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Probing the hadronic phase of large hadronizing system through the study of the Λ(1520) resonance with ALICE at the LHC

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Summary. — The measurement of hadronic resonance production in heavy-ion collisions at the LHC has led to observing a prolonged hadronic phase after hadronization. Due to their short lifetimes, resonances experience the competing effects of regeneration and rescattering of their decay products in the hadronic medium. Studying how these processes affect the experimentally measured yields can extend the current understanding of the properties of the hadronic phase and the mechanisms that determine the shape of particle $p_{\rm T}$ spectra. This contribution presents new preliminary results on the production of Λ(1520) resonance measured in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ALICE detector at the LHC. These results on Λ(1520) (lifetime, $\tau = 12.6$ fm/c) are compared with a set of hadronic resonances with a lifetime span of 1 to 46 fm/c such as $\rho(770)^0$, $K^*(892)^0$, $\Sigma(1385)^\pm$, $\Xi(1530)^0$ and $\phi(1020)$ measured by the ALICE experiment. The shape of particle transverse momentum ($p_{\rm T}$), mean $p_{\rm T}$ and particle ratios are compared with those predicted from the Blast-Wave, MUSIC with SMASH afterburner and statistical hadronization model predictions.

1. – Introduction and experiment details

For several years, enormous efforts have been put into a deep understanding of the properties of the hadronic matter of our universe through various experiments and theoretical calculations. From the lattice calculations of 2 + 1 flavors, the parameters of extreme energy ($T_c \approx 156 \pm 9\,\mathrm{MeV}$) and density ($\mu_B > 1$ GeV/fm^2) are extracted. At these conditions, ordinary nuclear matter undergoes a phase transition from the normal hadronic matter stage to a deconfined plasma of quarks and gluons (QGP). At the LHC, such extreme conditions are created by colliding nuclei at a relativistic speed. The momentous deconfined phase of QCD matter undergoes a transition to ordinary hadronic matter followed by chemical and kinetic freeze-out. At first, the chemical freeze-out occurs at a certain temperature where particle abundances get fixed. At this stage, the medium is still hot and dense enough to allow elastic interactions among the particles. Later in its evolution, the medium approaches a kinetic freeze-out when all the particles stop the elastic interactions and freely fly toward the detector. If the duration between the chemical and kinetic freeze-out is long enough, resonance particles can decay inside the hadronic medium due to their short lifetime (few fm/c). Their decay products interact with the surrounding particles by the rescattering phenomenon; this results in the loss of their correlation and reduces the measured resonance yield. Additionally, hadrons

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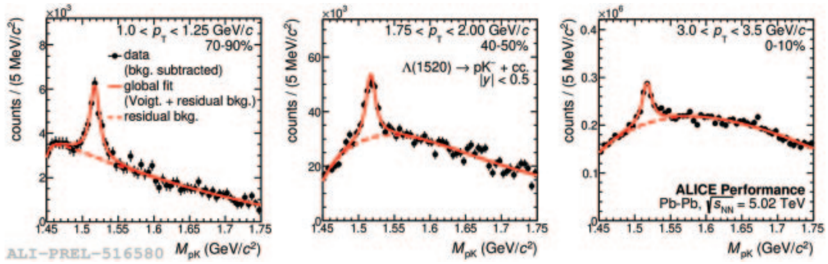

Fig. 1. – Invariant mass distribution of πK pairs after subtracting the mixed-event background distribution in different p_{T} and centrality intervals at mid-rapidity, $|y| < 0.5$ for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

might be able to interact with each other pseudoelastically to create a hadronic resonance depending upon the duration and density of the hadronic medium as well as the interaction cross-section of the two interacting species and therefore increases the measured resonance yield. The regeneration and rescattering phenomena directly depend on the time difference between the chemical and kinetic freeze-out, the density of the hadronic medium, the interaction cross-section of the relevant hadrons and the resonance lifetime. The Statistical Hadronization Model (SHM) calculations give the resonance yield at chemical freeze-out, which, in comparison to the measured yield, helps in decoding the rescattering and regeneration effect. Any deviation from these model results can confirm the presence of the hadronic phase. The ratio of resonance to stable particle yield should show an increasing/decreasing trend as a function of centrality to encode the rescattering and regeneration effects.

ALICE is an experiment at the LHC dedicated to the study of the properties of QCD matter at extreme energy. It is a detector specific for heavy-ion collisions with very strong particle identification (PID) capabilities from very low momentum regions ($\sim$100 MeV/c). A few detectors out of many ALICE subsystems have been used in this analysis. The Inner Tracking detector (ITS) is used for the event vertex, tracking, and event filtering. The Time Projection Chamber (TPC) is used for the tracking and PID by the particle's ionization energy loss technique. The Time-Of-Flight (TOF) is used for PID by using the time of flight of particles inside the detector medium.

