

Examining hadronic resonance dynamics at energies available at the CERN Large Hadron Collider: Insights from EPOS4

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Hadronic resonances, with lifetimes of a few fm/c are key tools for studying the hadronic phase in high-energy collisions. This work investigates resonance production in pp collisions at $\sqrt{s} = 13.6$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV using the EPOS4 model. The EPOS4 model provides the capability of switching the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) ON or OFF, allowing the study of final-state hadronic interactions in the hadronic phase. Although this study is primarily focused on understanding the production of hadronic resonances, we also investigate the production of strange and nonstrange hadrons in relation to rescattering, regeneration, baryon-to-meson production, and strangeness enhancement, using transverse momentum (p_T) spectra and particle ratios. Rescattering effects and strangeness enhancement play an important role in the low- p_T region, where soft, nonperturbative processes dominate particle production. At intermediate p_T , the baryon-to-meson yield ratios show an enhancement, and the strong mass-dependent radial flow observed for baryons in the most central Pb-Pb collisions reflects the interplay between hadronization dynamics and collective effects. The average p_T scaled with the reduced hadron mass (i.e., the mass divided by the number of valence quarks) is examined, revealing a deviation from a linear trend for short-lived resonances, attributed to hadronic phase effects. By analyzing the yield ratios of short-lived resonances to stable hadrons in pp and Pb-Pb collisions, the time duration (τ) of the hadronic phase as a function of average charged multiplicity is estimated. The results show that τ increases with increasing multiplicity and system size, also exhibiting a nonzero value for high-multiplicity pp collisions. It is found that the production of baryons such as nonstrange (p), strange (Λ), and multistrange (Ξ , Ω) in the most central Pb-Pb collisions is influenced by competing processes of strangeness enhancement and baryon-antibaryon annihilation. Comparing these findings with measurements at energies available at the CERN Large Hadron Collider offers valuable insights into the underlying dynamics of the hadronic phase and their production dynamics.

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I. INTRODUCTION

High-energy heavy-ion (AA) collisions offer a unique opportunity to study the properties of the quark-gluon plasma (QGP), a deconfined state of quarks and gluons, formed under extreme conditions of temperature and/or energy density [1]. As the dense medium created in these collisions evolves and cools, it eventually reaches a point where quarks and gluons recombine into hadrons, resulting in a hadron resonance gas (HRG). The study of the production yield of hadronic resonances offers valuable insight into the properties of the hadronic phase, which exists between chemical

freeze-out (when inelastic collisions stop) and kinetic freeze-out (when elastic collisions stop) [2]. The decay products of resonances can undergo regeneration or rescattering through elastic or pseudoelastic interactions, which involve scattering via intermediate resonance states. These processes can modify the original yields of resonances produced before chemical freeze-out. In the rescattering process, if at least one decay product interacts elastically with other hadrons, the four-momentum information of the parent resonance is altered. This alteration prevents accurate reconstruction of the resonance, and thus the parent resonance particle is said to be lost. Conversely, regeneration occurs when pseudoelastic interactions among hadrons recreate the parent resonance, leading to an increase in the reconstructed yield compared to the original resonance yield. The dominance of rescattering or regeneration can be explored by analyzing the yield ratios of resonances to longer-lived hadrons with similar quark content as a function of system size. To investigate hadronic resonance production and their interactions, various resonances with different lifetimes, valence-quark flavors, masses, and spins have been studied at energies available at the CERN Large Hadron Collider (LHC) [3–8] and the BNL Relativistic Heavy Ion

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Collider (RHIC) [9–11]. These studies provide insight into the dynamics of the hadronic phase and the modification of resonance yields in different collision systems.

Recent measurements show that the yields of short-lived mesonic resonances, such as $\rho(770)^0$ (1.335 fm/c) and $K^*(892)^0$ (4.16 fm/c), are significantly modified in the hadronic phase compared to longer-lived resonances like $\phi(1020)$ meson (46.26 fm/c). This is attributed to the fact that short-lived resonances decay within the hadronic medium, where processes such as rescattering and regeneration affect their yields. In contrast, longer-lived resonances typically decay after the hadronic phase, when the medium has expanded sufficiently and the interactions are minimal, resulting in a little or no yield modification [3,4,6]. For baryonic resonances, such as the $\Sigma(1385)^\pm$ (5.0–5.5 fm/c) and $\Lambda(1520)$ (12.54 fm/c), studies have shown the yield modification for $\Lambda(1520)$ but not for $\Sigma(1385)^\pm$, despite the latter having a shorter lifetime in most central Pb-Pb collisions [12]. Interestingly, such studies in small collision systems indicate that there is no significant yield modification for these resonances [6].

Recent experimental findings from high-multiplicity small system collisions show behavior similar to that observed in heavy-ion collisions, generating significant interest in such studies in these systems. The $K^*(892)^0$ measurement shows a decreasing trend in yield with multiplicity, indicating the presence of a nonzero hadronic phase duration in high-multiplicity pp and p -Pb collisions, as reported in Refs. [13,14].

To study the dynamics of resonance production and their yield modification due to the hadronic phase, various approaches have been developed that couple a hadronic cascade with or without fluid approximation for the dense medium formed in high energy collisions. EPOS with UrQMD combines hydrodynamic evolution with a hadronic afterburner, providing a hybrid framework that integrates both macroscopic and microscopic dynamics. In contrast, the AMPT model combines a partonic phase with a hadronic cascade based on the relativistic transport (ART) model to simulate final-state interactions, with the option to switch hadronic scattering effects on or off [15]. MUSIC with the SMASH model (Simulating Many Accelerated Strongly interacting Hadrons) is a standalone hadronic transport approach coupled to hydrodynamic evolution as an afterburner. The SMASH model accounts for hadronic cascade effects in a manner similar to the UrQMD, but as a more recent framework it treats all interactions through explicit resonance formation and decay, employing PDG-consistent lifetimes, branching ratios, and conservation laws [16]. In contrast, the UrQMD covers a broader energy range and remains a well-tested tool for hadronic cascades, having undergone decades of validation in several studies. On the other hand, the hadron resonance gas (HRG) model with partial chemical equilibrium (PCE) is modeled using the law of mass action. In this framework, short-lived resonances can decay and regenerate, and their abundances remain in equilibrium with the particles produced in their decays [17]. Moreover, the findings from experimental measurements and theoretical studies indicate that the final resonance yields are influenced not only by their lifetimes but also by additional factors, such as the duration of the

hadronic phase, the interaction cross section of decay daughters, the freeze-out temperature, and the mean free path of the resonances.

In this study, we present results of various hadrons, including hadronic resonances, at midrapidity ($|y| < 0.5$) for pp collisions at $\sqrt{s} = 13.6$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV using the EPOS4 with UrQMD hadronic afterburner both ON and OFF. The terms “with UrQMD” and “without UrQMD” are used interchangeably to refer to simulations with UrQMD ON and UrQMD OFF, respectively, and may appear throughout the text. The inclusion of UrQMD (Ultrarelativistic Quantum Molecular Dynamics) enables detailed modeling of the hadronic phase by simulating its effects on the system. These effects can significantly alter key observables such as transverse momentum (p_T) spectra, particle yields, and yield ratios, as well as collective phenomena such as flow and particle correlations. By comparing simulations with and without UrQMD to experimental data, the influence of the hadronic phase on resonance production has been explored. The study also examines how strangeness enhancement and baryon-to-meson ratios influence the production of hadronic resonances and multistrange hadrons. This comparison provides valuable insights into the dynamics of the hadronic phase and its impact on final-state observables. The highest energies and finer high-multiplicity events in small systems are chosen to improve upon previous studies [18,19] and to offer opportunities for future comparisons with experimental measurements.

Experimentally, hadronic resonances are reconstructed using the invariant-mass technique via the addition of four-momenta of their decay daughters. The longer-lived decay daughters, such as charged pions, charged kaons, and (anti)protons, reach the detectors and are often identified through measurements of energy loss (dE/dx) in a Time Projection Chamber (TPC) and/or velocity in a Time-of-Flight (TOF) detector. The weakly decaying daughters, such as K_S^0 , Λ , Ξ , and Ω can be selected based on their decay topologies, which sets further constraints. For this study, 5×10^6 events were generated for pp collisions, both with and without UrQMD, while 1.5×10^6 events were generated for Pb-Pb collisions under the same conditions. The events are divided into various multiplicity classes based on the number of charged particles present within the pseudorapidity ranges $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. This method follows an approach similar to that used by the ALICE experiment for pp and Pb-Pb collisions in the Run 2 studies.

Particles are selected from the generated data according to their unique EPOS IDs, with weak decays disabled to ensure that only primary particles contribute to the final yield calculations. After selecting resonances based on their unique EPOS IDs, they are flagged as either reconstructible or non-reconstructible. When a resonance decays, the EPOS4 model tracks its decay daughters. If any of the decay daughters undergo elastic interactions that alter their momenta, the parent resonance is flagged as nonreconstructible. As a result, the resonance is not included in the final yield measurements. This ensures that only resonances whose decay daughters

TABLE I. Properties of selected resonances, including their decay channels, branching ratios, and lifetimes in the rest frame.

Resonance	Shorthand	Decay channel	Branching ratio	Lifetime (fm/c)
$\rho(770)^0$	ρ^0	$\pi^+ + \pi^-$	1.0	1.335
$K^*(892)^0$	K^{*0}	$\pi^- + K^+$	0.667	4.16
$\phi(1020)$	ϕ	$K^+ + K^-$	0.489	46.26
$\Delta^{++}(1232)$	Δ^{++}	$\pi^+ + p$	1.0	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}	$\pi^+ + \Xi^-$	0.667	22

have not undergone significant elastic scattering are counted, following a similar approach to experimental measurements, where resonance particles are reconstructed based on the momenta and trajectories of their decay products. Table I lists the resonances and their properties, including decay channels, branching ratios, and lifetimes as in the UrQMD model. The decay channels included in Table I are those commonly analyzed in experiments at LHC energies [20]. The shorthand notation provided in the table will be used to represent the resonances throughout the text. The paper is organized as follows. Section I introduces hadronic resonances and their interactions within the hadronic gas. It also describes the event generation using the EPOS4 hydrodynamical model, along with particle selection methods and the criteria used for the estimation of multiplicity and centrality. Section II discusses the EPOS4 model, outlining its key concepts and emphasizing the major advancements and differences compared to its predecessor, EPOS3. Section III presents the results for various observables. Finally, Sec. IV summarizes the key findings of this study.

