Hadronic resonance production and interaction in $p$-$Pb$ collisions at LHC energies in EPOS3

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Using the EPOS3 model with UrQMD to describe the hadronic phase, we study the production of short-lived hadronic resonances and the modification of their yields and $p_T$ spectra in $p$-$Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. High-multiplicity $p$-$Pb$ collisions exhibit similar behavior to mid-peripheral $Pb$-$Pb$ collisions at LHC energies, and we find indications of a short-lived hadronic phase in $p$-$Pb$ collisions that can modify resonance yields and $p_T$ spectra through scattering processes. The evolution of resonance production is investigated as a function of the system size, which is related to the lifetime of the hadronic phase, in order to study the onset of collective effects in $p$-$Pb$ collisions. We also study hadron production separately in the core and corona parts of these collisions, and explore how this division affects the total particle yields as the system size increases.

I. INTRODUCTION

In heavy-ion collisions at LHC energies, the Quark Gluon Plasma (QGP), a state of partonic matter consisting of deconfined quarks and gluons, is expected to be created. As the system expands and cools, it undergoes a phase transition into a gas of hadrons. Inelastic interactions among the hadrons stop at the “chemical freeze out” at temperature $T_{ch}$ and elastic interactions stop at the “kinetic freeze out” at temperature $T_{kin}$. Hadronic resonances with lifetimes on the order of a few fm/c are sensitive probes of the “fireball” due to the fact that they can decay and re-form throughout the full evolution of the hadronic phase [24]. Even after chemical freeze out, long-lived particles may pseudo-elastically scatter through a resonance state, thus increasing the resonance yield. Conversely, if short-lived resonances decay during the hadronic phase, their decay products may scatter with other components of the hadron gas (either elastically or pseudo-elastically through a different resonance); such “re-scattering” inhibits the reconstruction of the original resonance and reduces the measured yield. Measurements of resonances may therefore help us understand the properties of the hadronic phase, which influence the relative $p_T$-dependent strengths of the regeneration and re-scattering effects.

Recent measurements from the LHC experiments have shown that high-multiplicity $p$-$p$ and $Pb$-$Pb$ collisions exhibit similar behavior to peripheral $Pb$-$Pb$ collisions. The “hadrochemistry” of the system (the abundances of different hadron species) depends primarily on the charged-particle multiplicity of the collision, i.e., for a given multiplicity, hadron abundances are the same regardless of the collision system [11, 12]. As the multiplicity increases in $p$-$p$ and $Pb$-$Pb$ collisions, hadron $p_T$ spectra harden and the $p/p_\pi$ and $A/K_S^0$ ratios are enhanced at intermediate $p_T$ [24]; qualitatively similar behavior is also seen in $Pb$-$Pb$ collisions, where it may be attributable to collective flow [13, 14]. There are also hints of a multiplicity-dependent suppression of the yields of $K^+$($892)^0$ mesons in $p$-$p$ and $Pb$-$Pb$ collisions [15, 16, 17]. These results raise the question of whether collective effects may be present in the smaller collision systems.

In a previous paper [18], we studied the production of resonances in $Pb$-$Pb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the EPOS3 framework [25, 26], which includes the UrQMD model [29, 31] for the description of hadronic interactions in the hadronic phase. This paper extends that study to $Pb$-$Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV and presents additional results for the $Pb$-$Pb$ collision system. We use hadronic resonances, specifically modifications of their yields and $p_T$ spectra, to test the existence of a hadronic phase with non-zero lifetime in $Pb$-$Pb$ collisions.
collisions. We have produced 1.8 million p-Pb collisions with UrQMD turned on and the same number with UrQMD turned off. We have followed the approach of the ALICE Collaboration [9] and divided the p-Pb event sample into multiplicity classes using the charged-particle multiplicity in the pseudorapidity range \(2.8 < \eta_{\text{abs}} < 5.1\) (in the direction of the Pb beam), which is the same range spanned by the ALICE V0A scintillator array [10].

