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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 and evolution of scattering 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 [1]. 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 p -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 [2, 3]. As the multiplicity increases in p - p and p -Pb collisions, hadron p_T spectra harden and the p/π and Λ/K_S^0 ratios are enhanced at intermediate p_T [3–5]; qualitatively similar behavior is also seen in Pb-Pb collisions, where it may be attributable to collective flow [6, 7]. There are also hints of a multiplicity-dependent suppression of the yields of $K^*(892)^0$ mesons in p - p and p -Pb collisions [3, 5], qualitatively similar to what is observed in Pb-Pb collisions [8, 9]. These results raise the question of whether the same mechanisms that determine the yields and momentum spectra of hadrons in A - A collisions are also present in the smaller collision systems.

In a previous paper [10], we studied the production of resonances in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the EPOS3 framework [11–13], which includes the UrQMD model [14–16] for the description of hadronic interactions in the hadronic phase. This paper extends that study to p -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 p -Pb 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 [4] and divided the p -Pb event sample into multiplicity classes using the charged-particle multiplicity in the pseudorapidity range $2.8 < \eta_{\text{lab}} < 5.1$ (in the direction of the Pb beam), which is the same range spanned by the ALICE V0A scintillator array [17].

The EPOS3 model [11–13] 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 [18]. The assignment of a particular string segment to the core or corona is based both on its initial momentum and on the density of string segments along its trajectory. High-momentum string segments and segments produced in low-density regions (*e.g.* near the surface of the system) tend to escape and become the corona, while the remaining strings become the core (bulk) part of the collision. (See Refs. [18, 19] for a more detailed discussion of this procedure.) The core is taken as the initial condition for QGP evolution, for which we employ 3+1D viscous hydrodynamics. In the corona, string segments become hadrons. The division between the core and corona parts of the collision is illustrated in Fig. 1, which shows the fractions of long-lived hadrons (π , K, p, Λ , Σ , Ξ , Ω , 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 [10]. Low-multiplicity (peripheral) collisions are dominated by 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 [20] of the fluid (core part), all hadrons, including those from the corona, are fed into UrQMD [14–16]. Each hadron that enters UrQMD is assigned the time, position, and four-momentum corresponding to the point at which it formed: for core particles, this is the point of formation on the freeze-out hypersurface, while for corona particles, it is the point of creation from a string decay. Within UrQMD, all particles are extrapolated back along their trajectories to a common start time, but are not permitted to interact until their formation time is reached. (Therefore, each particle effectively enters UrQMD at its formation spacetime point with its formation four-momentum.) UrQMD describes hadronic interactions in a microscopic approach, and the chemical and kinetic freeze outs occur within this phase. Resonance signals have been previously studied using the UrQMD model [16, 21–30]. The production of resonances in A - A collisions at various energies has also been studied using the PHSD transport approach [31, 32], as well as in [33], which uses relativistic hydrodynamics plus a hadronic afterburner (the SMASH [34] hadronic transport framework).

For more central collisions, the hadronic phase lasts longer (*i.e.*, 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 $\langle dN_{\text{ch}}/d\eta \rangle^{1/3}$, the cube root of the mean charged-particle multiplicity measured by ALICE [4, 35] at mid-rapidity ($|\eta_{\text{lab}}| < 0.5$), 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 [10], with the highest multiplicity p -Pb collisions (0-5%) having similar hadronic lifetimes (≈ 1.5 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.

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 Λ and Ξ , can be selected based on their decay topologies, which adds further constraints. Table I [36] lists the specific decay channels investigated in the EPOS3 approach, which are the same channels used experimentally by STAR [37–41] and ALICE [5, 8, 9, 42–45]. 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. The total yields include resonances that have been produced through regeneration in the UrQMD phase of the simulation (unless their decay products subsequently re-scatter). 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.

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 the mid-rapidity charged-particle multiplicity for Pb-Pb [10] collisions, along with our new calculations for p -Pb collisions. The abscissa $\langle dN_{\text{ch}}/d\eta \rangle$ 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 [46–48], 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 (but neglecting time dilation and regeneration), an exponential decrease in measured resonance yields as a function of the system radius or $\langle dN_{\text{ch}}/d\eta \rangle^{1/3}$ might be expected. The full EPOS3 simulation with UrQMD accounts for re-scattering, regeneration, and time dilation. Roughly exponential decreases in resonance yields might still be expected if re-scattering dominates over regeneration. The EPOS3 results are compared to experimental results from ALICE [5, 8, 9, 42–45]. In a few cases, ALICE measurements are unavailable and measurements from STAR [40, 41] 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.

