Energy and multiplicity dependence of hadronic resonance production with ALICE at the LHC

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Abstract. The study of hadronic resonances plays an important role both in pp and in heavy-ion collisions. Since the lifetimes of short-lived resonances are comparable with the lifetime of the fireball formed in heavy-ion collisions, regeneration and re-scattering effects can modify the measured yields, especially at low transverse momentum. Measurements in pp collisions at different energies constitute a baseline for studies in heavy-ion collisions and provide constraints for tuning QCD-inspired event generators. Furthermore, high multiplicity pp collisions, where the density and the volume of the system are expected to be larger compared to minimum bias pp collisions, can help in the search for the onset of collective phenomena. Here we present recent results on short-lived hadronic resonances obtained by the ALICE experiment at LHC energies in different collision systems (pp, p–Pb and Pb–Pb) including new results obtained in Xe–Xe collisions. The ALICE results on transverse momentum spectra, yields and their ratios to long-lived particles will be discussed.

1. Introduction
One of the main motivations for studying hadronic resonance production in heavy-ion collisions is to learn more about the properties (temperature and lifetime) of the hadronic phase, the late-stage evolution of these collisions. The decay products of short-lived resonances may re-scatter in the hadronic phase, leading to a reduction in the measurable resonance yields; conversely, resonance yields may also be regenerated by pseudo-elastic scattering of hadrons through a resonance state [1, 2, 3, 4]. Moreover, hadronic resonances, along with stable hadrons, allow the study of properties of heavy-ion collisions, both in the early (quark-gluon plasma) and late (hadronic) stages of their evolution. The various mechanisms that may determine the shapes of particle $p_T$ spectra, including parton fragmentation, quark recombination, hydrodynamic flow, re-scattering, and regeneration, can be studied through comparison of different measurements of multiple particle species with differing masses and quark content.

Particle production in pp collisions at collider energies originates from the interplay of perturbative (hard) and non-perturbative (soft) QCD processes, which can only be modeled phenomenologically. The measurements in pp collisions at different energies constitute a baseline for studies in heavy-ion collisions and provide constraints for tuning event generators such as PYTHIA [5] and EPOS-LHC [6]. Recent observations on the enhancement of (multi-)strange hadrons [7, 8], double-ridge structure [9, 10], non-zero $v_2$ coefficients [11] and mass ordering in hadron $p_T$ spectra [12, 13] indicate the presence of collective-like phenomena in small systems such as p–Pb and pp collisions at LHC energies. Furthermore, a continuous transition of light-flavour hadron to pion ratios as a function of charged particle multiplicity density $dN_{ch}/d\eta$ from...
Figure 1. Mean transverse momentum $\langle p_T \rangle$ values of K$^*$, p and $\phi$ in various collision systems [15, 13, 23] as a function of charged-particle multiplicity density at mid-rapidity.

pp to p–Pb and then to Pb–Pb collisions was observed [12, 13]. However the origin of these effects is not yet fully understood and it remains an open question whether the underlying mechanisms are the same in these three collision systems.

The ALICE experiment has measured the production of a rich set of hadronic resonances, such as $\rho$ (770)$^0$ [14], K$^*$ (892)$^0$ [15], $\phi$ (1020) [15], $\Sigma$ (1385)$^{\pm}$ [16, 17], $\Lambda$ (1520)$^0$ [18] and $\Xi$ (1530)$^0$ [16, 17] in pp, p–Pb and Pb–Pb collisions at various energies at the LHC, and also in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV collected in late 2017. This paper presents the recent results on hadronic resonance production from the ALICE experiment. A detailed review of the ALICE detector and its performance can be found in [19, 20].

2. Spectral shape and mean $p_T$

In Pb–Pb collisions and in elementary collisions $p_T$ spectra get harder with increasing multiplicity. While in Pb–Pb collisions this effect is attributed to collective expansion, the origin of collective flow-like effect in small collision systems is not clear. However some collective expansion models as EPOS-LHC [6] or models as PYTHIA [5] or DIPSY [21] with the color reconnection mechanism are able to mimic these collective effects in small collision systems.