II. EPOS4: FRAMEWORK OVERVIEW AND KEY FEATURES

The EPOS4 model is a general purpose framework designed to investigate a wide range of observables in relativistic collisions, from proton-proton to nucleus-nucleus collisions, at energies ranging from several GeV to multiple TeV per nucleon [21]. One of the key concepts underlying EPOS4 is parallel scattering, where multiple parton-parton scatterings occur simultaneously due to the extended reaction times in high-energy collisions. This is implemented using the Gribov-Regge (GR) theory [22–25], applying the S -matrix framework to manage multiple scatterings, which ensures the proper distribution of energy and momentum among the scatterings and the remnants of both the projectile and target. The EPOS4 model also accounts for those scenarios where the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) approach [24,26,27] becomes insufficient, particularly at small momentum fractions ($x \ll 1$), where the linear parton evolution assumed by DGLAP breaks down due to the increasing density of partons. These small- x regions, where parton densities are very high, require the inclusion of nonlinear effects arising from gluon-gluon fusion, leading to “saturation”

phenomena [28–32]. To address these saturation effects, EPOS4 introduces a saturation scale that ensures proper factorization and binary scaling, which were violated in the previous EPOS3 model [33]. With this new approach, the model also offers a unique opportunity to distinguish between the primary and secondary scatterings: primary scatterings refer to instantaneous interactions involving initial nucleons and their partonic constituents at very high energies, whereas the secondary scatterings involve interactions among the products of string decays.

In this model, the particle production is based on the core-corona approach. At an early proper time τ_0 of the collisions, prehadrons (which are intermediate states) are formed from pomerons or excited remnants [21]. These prehadrons are categorized as either core or corona, depending on their likelihood to interact with the surrounding medium. This classification is based on their modified transverse momentum. The core prehadrons are situated in dense regions and form a thermalized medium that evolves hydrodynamically. In contrast, the corona prehadrons experience minimal interaction and hadronize directly. The core undergoes hydrodynamic evolution with $\eta/s = 0.08$ and hadronizes on a hypersurface of constant energy density $\varepsilon_H = 0.57 \text{ GeV/fm}^3$. In EPOS4, hadronization is not performed using the standard (grand-canonical) Cooper-Frye prescription, which assumes a smooth fluid-to-particle transition. Instead, the model employs a fully microcanonical hadronization approach that captures the abrupt hadronization in a rapidly expanding system at the critical energy density, followed by a random multihadron decay that maximizes entropy. This is suitable for both small and large systems from proton-proton to heavy-ion collisions. It provides a more realistic description of hadronization by enforcing exact quantum-number conservation per event. This improves baryon production, strangeness enhancement, and event-by-event fluctuations, especially in small systems, whereas the previous EPOS3 with GCE relied on statistical sampling, leading to artificial fluctuations in particle yields and correlations. The model also improves on the core-corona procedure [34–36], dividing string segments based on energy loss and incorporating advanced methods to manage energy-momentum flow through the freeze-out hypersurface [21]. These changes, along with a new microcanonical procedure [21] to conserve energy-momentum and flavor throughout primary and secondary interactions, mark significant improvements over EPOS3, making EPOS4 a more robust tool for modeling high-energy collisions; detailed discussion can be found in Ref. [21]. Furthermore, to simulate the effects of the hadronic phase in high-energy collisions, the UrQMD model is employed as a hadronic afterburner. After hadronization, the produced hadrons are fed into the UrQMD, which is a microscopic transport model based on $2 \rightarrow n$ hadronic scatterings. The model uses experimentally measured reaction cross-sections for various resonances having different lifetimes, as its primary input. It includes baryon-baryon, meson-baryon, and meson-meson interactions, featuring approximately 60 baryonic species (along with their antiparticles) and around 40 mesonic states [37], thereby providing a comprehensive description to study hadronic interactions.

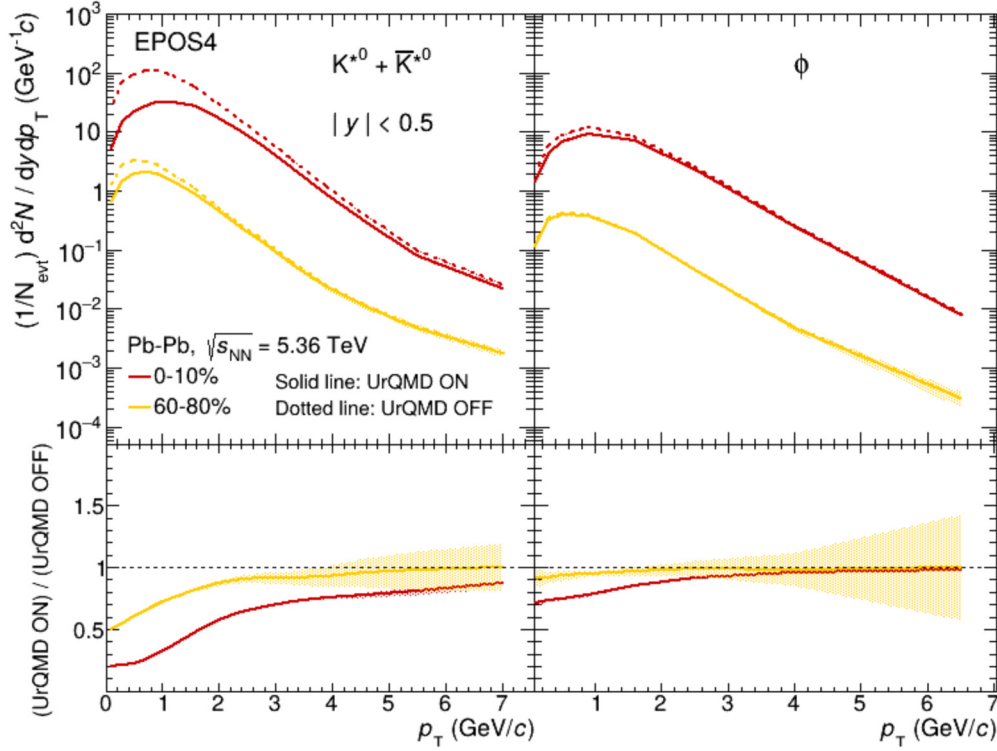


FIG. 1. Upper panel: The p_T spectra of K^{*0} and ϕ resonances in the midrapidity region for central (0–10%) and peripheral (60–80%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV with EPOS4 in UrQMD ON and UrQMD OFF tunes. The solid lines represent measurements with UrQMD ON while dotted lines represent measurements with UrQMD OFF. Lower panel: The p_T -differential yield ratios of K^{*0} and ϕ for UrQMD ON to UrQMD OFF tunes. The bands represent the statistical uncertainties in the measurements.

III. RESULTS AND DISCUSSION

This section includes the p_T spectra, the p_T -differential and integrated yield ratios (including resonance-to-stable hadron, baryon-to-meson, and hadron yields to pion), and the $\langle p_T \rangle$ as a function of system size from pp to Pb-Pb collisions at LHC energies. Additionally, the time duration of the hadronic phase is estimated for short-lived resonances. The discussion of these observables aims to provide insight into the hadronic phase. Whenever available, the results are compared with the experimental data from the ALICE Collaboration.

A. Transverse momentum spectra

To investigate the impact of the hadronic phase on resonance production, analyzing the shape of the p_T spectra can provide details about their production dynamics and interactions. The K^{*0} and ϕ mesons are ideal candidates for such studies due to their similar masses but significantly different lifetimes: K^{*0} has a relatively short lifetime of approximately 4.16 fm/c, while the ϕ meson is long-lived, with a lifetime of about 46.2 fm/c, differing by a factor of 10. The upper panels of Fig. 1 show the p_T spectra of K^{*0} (left) and ϕ (right) from EPOS4 with UrQMD ON (solid lines) and OFF (dotted lines) for the centrality classes 0–10% and 60–80% at midrapidity ($|y| < 0.5$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV). The lower panels represent the ratios of p_T spectra with UrQMD ON to those with UrQMD OFF. A significant

difference is observed between UrQMD ON and OFF at low p_T for K^{*0} . The effect is more pronounced for central (0–10%, red lines) collisions than peripheral (60–80%, yellow lines) collisions. Similarly, the same ratios for pp collisions in the multiplicity class 0–1% (red) and 70–100% (cyan) at $\sqrt{s} = 13.6$ TeV are shown in Fig. 2. A similar feature is also observed at low p_T in high-multiplicity (0–1%) pp collisions when comparing K^{*0} to ϕ . Moreover, the magnitude of this effect in high-multiplicity pp collisions is comparable to that observed in peripheral Pb-Pb collisions. The average charged-particle multiplicity ($\langle dN_{ch}/d\eta \rangle_{\eta < 0.5}$) in 0–1% high-multiplicity pp collisions ($\simeq 27$) approaches that observed in 60–100% peripheral Pb-Pb collisions ($\simeq 36$). As similar $\langle dN_{ch}/d\eta \rangle_{\eta < 0.5}$ values are achieved across different collision systems, the evolution of resonance yields can be primarily attributed to event multiplicity rather than colliding systems and energies. In the EPOS4 simulations with UrQMD, the suppression of K^{*0} yields is evident when compared to results without UrQMD and to the ϕ production. This suppression is attributed to the short lifetime of K^{*0} , as its decay daughters undergo rescattering in the hadronic phase, preventing reconstruction of the parent resonance and thereby reducing its observed yield compared to the original yield of the resonance. The effect is particularly pronounced at low p_T in central Pb-Pb collisions and high-multiplicity pp collisions, where a large and dense medium is formed and the probability of rescattering is high. At high p_T and in low-multiplicity events, the ratios approach unity because the high- p_T particles

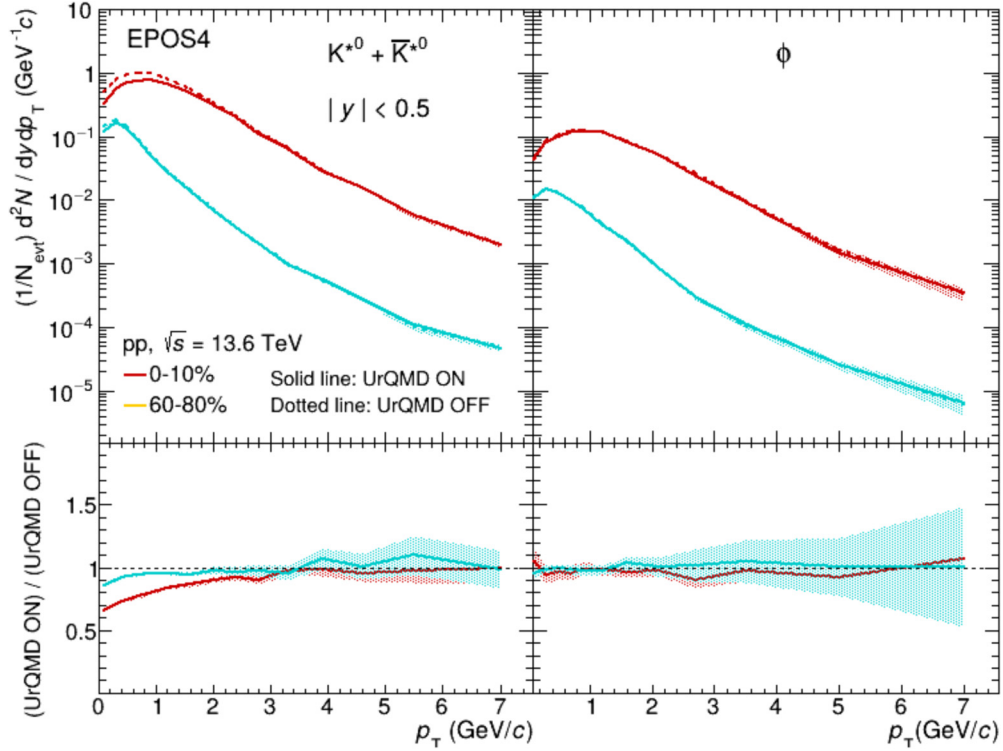


FIG. 2. Upper panel: The p_T spectra of K^{*0} and ϕ resonances in the midrapidity region for high multiplicity (0–1%) and low multiplicity (70–100%) in pp collisions at $\sqrt{s} = 13.6$ TeV with EPOS4 in UrQMD ON and UrQMD OFF tunes. The solid lines represent measurements with UrQMD ON while dotted lines represent measurements with UrQMD OFF. Lower panel: The p_T -differential yield ratios of K^{*0} and ϕ for UrQMD ON to UrQMD OFF tunes. The bands represent the statistical uncertainties in the measurements.