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 $\Sigma(1385)^\pm/\Lambda$ ratios in p -Pb and A-A collisions, consistent with ALICE [5, 8, 9, 42] and STAR [40] measurements. The ALICE data suggest a small multiplicity-dependent suppression of the $K^*(892)^0/K$ ratio in p -Pb collisions [5] and a similar suppression may also be visible in a preliminary measurement of the $\rho(770)^0/\pi^\pm$ ratio in the same collision system [49]. ALICE measurements of the $K^*(892)^0/K$ and $\rho(770)^0/\pi^\pm$ ratios in Pb-Pb collisions show a larger centrality-dependent suppression [8, 9, 43]. These trends in p -Pb and Pb-Pb collisions are qualitatively reproduced by EPOS3. The ALICE data indicate that the $\Lambda(1520)/\Lambda$ ratio does not change with multiplicity in p -Pb collisions [44] but is suppressed in central Pb-Pb collisions [45]; 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 [42], which are also consistent with a preliminary measurement in peripheral Pb-Pb collisions [50]. 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 [41] of this ratio in d -Au collisions. In summary, the multiplicity evolution of these various ratios are 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 Pb-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 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.

PHSD calculations [32] also show a centrality-dependent suppression of the measurable $K^*(892)^0/K$ ratio in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, consistent with the ALICE data [8] within uncertainties. In the PHSD framework, this is due to final-state interactions (re-scattering and absorption) of the decay products. In addition, a multiplicity-dependent suppression of the $\rho(770)^0/\pi^\pm$, $K^*(892)^0/K$, and $\Lambda(1520)/\Lambda$ ratios was reported in [33] and attributed to re-scattering in the hadronic phase.

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 $K/\pi^\pm$ ratio).

The decreases in the $\rho(770)^0/\pi^\pm$ and $K^*(892)^0/K$ ratios are partly explained by the core-corona transition, with further suppression coming from UrQMD. Turning on UrQMD causes a small increase in the $\phi(1020)/K$ 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 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 by comparing the “Core + Corona” and “Full” curves in Fig. 4 for a given $\langle dN_{\text{ch}}/d\eta \rangle$ value. Here, interactions in the hadronic phase cause a significant decrease of the proton and Λ yields, especially in central A-A collisions, due to particle-antiparticle annihilation.

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 [5, 42–44]. 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 re-scattering and regeneration 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 [10].

Figure 5 also shows comparisons of EPOS3 calculations (with UrQMD on) and ALICE measurements [42, 44] 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 [43]. As for our previous studies of the $K^*(892)^0$ and $\phi(1020)$ in Pb-Pb collisions [10], turning UrQMD on improves the agreement between the EPOS3 prediction for $\rho(770)^0$ in Pb-Pb collisions and the ALICE measurement at low p_T ; the EPOS3 description of these spectra also 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 Pb-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. For the $K^*(892)^0$ meson, an analogous ratio was calculated using the PHSD transport approach [32] for central Au-Au collisions at energies from 4.5-15 AGeV. This PHSD result in the FAIR/NICA energy regime is similar to our result at LHC energies: in particular, a large depletion of the ratio is observed at low p_T due to the re-scattering of the final-state pions and kaons.

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 [10]. The results of EPOS3 calculations with and without a hadronic cascade are compared to measurements from the ALICE Collaboration [4, 5, 7–9, 42–45, 51–53], when available. For K_S^0 , Λ , Ξ^- , and Ω 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 -Pb collisions and for peripheral and central Pb-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 Λ . The effect of the hadronic cascade tends to be the greatest in central Pb-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 -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.

VI. CONCLUSIONS

Our previous study of resonance production and modification with the EPOS3 model in Pb-Pb collisions has now been extended to the p -Pb collision system and we have also reported new results for Pb-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 -Pb and Pb-Pb collisions. While shorter-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 Pb-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 -Pb collisions; there are hints of a similar trend in the measured $K^*(892)^0/K$ ratio in p -Pb collisions reported by the ALICE Collaboration. The EPOS3 p_T spectra for resonances tend to agree best with the measured data for intermediate p_T ($2 \lesssim p_T \lesssim 4$ 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 Λ . These results highlight the importance of the hadronic phase, with an estimated

lifetime ~ 1 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 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 measurements. 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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TABLE I: The resonances are constructed experimentally via the decay channels listed [36]. These same decays are used in our studies of resonances in EPOS3 and UrQMD.