The mean transverse momentum $\langle p_T \rangle$ provides first-order characterization of spectral shapes. The $\langle p_T \rangle$ values of the K$^*$, p, and $\phi$ (which all have similar masses) are shown in Fig. 1 for different collision systems. In central A–A collisions, mass ordering of $\langle p_T \rangle$ values is observed; particles with similar masses have similar $\langle p_T \rangle$. This behavior has been interpreted as evidence that radial flow could be a dominant factor in determining the shapes of hadron $p_T$ spectra in central A–A collisions. However, this mass ordering breaks down for peripheral Pb–Pb collisions, as well as for p–Pb and pp collisions, where the proton is observed to have lower $\langle p_T \rangle$ values than the two mesonic resonances. The $\langle p_T \rangle$ values in pp and p–Pb collisions also follow different trends and rise faster with multiplicity than in Pb–Pb collisions. The slope of $p_T$ spectra in selected multiplicity interval, normalized to the corresponding minimum bias spectra, show an increase with increasing multiplicity in the transverse momentum region $p_T < 4$ GeV/$c$ and have the same slope/shape for higher $p_T$ [12]. The multiplicity dependence of the slope of the spectra
at low $p_T$ was also observed for stable hadrons [22].

It is interesting to note that the yield of $K^{*0}$ and $\phi$, normalized by the mean charge particle multiplicity density $\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$ for $K^{*0}$ (left panel) and $\phi$ (right panel), shows a behavior with $\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$ that is independent of collision energy and system for pp and p–Pb collisions.

3. Resonance ratios

The measured hadronic resonance yields may be influenced by several factors: initial yield at chemical freeze-out, resonance lifetime, scattering cross-section of resonance decay daughters and lifetime of the hadronic phase of the system evolution. A comparison of measured resonance yields to the production rate of its stable counterpart can provide information about the late stage of the system evolution. Hadronic resonances reported here are reconstructed via the detection of their strong-decay daughters. In order to check the presence of a suppression in the production of the resonances and to study whether the strength of the suppression is related to the system size, the ratios of the $p_T$-integrated particle yields $\rho^0/\pi$, $K^{*0}/K$, $\Sigma^{*+}/\Sigma$, $\Lambda^*/\Lambda$, $\Xi^+/$ and $\phi/K$ have been reported as a function of the cubic root of the charged particle multiplicity density $\langle dN_{ch}/d\eta\rangle^{1/3}$ for different colliding systems; pp at 7 TeV, p–Pb at 5.02 TeV, Pb–Pb at 2.76 and 5.02 TeV and Xe–Xe collisions at 5.44 TeV nucleon-nucleon centre of mass energies (Fig. 3). The lifetimes of the resonances reported in this figure increase from the top down ($1.3$ fm/$c$ ($\rho(770)^0$) $< 4.2$ fm/$c$ ($K^{*}(892)^0$) $< 5.5$ fm/$c$ ($\Sigma(1385)^{\pm}$) $< 12.6$ fm/$c$ ($\Lambda(1520)^0$) $< 21.7$ fm/$c$ ($\Xi(1530)^0$) $< 46.4$ fm/$c$ ($\phi(1020)$)). A centrality-dependent suppression is clearly observed for $\rho^0/\pi$, $K^{*0}/K$ and $\Lambda^*/\Lambda$ in Pb–Pb collisions. The observed suppression may indicate the dominance of re-scattering mechanisms, compared to the regeneration ones. No centrality dependence across the different systems is observed for resonances such as the $\phi$ and the $\Xi^+$ which live longer than the $K^{*0}$ and the $\rho^0$. They decay predominantly after the end of the hadronic phase and their yield should not be affected by the regeneration and the re-scattering effect.

The behaviour of the $\Sigma^{*+}/\Lambda$ is peculiar considering that $\Sigma^{*+}$ and $K^{*0}$ have similar lifetime. The distribution of this ratio is flat in small system (d–Au and p–Pb) [17] and similar values are measured at RHIC and LHC energies. Furthermore, no suppression is observed in central Au–Au collisions at RHIC energies [24]. The constant behaviour of the yield ratios of excited
Figure 3. Ratios of resonances and ground state yields $\rho^0/\pi$ [14], $K^*0/K$ [15], $\Sigma^{\pm}/\Sigma$ [17], $\Lambda^*/\Lambda$ [18], $\Xi^*/\Xi$ [16, 17] and $\phi/K$ [15] as a function of the cubic root of the charged particle multiplicity density $dN_{ch}/d\eta$ for various collision systems. STAR data are also shown for $\Sigma^*/\Sigma$ [24]. The error bars show the statistical uncertainty, while the empty and dark-shaded boxes show the total systematic uncertainty and the uncorrelated contribution across multiplicity bins, respectively. Continuous lines show the distributions obtained by EPOS3 model [25]. The dashed lines represent the distributions estimated by EPOS3 if no final state interactions are taken into account.