The EPOS3 model [25–27] describes the full evolution of a heavy-ion collision. The initial stage is treated via a multiple-scattering approach based on Pomerons and strings. The produced string segments are divided into core and corona contributions [28]. The core is taken as the initial condition for QGP evolution, for which we employ 3+1D viscous hydrodynamics. The corona part is simply composed of hadrons from string decays. The division between the core and corona parts of the collision is illustrated in Fig. 1, which shows the fractions of long-lived hadrons \((\pi, K, p, \Lambda, \Sigma, \Xi, \Omega, \text{and their antiparticles})\) produced in the different parts of the collisions, for both p-Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV and the Pb-Pb collision at \(\sqrt{s_{NN}} = 2.76\) TeV used in our previous paper [9]. Low-multiplicity (peripheral) collisions are dominated the corona, while central Pb-Pb collisions are core-dominated. High-multiplicity p-Pb collisions have approximately equal contributions from the core and the corona. After hadronization [32] of the fluid (core part), all hadrons, including those from the corona, are fed into UrQMD [29–31], which describes hadronic interactions in a microscopic approach. The chemical and kinetic freeze out occurs within this phase. Resonance signals have been previously studied using the UrQMD model [31–33–42].

![FIG. 1: (a): Fraction of particles originating from the core and corona parts of p-Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV and Pb-Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV when UrQMD is turned off.](image)

For more central collisions, the hadronic phase lasts longer \((i.e., \text{the time between chemical and kinetic freeze out increases})\), which would imply more hadronic interactions and could result in greater modification of resonance \(p_T\) spectra and yields. The hadronic lifetime estimated from EPOS3 calculations increases from 0.5 to 10 fm/c depending on centrality in Pb-Pb collisions as shown in Fig. 2. Here, we use \((dN_{ch}/d\eta)^{1/3}\), the cube root of the mean charged-particle multiplicity measured by ALICE [9] [11] at mid-rapidity \((|\eta_{\text{abs}}| < 0.5)\), as a proxy for the system size. Our new estimates for the hadronic-phase lifetime in p-Pb collisions appear to follow a similar trend to that seen in Pb-Pb collisions [9], with the highest multiplicity p-Pb collisions (0-5%) having similar hadronic lifetimes \((\approx 1.5 \text{ fm/c})\) and multiplicities to peripheral Pb-Pb collisions (70-80%). It should be noted that while these collisions produce similar charged-hadron multiplicities, they have quite different geometries. The multiplicity of charged hadrons (mostly pions) scales with the number of participant nucleons, and therefore scales with the event activity.

![FIG. 2: Lifetime of hadronic phase in p-Pb (red full circles) and Pb-Pb (black open circles) [9] collisions.](image)

### II. RESONANCE RECONSTRUCTION

Experimentally, hadronic resonances are reconstructed using the invariant mass method via measurements of the momenta of their decay daughters. Charged pions, charged kaons, and (anti)protons are often identified through measurements of energy loss \((dE/dx)\) in a Time Projection Chamber (TPC) and/or the velocity in a Time-of-Flight (TOF) detector. Weakly decaying particles, such as \(\Lambda\) and \(\Xi\), can be selected based on their decay topologies, which adds further constraints. Table [II][42] lists the specific decay channels investigated in the EPOS3 approach, which are the same channels used experimentally by STAR and ALICE. In these model calculations, resonances that decay via the channels listed in Table I are flagged and the decay...
products are followed throughout the system evolution. If neither decay product undergoes a re-scattering, the resonance is flagged as reconstructable. Throughout this paper, the resonance yields, both from these calculations and from experiment, are corrected by the appropriate branching ratio. The shorthand notations listed in the second column of Table I will sometimes be used to denote these resonances. Results for particles and antiparticles are always combined, even when not explicitly noted.

