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Exploring the hadronic phase of relativistic heavy-ion collisions with resonances in ALICE

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Short-lived resonances are a good tool to study the hadronic phase that characterizes the late-stage evolution of heavy-ion collisions. Regeneration and rescattering processes taking part for resonances in the hadronic phase modify their measured yields. This can be studied by measuring resonance to stable particle yield ratios as a function of system size and comparing them to model predictions with and without hadronic interactions. With the excellent tracking and particle identification capabilities that ALICE has been endowed with, a comprehensive set of both mesonic and baryonic resonances have been measured. Recent results on resonance production in pp, p−Pb, Xe−Xe and Pb−Pb collisions at various centre of mass energies are presented. Recent results on $K^{*\pm}(892)$, $\Sigma^{*\pm}(1385)$ and $\Xi^{*0}(1820)$, are presented. The results are further compared to lower energy measurements and different model predictions wherever available.

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1. Introduction

Ultra-relativistic heavy-ion collisions allow one to study the deconfined phase of quarks and gluons called the quark–gluon plasma (QGP) [1]. The collision results in formation of a hot and dense matter which evolves and cools down with time finally resulting in the formation of hadrons. After a certain temperature, called chemical freeze-out temperature, the inelastic interactions among the hadrons stop and the yields of the primary produced particles (except the resonances) gets fixed. The hadrons continue to interact among themselves elastically which further changes the shape of their transverse momentum spectra. These elastic collisions get frozen at a surface called kinetic freeze-out and after which the hadrons stream freely to the detectors. The phase between the chemical and kinetic freeze-out is called the hadronic phase whose dynamics can be probed by resonances. Resonances having lifetime comparable to that of hadronic phase take part in two processes called regeneration and rescattering effects via elastic and pseudo-elastic scatterings. This leads to the modification of their yields. The yields at kinetic freeze-out surface depend on their lifetime, hadronic cross-section of resonances and their decay products and hadronic phase lifetime. One of the decay products can interact elastically with other hadrons in the medium or scatters pseudo-elastically via a different resonance state. This results in losing the four momentum information of the mother particle and thus its reconstruction using the invariant mass analysis is not possible. In the same way pseudo elastic scattering via the same resonance state can also regenerate the resonances thereby enhancing their yields. Ratio of resonances to stable particle yields can shed light on both these competing effects taking place in the hadronic phase of heavy-ion collisions.
Recent measurements of the particle yield ratios of resonances to stable hadrons such as $\mathrm{K}^{*0}/\mathrm{K}$ and $\mathrm{K}^{*\pm}/\mathrm{K}$ show a decreasing trend with charged particle multiplicity in heavy-ion collisions [2]. The $\mathrm{K}^{*0}/\mathrm{K}$ and $\mathrm{K}^{*\pm}/\mathrm{K}$ values in central collisions is found to be suppressed compared to peripheral Pb−Pb collisions and pp collisions. On the other hand ϕ/K remains fairly constant with charged particle multiplicity. This observation is consistent with the picture of dominance of rescattering effect over regeneration in the hadronic phase of heavy-ion collisions. Recent theoretical studies [3] suggests that suppression of hadronic resonances depends not only on the resonances lifetime but also on other factors such as mean free path, chemical freeze-out temperature. The systematic measurements of various resonances with different lifetimes, quark contents and masses may help to probe the dynamics and lifetime of the hadronic phase.

2. Analysis details

Resonances, due to their short lifetime, cannot be detected directly. They are reconstructed from their decay products using the invariant-mass method. A brief description of the ALICE detectors is given in [4]. The main detectors used for analysis are the Inner Tracking System (ITS), Time Projection Chamber (TPC), Time-Of-Flight (TOF) covering the pseudorapidity range $|\eta| < 0.9$ and the V0-A ($2.8 < \eta < 5.1$) and V0-C ($-3.7 < \eta < -1.7$) detectors. Charged-particle tracking and primary collision vertex reconstruction is done using ITS and TPC detectors. These detectors span the full azimuthal angle. They are surrounded by a large solenoidal magnet with a magnetic field strength of 0.5 T.

The ITS is a silicon detector consisting of 6 cylindrical and concentrical layers. It is used for tracking and reconstruction of primary and secondary vertices. The TPC is the main tracking detector. It is also used for particle identification via the measurement of the specific energy loss $\mathrm{d}E/\mathrm{d}x$ of charged particles in the TPC gas. The particle identification at high momentum is complemented by the measurement of the time of flight, provided by the TOF detector. V0A and V0C detectors are two scintillators, placed on both sides of the interaction point, which are used to reject beam-gas interactions and to classify events based on their multiplicity.

