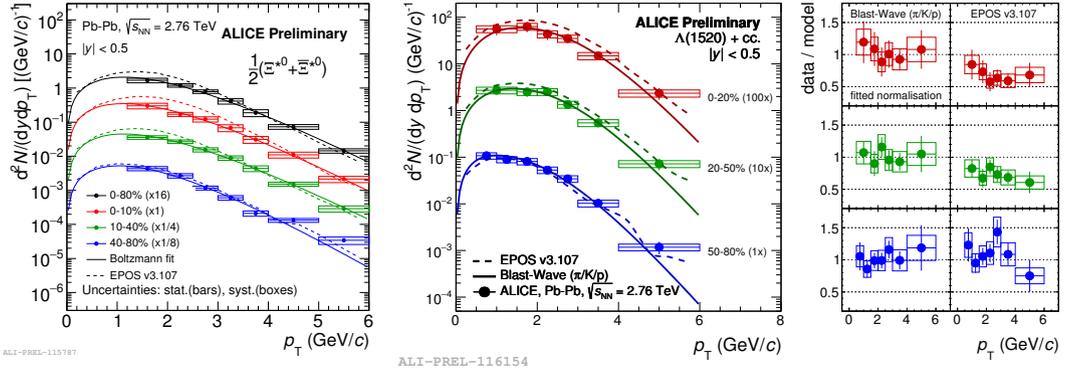
lifetime. The Statistical Hadronisation Model (SHM) predicts ratios of resonance yields to stable particle yields at the chemical freeze-out stage [5–7]. Deviation from the model predictions can be useful to identify the possibility of the presence of hadronic phase. Figure 1 shows the ratio of  $K^*(892)^0$  ( $\tau = 4.2$  fm/c) and  $\phi$  ( $\tau = 46.2$  fm/c) to kaons as a function of  $\langle dN_{ch}/d\eta \rangle^{1/3}$  [8]. The production of the short-lived  $K^*(892)^0$  is suppressed in central Pb–Pb collisions, suggesting that the phenomenon might be due to the rescattering of the  $K^*(892)^0$  decay products within the dense hadronic medium before the kinetic freeze-out. No suppression is observed for the  $\phi(1020)$  mesons which could indicate that it mostly decays outside the fireball due to its longer lifetime.

## 2 Analysis Method and Results

Several hadronic resonances with different lifetimes have been measured by ALICE at midrapidity ( $|y| < 0.5$ ) in pp, p–Pb and Pb–Pb collisions at various centre-of-mass energies. The properties of these resonances are listed in Table 1. The resonance signal is reconstructed using an invariant mass technique. The decay products are identified using the information from the TPC and TOF detectors. The invariant mass distribution of the correct-sign pair of decay daughters is constructed for each centrality/multiplicity class and  $p_T$  interval. The combinatorial background is estimated from either mixed events or like-charged tracks from the same event and subtracted from the signal distribution; the result is then fitted to extract the resonance yield. The  $p_T$ -integrated yields are obtained for all resonances and collision systems and are corrected for the decay channel branching ratio, detector

**Table 1.** Hadronic resonances with their lifetime, decay width, valance quark content, decay mode exploited for the measurements and corresponding branching ratio (BR) [9].

resonances	$\tau$ (fm/c)	$\Gamma$ (MeV)	valance quark contents	decay mode	BR[%]
$\rho(770)^0$	1.3	$149.1 \pm 0.8$	$(u\bar{u} + d\bar{d})/\sqrt{2}$	$\pi^+ + \pi^-$	100
$K^*(892)^0$	4.2	$47.3 \pm 0.5$	$d\bar{s}$	$K^+ + \pi^-$	66.6
$\phi(1020)$	46	$4.3 \pm 0.02$	$s\bar{s}$	$K^+ + K^-$	48.9
$\Sigma(1385)^+$	5.5	$36.0 \pm 0.7$	$uus$	$p + \pi^- + \pi^+$	87.0
$\Lambda(1520)$	12.6	$15.6 \pm 1.0$	$uds$	$K^- + p$	22.5
$\Xi(1530)^0$	21.7	$9.1 \pm 0.5$	$uss$	$p + 2\pi^- + \pi^+$	66.7