2. – Analysis description and results

The $\Lambda(1520)$ resonance is measured by the ALICE at mid-rapidity ($|y| < 0.5$) in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The resonance is reconstructed via invariant-mass analysis of its hadronic decay channel $\Lambda(1520) \rightarrow p\mathrm{K}^-$ (and charge conjugate, cc.), with a branching ratio of 22.5 $\pm$ 0.5%. Kaons and protons are selected by using the information from TPC and TOF detectors. The invariant-mass distribution from unlike-sign pairs of selected kaon and proton tracks is constructed for each centrality class and p_{T} interval. The background from random uncorrelated kaon and proton pairs contributes to the invariant mass spectrum. The mixed-event technique is used to estimate combinatorial background by taking protons and kaons from different events with similar characteristics. The background is normalized and corrected due to event shape distortions. Figure 1 shows an example of $\Lambda(1520)$ invariant mass distribution after subtracting the background distribution, which is fitted by a Voigtian function as a signal and the Maxwell-Boltzmann like background function to extract the resonance yield. The raw yields are corrected for branching ratio (BR), detector acceptance, and reconstruction efficiency using a detailed Monte Carlo simulation of the ALICE detec-

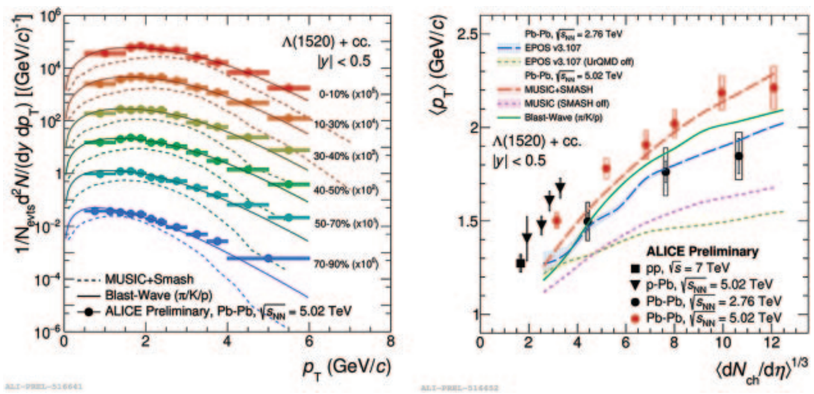

Fig. 2. – The p_{T} spectrum (left) and mean-p_{T} values (right) of $\Lambda(1520)$ for the measured centralities for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}\ = 5.02$ TeV. The solid and dashed lines show the predictions from Blast-Wave and MUSIC with Smash afterburner, respectively. The mean-p_{T} values are calculated from several models and compared with the data values.

tor. Figure 2 (left) shows the $\Lambda(1520)$ spectral shapes in p_{T} range 0.5–6.0 GeV/c for six measured centralities. The spectral shapes are compared with predictions from the Blast-Wave model, which assumes particle production from thermal sources expanding with a common transverse velocity and with a MUSIC hydrodynamic model embedded with a SMASH [1] model for the hadronic phase description. The Blast-Wave model is parameterized by reproducing π/K/p production in Pb–Pb collision. The agreement of the predicted spectral shapes with data confirms the hydrodynamical evolution of $\Lambda(1520)$ similar to the π/K/p, with a common transverse expansion velocity which increases with centrality.

Figure 2 (right) and 3 show the average transverse momentum, $\langle p_{\mathrm{T}}\rangle$ and $\Lambda(1520)/\Lambda$ yield ratio, respectively as a function of the cubic root of the charged-particle multiplicity density at mid-rapidity, $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle^{1/3}$, computed by integrating the data and using

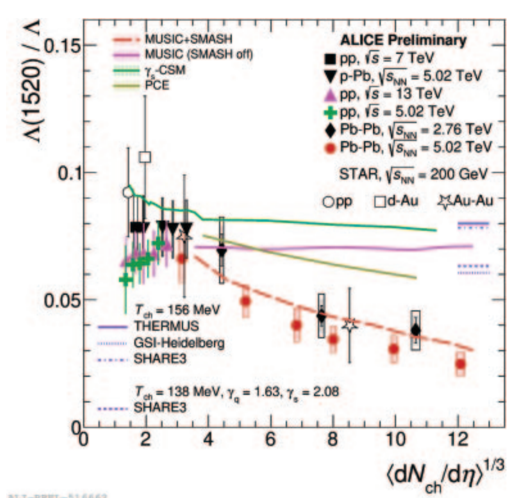

Fig. 3. – p_{T}-integrated ratio of $\Lambda(1520)/\Lambda$ production as a function of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle^{1/3}$. Predictions from several SHMs and from MUSIC with the SMASH model are also shown. Statistical and systematic uncertainties are shown as bars and boxes, respectively.