The resonances are measured at midrapidity ($|y| < 0.5$). The events analysed are recorded using a minimum-bias trigger which requires coincident signals in both V0 scintillators to be synchronous with the beam crossing time defined by the LHC clock. The signal amplitude measured by V0, called V0M amplitude, is proportional to the sum of charged-particle multiplicities in V0A and V0C, is used for classifying Pb−Pb and Xe−Xe events into different centrality classes and pp into different multiplicity classes. The yields of resonances are extracted from the invariant-mass distribution of their hadronic decay products. Combinatorial background is estimated using the like sign method or event mixing technique. The signal yields in different centrality classes and in various p_{T} ranges is obtained by subtracting the combinatorial background from the same event invariant mass distribution. The residual background after subtraction of combinatorial background is described by a polynomial function with parameters fitted to data.

3. Results

The transverse momentum spectra of $\mathrm{K}^{*\pm}$ in Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV are shown in Fig. 1. Transverse momentum spectra harden while moving from peripheral to central collisions. Also the mean of the distribution shifts towards higher value with increasing multiplicity due to increasing radial flow.

To study the interplay between rescattering and regeneration effects in the hadronic phase, the yield ratios of resonances to stable hadrons are calculated as a function of the system size, which is proportional to $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle^{1/3}$. The left panel of Fig. 2 shows a compilation of different measurements obtained in different collision systems and center-of-mass energies. These measurements are compared with EPOS predictions with and without UrQMD [5]. The yield ratios for resonances having lifetime comparable to that of hadronic phase (for e.g. ρ^0, K^*, $\Lambda(1520)$, $\Sigma^{*\pm}$) is observed to decrease with increasing system size. In contrast, the yield ratios for longer-lived resonances, like the ϕ, remain fairly constant with increasing multiplicity. This suppression of the yield of short-lived resonances with multiplicity is qualitatively consistent with EPOS with UrQMD calculations. This observation hints at the dominance of rescattering over regeneration effects in the hadronic phase of heavy-ion collisions.

The right panel of Fig. 2 shows the transverse momentum spectra of K^{*0} and ϕ compared to Blast Wave predictions for 0−10% centrality class in Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. The Blast Wave parameters are obtained from a simultaneous fit of π, K, and p spectra. It is observed that ϕ p_{T} spectra are well described by Blast Wave predictions whereas K^{*0} p_{T} spectra are overestimated for $p_{\mathrm{T}} < 3.5$ GeV/c. This suggests that rescattering dominates at low transverse momentum.

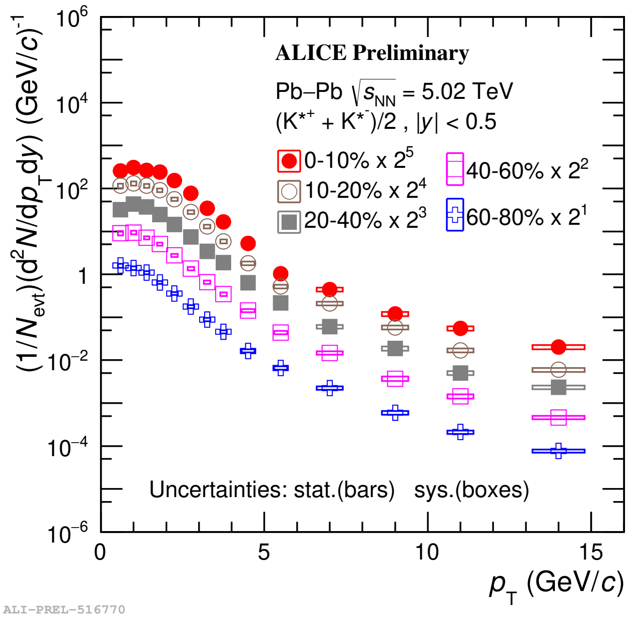

Figure 1: p_T spectra of $K^{*\pm}$ for different centrality classes in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