While EPOS3 tends to overestimate the values of the ratios, it gives a good qualitative description of their system-size evolution. EPOS3 indicates no significant suppression of the $\phi(1020)/K$ and $\Sigma(1385)^{\pm}/A$ ratios in $p$-Pb and $A$-$A$ collisions, consistent with ALICE [4] [7] [8] [12] and STAR [13] measurements. The ALICE data suggest a small multiplicity-dependent suppression of the $K^*(892)^0/K$ ratio in $p$-Pb collisions [4] and a similar suppression may also be visible in a preliminary measurement of the $\rho(770)^0/\rho^{\pm}$ ratio in the same collision system [13]. ALICE measurements of the $K^*(892)^0/K$ and $\rho(770)^0/\rho^{\pm}$ ratios in Pb-Pb collisions show a larger centrality-dependent suppression [7] [8] [10]. These trends in $p$-Pb and Pb-Pb collisions are qualitatively reproduced by EPOS3. The ALICE data indicate that the $\Lambda(1520)/A$ ratio does not change with multiplicity in Pb-Pb collisions [17] but is suppressed in central Pb-Pb collisions [19]. This trend is also qualitatively described by EPOS3. The ALICE measurement of the $\Xi(1530)^{0}/\Xi$ ratio is multiplicity-independent for $p$-Pb collisions [12], which are also consistent with a preliminary measurement in peripheral Pb-Pb collisions [15]. This behavior is also qualitatively reproduced by EPOS3. However, the preliminary ALICE measurement suggests a weak suppression of the $\Xi(1530)^{0}/\Xi$ ratio in (mid-)central Pb-Pb collisions (with values in the range 0.16–0.26); the magnitude of this suppression is not described by EPOS3. The EPOS3 model predicts that the $\Delta(1232)^{++}/p$ ratio should not depend on multiplicity in $p$-Pb collisions, which is a reasonable expectation in light of STAR’s measurement [14] of this ratio in $d$-$Au$ collisions.

In summary, the multiplicity evolution of these various ratios is qualitatively well described by EPOS3, with the possible exception of the $\Xi(1530)^{0}/\Xi$ ratio in large collision systems. Furthermore, we observe smooth evolution of the particle yield ratios from the lowest multiplicity $p$-Pb collisions to central Pb-Pb collisions, with little or no difference between $p$-Pb and Pb-Pb collisions at similar charged-particle multiplicities.

The role played by the resonance lifetime should be noted. The two resonances with the clearest suppression, $\rho(770)^0$ and $K^*(892)^0$, are both short-lived. In contrast, the $\phi(1020)$ has a long lifetime and is not suppressed. $\Lambda(1520)$ and $\Xi(1530)^{0}$ have intermediate lifetimes within the range considered, and neither is suppressed in $p$-Pb collisions. In $p$-Pb collisions, $\Lambda(1520)$ is suppressed and there is weaker suppression of $\Xi(1530)^{0}$, with a lifetime approximately half that of the $\phi(1020)$ and twice that of the $\Lambda(1520)$. However, the $\Sigma(1385)^{\pm}$ and $\Delta(1232)^{++}$ are short-lived, but are not suppressed (indeed, they are enhanced from low to high multiplicity beyond the statistical uncertainties of the EPOS3 calculations). Taken together, these results indicate that while the lifetime is an important factor in determining whether a resonance yield is suppressed, it is not the only factor. One must also account for (1) the various scattering cross-sections of the decay products; (2) the different

### TABLE I: The resonances are constructed experimentally via the decay channels listed [13]. These same decays are used in our studies of resonances in EPOS3 and UrQMD.

| Resonance     | Shorthand | Decay Channel | Branching Ratio | Lifetime (fm/c) |
|---------------|-----------|---------------|-----------------|-----------------|
| $\rho(770)^0$ | $\rho^0$  | $\pi^+ + \pi^-$ | 1               | 1.335           |
| $K^*(892)^0$  | $K^{*0}$  | $\pi^+ + K^+$ | 0.67            | 4.16            |
| $\phi(1020)$  | $\phi$    | $K^+ + K^-$   | 0.492           | 46.26           |
| $\Delta(1232)^{++}$ | $\Delta^{++}$ | $\pi^+ + p$   | 1               | 1.69            |
| $\Sigma(1385)^+$ | $\Sigma^{+}$   | $\pi^+ + A$   | 0.870           | 5.48            |
| $\Sigma(1385)^-$ | $\Sigma^{-}$   | $\pi^- + A$   | 0.870           | 5.01            |
| $\Lambda(1520)$ | $\Lambda^*$ | $K^- + p$     | 0.225           | 12.54           |
| $\Xi(1530)^0$ | $\Xi^{0}$  | $\pi^+ + \Xi^-$ | 0.67           | 22              |