escape the hadronic medium more rapidly and the likelihood of rescattering effect is negligible. In comparison, the effect is less pronounced for ϕ , as expected due to its longer life. The EPOS4 results with UrQMD qualitatively support the observations reported by the ALICE Collaboration at LHC energies [13], demonstrating that the EPOS4 model with UrQMD effectively captures the impact of the hadronic phase on resonance production. In particular, the rescattering of decay daughters plays a dominant role at low p_T for short-lived resonances. To further investigate the effects of the hadronic phase, the ratios of p_T -differential yields with UrQMD ON to those with UrQMD OFF are studied for various hadronic resonances with lifetimes ranging from 1 to 47 fm/c. The results for central (0–10%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV are shown in Fig. 3. A clear trend is observed in the suppression pattern, ordered as $\rho^0 < \Delta^{++} < K^{*0} < \Sigma^{\pm*} \sim \Lambda^* < \Xi^{*0} < \phi$. The suppression becomes more pronounced as the resonance lifetime decreases, assuming negligible regeneration effects. However, the $\Sigma^{\pm*}$ shows a suppression similar to that of Λ^* despite having a significantly shorter lifetime. This can be attributed to the contribution from regeneration, which is more effective for the $\Sigma^{\pm*}$ than for the Λ^* . Since regeneration counteracts the effects of rescattering, it partially offsets the suppression. As a result, even though the $\Sigma^{\pm*}$ has a lifetime nearly half that of the Λ^* , the net suppression appears comparable. These observations show that the final yields of resonances depend not only on their lifetimes but also on additional factors such as decay daughters cross

section, chemical freeze-out conditions, and the lifetime of the hadronic phase. In particular, for baryonic resonances, the interaction cross sections of their decay daughters play a crucial role in modifying the yields during the hadronic phase.

The particle ratios are used as key tools for distinguishing various processes such as rescattering, regeneration, strangeness enhancement, and baryon-to-meson production mechanisms, which give information about the production and interactions of hadrons in the hadronic medium produced in high-energy collisions. Specifically, (a) resonance-to-stable hadron yield ratios provide insight into the p_T distributions of hadrons with similar quark content but differing masses; (b) baryon-to-meson resonance yield ratios enable the comparison of hadrons with similar masses but differing baryon numbers and quark compositions; and (c) strangeness enhancement is observed through relative yield ratios of hadrons to pions. To quantify the p_T -dependence of the rescattering effect, the upper panels of Fig. 4 present a comparison of the p_T -differential yield ratios K^{*0}/K (left) and ϕ/K (right) in central (0–10%) and peripheral (60–80%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV, as well as in high-multiplicity (0–1%) pp collisions at $\sqrt{s} = 13.6$ TeV, all with the UrQMD hadronic afterburner ON. The lower panels display the double ratios, where the Pb-Pb results are divided by those from high-multiplicity pp collisions. Although the center-of-mass energies differ between the pp and Pb-Pb systems, earlier observations as mentioned in Fig. 1 and ALICE measurements [12,13] have shown that resonance yields evolve smoothly

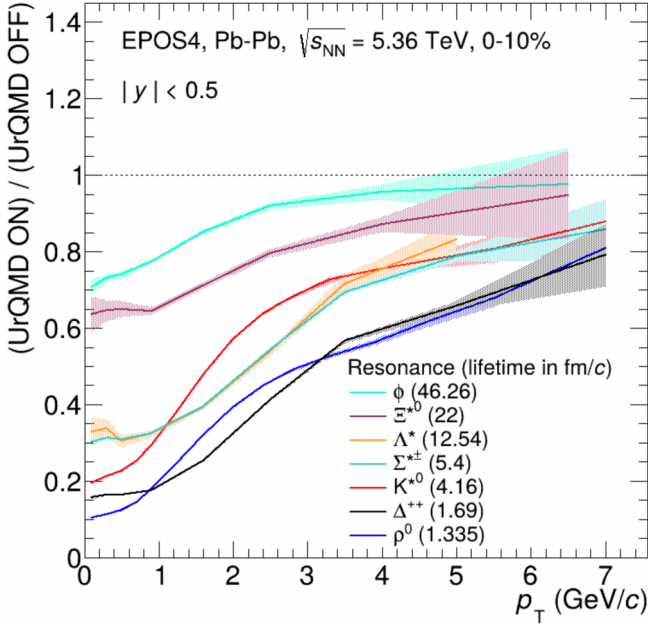


FIG. 3. The comparison of p_T -differential spectra of hadronic resonances with UrQMD to the spectra without UrQMD in central (0–10%) Pb-Pb collisions with EPOS4. The bands in the measurements represent the statistical uncertainty.

with charged-particle multiplicity rather than with the collision system or energy. Therefore, the 0–1% high-multiplicity pp collisions serve as an appropriate baseline for comparison, particularly with peripheral Pb-Pb collisions, providing further insights into the role of the hadronic phase in describing the resonance yield. For K^{*0}/K , the double ratio is found to be suppressed at low p_T , particularly in central Pb-Pb collisions compared to peripheral ones. This suppression is primarily driven by rescattering effects in the hadronic phase, which affect the K^{*0} yield. The use of the K^{*0}/K ratio effectively cancels out any strangeness-related effects, isolating the impact of rescattering. In contrast, the ϕ/K double ratio does not exhibit significant suppression or centrality dependence, consistent with the longer lifetime of the ϕ meson and its reduced sensitivity to hadronic phase interactions. Peripheral Pb-Pb collisions and high-multiplicity pp collisions exhibit similar p_T -differential yield ratios. The observed similarities demonstrate that the production of resonances is mainly governed by charged-particle multiplicity, irrespective of the colliding system. Similar behavior has also been reported by the ALICE experiment, and the model results support the experimental measurements. Similarly, p_T -differential yield ratios for various hadronic resonances are shown in Fig. 5 for central (0–10%, left) and peripheral (60–80%, right) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV. At low p_T , these ratios exhibit a specific ordering: $\Lambda^*/\Lambda < \rho^0/\pi < K^{*0}/K < \Xi^{*0}/\Xi^- \approx \Sigma^{*+}/\Lambda < \Delta^{++}/p < \phi/K$. Despite the longer lifetime of Λ^* , it exhibits a larger suppression compared to other short-lived resonances, a trend also observed in the p_T -integrated yield ratios for the most central Pb-Pb collisions (discussed later in Sec. III D). This can be attributed to its relatively low regeneration probability in the hadronic phase. Although

short-lived resonances such as K^{*0} and Σ^{*+} are more affected by rescattering, their suppression is partially compensated for by stronger regeneration due to larger hadronic cross sections with their decay daughters. In contrast, Λ^* , although less prone to rescattering due to its longer lifetime, experiences less regeneration, leading to a stronger overall suppression. EPOS4 with UrQMD supports this interpretation, showing that the regeneration contributions follow the order $R_{K+p} < R_{K+\pi} < R_{\Lambda+\pi}$.

B. Baryon-to-meson ratios

Particle ratios, particularly baryon-to-meson ratios, are essential for understanding mass-dependent radial flow and the production mechanisms of baryons and mesons. The baryon-to-meson ratios of several hadrons, including resonances such as K^{*0} , ϕ , Λ^* , and Σ^{*+} , are discussed using EPOS4 calculations with and without UrQMD. The baryon-to-meson ratios (Λ , Λ^* , and Σ^{*+} to K_S^0) for the most central (0–10%) and peripheral (60–80%) Pb-Pb collisions using EPOS4 with UrQMD are shown in Fig. 6. A clear mass-dependent enhancement ($\Lambda^*/K_S^0 < \Sigma^{*+}/K_S^0 < \Lambda/K_S^0$) is observed at intermediate p_T . The enhancement in the ratios decreases and the peak position shifts toward the higher p_T region with increasing baryon masses. Similar behavior is also observed in the ratios p/π and Λ/K_S^0 for central Pb-Pb collisions, consistent with observations reported by the ALICE Collaboration in Refs. [38,39]. The effect of radial flow is evident in Fig. 6 for the most central collisions, where a clear mass-dependent trend is observed. Radial flow boosts low-momentum particles to intermediate p_T , with a more pronounced effect for heavier particles.

To further investigate whether the enhancement at intermediate p_T arises primarily from radial flow and hadronization, the particles with similar masses (p , K^* , and ϕ) are studied. This choice helps minimize the influence of mass-dependent effects associated with radial flow. The ratios p/ϕ and p/K^* are calculated using EPOS4 with and without UrQMD for 0–10% central Pb-Pb collisions and compared with ALICE measurements, as shown in Fig. 7. The EPOS4 model with UrQMD shows a relatively flat behavior in the p/ϕ ratio up to $p_T < 1.5$ GeV/c, but overestimates the ALICE data at higher p_T . In contrast, the ALICE data exhibit a nearly flat p/ϕ ratio up to $p_T \approx 4$ GeV/c. Although the model qualitatively captures the trend, further improvements are needed for a more quantitative agreement with the experimental data. The p/K^{*0} ratio measured by ALICE exhibits a slight decreasing trend, which is consistently reproduced by the model with the UrQMD hadronic afterburner. This behavior is expected, as the K^{*0} spectral shape is strongly modified by hadronic phase effects, particularly in the low- p_T region. Furthermore, no significant enhancement is observed in the p/K^{*0} ratio at intermediate p_T . In contrast, the p/π ratio shows a clear enhancement at intermediate p_T , as observed in measurements by the ALICE Collaboration. This enhancement is primarily due to radial flow, which preferentially boosts protons to higher momentum compared to pions because of their larger mass at a common velocity. In the EPOS4 model, the core of the system evolves hydrodynamically, followed