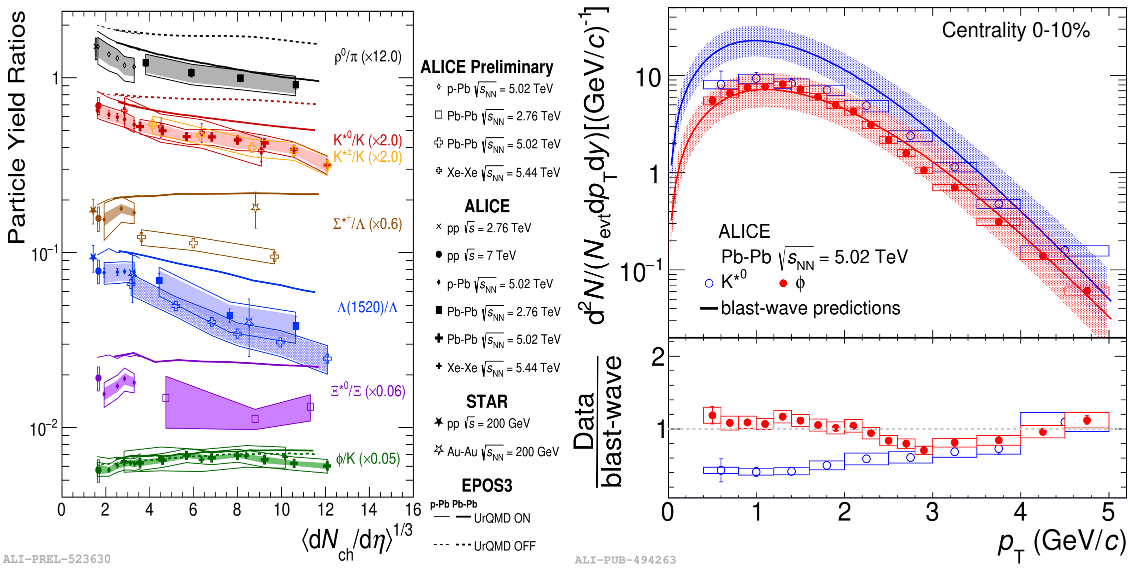

Figure 2: (Left Panel): Particle yield ratios as a function of $\langle dN_{ch}/d\eta\rangle^{1/3}$ in pp, p−Pb, Xe−Xe and Pb−Pb collisions. (Right panel): p_T spectra of K^{*0} (blue marker) and ϕ (red marker) mesons compared with Blast Wave model predictions in 0−10% centrality.

The lifetime between chemical and kinetic freeze-out for different multiplicities is estimated under the simplistic assumption of no rescattering effects. The yield ratio measured in pp collisions is used as a proxy for that at chemical freezeout and that measured in Pb−Pb collisions is assumed to be $r_{kin} = r_{chem} \times e^{(\tau_{kin}-\tau_{chem})/\tau_{res}}$, where $(\tau_{kin} - \tau_{chem})$ is the proper lifetime of the hadron gas phase, and τ_{res} the resonance lifetime. Fig. 3 shows the estimated lifetime as a function of multiplicity for different resonances. An increasing trend is observed hinting at a longer lifetime when going from peripheral to central collisions.

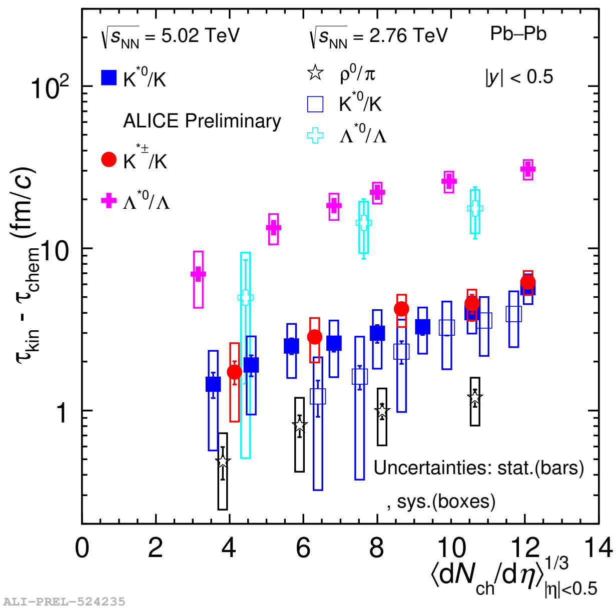

Figure 3: Lower limit on hadronic phase lifetime as a function of system size for various resonances in Pb−Pb collisions at LHC energies.

4. Conclusion

Measurements of various resonances with different lifetimes, mass, quark content in different colliding system and energies have been carried out by ALICE. A suppression is observed in central heavy-ion collisions in the p_T integrated yield ratios of short lived resonances to stable hadrons. The measured K^{*0} p_T spectrum is found to be lower than the Blast Wave model predictions, thus suggesting the dominance of the rescattering effects at low transverse momentum. A simple exponential decay model, which does not include regeneration effects and assumes simultaneous freeze-out of all particles, is used to estimate the lower limit of the hadronic phase lifetime in Pb−Pb collisions. The estimated lifetime increases with system size and the value obtained using Λ^* resonance is higher than that obtained with K*. New and precise measurements in Run 3 along with realistic parameterization for modification of resonance yields in the hadronic phase may help us in understanding better the hadronic phase and its lifetime in heavy-ion collisions at LHC energies.

References

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