Resonance production in ALICE

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Abstract. Short-lived hadronic resonances provide the means to study properties of the quark-gluon plasma and the hadronic phase produced in heavy-ion collisions at the LHC. In these proceedings we review the most recent ALICE results on resonance production in pp, p-Pb and Pb-Pb collisions at different energies.

1. Introduction
Resonances are excited hadronic states with lifetimes comparable to that of the fireball produced in heavy-ion collisions. Resonances are copiously produced and can be measured in different collision systems even at the highest multiplicities achieved in central heavy-ion collisions at the LHC energies. Hadronic resonances are well suited to study different aspects of heavy-ion collisions. The hot and dense medium produced in such collisions can modify the spectral shapes of resonances. Due to their short lifetimes, resonances are sensitive to rescattering and regeneration in the time interval between the chemical and kinetic freeze-outs. Therefore they can be used as probes to infer properties of the hadronic phase. Along with stable hadrons, resonances contribute to the systematic study of parton energy loss and of the anomalous baryon to meson ratio at intermediate transverse momentum ($p_T$). Measurements in small systems are used as a reference and are studied as a function of multiplicity in search of the potential onset of collective phenomena.

2. Suppression of high-$p_T$ hadron production
For rare hard scattering processes nuclear matter effects are studied by means of the nuclear modification factor $R_{AA}$, which is defined as a ratio of particle yields measured in heavy ion and pp collisions scaled by the corresponding number of binary inelastic nucleon-nucleon collisions. Figure 1 reports the nuclear modification factors measured in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for charged pions, kaons and (anti)protons [1] compared to factors for $\phi(1020)$ and $\rho(770)^0$ mesons (hereafter $\phi$ and $\rho^0$). One can see that in central Pb-Pb collisions production of all hadrons is similarly suppressed and there is no dependence of suppression on particle mass or quark composition within uncertainties. There is a clear species dependence of $R_{AA}$ at intermediate transverse momentum, however this difference can not be interpreted from these measurements only.
Figure 1. Nuclear modification factors $R_{AA}$ measured for charged pions, kaons and protons [1] in most central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In plots (a) and (b) measurements for charged hadrons are compared to that for $\phi$ and $p^0$ mesons, respectively.

3. Baryon anomaly and resonance production at intermediate transverse momentum
At intermediate $p_T$ the baryon anomaly is observed in central heavy-ion collisions, which manifests itself in increased baryon to meson ratios like $p/\pi$ or $\Lambda/K^0$ [2,3]. The mechanism responsible for this enhancement is not yet fully understood. It could be a particle mass effect consistent with hydrodynamic models [4,5] or a quark count effect predicted by recombination models [6,7]. In this respect the $\phi$ meson, consisting of the two valence quarks and having a mass very close to that of a proton is very well suited for discriminating between these mechanisms.

Figure 2 shows $p/\phi$ ratios measured as a function of transverse momentum in pp and most central p-Pb and Pb-Pb collisions [8,9]. The ratio evolves and flattens in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. It means that protons and $\phi$ mesons production spectra have very similar shapes at intermediate transverse momentum. It indicates that shapes of the particle spectra are mostly determined by particle masses as predicted by hydrodynamic models. The same figure also shows the $p/\phi$ ratio in central p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. One can see that in such collisions the $p/\phi$ ratio also flattens at very low momentum, which could indicate onset of collectivity.

Figure 2. Ratio $p/\phi$ as a function of transverse momentum in pp, and central p-Pb and Pb-Pb collisions at different energies [8,9].
4. Resonance production at low-\(p_T\) and properties of the hadronic phase

Low-\(p_T\) phenomena are studied by measuring integrated particle yields and mean transverse momenta for \(\rho^0\), \(K^*(892)^0\) (hereafter \(K^0\)) and \(\phi\) mesons. Figure 3 presents the system size dependence of \(K^0/K\), \(\phi/K\) and \(\rho^0/\pi\) ratios measured in pp, p-Pb and Pb-Pb collisions [8,9]. The \(\phi/K\) ratio is consistent between pp, p-Pb and Pb-Pb collisions within uncertainties. It is also consistent with prediction of grand-canonical thermal model with a chemical freeze-out temperature of 156 MeV [10,11]. At the same time the \(K^0/K\) and \(\rho^0/\pi\) ratios exhibit a suppression from pp to central Pb-Pb collisions and the thermal model calculations are consistent with data in peripheral collisions only. This behavior is in qualitative agreement with expectations from rescattering of daughter particles of very short lived \(K^0\) and \(\rho^0\) mesons in the hadronic phase. At the same time \(\phi\) meson behaves as a stable particle because of its much longer lifetime.

It is interesting to note that multiplicity dependent measurements in pp and p-Pb show smooth transition of \(K^0/K\) ratio to peripheral Pb-Pb points, hinting to the possible presence of a finite-lifetime hadronic phase in the highest multiplicity collisions of small systems.

The measured \(K^0/K\) and \(\rho^0/\pi\) ratios are compared to EPOS3 [12] calculations in figure 3. Calculations were performed with and without hadronic cascade modeled with UrQMD [13,14]. Without UrQMD no significant system size dependence is predicted for the ratios. When UrQMD is enabled the measured evolution of \(K^0/K\) and \(\rho^0/\pi\) ratios with multiplicity in Pb-Pb collisions is well reproduced. This suggests that the observed suppression for \(K^0\) and \(\rho^0\) originates from rescattering of daughter particles in the hadronic phase.

![Figure 3](image)

**Figure 3.** System size dependence of (a) \(K^0/K\), \(\phi/K\) and (b) \(\rho^0/\pi\) ratios measured in pp, p-Pb and Pb-Pb collisions at different energies. Results are compared to EPOS3 and thermal model calculations.

Several models relate particle ratios to chemical freeze out temperature and hadronic phase lifetime [15,16]. The temperature was estimated equal to 156 MeV in 0-20% central Pb-Pb collisions from thermal model fits to ratios of stable particles [10,11]. Using the measured ratio of \(K^0/K = 0.20 \pm 0.01\) (stat) \(\pm 0.03\) (syst) in 0-20% central Pb-Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV one can estimate hadronic phase lifetime to be larger than 2 fm/c.

Any modifications in the shapes of the production spectra should change the mean transverse momentum (\(\langle p_T \rangle\)). Figure 4 shows multiplicity dependence of \(\langle p_T \rangle\) measured for \(K^0\), \(\phi\) mesons and protons in pp, p-Pb and Pb-Pb collisions [8,9]. In central Pb-Pb collisions, particles of similar mass have the same \(\langle p_T \rangle\), which is consistent with hydrodynamics. Multiplicity dependent measurements in pp and p-Pb show a very smooth transition between the systems and \(\langle p_T \rangle\) rises faster with multiplicity reaching values similar to central Pb-Pb. This may indicate stronger radial flow or different particle production mechanisms in small systems.
Figure 4. Mean transverse momenta measured for $K^0$, $\phi$ mesons and protons as a function of multiplicity in pp, p-Pb and Pb-Pb collisions at different energies.

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