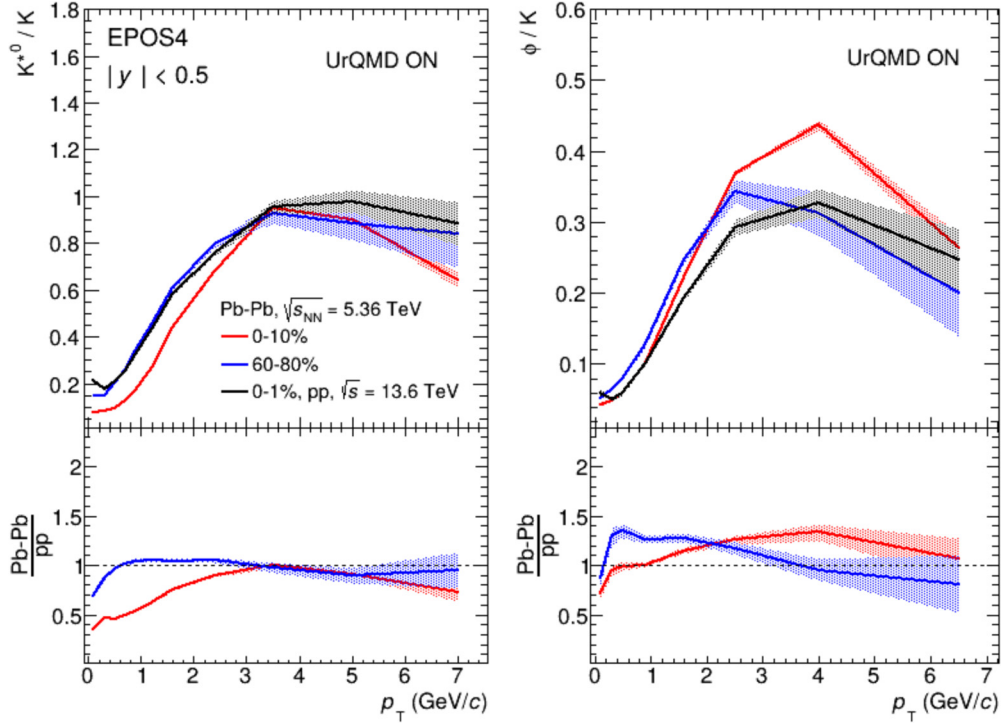


FIG. 4. Upper panel: The p_T -differential ratios K^{*0}/K (left) and ϕ/K (right) in central (0–10%) and peripheral (60–80%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV and also in high multiplicity (0–1%) pp collisions at $\sqrt{s} = 13.6$ TeV with UrQMD. Lower panel: The comparison of p_T -differential ratios in the central and peripheral Pb-Pb collisions to the high multiplicity pp collisions. The bands in the measurements represent statistical uncertainty.

by MCE hadronization that converts the fluid into particle degrees of freedom to form final-state hadrons. The subsequent hadronization, combined with collective flow, imparts a mass-dependent momentum boost ($p = mv$, where m and p are the hadron mass and momentum, and v is the col-

lective flow velocity). This boost shifts heavier hadrons to higher momentum compared to lighter ones, reproducing the mass-dependent behavior in the p_T -spectra, particularly in the most central collisions. In addition to collective flow, differences in production mechanisms for baryons and mesons also

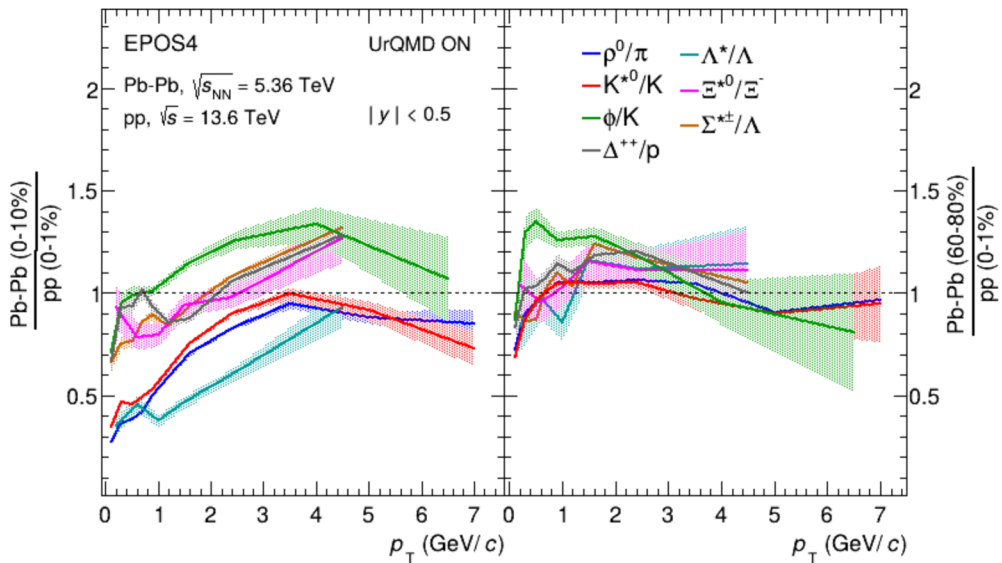


FIG. 5. The comparison of p_T -differential ratios ρ^0/π , K^{*0}/K , ϕ/K , Δ^{++}/p , Λ^*/Λ , Ξ^{*0}/Ξ^- , and Σ^{*+}/Λ in central (0–10%, left) and peripheral (60–80%, right) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV to the high multiplicity (0–1%) pp collisions at $\sqrt{s} = 13.6$ TeV with UrQMD. The bands in the measurements represent statistical uncertainty.

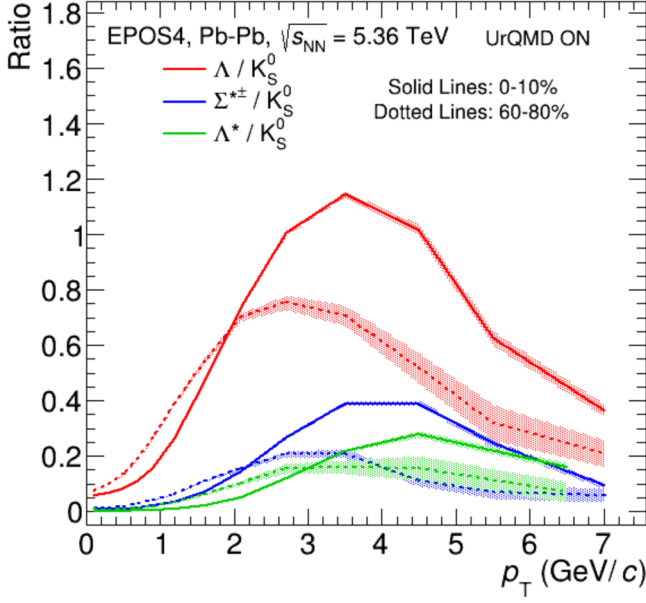


FIG. 6. The p_T -differential ratios Λ/K_S^0 , $\Sigma^{\pm}/K_S^0$, and Λ^*/K_S^0 in central (0–10%, solid lines) and peripheral (60–80%, dotted lines) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV, simulated using EPOS4 with UrQMD. The shaded bands represent statistical uncertainties in the measurements.

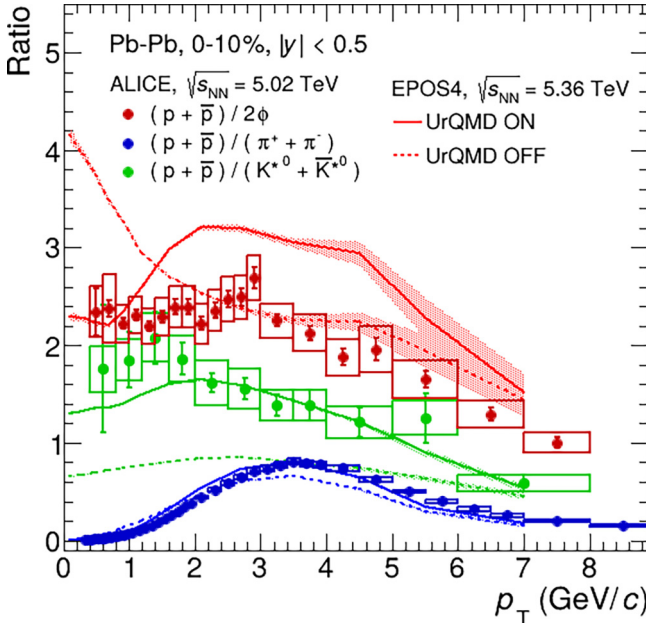


FIG. 7. The p_T -differential ratios p/ϕ , p/π , and p/K^{*0} in central Pb-Pb collisions with ALICE at $\sqrt{s_{NN}} = 5.02$ TeV (markers) and using the EPOS4 model with UrQMD (solid lines) and without UrQMD (dotted lines) at $\sqrt{s_{NN}} = 5.36$ TeV. The bars and boxes in the ALICE measurements represent statistical and systematic uncertainties, respectively. The shaded area in the model calculations represent statistical uncertainty.

contribute to the enhancement of these ratios. This is particularly evident in peripheral collisions, where strong radial flow is not expected, yet an enhancement at intermediate p_T is still observed. It arises from the core-corona picture and the exact conservation handled by MCE hadronization [21], leading to species-dependent behavior. These effects provide a possible explanation for baryon-to-meson enhancement in the EPOS4, complementary to quark coalescence mechanisms [40]. At high p_T , both experimental data and EPOS4 predictions show a decreasing trend across all particle species. In EPOS4, particles at high p_T are predominantly produced from the corona, where fragmentation rather than collective hydrodynamics governs the production. Consequently, the baryon-to-meson ratios decrease with p_T , reflecting the dominance of a common fragmentation mechanism in the production of both baryons and mesons at high p_T [21]. Furthermore, the EPOS4 model without UrQMD fails to describe the p/K^{*0} ratio except at high p_T , and also does not reproduce the observed enhancement in the p/π ratio at intermediate p_T . Thus, incorporating the UrQMD hadronic afterburner is essential in EPOS4 to accurately describe the measured baryon-to-meson ratios. This shows that, although protons, K^{*0} , ϕ have different quark content, the mass of hadrons and the hadronic phase effects on short-lived resonances play an important role in the determination of the spectral shapes of these particles. From the above discussion, it is clear that radial flow dominates over the hadronization mechanism in driving the enhancement of baryon-to-meson ratios in the intermediate p_T region for the most central collisions. When one of the hadrons is a resonance, UrQMD is required to properly account for additional hadronic phase effects to describe these ratios.