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

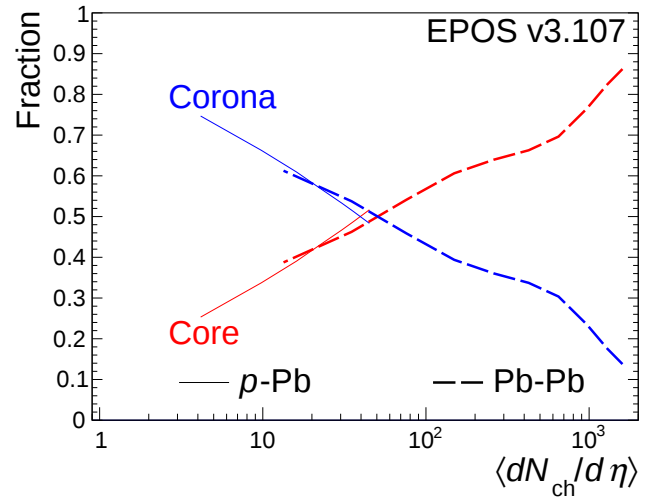


FIG. 1: (a): Fraction of particles originating from the core and corona parts of p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV when UrQMD is turned off.

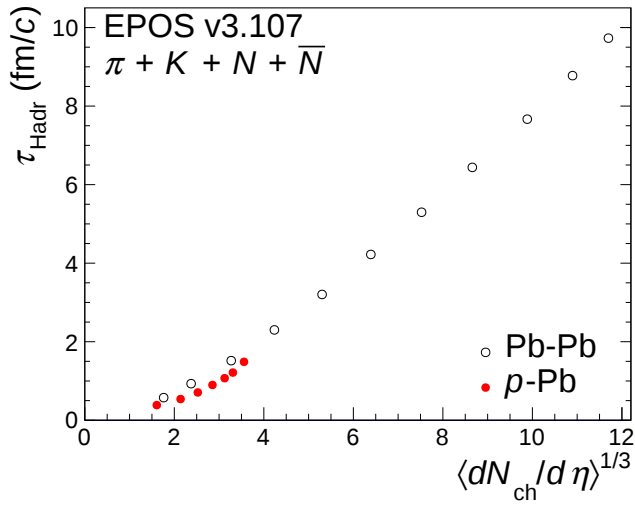


FIG. 2: Lifetime of hadronic phase in p -Pb (red full circles) and Pb-Pb (black open circles) [10] collisions.