III. RESONANCE YIELDS AND RATIOS

Figure 3 shows a summary of EPOS3 calculations of the ratios of resonance yields to those of long-lived hadrons (usually with the same strange-quark content) as a function of event multiplicity for Pb-Pb [9] collisions, along with our new calculations for $p$-Pb collisions. The abscissa $\langle dN_{ch}/dp \rangle$ is commonly used as a proxy for the event activity and is often used to compare results from different collision systems. Its use in nucleus-nucleus collisions is connected to femtoscopy studies [4] [16], which suggest that it scales in proportion to the radius of the collision system. Under the simple assumption that the probability of re-scattering is proportional to the distance traveled through the hadronic medium, an exponential decrease in measured resonance yields as a function of the system radius or $\langle dN_{ch}/dp \rangle^{1/3}$ might be expected. The EPOS3 results are compared to experimental results from ALICE. In a few cases, ALICE measurements are unavailable and measurements from STAR are used instead. It should be noted that while the STAR results are from lower energies than the EPOS3 calculations, these ratios do not generally depend strongly on collision energy. It is notable that particle yield ratios calculated by EPOS3 in $p$-Pb collisions are consistent with the Pb-Pb values for similar multiplicities, even though the initial geometries of the collision systems are very different.
Q values of the decays; (3) the complicated interplay among re-scattering, regeneration, and feed-down; and (4) the interplay between the core and corona parts of the collision.

Figure 4 shows the system-size evolution of various particle ratios given by EPOS3 for p-Pb and Pb-Pb collisions. The figure shows separately the ratios for particles produced in the core and in the corona, as well as for the combined core+corona system. The core+corona ratio is then further modified by interactions in the hadronic phase to give the final ratios. The core+corona ratio can be viewed as an interpolation between the extreme cases: the corona-only and core-only ratios. The system is mostly corona in small collisions and mostly core in large collisions, so the core+corona ratio can evolve with multiplicity even if the corona-only or core-only ratios are multiplicity-independent (e.g. the K/π⁺ ratio).

The decreases in the ρ(770)/π⁺ and K*(892)/K ratios are partly explained by the core-corona transition, with further suppression coming from UrQMD. Turning on UrQMD causes a small increase in the φ(1020)/K ratio for all multiplicities. The suppression in p-Pb collisions of the yields of short-lived resonances is therefore partly explained by the existence of a hadronic phase with a non-zero lifetime (about 2 fm/c in high-multiplicity p-Pb collisions). The question of whether an extended partonic phase is the precursor for the

FIG. 3: Ratios of resonance yields to long-lived hadrons as functions of the charged-particle multiplicity measured at mid-rapidity. EPOS3 data are shown for Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) [9] (thick lines) and p-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) (thin lines), with bands representing statistical uncertainties. The EPOS3 results are compared to experimental results, mostly from ALICE [4, 7, 8, 12, 16, 17, 19]. In a few cases, ALICE data are not available and STAR data for \( \sqrt{s_{NN}} = 200 \text{ GeV} \) are shown instead [13, 14]. For the experimental data, bars represent statistical uncertainties, open boxes represent the total systematic uncertainties, and shaded boxes represent systematic uncertainties uncorrelated between multiplicity classes. The particle symbols denote both particles and antiparticles.
extended hadronic phase is not answered here. It is also interesting to note the effect of the hadronic phase on the $p/\pi^\pm$ and $\Lambda/\pi^\pm$ ratios: interactions in the hadronic phase cause a significant suppression of the proton and $\Lambda$ yields, especially in central $A-A$ collisions, due to particle-antiparticle annihilation and absorption effects.

IV. RESONANCE TRANSVERSE MOMENTUM DISTRIBUTIONS

Figures 5 and 6 show the $p_T$ distributions of various resonances, as calculated using EPOS3 and measured by ALICE [12, 17]. The $p_T$ spectra of $K^*(892)^0$ and $\phi(1020)$ in $p$-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown in Fig. 5. In general, the EPOS3 spectra are softer (steeper negative slopes) than the measured spectra at low $p_T$ and harder (flatter slopes) at high $p_T$, with the best qualitative description of the shapes in the approximate range $2 \lesssim p_T \lesssim 4$ GeV/c. The agreement between the EPOS3 calculations and the measured spectra improves for lower multiplicity $p$-Pb collisions. EPOS3 calculations are shown with UrQMD (“UrQMD ON”) and without it (“UrQMD OFF”). The effect of turning UrQMD on is greatest for $p_T \lesssim 1$ GeV/c, resulting in a notable improvement in the description of the $K^*(892)^0$ meson $p_T$ spectra at low $p_T$. This behavior is consistent with the expectation that rescattering should be most important at low momenta.