C. Average transverse momentum

The $\langle p_T \rangle$ of various hadronic resonances as a function of average charged particle multiplicity is shown in Fig. 8 for midrapidity in pp collisions at $\sqrt{s} = 13.6$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV. These calculations are obtained using EPOS4 with and without the UrQMD hadronic afterburner. The results are also compared with the measurements from ALICE Collaboration for pp collisions at $\sqrt{s} = 2.76$ and 13 TeV [3–5] and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [3,8,42], when available. The $\langle p_T \rangle$ increases with both charged particle multiplicity and the mass of the hadron species. The steeper increase of $\langle p_T \rangle$ with charged particle multiplicity observed in pp collisions compared to Pb-Pb collisions is well reproduced by the EPOS4 model and is consistent with ALICE measurements. This trend reflects the distinct underlying dynamics governing small and large systems and can be attributed to the interplay of several mechanisms. In particular, treatment of the core-corona picture, where a core evolves hydrodynamical with strong collective flow coexists with a no-flowing corona, microcanonical hadronization of the core, exact conservation, and possible parton saturation phenomena contribute to the observed behavior. These factors result in a sharper rise of $\langle p_T \rangle$ in pp events, especially at high multiplicities, while in Pb-Pb collisions they lead to a smoother evolution of $\langle p_T \rangle$. A more

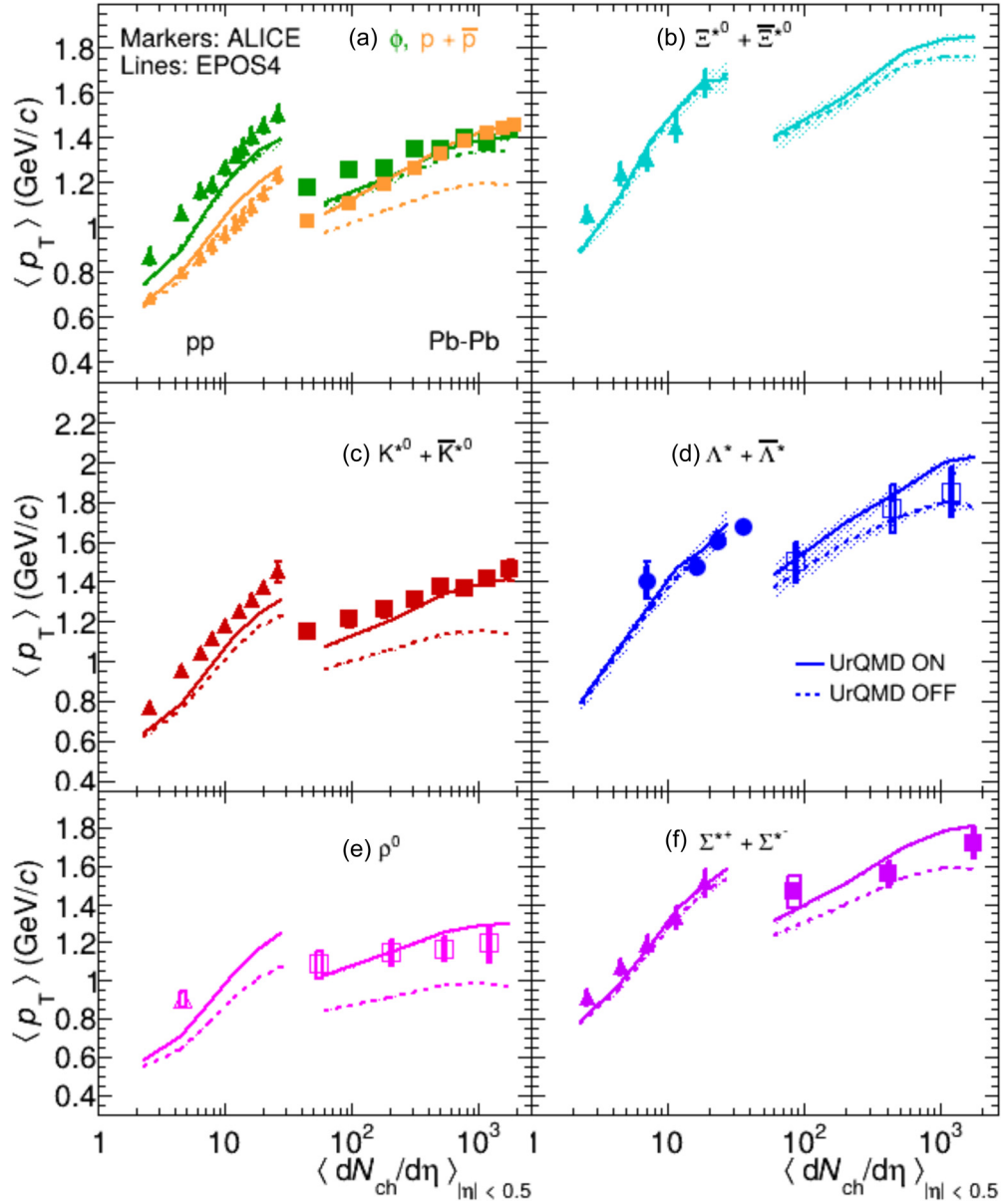


FIG. 8. Average transverse momentum of protons, mesonic resonances (ρ^0 , K^{*0} , and ϕ) and baryonic resonances ($\Sigma^{*\pm}$, Λ^* , Ξ^{*0}) as a function of charged particle multiplicity density at intermediate rapidity. Markers indicate ALICE measurements in the pp system at $\sqrt{s} = 2.76$ TeV (open triangles) [5] and $\sqrt{s} = 13$ TeV (solid triangles) [3,4,41], in the p -Pb system at $\sqrt{s_{NN}} = 5.02$ TeV (solid circles) [6], and in the Pb-Pb system at $\sqrt{s_{NN}} = 2.76$ TeV (open squares) [5,12] and $\sqrt{s_{NN}} = 5.02$ TeV (solid squares) [8,13,38]. The lines represent EPOS4 predictions for pp collisions at $\sqrt{s} = 13.6$ TeV and for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV with UrQMD (solid lines) and without UrQMD (dotted lines). The statistical and systematic uncertainties in the ALICE data are represented by bars and boxes, respectively, while the statistical uncertainty in the model measurements are represented by bands.

detailed discussion of the nonmonotonic behavior of $\langle p_T \rangle$ as a function of multiplicity can be found in Ref. [21].

The EPOS4 model generally reproduces the observed $\langle p_T \rangle$ trends in Pb-Pb collisions, demonstrating good agreement with experimental data across various centrality classes. In contrast, for pp collisions, EPOS4 tends to slightly underestimate the $\langle p_T \rangle$ values, particularly at higher multiplicities. The $\langle p_T \rangle$ values for short-lived resonances such as ρ^0 and K^{*0} show significant changes between cases with and without UrQMD for Pb-Pb collisions, whereas the effect is less pronounced for pp collisions. For the ϕ meson, the difference

in $\langle p_T \rangle$ between the two cases (with and without UrQMD) is smaller because its decay daughters interact less with the hadronic medium due to its longer lifetime. The change in $\langle p_T \rangle$ can be attributed to modifications in the spectral shape, as shown in Figs. 1 and 2. For short-lived resonances, their decay daughters undergo substantial hadronic interactions in the hadronic phase, leading to pronounced modifications. This effect is strongest in central Pb-Pb collisions and decreases with lower multiplicity, consistent with the shorter hadronic phase lifetimes discussed later in Sec. III E. For baryonic resonances such as $\Sigma^{*\pm}$, Λ^* , and Ξ^{*0} , no significant change

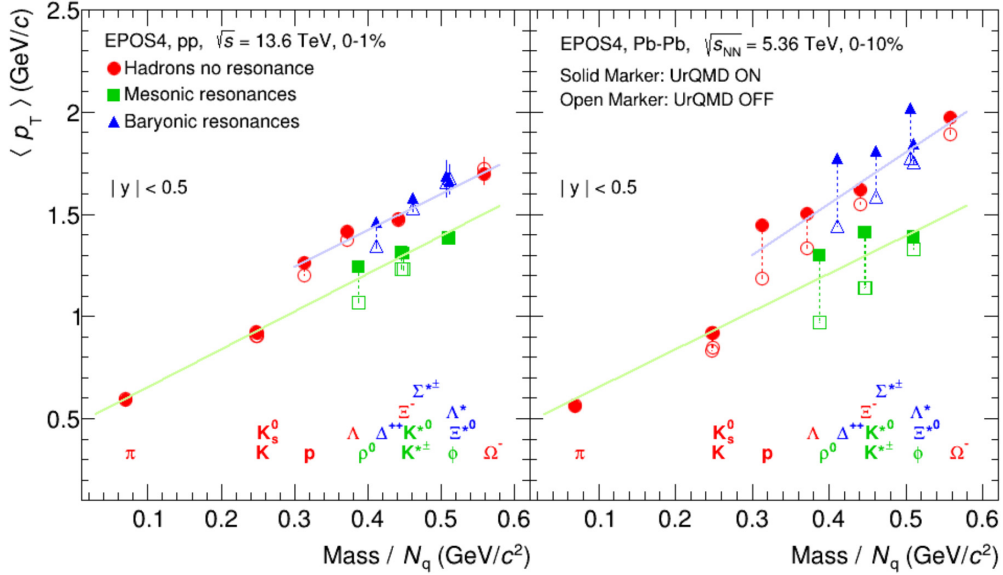


FIG. 9. The average transverse momentum of hadrons in the midrapidity region plotted as a function of the hadron mass, scaled by the number of valence quarks, in high multiplicity (0–1%) pp collisions at $\sqrt{s} = 13.6$ TeV (left panel) and in central (0–10%) $Pb-Pb$ collisions at $\sqrt{s_{NN}} = 5.36$ TeV (right panel) using the EPOS4 model with UrQMD (solid markers) and without UrQMD (open markers). The green and blue lines represent linear functions. The statistical uncertainty in the measurements is represented by bars.

in $\langle p_T \rangle$ is observed for small systems (up to $\langle dN_{ch}/d\eta \rangle_{|\eta| < 0.5} \approx 27$). However, in $Pb-Pb$ collisions, both the spectral shape and the $\langle p_T \rangle$ values exhibit significant modifications due to the extended hadronic phase. Particles with similar masses, such as the proton and the ϕ meson, show comparable $\langle p_T \rangle$ values in central $Pb-Pb$ collisions, consistent with observation reported by ALICE measurements [13,38]. This behavior is consistent with expectations from hydrodynamical models, which predict that $\langle p_T \rangle$ depends mainly on particle mass in such collisions. The EPOS4 model calculations also support this trend. The $\langle p_T \rangle$ value of protons show a slight difference between with and without UrQMD. This indicates that feed-down contributions from higher resonance decay daughters in the hadronic phase also modified the final proton p_T spectrum. It is important to properly handle feed-down contributions to the experimental measurement. The $\langle p_T \rangle$ of protons shows only a slight difference with and without UrQMD. This indicates that decay daughters from higher-mass resonances in the hadronic phase also modify the final proton p_T spectrum. Properly accounting for these feed-down contributions from higher-mass resonances is important in experimental measurements. In contrast, the p_T spectra of the ϕ meson is minimally affected by the hadronic phase, owing to its relatively long lifetime and small interaction cross section with the hadronic medium (In Fig. 7, the p_T -differential p/ϕ ratio from EPOS4 exhibits a flat behavior at low p_T , consistent with the data, while it overestimates the measurements for $p_T > 1.5$ GeV/c). Turning on the hadronic cascade (UrQMD ON) generally increases $\langle p_T \rangle$, bringing the prediction of the model closer to the experimental measurements. This effect demonstrates the crucial role of hadronic rescattering in modifying the p_T spectra during the late stages of the collision.