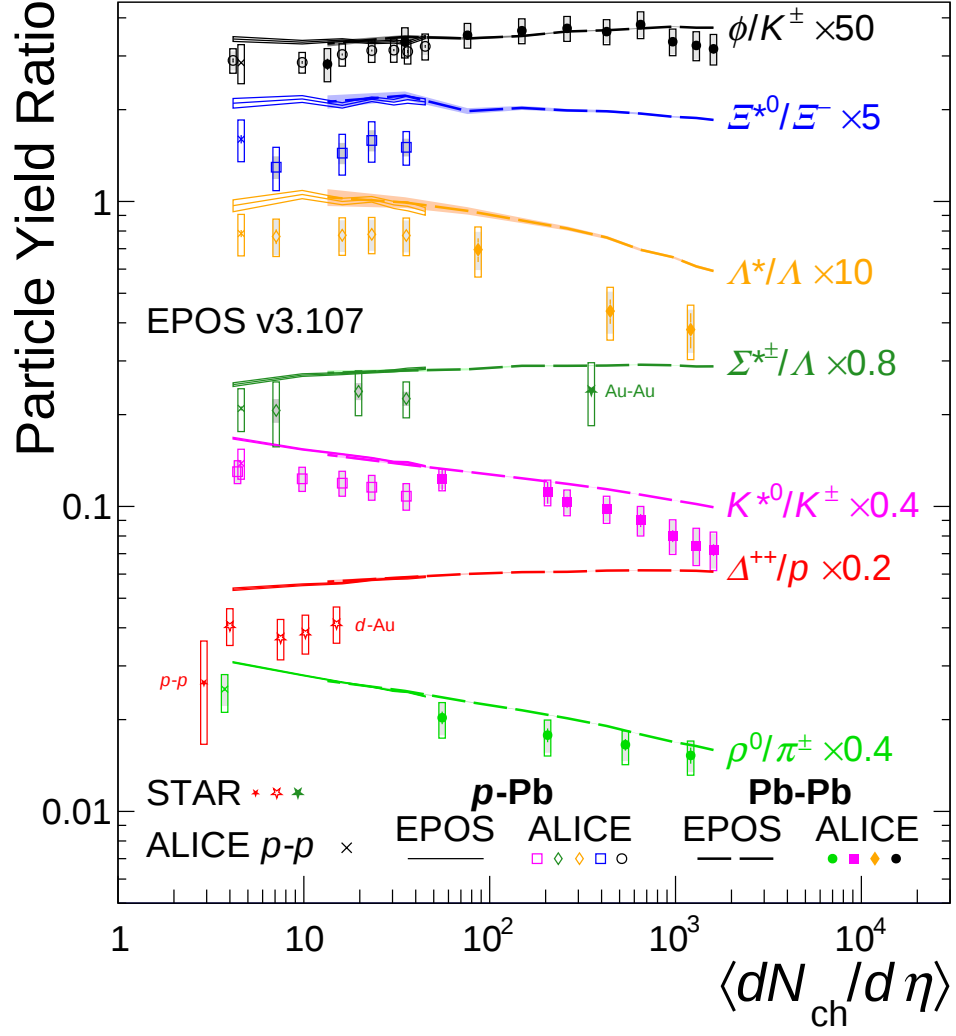


FIG. 3: Ratios of resonance yields to long-lived hadrons as functions of the charged-particle multiplicity measured at mid-rapidity. EPOS3 data are shown for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [10] (thick lines) and p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (thin lines), with bands representing statistical uncertainties. The EPOS3 results are compared to experimental results, mostly from ALICE [5, 8, 9, 42–45]. In a few cases, ALICE data are not available and STAR data for $\sqrt{s_{NN}} = 200$ GeV are shown instead [40, 41]. 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.

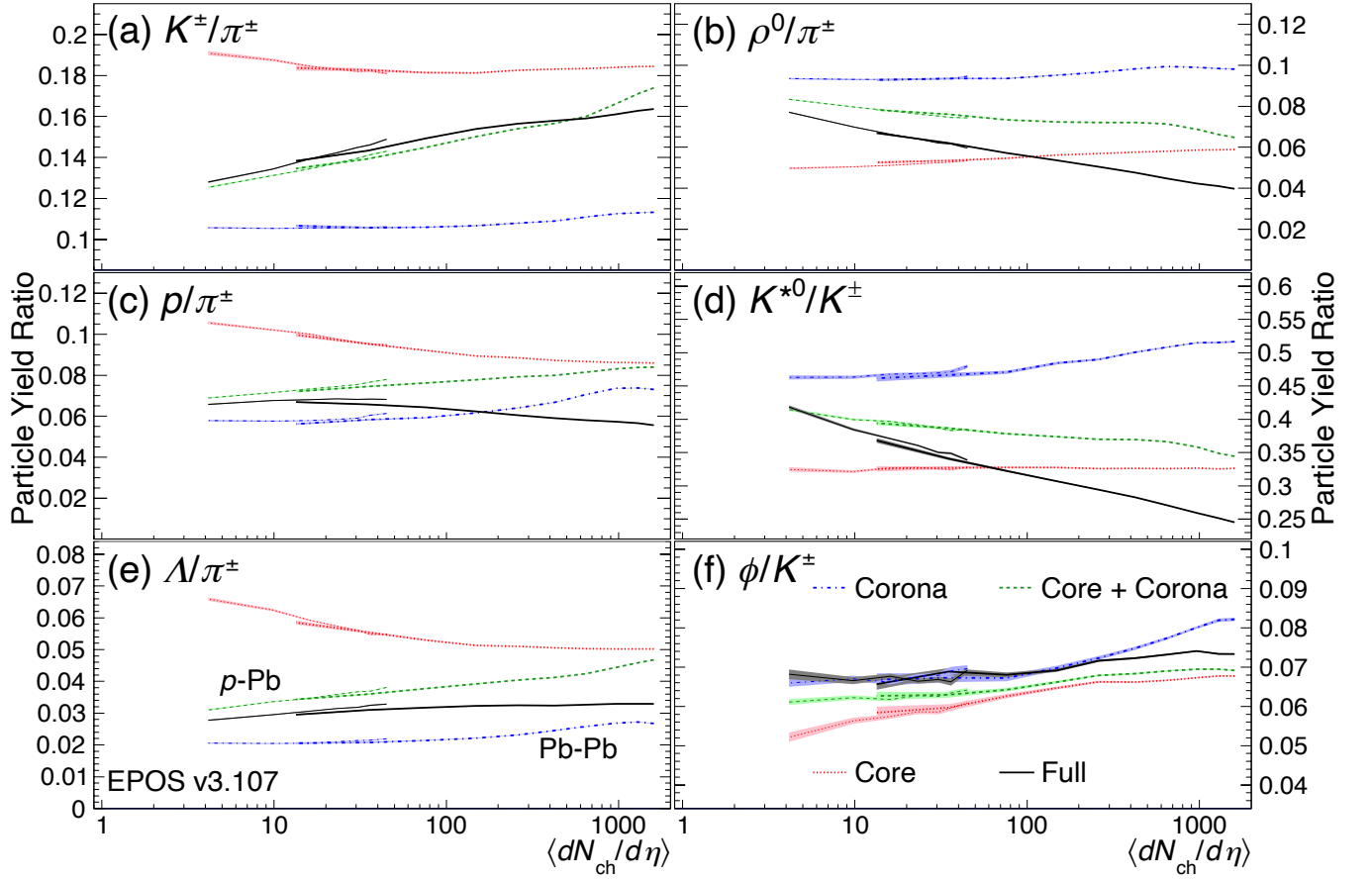


FIG. 4: Particle yield ratios in p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [10] (thin and thick lines, respectively). Results are shown for core only, corona only, summed core+corona (*i.e.* UrQMD turned off), and full simulations (with core, corona, and UrQMD).