The effects of UrQMD on $\phi(1020)$ $p_T$ spectra are fairly small. Similar behavior was observed for these resonances in Pb-Pb collisions.

Figure 6 also shows comparisons of EPOS3 calculations (with UrQMD on) and ALICE measurements [12, 17] of the $p_T$ spectra of three baryonic resonances in $p$-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV: $\Sigma(1385)^\pm$, $\Xi(1530)^0$, and $\Lambda(1520)$. The EPOS3 spectra tend to be softer than the measured ALICE spectra. The EPOS3 spectra for $\Sigma(1385)^\pm$ and $\Lambda(1520)$ provide fair descriptions of the ALICE data, while EPOS3 overestimates the $\Xi(1530)^0$ yields at low $p_T$.

Figure 6 shows the $p_T$ spectra given by EPOS3 in $p$-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for future comparison with experimental results. Note that turning on UrQMD leads to a large suppression of the $\rho(770)^0$ yield at very low $p_T$ ($p_T < 0.5$ GeV/c). Figure 6 also shows a comparison of the EPOS3 and ALICE $p_T$ spectra for $\rho(770)^0$ mesons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [16]. As for our previous studies of the $K^*(892)^0$ and $\phi(1020)$ in Pb-Pb collisions [9],
Lower subpanels: the ratios of the EPOS3 results to the ALICE measurements as functions of $p_T$ for the different centrality intervals. The shaded bands around unity represent the uncertainties of the measured data. (a-b): $K^+(892)^0 + K^-(892)^0$ without (a) and with (b) UrQMD. The ALICE data are the same in both panels. (c-d): $\phi(1020)$ without (c) and with (d) UrQMD. The ALICE data are the same in both panels. (e): $\Sigma(1385)^+ + \Sigma(1385)^-$ without. (f): $\Lambda(1520) + \bar{\Lambda}(1520)$ without. (g): $\Xi(1530)^0 + \bar{\Xi}(1530)^0$ without.

turning UrQMD on improves the agreement between the EPOS3 calculation and the ALICE data at low $p_T$, while the EPOS3 description of the spectra improves for more peripheral collisions.

Figure 7 shows the effect of UrQMD on the $p_T$ spectra of the $\rho(770)^0$, $K^+(892)^0$, and $\phi(1020)$ resonances in both $p$-Pb and $p$-Pb collisions. The effect is quantified by a ratio: the $p_T$ spectra obtained from the event samples produced with UrQMD are divided by the corresponding $p_T$ spectra produced without UrQMD. For both collision systems, a depletion is observed at low $p_T$, below 1-2 GeV/$c$. This depletion is due to scattering effects, but may be partly filled in due to regeneration. The depletion is much more pronounced for Pb-Pb collisions than for $p$-Pb and larger for the shorter lived resonances $\rho(770)^0$ and $K^+(892)^0$ than for $\phi(1020)$. There is also an enhancement of these resonances for intermediate $p_T$ in Pb-Pb collisions.
V. MEAN TRANSVERSE MOMENTA

The mean transverse momenta $\langle p_T \rangle$ of various common light-flavor hadron species, including several resonances, are shown in Fig. 8 for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [19]. The results of EPOS3 calculations...
FIG. 8: Mean transverse momenta $\langle p_T \rangle$ of different particle species in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (thin and thick lines, respectively). EPOS3 calculations were performed with and without a hadronic cascade modeled with UrQMD (solid and dashed lines, respectively). Values of $\langle p_T \rangle$ derived from measurements by the ALICE Collaboration are also shown for p-Pb [3, 4, 22] and Pb-Pb collisions [6–8, 16, 20, 21] (open and filled symbols, respectively).