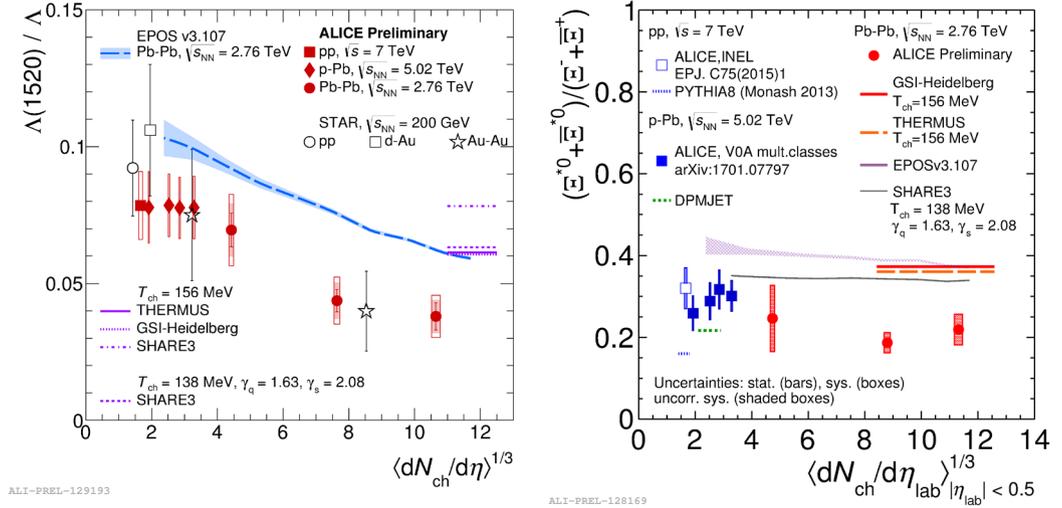
**Figure 2.** The  $p_T$  spectra of  $\Xi^{*0}$  (left) and  $\Lambda(1520)$  (middle) in Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The  $\Lambda(1520)$  spectra ratios with respect to Blast-Wave and EPOS3 predictions (right).

acceptance and reconstruction efficiency. For example, Figure 2 shows the  $p_T$ -spectrum of  $\Xi^{*0}$  (left) ( $\tau = 21.7$  fm/c) and  $\Lambda(1520)$  (middle) ( $\tau = 12.6$  fm/c) in Pb–Pb collisions measured in the  $p_T$  range 1.2–6.0 GeV/c and 0.5–6.0 GeV/c, respectively. The  $p_T$  spectra are fitted with appropriate parametrisations (Boltzmann for  $\Xi^{*0}$  and Blast-Wave for  $\Lambda(1520)$ ) to obtain the particle yield in the unmeasured  $p_T$  region. The  $p_T$  distribution have also been compared with predictions from the EPOS3 model [10] (Figure 2 middle), which describes the full evolution of heavy ion collisions and embeds the UrQMD model for the description of the hadronic phase. This model reproduces the  $p_T$  distribution reasonably well but over-predicts the yield for central Pb–Pb collisions.

The integrated yield ratios of resonances to stable hyperons with the same strangeness content is calculated in order to investigate the impact of the hadronic phase on the reconstructed resonance yield. Figure 3 shows the  $\Lambda(1520)/\Lambda$  (left) and  $\Xi^{*0}/\Xi$  (right) ratios as a function of  $\langle dN_{ch}/d\eta \rangle^{1/3}$  in pp, p–Pb and Pb–Pb collisions at 7, 5.02 and 2.76 TeV, respectively. Predictions from Monte Carlo generators commonly used in pp and p–Pb collisions, EPOS3 and various SHM predictions [5–7] for Pb–Pb collisions are also shown. The  $\Lambda(1520)/\Lambda$  shows suppression in central Pb–Pb collisions with respect to peripheral Pb–Pb and p–Pb and pp collisions. The SHM predictions for Pb–Pb collisions overestimate the data. On the other hand, EPOS3 qualitatively reproduces the suppression trend of ratio, however, it overestimates the value. The  $\Lambda(1520)/\Lambda$  ratio suppression trend indicates the dominance of rescattering of the decay daughters over regeneration. The  $\Xi^{*0}/\Xi$  ratio shows relatively weak suppression from pp, p–Pb, peripheral Pb–Pb to central Pb–Pb collisions. The ratio values are underestimated by PYTHIA8 in pp, DPMJET in p–Pb and overestimate by various SHM calculations in Pb–Pb collisions. In addition, EPOS3 with UrQMD predicts a slight decrease of the  $\Xi^{*0}/\Xi$  ratio from peripheral to central Pb–Pb collisions and a yield value which is consistent with the SHM predictions for most central Pb–Pb. The trend is qualitatively consistent with the observed one, given the present uncertainties of the measurement, however the measured yield ratio is lower than the predictions.

