

Production of multistrange hadrons in Pb+Pb collisions at energies available at the CERN Large Hadron Collider using the HYDJET++ model

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For the present work, we have used the HYDJET++ model to explore the production of pure multi-strange hadrons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV collision energies, respectively. We have performed simulations to investigate transverse momentum (p_T) spectra and elliptic flow (v_2) for ϕ mesons and Ω baryons, and compared the results both with the ALICE experimental data and available model predictions for selected central classes. Furthermore, we have calculated the nuclear modification factors (R_{AA} and R_{CP}), which provide a perception of jet quenching phenomena. Hence, our findings enable the study of the energy and system dependence of ϕ and Ω hadrons production over a wide range of ultrarelativistic collision energies. We also present the particle ratios (Ω/ϕ , $\bar{\Omega}^+/\Omega^-$, Ω/π , and ϕ/π), offering insights into the strangeness enhancement and chemical properties of the medium at both CERN Large Hadron Collider collision energies. Additionally, we also explore the predictions for the Ω baryon in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, focusing on R_{AA} , R_{CP} , and particle ratios within the HYDJET++ framework, offering insights into future measurements and particle dynamics in high-energy heavy-ion collisions.

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I. INTRODUCTION

One of the most important theoretical tasks for quark gluon plasma (QGP) formation in heavy ion collisions at ultrarelativistic energies is to separate or account for the influence of the QGP phase and hadron gas expansion from true signals of phase transformation. To solve this task, one needs a reliable theoretical and experimental description of hadron gas properties emitted from the hypersurfaces of chemical and thermal freeze-out [1–5].

Both ϕ and Ω particles decouple from the surrounding system earlier than nonstrange hadrons due to their smaller hadronic interaction cross sections, higher mass, and lower interaction rates [6,7]. This early decoupling refers to the process by which particles cease interacting strongly with the surrounding medium, providing more direct information about the chemical/thermal freeze-out stage which is expected near the quark-hadron transition temperature [6,7]. These particles experience little to no distortion due to hadronic rescattering and are less affected by the pressure generated by the hadronic matter in the later stages of the reaction [8].

As a result, ϕ and Ω particles provide a unique tool for probing the transition from partonic to hadronic dynamics [9]. Additionally, the study of ϕ strongly suggests a baryon versus meson dynamic and strangeness enhancement, as opposed to a simple mass dependence, as would be the case for radial flow developed during the hadronic phase [10]. It arouses a great interest in QGP fireball formation as a function of energy [11,12] and system size [13,14] at ultrarelativistic nuclear collisions.

The mechanism of strangeness production in ultrarelativistic heavy-ion collisions can be explored by analyzing the particle spectra, $\langle p_T \rangle$, and anisotropic flow. The shape of p_T spectra varies for different particles, indicating that heavier particles gain more momentum at a given velocity when thermally produced from the QGP fluid due to the collective flow in the expanding medium and also provides information about initial energy density. Mean $\langle p_T \rangle$ of particles produced in a collision is related to the initial transverse size of the fireball, where a higher $\langle p_T \rangle$ value is indicating a smaller initial area [11]. These measurements reveal possible flavor dependencies and help to distinguish between soft and hard processes based on quark content [15–17]. Likely, the ratio of the p_T spectra at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV as a function of p_T may help to understand the strangeness enhancement and medium effect through nuclear modification factors (R_{AA} and R_{CP}) [18]. The enhanced multiplicity of strange particles in the QGP compared to the hadron gas (HG) phase can be referred to the increased reaction volume of large nuclei, as described in Braun-Munzinger's work [19].

In addition to the volume effect, the undersaturation of strange particle phase space introduces a strangeness

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suppression factor (γ_s) [19]. The deviation of the strange particle yields from a hadron gas in full equilibrium was quantified by γ_s . This suppression is weaker in heavy-ion collisions and fitting hadron multiplicities in full-phase space still require consideration of γ_s . One reasonable explanation is that the total strangeness available for hadronization is set during a prehadronic stage of the collision. Thus, a change in γ_s between $p + p$ and $A + A$ collisions may reflect differences in the initial conditions of the different fireballs [20].

Furthermore, anisotropic flow (v_2) [21–24] as a function of p_T and centrality provides information about the pressure gradients, the effective degrees of freedom, the degree of thermalization, and the equation of state of the matter created at the early stage in noncentral collisions. At low p_T , flow shows a hydrodynamic expansion in the system and mass orders of v_2 . At intermediate to high p_T , there is a noticeable separation in the baryon-meson spectra as a function of p_T . However, no distinction is observed between baryons and mesons as a function of centrality, supporting the NCQ scaling [21,22]. v_2 of baryons is larger than v_2 of mesons at intermediate to high p_T gives additional insight into hadronization through quark coalescence [21] and includes interactions of jet fragments with bulk matter. In this p_T range, a nonzero value of v_2 is generated when hard partons propagating through the system lose energy via radiative and collisional loss processes [18,25]. This allows us to safely assume that both jet quenching and v_2 at high p_T are dominated by energy loss [26]. The influence of flow would result in an underestimation (overestimation) of the quenching contribution in (out) of the plane during heavy ion collisions [21–23,26].