extrapolations to estimate the yields in the unmeasured regions. The $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle^{1/3}$ is used as a proxy for the system size radius to emphasize the system size dependence of the study. The $\langle p_{\mathrm{T}} \rangle$ increases with the increasing charged-particle multiplicity or centrality and the model calculations such as MUSIC with SMASH, Blast-Wave, and EPOS3 with UrQMD also show a similar trend ensuring the consistency of the $\Lambda(1520)$ data with a common hydrodynamic evolution scenario. However, when SMASH and UrQMD transport stages are disabled, MUSIC and EPOS3 fail to predict the data. This observation emphasizes the importance of these models in the description of heavy-ion collisions. From fig. 3, a steady decrease of the $\Lambda(1520)/\Lambda$ yield ratio is seen from peripheral to central Pb–Pb collisions. The amount of this decrease is estimated through a double ratio of the ratio in central to peripheral Pb–Pb collisions $R_{\mathrm{cp}}^{\Lambda^*/\Lambda} = [\Lambda(1520)/\Lambda]_{0\text{–}10\%} \ / [\Lambda(1520)/\Lambda]_{70-90\%} = 0.375 \pm 0.014\ (\mathrm{stat}) \pm 0.078\ (\mathrm{syst})$, while common uncertainties cancel out. The $\Lambda(1520)/\Lambda$ yield ratio is suppressed by 62% in central collisions with respect to peripheral collisions. This result provides evidence of $\Lambda(1520)$ suppression in Pb–Pb collisions at a 7.9 σ confidence, which is so far best achieved by a nuclear experiment for a resonance candidate. The results are compared to Statistical Hadronization Models (SHMs) such as THERMUS, GSI-Heidelberg, and SHARE3 with the parameters obtained by their fits to stable particle yields. The results are also compared to the canonical statistical hadronization model (γ_{S}-CSM) [2] which includes incomplete equilibration of strangeness ($\gamma_{\mathrm{S}} \leq 1$) and thermal model such as partial chemical equilibrium (PCE) [3]. $\Lambda(1520)/\Lambda$ yield ratio in the central collisions is lower than all of these models by 60 to 70%, depending on the model.

The results from the previous measurement from ALICE in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV [4] and from STAR in pp, Au-Au and d-Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV, are also shown in fig. 3, which were showing a difference at 3.1σ and 1.8σ level confidence, respectively. The $\Lambda(1520)/\Lambda$ yield ratio by the MUSIC with SMASH model best describes the data and trend of the suppression. It is worth noticing that MUSIC without the SMASH model gives a flat curve with values similar to those in peripheral collisions. MUSIC is the first-ever prediction without an afterburner responsible for the hadronic interactions in the hadronic medium and underlines the importance of properly describing the later stages in the evolution of heavy-ion collisions.

3. – Conclusion

The measurement of $\Lambda(1520)$ production in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV at the LHC is presented. The spectral shapes and $\langle p_{\mathrm{T}} \rangle$ results show that the hydrodynamic evolution and collective radial expansion of $\Lambda(1520)$ are consistent with the common transverse velocity observed for pions, kaons, and protons. The p_{T}-integrated ratio $\Lambda(1520)/\Lambda$ is suppressed in central Pb–Pb collisions with respect to peripheral Pb–Pb collisions and is lower than the value predicted by thermal and statistical hadronization models. These results are achieved at a 7.9σ confidence level and confirm the presence of a hadronic phase which lasts long enough to suppress the short-lived hadronic resonance yield.

REFERENCES

[1] Oliinychenko D. and Shen C., arXiv:2105.07539 [hep-ph].
[2] Vovchenko V., Dönigus B. and Stoecker H., *Phys. Rev. C*, **100** (2019) 054906.
[3] Motornenko A., Vovchenko V., Greiner C. and Stoecker H., *Phys. Rev. C*, **102** (2020) 024909.
[4] ALICE Collaboration (Acharya S. *et al.*), *Phys. Rev. C*, **99** (2019) 024905. arXiv:1805.04361 [nucl-ex].