The $\langle p_T \rangle$ as a function of reduced mass (mass/N_q), where the mass of hadron is scaled by the number of valence quarks,

is calculated for various light-flavor hadrons, including resonances for high multiplicity (0–1%) pp collisions at $\sqrt{s} = 13.6$ TeV and central (0–10%) $Pb-Pb$ collisions at $\sqrt{s_{NN}} = 5.36$ TeV using the EPOS4 model, both with and without UrQMD, as shown in Fig. 9. The $\langle p_T \rangle$ follows a linear trend with increasing mass. Stable mesons (red markers) and mesonic resonances (green markers) are observed to generally follow a linear trend, aligning closely with the linear fit function represented by the green line for both UrQMD ON and OFF. This behavior is expected for a system that has a common transverse expansion velocity ($\langle \beta_T \rangle$), where the mean transverse momentum of the hadrons is approximately proportional to their mass, $\langle p_T \rangle \approx m \times \langle \beta_T \rangle$, resulting in a linear increase of $\langle p_T \rangle$ with particle mass. Similar observations were observed in the experimental measurements, as discussed in Ref. [39].

The observation that baryons and mesons group separately in $\langle p_T \rangle$ after scaling the hadron mass with their constituent quark numbers, with roughly parallel trends rather than collapsing onto a single curve, shows that collectivity is not fully carried over from the partonic stage to the hadronic final state and that hadronization dynamics affect baryons and mesons differently. It also indicates that hadronization is not purely coalescence driven, even though $\langle p_T \rangle$ is dominated mainly by low- p_T regions, where radial flow is the major contributor. Since EPOS4 does not explicitly implement a coalescence picture, the different grouping of baryons and mesons arises from hadronization mechanisms, including the core-corona picture, MCE hadronization, and hadronic rescattering, all of which introduce species-dependent effects. The ideal grouping of baryons and mesons can be understood through purely recombination-based hadronization models, and testing similar scaling with other observables, such as azimuthal anisotropy flow coefficients (v_n), could provide

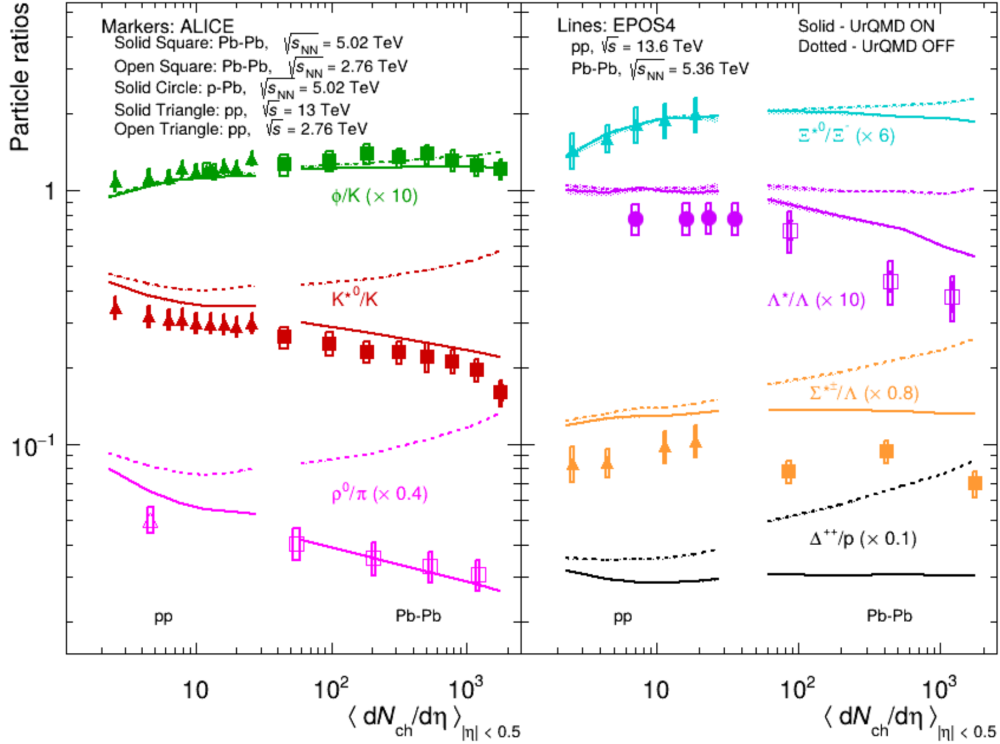


FIG. 10. Left panel shows the yield ratios of mesonic resonances to stable mesons while the right panel shows the yield ratios of baryonic resonances to stable baryons. Different markers represent ALICE results in pp collisions at $\sqrt{s_{NN}} = 13$ TeV (solid triangles) [3,4] and $\sqrt{s_{NN}} = 2.76$ TeV (open triangles) [5], p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (solid circles) [6], and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (open squares) [5] and $\sqrt{s_{NN}} = 5.02$ TeV (solid squares) [7,8]. The statistical and systematic uncertainties in the data are represented by bars and boxes, respectively. The lines represent predictions from EPOS4 in pp collisions at $\sqrt{s_{NN}} = 13.6$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV with UrQMD (solid) and without UrQMD (dotted). The shaded area indicates the statistical uncertainty in the model calculations.

further insight into the observed differences, which is beyond the current scope of this study.

However, the resonances ρ^0 , K^{*0} , $K^{*\pm}$, and Δ^{++} slightly deviate from the linear trend, with different values observed between UrQMD ON and OFF. This deviation is expected due to the finite hadronic phase in high-multiplicity (0–1%) pp collisions, which leads to the modification of the spectral shape of short-lived resonances. Similarly, the observed deviation from the linear function increases for Pb-Pb collisions compared to pp collisions. Hadronic resonances such as ρ^0 , K^{*0} , $K^{*\pm}$, Δ^{++} , $\Sigma^\pm$, and Λ^* show significant deviations from the expected linear trend due to the larger size of the system. The value of $\langle p_T \rangle$ is higher for short-lived resonances when UrQMD is ON compared to when it is OFF for the most central Pb-Pb collisions. This shows that the rescattering effect leads to an increased value of $\langle p_T \rangle$. Additionally, for stable hadrons such as the proton and Λ , the $\langle p_T \rangle$ values deviate from the linear trend and differ between the cases with UrQMD ON and OFF. This indicates that the spectral shape and $\langle p_T \rangle$ of protons and Λ are modified in the hadronic phase due to contributions from the decay of higher resonance states, since they are likely decay daughters.

D. Resonance to non-resonance yield ratios

The resonance-to-stable-hadron yield ratios as a function of charged-particle multiplicity ($\langle dN_{ch}/d\eta \rangle_{|\eta| < 0.5}$) at

midrapidity for pp and Pb-Pb collisions at LHC energies are presented in Fig. 10. Recent measurements of the ρ^0/π and K^{*0}/K ratios show a decreasing trend with increasing multiplicity. These ratios have been investigated using the EPOS4 model, both with and without the UrQMD hadronic afterburner. A significant difference is observed between the predictions of the model with and without UrQMD, with the difference being more pronounced in central Pb-Pb collisions compared to pp collisions. Furthermore, this difference is more significant for resonances with shorter lifetimes compared to those with longer lifetimes. The EPOS4 model, with the UrQMD hadronic afterburner enabled, successfully captures the features and qualitatively describes the behavior observed in the data. The K^{*0} and ϕ resonances are ideal candidates for these ratios because they have similar masses and contain strange quarks, while differing by lifetimes of an order of magnitude of 10. The ratios are chosen in such a way that the strangeness enhancement on the production yield is canceled out, allowing for a more direct comparison of resonance yields relative to stable hadrons. Suppression in the K^{*0}/K ratio occurs because the decay daughters of the resonance undergo rescattering processes in the hadronic phase, resulting in a modified final yield of the resonance compared to what was originally produced before chemical freeze-out. This suppression becomes more pronounced with increasing system size. The observed suppression in the K^{*0}/K ratio, compared to the ϕ/K ratio in small to large

collision systems, supports the idea that the shorter lifetime of K^{*0} plays a significant role in modifying the resonance yield in the hadronic phase. Similarly, the short-lived ρ^0/π ratio also shows suppression with increasing multiplicity. Observations from both data and model results indicate that re-scattering effects dominate over regeneration in the hadronic phase for short-lived mesonic resonances.

Similarly, Fig. 10 (right) shows the ratios of baryonic resonances to stable hadrons as a function of $dN_{ch}/d\eta$ at midrapidity. The Ξ^{*0}/Ξ^- ratio increases with multiplicity, whereas the Λ^*/Λ and $\Sigma^{*\pm}/\Lambda$ ratios show no significant change with multiplicity in pp collisions. In the Pb-Pb collisions, the Λ^*/Λ ratio decreases with increasing multiplicity, while the Ξ^{*0}/Ξ^- and $\Sigma^{*\pm}/\Lambda$ ratios remain largely unaffected, despite the fact that the $\Sigma^{*\pm}$ has a shorter lifetime compared to the Λ^* . This behavior may be attributed to the fact that the decay daughters of these resonances undergo regeneration and rescattering through (pseudo)elastic interactions in the hadronic phase. In the case of $\Sigma^{*\pm}$, the regeneration and rescattering effects are expected to cancel each other out, resulting in minimal changes in the yield with increasing system size. In contrast, the decreasing trend of the Λ^*/Λ ratio with multiplicity is primarily driven by rescattering effects. However, recent studies reported in Ref. [16] suggest that the mean free path of resonances also plays a significant role in modifying the final yield.

The Ξ^{*0}/Ξ^- also show a weak dependence with multiplicity due to larger lifetime compared to Λ^* . For Δ^{++} resonance, it is observed that Δ^{++}/p shows flat behavior with multiplicity for Pb-Pb collisions, whereas the same ratios exhibit a decreasing trend for pp collisions. Based on experimental data and model calculations, baryonic resonances exhibit distinct behaviors in pp and Pb-Pb collisions. This shows that the modification of the final reconstructed resonance yields in the hadronic phase is not solely determined by the resonance lifetime but also by other factors mentioned already in Sec. III A.

E. Lifetime of hadronic phase

The suppression of short-lived resonances is seen in both ALICE data and the EPOS4 model results with UrQMD. The suppression in the resonance to stable hadron yield is caused by the rescattering of decay products of resonances in the hadronic phase. These ratios act as useful tools for estimating the time span between chemical and kinetic freeze-outs using the exponential decay law, under the following assumptions:

- (1) Negligible regeneration effects.
- (2) Simultaneous freeze-out for all particle species. The relation is given by

$$[h^*/h]_{\text{kinetic}} = [h^*/h]_{\text{chemical}} \times e^{-\tau/\tau_{h^*}} \quad (1)$$

where $[h^*/h]_{\text{kinetic}}$ denotes the ratio of resonance to stable hadron yield at kinetic freeze-out, τ_{h^*} is the lifetime of the resonance particle in its rest frame and τ is the time span of the hadronic phase. Under these assumptions, all resonance particles decaying before kinetic freeze-out are lost due to rescattering of their decay daughters in the hadronic gas, with no

regeneration of resonances through elastic scattering. Thus, the estimated time duration is considered as the lower limit for the timespan between chemical and kinetic freeze-outs.