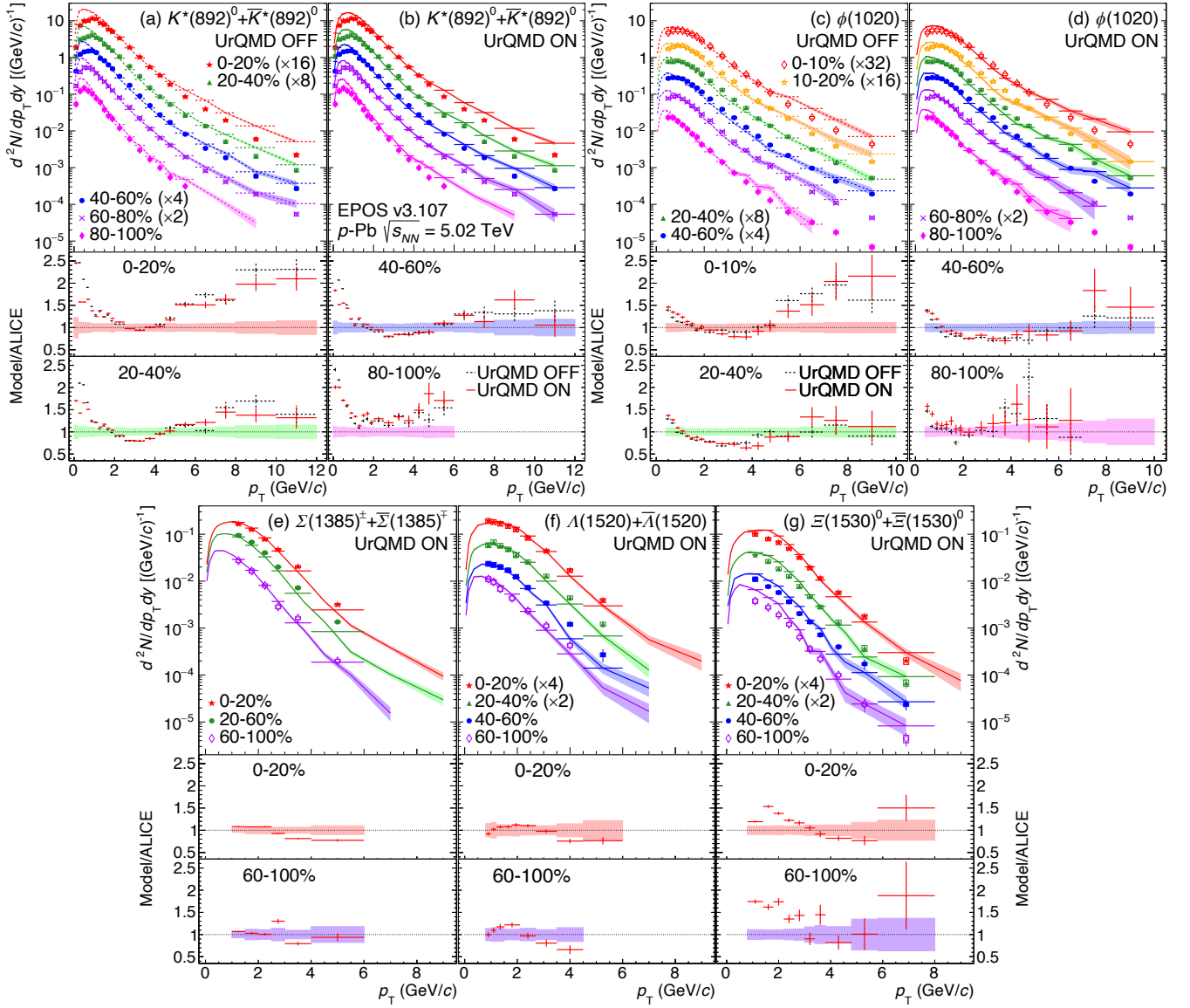


FIG. 5: Comparison of EPOS3 results and ALICE measurements for resonances in p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for various multiplicity intervals. The curves are the EPOS3 p_T distributions with fine bins and the shaded bands are the statistical uncertainties of the EPOS3 results. The horizontal lines are the EPOS3 results in the same p_T bins as the ALICE measurements. **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):** $K^*(892)^0 + \bar{K}^*(892)^0$ [5] without (a) and with (b) UrQMD. The ALICE data are the same in both panels. **(c-d):** $\phi(1020)$ [5] without (c) and with (d) UrQMD. The ALICE data are the same in both panels. **(e):** $\Sigma(1385)^\pm + \bar{\Sigma}(1385)^\mp$ [42], **(f):** $\Lambda(1520) + \bar{\Lambda}(1520)$ [44], **(g):** $\Xi(1530)^0 + \bar{\Xi}(1530)^0$ [42].

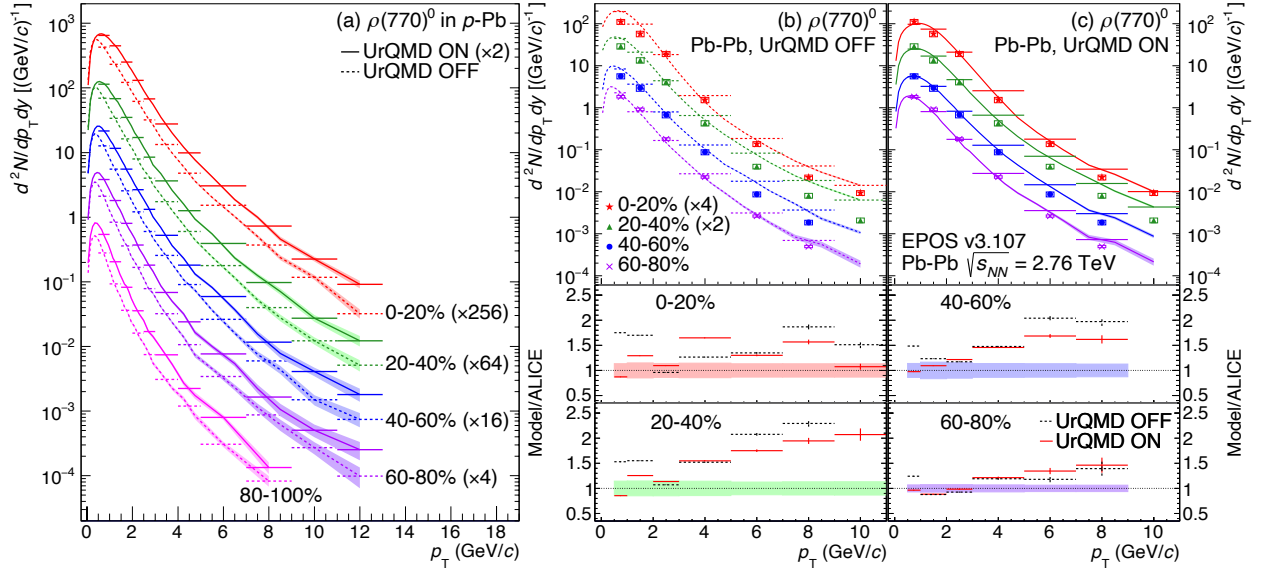


FIG. 6: **(a)**: EPOS3 p_T spectra for $\rho(770)^0$ mesons in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV in various multiplicity intervals with UrQMD off (dashed lines) and UrQMD on (solid lines, scaled by an extra factor of 2). The curves are the EPOS3 p_T distributions with fine bins and the shaded bands are the statistical uncertainties of the EPOS3 results. The horizontal lines are the EPOS3 results in wider p_T bins. **(b-c)**: Comparison of EPOS3 results [10] and ALICE measurements [43] for the $\rho(770)^0$ meson in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in various centrality intervals. **Upper panels**: transverse momentum distributions of $\rho(770)^0$ from EPOS3 with UrQMD OFF (left) and UrQMD ON (right). These results are compared to measurements from the ALICE Experiment (same data on left and right). The curves are the EPOS3 p_T distributions with fine bins and the shaded bands are the statistical uncertainties of the EPOS3 results. The horizontal lines are the EPOS3 results in the same p_T bins as the ALICE measurements. **Lower panels**: the ratio 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.