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to ground-state hyperons with same strangeness content has to be confirmed at LHC energies in ion-ion collisions and should indicate that neither regeneration nor re-scattering dominates with increasing collision system size. It is interesting to note that the behaviour of the ratios is at least qualitatively reproduced by calculations using the EPOS3 model [25], which takes the regeneration and re-scattering effects of the resonance decay particles in the hadronic phase explicitly into account by UrQMD [26] (see continous curves in Fig. 3). The same model EPOS3 without an afterburner, i.e. with URQMD off, (dashed cureves in Fig. 3) is not able to reproduce the observed trend.

Furthermore, a hint of multiplicity-dependent suppression of the $K^*0/K$ and $\rho^0/\pi$ ratios has been observed in pp and p–Pb collisions, which may be an indication of the presence of a hadron-gas phase in high-multiplicity pp and p–Pb collisions.

4. Energy dependence of resonance production in pp collisions

The evolution of the transverse momentum spectra with collision energy is clearly seen in Fig. 4. The left and right panels of this figure show the ratios of the $K^*(892)^\pm$ transverse-momentum spectra obtained in pp collisions at $\sqrt{s} = 8$ and 13 TeV to $\sqrt{s} = 5.02$ TeV and the ratios of $\pi$ transverse momentum spectra measured in pp collisions at $\sqrt{s} = 5.02, 7$ and 13 TeV to $\sqrt{s} = 2.76$ TeV. Both resonance and stable hadrons exhibit the same behaviour. For $p_T > 1$ GeV/c a clear hardening of the $p_T$ spectrum is observed when increasing the energy, while at low $p_T$ the same yield is measured, within the estimated uncertainties, at the studied
Figure 4. (Left panel) Ratios of transverse momentum spectra of $K^{±}$ (left panel) and $\pi$ (right panel) in inelastic pp events at $\sqrt{s} = 8$ and 13 TeV to 5.02 TeV and $\sqrt{s} = 5.02, 7$ and 13 TeV to 2.76 TeV, respectively.

Figure 5. Particle ratios $\phi/K$ (left panel) and $K^{±}/K$ and $K^{*0}/K$ (right panel) in pp, d–Au, p–Pb, Au–Au and Pb–Pb collisions [15, 27, 28, 29, 30] as a function of the collision energy $\sqrt{s_{NN}}$. Some of the data have been shifted horizontally for visibility. The expectations from a thermal model calculation with a chemical freeze-out temperature of 156 MeV [32] for the most central collisions Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are also shown.

energies. This suggests that the particle production mechanism in the soft region is independent of the collision energy, while the increase of the slope for $p_{T} > 1$ GeV/$c$ suggests an increasing contribution of hard scattering processes in particle production with the collision energy. Similar behaviour has been also observed for other resonances and stable hadrons [31].

The $K^{*}/K$ and $\phi/K$ yield ratios (see Fig. 5) do not show a strong dependence on the colliding system or the center of mass system energy, and have values equal to the ratios estimated in thermal model calculations with a chemical freeze-out temperature of 156 MeV [32]. Only $K^{*0}/K$ ratios measured in central A–A collisions both at RHIC and LHC energies are lower, which should be the result of re-scattering and regeneration effects, with the first dominating over the second.
5. Conclusions
The latest measurements on resonance production performed for various systems (from pp to Pb–Pb including Xe–Xe) are reported here. One can observe that particle production in elementary collisions also. The origin of this collective flow-like effect in small collision systems to collective expansion, i.e. a hardening of the $p_T$ spectra with increasing multiplicity, is observed in elementary collisions also. Moreover a characteristic behaviour of heavy-ion collision spectra attributed independent of collision system and collision energy at LHC energies and it is driven by the most central collisions compared to small collision systems, while no suppression is present for resonances such as $\Xi(1530)^0$ and $\phi(1020)$ with a lifetime larger than the fireball one at these energies (about 10 fm/c). The trend of the resonance over stable particle ratios is qualitatively described by the EPOS3 model with UrQMD as afterburner to take into account hadronic interactions. An intriguing hint of suppression for short-lived resonances is also observed in high multiplicity pp and p–Pb collisions, suggesting the presence of a hadronic phase also in these elementary collisions. In pp collisions a hardening of the $p_T$ spectrum is observed when increasing the energy while the relative particle abundance is rather independent of the c.m. system energy.

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