

Exploring the hadron gas phase of relativistic heavy-ion collisions at the LHC

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Abstract.

The lifetimes of hadronic resonances are comparable to the one of the hadron gas phase created in the late stages of high-energy nuclear collisions. Therefore, a significant fraction of resonances decay inside a high-density medium and their decay daughters rescatter with nearby hadrons destroying their initial kinematic correlations. The competing effect of resonance regeneration via pseudo-elastic interactions of hadrons interplays between the rescattering effect, modifying the measured yields and transverse-momentum spectra of hadronic resonances. These effects are studied by measuring the production yield ratio of resonances to the corresponding long-lived particle as a function of the hadronic lifetime, i.e. charged-particle multiplicity. In addition, measurements of the differential yields of resonances with different masses, quark content, and quantum numbers help in understanding particle production mechanisms, strangeness production, and parton energy loss. This article reports recent ALICE measurements on resonances and the use of the experimental input in a partial chemical equilibrium-based thermal model to constrain the kinetic freeze-out temperature. This is a novel procedure that is independent of assumptions on the flow velocity profile and the freeze-out hypersurface.

1 Introduction

At the LHC, the ordinary nuclear matter transits to a deconfined state of quarks and gluons known as Quark-Gluon Plasma (QGP) by colliding the heavy ions at a high center-of-mass energy (\sim few TeV). In such collisions a hot, dense, and highly interacting QGP medium fireball is expected to form for a very short time (\sim few fm/c) in the early stage of the collision. Due to the large pressure and energy density created in the heavy-ion collisions at the LHC, the fireball expands and cools down to make a subsequent transition to confined hadronic matter within a few fm/c. This QGP phase is followed by chemical and kinetic freeze-out ones, and then the produced particles reach the detectors. The interactions and phenomenon inside the hadronic phase that exists between the chemical and kinetic freeze-out have been in discussion since the very first studies using heavy-ion collisions. The hadronic resonances are suitable probes as they are produced during the hadronization phase that takes place after the QGP phase and can decay inside the hadronic medium phase. Depending upon the time scale of the hadronic medium and its density volume, the decay daughters of resonances might experience re-scattering via elastic scattering from nearby particles inside the medium which

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Table 1. Hadronic resonances measured by the ALICE experiment at the LHC.

Resonance	lifetime (fm/c)	decay	B. R. (%)	constituent quarks
$\rho(770)^0$	1.3	$\pi\pi$	100	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$
$K^*(892)^\pm$	3.6	$K_s^0\pi$	33.3	$u\bar{s}, \bar{u}s$
$K^*(892)^0$	4.2	$K^+\pi^-$ and cc.	66.6	$d\bar{s}, \bar{d}s$
$f_0(980)$	large unc.	$\pi\pi$	46	unknown
$\Sigma(1385)^\pm$	5 - 5.5	$\Lambda\pi^\pm$ and cc.	87	uus, dds
$\Xi(1820)^\pm$	8.1	ΛK^\pm and cc.	unknown	$dss, \bar{d}ss$
$\Lambda(1520)$	12.6	pK^- and cc.	22.5	uds
$\Xi(1530)^0$	21.7	$\Xi^-\pi^+$	66.7	uss
$\phi(1020)^0$	46.4	KK	48.9	$s\bar{s}$

can modify their correlations. A lower reconstructed yield might be observed as compared to the actual resonance yield. The possible effect of the re-generation of resonances by interactions of primary particles produced in chemical freeze-out inside the hadronic medium can, on the other hand increase the measured resonance yield. The re-scattering and re-generation effects are mostly sensitive to the relative interaction cross-section of the decay daughters inside the hadronic phase, resonance lifetime, density, and duration of the hadronic phase. In the Statistical Hadronisation Models (SHMs) [1–3], hadronic resonances are expected to be produced at chemical equilibrium, however, due to the presence of the hadronic medium, the resonance yield in data might deviate from the model predictions. Table 1 shows the list of light-flavored hadronic resonances measured by ALICE experiment at the LHC in the order of increasing lifetime order, hadronic decay mode with their branching ratio (B.R.), and constituent quarks.

2 Detector and analysis method

ALICE [4] is a heavy ion dedicated experiment designed to explore the QGP and its features. The measurements reported in this article use the ALICE data from pp, p–Pb, Xe–Xe and Pb–Pb collisions at various center-of-mass energies. The main sub-detectors of ALICE used in the measurement are the V0 detector, the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Time-Of-Flight (TOF). The V0 detector is used for the collision centrality determination, triggering, and background suppression at the event level. The vertex reconstruction and charged particle tracking are performed by the ITS and TPC detectors. Charged hadrons are identified by their specific ionization energy loss (dE/dx) in the TPC gas and, if available, by using the timing information from the TOF detector. The dE/dx resolution of TPC is about 6.5% in most central (0-5%) Pb–Pb collisions and particle identification is possible up to about 1 GeV/c. The TOF has an excellent global time resolution of about 80 ps in Pb–Pb collisions which allows the identification of hadrons at higher momentum, also above 1 GeV/c.