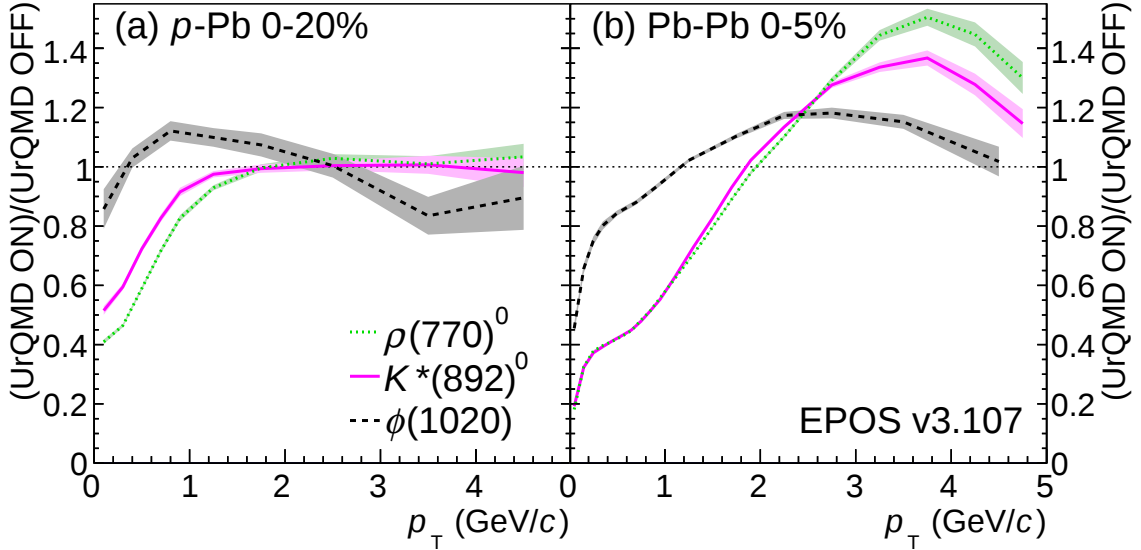


FIG. 7: **(a)**: The effect of the UrQMD phase on the p_T spectra of the $\rho(770)^0$, $K^*(892)^0$, and $\phi(1020)$ mesons is illustrated by this p_T -dependent ratio: the p_T spectra from EPOS3 with UrQMD ON divided by the spectra with UrQMD OFF. Results are shown for (a) high-multiplicity p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and (b) central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [10]. The shaded bands represent the statistical uncertainties of the ratio.