For this calculation, it is further assumed that no hadronic phase forms in pp collisions due to the small system size. Therefore, the yield ratio in minimum bias pp collisions is used as a proxy for $[h^*/h]_{\text{chemical}}$. A Lorentz boost factor is also applied in the calculation of τ because the lifetime of resonance is dilated when transitioning from the rest frame of the resonance to the laboratory reference frame. This factor is approximated as $\sqrt{1 + (\langle p_T \rangle / mc)^2}$, where $\langle p_T \rangle$ is the average transverse momentum and m is the rest mass of the resonance particle. The methodology used to estimate τ is the same as that discussed in Ref. [7]. The results for the estimated duration of the hadronic phase (τ) as a function of $(dN_{ch}/d\eta)^{1/3}$ from ALICE measurements and EPOS4 with UrQMD using resonances (ρ^0 , K^{*0} , and Λ^*) at LHC energies for pp and Pb-Pb collisions, are shown in Fig. 11. An increasing trend in the lifetime of hadronic phase is observed for these resonances in both data and model, corresponding to the decreasing yield ratios (as shown in Fig. 10) as a function of system size. This trend is expected, as a larger system size at a fixed chemical freeze-out leads to a decrease in the kinetic freeze-out temperature, thereby a longer timespan exists between chemical and kinetic freeze-outs. This pattern is consistent with the simultaneous blast-wave fits of the identified particle p_T distributions [38]. The time span of the hadronic phase calculated from the ρ^0/π and K^{*0}/K ratios is lower than that from the Λ^*/Λ ratio. The model predictions for estimation of τ using the Λ^*/Λ ratios underestimate the data, whereas ρ^0/π overestimate the data. Although the experimental data and model predictions are obtained at slightly different energies, the comparison reveals only minor differences. Since particle production is primarily driven by charged-particle multiplicity, the dependence on collision energy is expected to be weak or negligible. However, the model predictions for the K^{*0}/K ratio are in good agreement with the data. Contrary to the expectation of a common hadronic phase duration for all resonances, different values are found for the ρ^0 , K^{*0} , and Λ^* yields, with longer-lived resonances showing longer timescales. The observed different values in the time duration of the hadronic phase across different species may be attributed to additional factors beyond rescattering, which also contribute to the final modification of resonance yields. These factors are not accounted for in the simple exponential decay model, as described in Eq. (1). If regeneration is significant, the estimated duration from the yield ratios represents the timescale between delayed resonance production (caused by regeneration) and kinetic freeze-out. This duration reflects a lower limit for the actual hadronic-phase duration. To find the exact duration, the delay from regeneration needs to be added to this estimate. Recent calculations using a hybrid approach, where hydrodynamic evolution is followed by the SMASH hadronic transport model, reported that the mean free path of resonances also plays an important role in their final yields [16]. Similar studies, particularly of high multiplicity pp collisions, are of significant interest for better understanding the microscopic

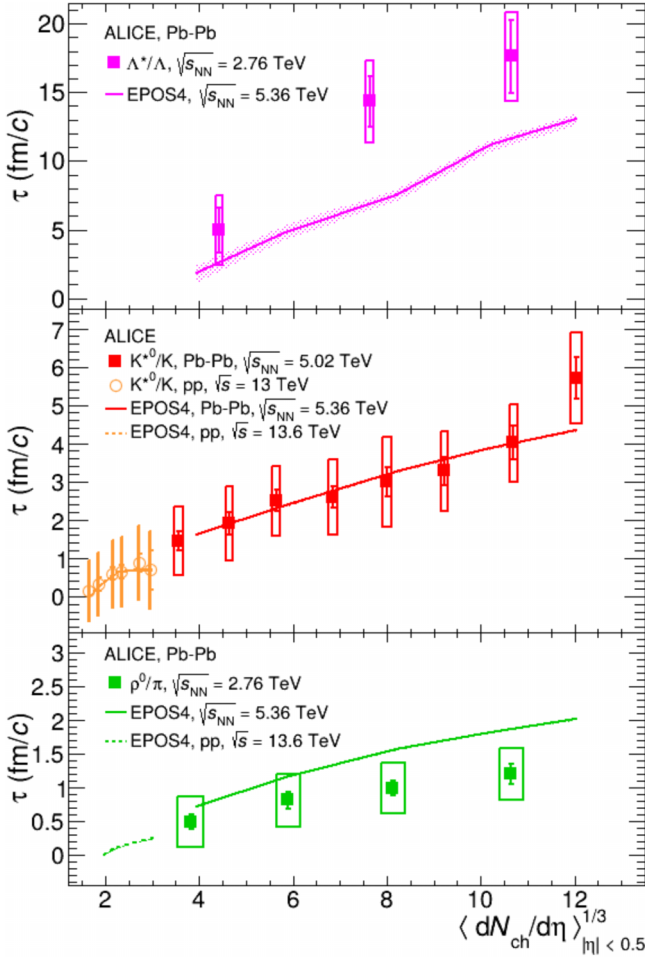


FIG. 11. Lower limit on the lifetime of the hadronic phase between chemical and kinetic freeze-outs in Pb-Pb collisions across different VOM multiplicity classes, where VOM denotes the combined signal amplitude measured by the ALICE forward multiplicity estimators V0A and V0C, obtained from yield ratios Λ^*/Λ at $\sqrt{s_{NN}} = 2.76$ TeV (magenta markers) [12], K^*/K at $\sqrt{s_{NN}} = 5.02$ TeV (red markers) [7], and ρ^0/π at $\sqrt{s_{NN}} = 2.76$ TeV (green markers) [5]. EPOS4 predictions for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV are shown as lines, with shaded areas representing statistical uncertainties. Statistical and systematic uncertainties in the ALICE data are depicted by bars and boxes, respectively. The figure also includes ALICE measurements of K^*/K in pp collisions at $\sqrt{s} = 13$ TeV (orange markers) [3] and EPOS4 predictions for pp at $\sqrt{s} = 13.6$ TeV (orange line), highlighting the system size dependence of the hadronic phase lifetime.

origin of resonance suppression. The EPOS4 model results for K^* with UrQMD in high-multiplicity pp collisions also show a nonzero hadronic phase duration, approximately matching the value in peripheral Pb-Pb collisions, thus highlighting the system size dependence of the hadronic phase lifetime, as shown in Fig. 11.

F. Strangeness enhancement

The relative yield ratios of various hadrons to pions serve as a key observable to understand the origin of strangeness

production and the hadronization mechanism. Figure 12 shows the yield ratios of protons, K_S^0 , and, multistrange baryons (left), along with hadronic resonances (right), normalized to pions as a function of charged-particle multiplicity for pp to Pb-Pb collisions at LHC energies. The results of EPOS4 with and without UrQMD are represented by solid and dotted lines, respectively, and are compared with the available measurements from the ALICE Collaboration [3,4,8,12,38,39,41,43,44]. The yield ratios exhibit a smooth evolution with multiplicity from pp to Pb-Pb collisions, whereas the $\langle p_T \rangle$ shows a nonmonotonic pattern with multiplicity, as seen in Fig. 8 and also explained in Sec. III C.

The observed enhancement in the production of strange hadrons relative to pions is primarily driven by their strange-quark content rather than their mass. This effect becomes more pronounced for hadrons with higher strangeness. The change in the slope of the ratios with multiplicity in the pp collisions shows a steeper rise compared to the Pb-Pb collisions. The same ratios exhibit a saturation trend for hadrons that contain strange quarks at higher multiplicities for Pb-Pb collisions. This behavior is understood to be the case that their production reaches a chemical equilibrium within the thermalized environment, where the yields of strange and multi-strange hadrons become independent of further enhancement with increases in multiplicity at LHC energies. The EPOS4 model with MCE framework, which reproduces the observed behavior seen in the experimental measurements. However, when the size of the system gets very small, one gets suppression in the production of heavy particles due to the microcanonical treatment of strange particle production, which imposes constraints on energy and flavor conservation. This effect becomes more pronounced with increasing particle mass and is more significant for Ω and Ξ baryons in pp collisions. In Pb-Pb collisions, the model results with and without UrQMD show differences for protons and multistrange hadrons, highlighting the role of hadronic phase effects. In contrast, no significant difference is observed for pp collisions. Moreover, the proton-to-pion yield ratios from EPOS4 simulations with UrQMD show a decreasing trend with multiplicity in Pb-Pb collisions, in qualitative agreement with experimental observations, but the model slightly overestimates the measured values. One of the possible explanations for this suppression is baryon-antibaryon annihilation that occurs in the hadronic phase within the high-multiplicity, high-density environment of PbPb collisions, which reduces the overall proton yield relative to pions. However, the same ratios for Λ show only a weak decrease, while for heavier strange baryons such as Ξ^- and Ω^- there is no decreasing trend with multiplicity.

To further understand the behavior, the double yield ratios of Δ^{++} , Λ , Ξ^- , and Ω^- to protons have been calculated. These ratios are normalized to their respective values measured in inelastic pp collisions. Calculations were performed as a function of charged particle multiplicity using EPOS4 with the UrQMD hadronic afterburner. The results, shown in Fig. 13, demonstrate that the multiplicity-dependent enhancement relative to inelastic pp collisions follows a hierarchy determined by strangeness content of hadrons. To follow up on the earlier discussion about the decreasing trend in proton-

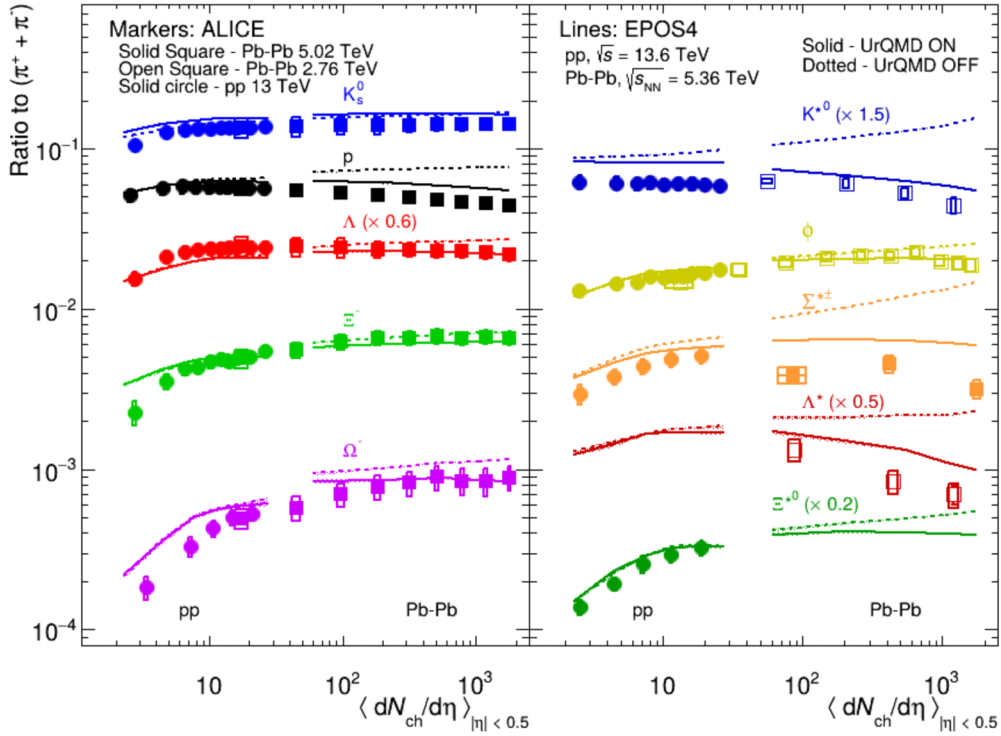


FIG. 12. The left panel shows the yield ratios of protons, strange hadrons, and multistrange hadrons while the right panel shows the ratios of hadronic resonances, normalized to pion yield. Different markers represent ALICE results in pp collisions at $\sqrt{s_{NN}} = 13$ TeV (solid circles) [3,4,39,41,43] and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (open squares) [12,44] and $\sqrt{s_{NN}} = 5.02$ TeV (solid squares) [8,38]. The statistical and systematic uncertainties in the data are represented by bars and boxes, respectively. The lines represent predictions from EPOS4 in pp collisions at $\sqrt{s_{NN}} = 13.6$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV with UrQMD (solid) and without UrQMD (dotted). The shaded area indicates the statistical uncertainty in the model calculations.