The resonance signal is reconstructed by computing the invariant mass of the decay daughters and charge conjugate at midrapidity, $|y| < 0.5$, in each centrality/multiplicity class and transverse momentum, p_T interval. The mixed-event technique is incorporated to reconstruct a large amount of combinatorial background present due to the random combination of uncorrelated hadrons from the same event affecting the invariant-mass distribution. In the mixed-event technique, the decay daughters from different events having similar characteristics have been combined to reconstruct the invariant mass spectrum, which is further normalized and subtracted from the same event invariant mass spectrum to reveal the clear

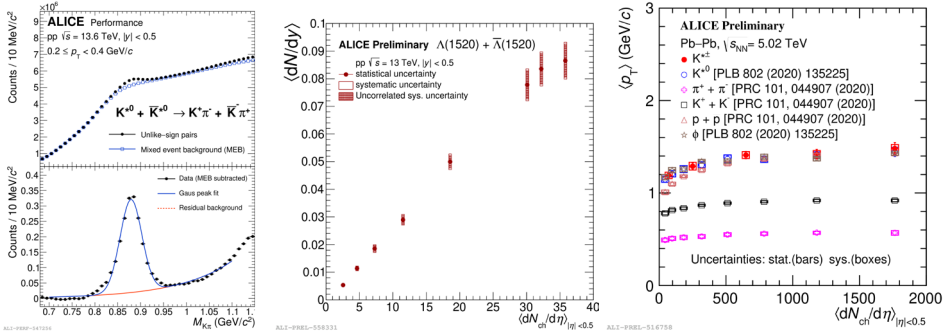


Figure 1. The invariant mass distribution of $K^*(892)^0$ (left) and p_T -integrated yield of $\Lambda(1520)$ (middle) for pp collisions at 13.6 TeV and 13 TeV, respectively. (Right) The $\langle p_T \rangle$ of hadronic resonances and $\pi/K/p$ in Pb–Pb collisions at $\sqrt{s} = 5.02$ TeV.

resonance signal. A fit with (non) relativistic Breit-Wigner or Voigtian function combined with a residual background function (polynomial or Maxwell-Boltzmann) to the signal is performed for the raw yield extraction for each measured p_T interval for different centrality/multiplicity. Figure 1 shows examples of the reconstructed $K^*(892)^0$ (left) in differential p_T bin after background subtraction in pp collisions at 13.6 TeV. To measure the resonance yield per unit of p_T and rapidity per event, corrections such as vertex reconstruction efficiency, trigger efficiency, signal loss correction factor, branching ratio correction and detector acceptance times the resonance reconstruction efficiency, calculated by detailed Monte Carlo study are applied. A detailed study of the systematic uncertainty of the measurement, associated with the selection of events, tracks, particle identification, yield extraction method, and detector-related interactions is performed for each hadronic resonance measurement. The total systematic uncertainties is obtained by adding in quadrature each of these contributions.

2.1 Results and Discussion

After the resonance signal and fully corrected invariant mass spectrum, the mean- p_T , particle integrated yield, and particle yield ratio are calculated. Figure 1 shows the p_T -integrated yield of $\Lambda(1520)$ (middle) in high-multiplicity pp collisions at 13 TeV and the $\langle p_T \rangle$ of $K^*(892)^\pm$, $K^*(892)^0$ and $\phi(1020)^0$ compared to $\pi/K/p$ in Pb–Pb collisions at $\sqrt{s} = 5.02$ TeV. The $\langle p_T \rangle$ increases with increasing centrality due to the boost in momentum due to interactions with nearby hadrons. The $\langle p_T \rangle$ shows the mass ordering of the particle species except for protons in the low multiplicity region.