with and without a hadronic cascade are compared to measurements from the ALICE Collaboration [3, 4, 6–8, 12, 16, 17, 19, 22], when available. For $K^0_S$, $\Lambda$, $\Xi^-$, and $\Omega$ in Pb-Pb collisions, we have found the $\langle p_T \rangle$ values by fitting the published ALICE $p_T$ spectra to extrapolate the yields at low $p_T$. EPOS3 provides a good description of most of the measured $\langle p_T \rangle$ trends in Pb-Pb collisions, but has a tendency to slightly underestimate the $\langle p_T \rangle$ values for p-Pb collisions. Turning on the hadronic cascade (i.e., turning on UrQMD) frequently increases the $\langle p_T \rangle$ values and generally results in a better description of the measured data. The effect of turning on UrQMD is quantified in Fig. 9, which shows the ratio of $\langle p_T \rangle$ values with and without UrQMD.
for low- and high-multiplicity \( p \)-\( \text{Pb} \) collisions and for peripheral and central \( p \)-\( \text{Pb} \) collisions for each particle species. UrQMD produces the largest changes for the short-lived resonances (\( \rho(770)^0 \) and \( K^*(892)^0 \)), as well as the proton and \( \Lambda \). The effect of the hadronic cascade tends to be the greatest in central \( p \)-\( \text{Pb} \) collisions and decreases for smaller collision systems (consistent with the decreasing hadronic phase lifetimes discussed above). Interestingly, the short-lived \( \rho(770)^0 \) meson is affected even in low-multiplicity \( p \)-\( \text{Pb} \) collisions, although it should be noted that even in that multiplicity class (80-100%), the estimated hadronic phase lifetime is still the same order of magnitude as the lifetime of the \( \rho(770)^0 \) meson.

Turning on UrQMD greatly improves the description of the measured proton \( R_{AA} \). For the three resonances, \( \rho(770)^0 \), \( K^*(892)^0 \), and \( \phi(1020) \), the measured nuclear modification factors are well described by EPOS3 with UrQMD. In contrast, removing the hadronic cascade results in a worse description for the \( K^*(892)^0 \) at low \( p_T \), indicating that scattering effects do indeed modify the yields of this resonance at low \( p_T \). Similarly, the description of \( R_{AA} \) of the \( \rho(770)^0 \) meson is greatly improved in the range \( 1 \leq p_T \leq 2 \text{ GeV}/c \) when UrQMD is turned on.

VII. CONCLUSIONS

Our previous study of resonance production and modification with the EPOS3 model in \( p \)-\( \text{Pb} \) collisions has now been extended to the \( p \)-\( \text{Pb} \) collision system and we have also reported new results (e.g., nuclear modification factors) for \( p \)-\( \text{Pb} \) collisions. While EPOS3 tends to overestimate the yield ratios of resonances to ground-state particles, it is able to qualitatively describe the evolution of most of those ratios with system size across \( p \)-\( \text{Pb} \) and \( \text{Pb} \)-\( \text{Pb} \) collisions. While short-lived resonances tend to be suppressed in the larger collision systems, our calculations predict that the \( \Sigma(1385)^\pm/\Lambda \) and \( \Delta(1232)^{++}/p \) ratios should not be suppressed even in central \( p \)-\( \text{Pb} \) collisions. This prediction may be testable in future measurements at the LHC. Our calculated \( K^*(892)^0/K \) and \( \rho(770)^0/\pi^\pm \) ratios are suppressed in high-multiplicity \( p \)-\( \text{Pb} \) collisions; there are hints of a similar trend in measurements from
the ALICE Collaboration. The EPOS3 $p_T$ spectra for resonances tend to agree best with the measured data for intermediate $p_T$ ($2 \lesssim p_T \lesssim 4 \text{ GeV}/c$) and when UrQMD, which models interactions in the hadronic phase, is turned on. Turning on UrQMD also tends to improve the description of the mean transverse momentum values of many species of light-flavor hadrons and results in large increases in $\langle p_T \rangle$ for short-lived resonances, protons, and $\Lambda$. EPOS3 is also able to reproduce the nuclear modification factors of resonances in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. These results highlight the importance of the hadronic phase, with an estimated lifetime $\sim 1 \text{ fm}/c$ in $p$-Pb collisions and 0.5–10 fm/$c$ in Pb-Pb collisions, in determining the final resonance yields and $p_T$ distributions. Additional effects arise from the interplay between particle production in the core and corona parts of the collision. The effects of the hadronic phase are found to be most important at low $p_T$ ($\lesssim 1-2 \text{ GeV}/c$) in both $p$-Pb and Pb-Pb collisions, which modifies the $p_T$ distributions of these resonances and their decay products. Modifications of the $p_T$ distributions, including re-scattering, regeneration, annihilation, and radial flow, will also affect hadron correlation measurement. A rigorous description of the hadronic phase, even in small collision systems such as $p$-Pb, is therefore essential for a complete understanding of many different observables in studies of ion-ion collisions.

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