to-pion ratios, another nonstrange baryon, Δ^{++} , is chosen. Since Δ^{++} contains no strange quarks and shows no hadronic phase effects (as discussed in Fig. 10), it serves as a useful candidate. The double yield ratios for Δ^{++} exhibit a flat trend with multiplicity in Pb-Pb collisions, reflecting that baryon-antibaryon annihilation affects Δ^{++} in a similar manner as protons in the hadronic phase. In contrast, the Λ -to-pion ratio shows only a weak dependence on multiplicity, while Ξ^- and Ω^- exhibit no decreasing trend, even in the most central Pb-Pb collisions. According to the strangeness enhancement picture, the yield ratios reach a saturation trend at higher multiplicities. The slight decrease in the Λ -to-pion ratio at the most central collisions could be attributed to additional contributions from baryon-antibaryon annihilation during the hadronic phase. This modifies strange-baryon productions and acts oppositely to the strangeness enhancement scenario. Therefore, the net effect on baryon-to-pion ratios depends on the interplay between strangeness enhancement and baryon-antibaryon annihilation. Strangeness enhancement is found to be the dominant mechanism for strange baryon production, whereas the contribution from baryon-antibaryon annihilation is negligible, particularly for heavier strange baryons, due to their lower abundance resulting from larger mass and reduced production probability. Moreover, the heavier multistrange baryons are expected to freeze-out earlier, reducing their interactions in the hadronic phase and lowering the likelihood of annihilation compared to protons [45]. Future experimental

precision measurements of these ratios at the LHC will provide deeper insight, helping to distinguish between the effects of strangeness enhancement and baryon-antibaryon annihilation.

Furthermore, the ratios of short-lived hadronic resonances (ρ , K^{*0} , and Λ^*) to pions show a decreasing trend with multiplicity in Pb-Pb collisions. A similar trend is observed in the experimental measurements, and the trend is also reproduced by EPOS4 with UrQMD. This behavior is understood as the rescattering effect dominating over strangeness enhancement for short-lived resonances. Similarly, for the long-lived ϕ meson, a weak enhancement trend is observed, except in the most central Pb-Pb collisions, where measurements reveal a decreasing trend, which is reproduced by UrQMD. Future measurements will provide further constraints to better understand this behavior. The relative yield ratios of hadrons to pions are determined by the combined contributions of various processes, including strangeness production, baryon-antibaryon annihilation, and hadronic phase effects, with the significance of each process varying based on the specific hadron species.

IV. SUMMARY

In this work, we present the study of various hadronic resonances to explore production dynamics and their interactions, along with other stable strange and nonstrange hadrons at

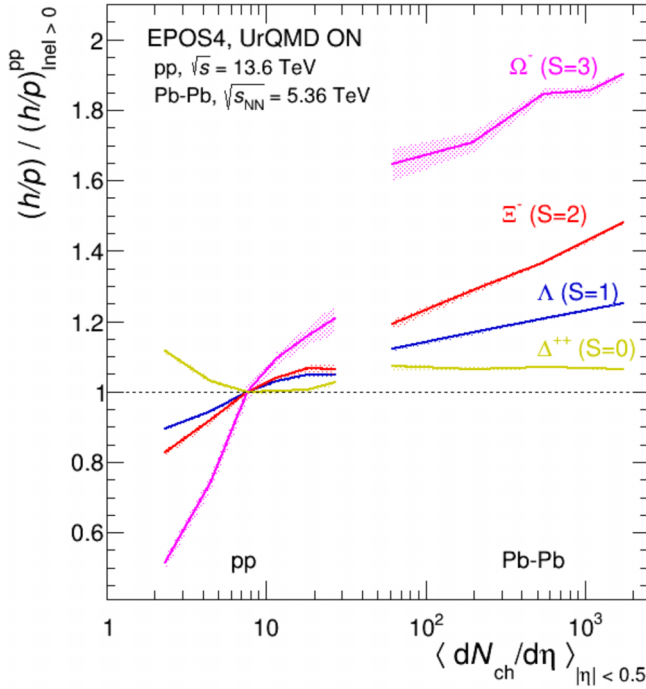


FIG. 13. Ratios of particle yields relative to protons, normalized to the values measured inelastic pp collisions, as predicted by the EPOS4 model with UrQMD. The results are shown for Δ^{++} and multi-strange baryons in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV and in pp collisions at $\sqrt{s} = 13.6$ TeV. The bands in the measurements represent statistical uncertainty.

midrapidity in pp and Pb-Pb collisions at $\sqrt{s} = 13.6$ TeV and $\sqrt{s_{NN}} = 5.36$ TeV, using the EPOS4 simulation. The results are new findings with the latest EPOS4 model, extending such studies for the first time to high-multiplicity pp collisions and the highest energies for Pb-Pb collisions at the LHC. EPOS4, with UrQMD as the hadronic afterburner, is a well-suited model to describe experimental measurements of resonance production in high-energy collisions. It reproduces the qualitative trend of resonance-to-ground-state particle yield ratios as a function of system size, from pp to Pb-Pb collisions. The ratios of shorter-lived resonances (ρ^0 , K^{*0} , Λ^*) are suppressed, while Ξ^{*0} exhibits a weak suppression, and $\Sigma^{*\pm}$ and Δ^{++} remain unaffected. This suppression is not observed in the ϕ meson due to its longer lifetime compared to other resonances. Precision studies of heavier baryonic resonances (Ξ^{*0} , $\Sigma^{*\pm}$) and predictions for Δ^{++} await confirmation through future measurements in heavy-ion collisions at the LHC. Similar ratios generate strong interest in small systems, since model calculations of the ρ/π and K^{*0}/K ratios show a decreasing trend, with stronger suppression at high multiplicity. This trend is consistent with the measured K^{*0}/K ratio in pp collisions by the ALICE Collaboration. The lower limit of the time duration (τ) of the hadronic phase can be estimated using the yield ratios of ρ/π , K^{*0}/K , and Λ^*/Λ , and it increases with the system size. A nonzero time duration (~ 0.5 – 1 fm/c) is found in high-multiplicity pp collisions. The suppression in these ratios arises from modifications of resonance yields in the hadronic phase, where rescattering

processes dominate over regeneration. This effect is more pronounced in the low- p_T region and is particularly significant for short-lived resonances.

Enabling UrQMD improves the description of the $\langle p_T \rangle$ values for various hadronic resonances and protons. In central Pb-Pb collisions, the mass ordering of $\langle p_T \rangle$ for particles with similar masses (e.g., p and ϕ) aligns with hydrodynamic predictions, but this ordering breaks down in peripheral Pb-Pb and pp collisions. $\langle p_T \rangle$ as a function of reduced mass (scaled by the number of valence quarks) shows a linearly increasing trend. The baryons and mesons form distinct groups that are parallel to each other. For short-lived resonances such as ρ^0 and K^{*0} , deviations from the linear trend are observed in high-multiplicity pp collisions and are more significant in central Pb-Pb collisions. This observation is a consequence of rescattering effects in the hadronic phase, which lead to an increase in the $\langle p_T \rangle$ values of short-lived resonances. Moreover, for stable hadrons such as proton and Λ , the $\langle p_T \rangle$ values differ significantly with and without UrQMD; particularly in central Pb-Pb collisions, their spectral shapes and $\langle p_T \rangle$ values are influenced by the decays of higher-mass resonances.

The baryon-to-meson ratios in central and peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV have been measured. This confirms that the radial flow plays a dominant role in enhancing the Λ^*/K_S^0 and $\Sigma^{*\pm}/K_S^0$ ratios in the intermediate- p_T region. Additionally, the p/ϕ and p/K^{*0} ratios remain nearly flat for intermediate p_T . At high p_T , all the ratios exhibit a similar decreasing trend that indicates the common fragmentation process influencing their production. To understand the microscopic origin of the strangeness production, the strange and multi-strange hadrons along with resonances are investigated. The relative yield ratios of hadrons to pions smoothly increase with multiplicity, with the rate of increase depending on the strange quark content of the hadrons. However, the ratios reach the saturation trend at higher multiplicities ($\langle dN_{ch}/d\eta \rangle_{|\eta| < 0.5} > 100$), consistent with expectations that strangeness production approaches the grand-canonical limit at large system size and high density, where canonical effects become negligible. The p/π ratios exhibit a decreasing trend with increasing multiplicity, a behavior that becomes more pronounced at higher multiplicities for Pb-Pb collisions. This trend is observed in both experimental data and model predictions. The suppression at higher densities is primarily driven by baryon-antibaryon annihilation for nonstrange hadrons (p) whereas this effect is less pronounced for heavier multi-strange baryons (Λ , Ω , and Ξ). The p_T spectra and yields of various hadrons, including resonances, have been studied to understand the effects of the late-stage hadronic phase from EPOS4 with UrQMD.

From these studies, it is concluded that hadronic phase effects, such as rescattering and regeneration, play an important role in the modification of resonance yields relative to stable hadrons. For mesonic resonances (ρ , K^{*0} , ϕ), the observed suppression pattern follows their vacuum lifetimes, consistent with expectations from rescattering in the hadronic medium. In contrast, baryonic resonances exhibit a more complex behavior: the short-lived Σ^* shows no significant suppression, whereas Λ^* exhibits a stronger suppression than the K^{*0} meson. This could be because regeneration contributions depend

on the decay products and their interaction cross sections in the hadronic phase. The final modification of resonance yields cannot be attributed to a single factor, but rather results from the combined effects of decay product cross sections, lifetime of resonance, the time span of the system created, and the assumption of a single freeze-out temperature for all hadrons.

Further, differential studies, such as resonance flow and correlations with jets, will provide insights into the hadronic phase created in high-energy collisions at LHC energies. A comprehensive understanding of the hadronic phase, even in small collision systems, is therefore essential for accurately interpreting observables that reflect the underlying production dynamics. Future measurements of resonances such as Δ^* , $f_0(980)$, $\Lambda(1405)$, $N(1535)$, and $K_1(1270)$ will provide additional input on the late-stage interactions in high-energy collisions.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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