### 3 Conclusion

In this paper, we have presented the first measurement of  $\Lambda(1520)$  and  $\Xi^{*0}$  in pp, p–Pb and Pb–Pb collisions at  $\sqrt{s} = 7$ ,  $\sqrt{s_{NN}} = 5.02$  and 2.76 TeV, respectively. The  $\Lambda(1520)/\Lambda$  ratio is suppressed in central collisions compared to the values observed in peripheral Pb–Pb, pp and p–Pb collisions. This is similar to the behaviour observed in the  $\rho/\pi$  and  $K^*(892)^0/K^-$  ratios. The suppression of  $\Lambda(1520)$  in central Pb–Pb collisions suggests the dominance of (pseudo)elastic rescattering of decay daugh-



**Figure 3.** The  $p_T$ -integrated ratio of  $\Lambda(1520)/\Lambda$  (left) and  $\Xi^{*0}/\Xi$  (right) as a function of  $\langle dN_{ch}/d\eta \rangle^{1/3}$  measured in Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$ . The statistical errors, systematic uncertainties and centrality uncorrelated systematic uncertainties are represented by the bars, empty boxes and shaded boxes, respectively. Predictions from several SHM models [5–7] as well as the prediction from EPOS3 [10] are compared to the data.

ter particles in the hadronic phase. Moreover, the suppressed value of  $\Lambda(1520)/\Lambda$  ratio at highest  $\langle dN_{ch}/d\eta \rangle^{1/3}$  could be attributed to a larger fireball size and its life-time ( $\tau_{Had} \sim 10$  fm/c) accessible at LHC energies. The  $\Xi^{*0}/\Xi$  ratio exhibits a very weak suppression from pp, p–Pb, peripheral Pb–Pb to central Pb–Pb collisions. The  $\Lambda(1520)/\Lambda$  and  $\Xi^{*0}/\Xi$  ratios in central Pb–Pb collisions are compared and found to be lower than the calculations from several implementations of the Statistical Hadronisation Models in Grand Canonical description and one non-equilibrium model. The deviations of these ratios in the data as compared to the SHM models are useful to decode effects related to the interactions in hadronic medium. The use of SHM models in combination with a microscopic description of the interactions in the hadronic phase (UrQMD) allow one to estimate the time span between chemical and kinetic freeze-out. These results further support the existence of a hadronic phase lasting long enough to cause a significant reduction of the reconstructible yield of short-lived resonances.

## References

- [1] F. Karsch, Lect. Notes Phys. **583**, 209 (2002), hep-lat/0106019
- [2] G. Roland, K. Safarik, P. Steinberg, Prog. Part. Nucl. Phys. **77**, 70 (2014)
- [3] A. Ohnishi, Prog. Theor. Phys. Suppl. **193**, 1 (2012), 1112.3210
- [4] K. Aamodt et al. (ALICE), Phys. Lett. **B696**, 328 (2011), 1012.4035
- [5] A. Andronic et al., Nucl. Phys. **A772**, 167 (2006), nucl-th/0511071
- [6] S. Wheaton, J. Cleymans, J. Phys. **G31**, S1069 (2005), hep-ph/0412031
- [7] M. Petran et al., Comput. Phys. Commun. **185**, 2056 (2014), 1310.5108
- [8] B. Abelev et al. (ALICE), Eur. Phys. J. **C72**, 2183 (2012), 1208.5717
- [9] C. Patrignani et al. (Particle Data Group), Chin. Phys. **C40**, 100001 (2016)
- [10] A.G. Knospe et al., Phys. Rev. **C93**, 014911 (2016), 1509.07895
- [11] J. Adam et al. (ALICE), Phys. Rev. **C93**, 024905 (2016), 1507.06842