Figure 2 shows (left) the estimation of the kinetic freezeout temperature (T_{kin}) from the measurement of the $K^*(892)^0$ yield by using the hadron resonance gas model in partial chemical equilibrium, HRG-PCE model, in Xe–Xe and Pb–Pb collisions. The measured resonance yield to charge particle yield ratio is used for the estimate of the hadronic medium lifetime by considering a negligible regeneration of the resonance yield inside the hadronic medium. Figure 2 (middle) shows the estimated hadronic lifetime by using the measurements of $\rho(770)^0$ [5], $K^*(892)^0$, $K^*(892)^\pm$ [6] and $\Lambda(1520)$ [7] resonances in Pb–Pb collisions at 2.76 and 5.02 TeV. The lack of knowledge of the fraction of regenerated resonance yield from the hadronic medium is a key driving factor for providing the different hadronic phase lifetimes. Figure 2 (right) shows the summary of the measured resonance yield ratios to stable particles with similar quark content, i.e. $\rho(770)^0/\pi$, $K^*(892)^0/K$, $K^*(892)^\pm/K$, $\Sigma(1385)^\pm/\Lambda$,

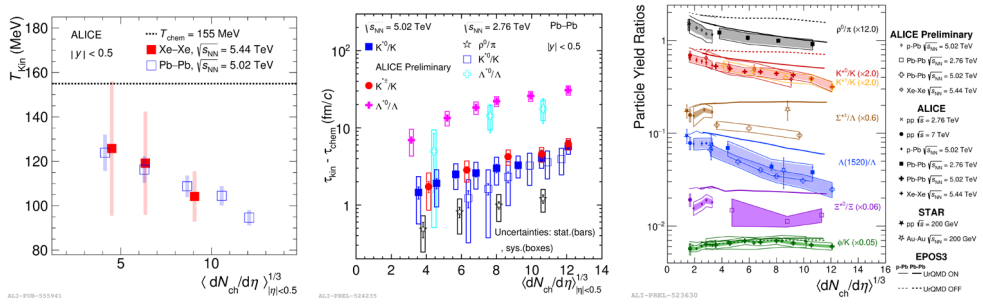


Figure 2. The estimation of kinetic-freezeout temperature, (T_{kin}) by using PCE model (left) and calculated hadronic medium lifetime from short-lived hadronic resonances in Pb–Pb collisions at 2.76 and 5.02 TeV. (Right) A set of light-flavored resonance particle yield ratios measured by ALICE and their comparison with EPOS3 with and without UrQMD model used for the hadronic medium interactions.

$\Lambda(1520)/\Lambda$, $\Xi(1530)^0/\Xi$ and $\phi(1020)^0/K$ in pp, p–Pb, and Pb–Pb collisions for various sets of collision energies measured by ALICE. These results show a suppression of the short-lived resonances i.e. $\rho(770)^0$, $K^*(892)^0$, $K^*(892)^\pm$ [6], Ξ , $\Sigma(1385)^\pm$ and $\Lambda(1520)$, which is expected due to rescattering of their decay daughters inside the hadronic medium produced in central/high multiplicity heavy-ion collisions as compared to peripheral Pb–Pb, p–Pb and pp collisions. The predictions from EPOS3 [8] Monte Carlo model predictions with/without an UrQMD afterburner including/excluding the hadronic medium interaction are also shown for each resonance. The longer-lived $\phi(1020)^0$ is not suppressed in central collisions as it decays outside the hadronic medium and the decay daughters are unaffected by it.

3 Conclusion

The overview of the most recent measurements of the hadronic resonance by ALICE is presented. The results from short-lived resonances such as $\rho(770)^0$, $K^*(892)^0$, $K^*(892)^\pm$, $\Xi(1530)^0$, $\Lambda(1520)$ show a suppressed yield in the high multiplicity/centrality as compared to low multiplicity/centrality and pp collisions. These results suggest the dominance of (pseudo) elastic re-scattering of the decay daughters over re-generation in the dense and interacting hadronic medium that exists between the chemical and kinetic freezeout stages of the heavy-ion collisions. The long-lived ϕ -meson does not show any suppression in Pb–Pb, pp and p–Pb collisions and suggesting that it decays outside of the fireball. These measurements further support that the hadronic phase lasts long enough to cause a significant reduction of the reconstructible yield of the short-lived hadronic resonances.

References

- [1] A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **772** (2006), 167-199
- [2] F. Becattini and R. Fries, Landolt-Bornstein **23** (2010), 208
- [3] J. Cleymans and K. Redlich, Phys. Rev. Lett. **81** (1998), 5284-5286
- [4] ALICE Collaboration, K. Aamodt *et al.* [ALICE], JINST **3** (2008), S08002
- [5] ALICE Collaboration, S. Acharya *et al.* [ALICE], Phys. Rev. C **99** (2019) no.6, 064901
- [6] ALICE Collaboration, S. Acharya *et al.* [ALICE], [arXiv:2308.16119 [nucl-ex]]
- [7] ALICE Collaboration, S. Acharya *et al.* [ALICE], Phys. Rev. C **99** (2019), 024905
- [8] A. G. Knospe, C. Markert, K. Werner, J. Steinheimer and M. Bleicher, Phys. Rev. C **93** (2016) no.1, 014911