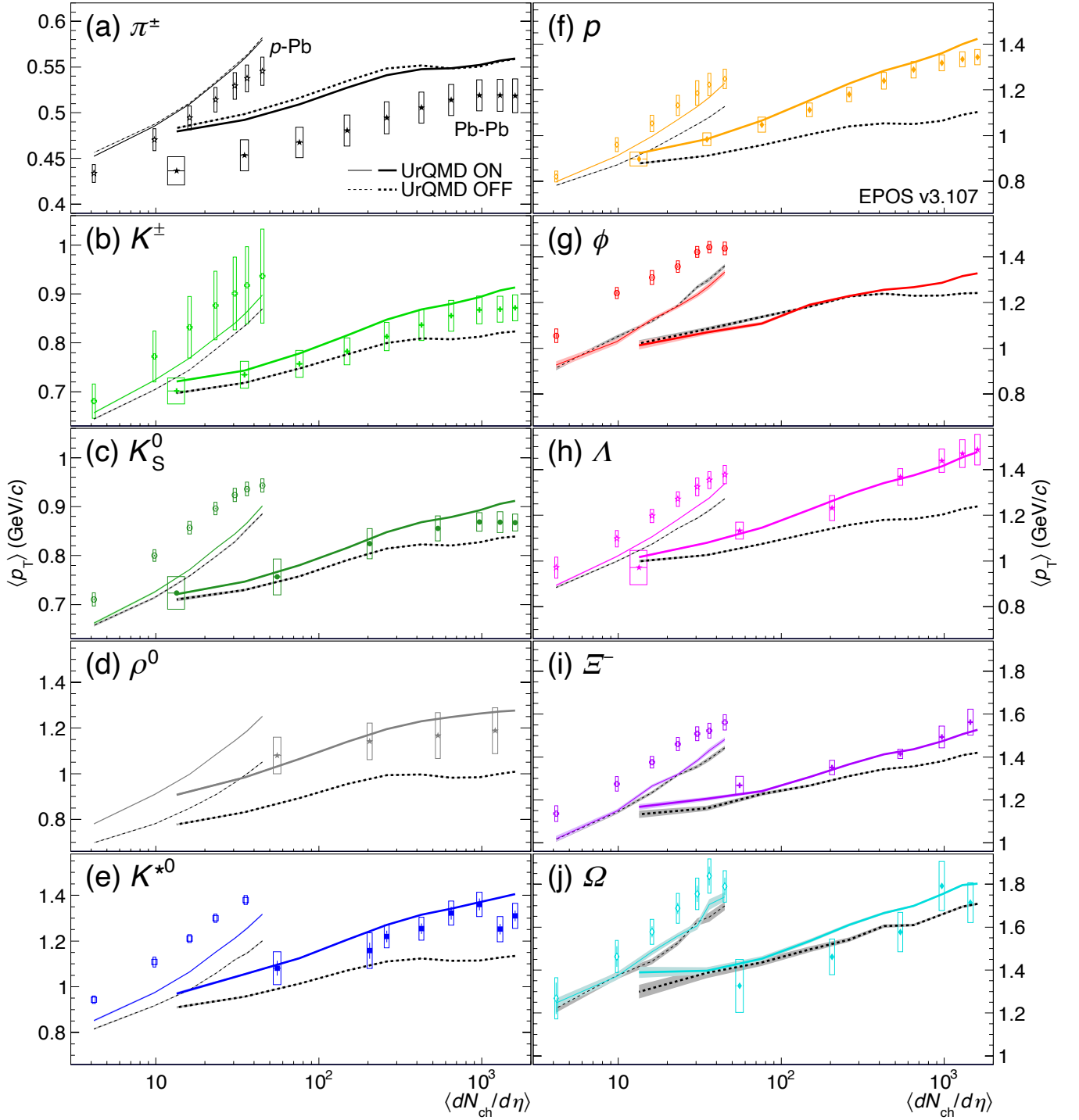


FIG. 8: Mean transverse momenta $\langle p_T \rangle$ of different particle species in p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (thin and thick lines, respectively). EPOS3 calculations were performed with and without a hadronic cascade modeled 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 [4, 5, 53] and Pb-Pb collisions [7–9, 43, 51, 52] (open and filled symbols, respectively).

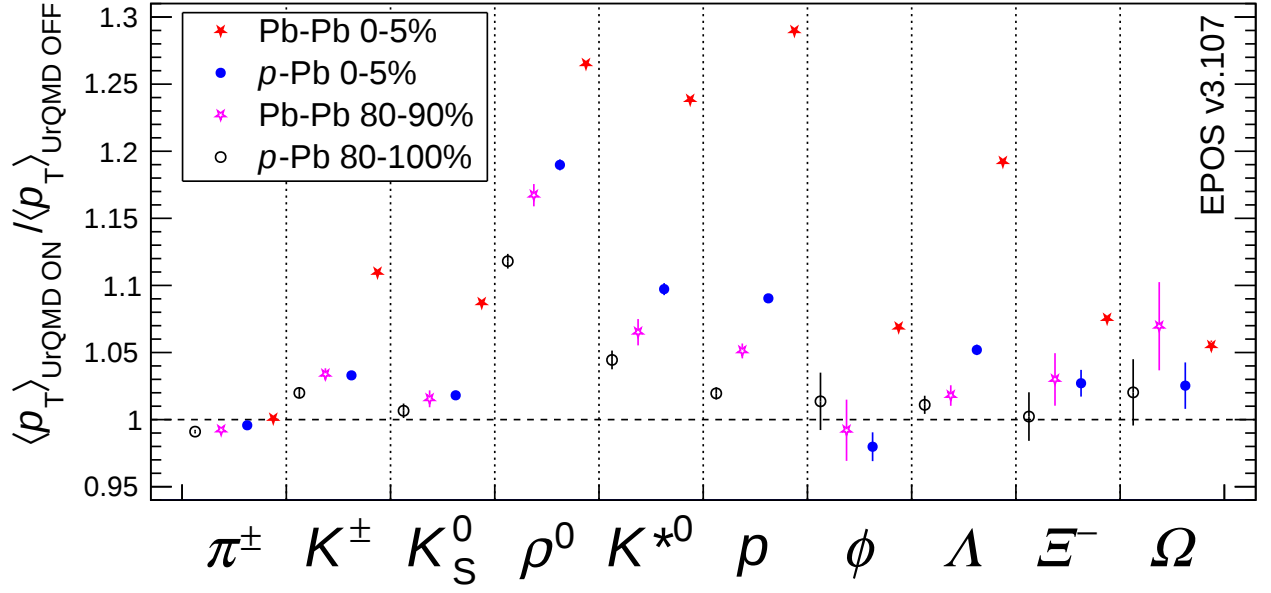


FIG. 9: The fractional modification of $\langle p_T \rangle$ values that occurs when UrQMD is turned on, *i.e.*, the ratio of $\langle p_T \rangle$ values with UrQMD on to results without UrQMD. This ratio is calculated four times for each particle in different multiplicity/centrality classes: for low-multiplicity p -Pb (80-100%, open circles), peripheral Pb-Pb (90-100% open stars), high-multiplicity p -Pb (0-5%, filled circles), and central Pb-Pb (0-5%, filled stars).