In this paper, we employ the HYDJET++ model [27–29] to describe the behavior of (multi)strange hadrons in heavy-ion collisions and also compare its results with predictions from other well-known simulation models such as a multi-phase transport (AMPT), VISHNU, EPOS, HIJING/ $B\bar{B}$, and the Krakow model [5,30–39], each offering different approaches to simulating particle production and dynamics in heavy-ion collisions.

AMPT [31,32] describes heavy-ion collisions by incorporating fluctuating initial conditions, two-body elastic parton scatterings, hadronization, and hadronic interactions. The default version of the AMPT model, which includes only minijet partons in the parton cascade and employs the Lund string fragmentation [40] for hadronization, can well describe the rapidity distributions and p_T spectra of identified particles in heavy-ion collisions from CERN Super Proton Synchrotron (SPS) to CERN Large Hadron Collider (LHC) energies. However, it significantly underestimates the elliptic flow at the BNL Relativistic Heavy Ion Collider (RHIC) and (multi)strange spectra at RHIC and LHC. To address this, the AMPT model with string melting (SM) incorporates a quark coalescence mechanism for hadronization [39]. While the improved coalescence mechanism in the AMPT-SM model enhances the better description of strange particle ratios, anisotropic flow, it still underpredicts the strange yield [32]. This deviation is likely due to limitations in the coalescence model's treatment of strange quark production and dynamics, as well as the initial conditions provided by HIJING that further discussed in the HIJING description, which may not

fully capture the abundance of strange quarks necessary to match experimental data.

In the same context, the EPOS and Krakow models are based on the core-corona concept [17]. In EPOS, this separation depends on the initial energy density areas with high energy density are called the core, while low-density areas are the corona [35]. This helps in explaining how particle production changes with collision centrality. In central collisions, the core dominates and plays a major role in producing heavier and multistrange particles because of the dense environment and higher energy, leading to particles with larger transverse momentum (p_T). In contrast, the corona contributes more in peripheral collisions, where the density is lower.

The Krakow [36] is a (3 + 1)-dimensional hydrodynamic model that includes essential parameters like bulk and shear viscosities. In this model, nonequilibrium corrections can be described through the bulk viscosity coefficient in the expanding fireball, increasing the effective chemical freeze-out temperature [36]. However, this effect is not strong enough to reproduce the observed yield of heavy hadrons. This agreement could be improved using different equilibration rates and different freeze-out temperatures for different particle species [36].

Another important model in this context is VISHNU, which combines VISH2 + 1 for QGP fluid expansion and ultrarelativistic quantum molecular dynamics (UrQMD) for hadron resonance gas evolution. However, the UrQMD module only includes strong resonance decays and neglects weak decays and baryon-antibaryon ($B\bar{B}$) annihilations. This omission leads to a significant reduction in the yields of strange and multistrange baryons about 30% for Λ and 20% for Ξ and Ω in the most central Pb+Pb collisions [31,33]. Additionally, the differences between the calculated p_T spectra and the experimental data, along with the mismatch in mass ordering among p , Λ , and Ξ , suggesting that the results cannot be fully explained by assuming a single chemical freeze-out temperature [31,33]. Following this, HIJING/ $B\bar{B}$ model [37,38] is an upgraded version of regular HIJING within the new parameters, strong color field (k), and various suppression factors (i.e., diquark, strangeness, suppression of spin 1 diquarks relative to spin 0 ones, and normal) based on the HIJING/ $B\bar{B}$ v1.10 and HIJING models [4]. These modifications enhance the production of (multi)strange particles compared to the regular HIJING model but still fall short of matching experimental data. Similar to HYDJET++, these changes have little impact on bulk particle yields, allowing the model to describe both nonstrange and multistrange hadrons simultaneously. Additionally, it supports the theoretically and experimentally [2,3,41,42] observed early thermal freeze-out of multistrange hadrons through fluctuations of the transient strong color field [4].

The paper is organized as follows. Section II briefly describes the HYDJET++ model, which supports the early thermal and chemical freezeout of multistrange particles. Section III A highlights the measurements of ϕ and Ω hadrons spectra obtained by the HYDJET++ model. These results are compared to available ALICE experiment data and other available models AMPT, VISHNU, and EPOS results, focusing on collisions at LHC energies [43,44] as a function of

p_T . Section III B discusses the factors, R_{CP} and R_{AA} . Section III C explores the Ω/ϕ , $\phi/\pi^- + \pi^+$, $\bar{\Omega}^+ + \Omega^-/\pi^- + \pi^+$, and $\bar{\Omega}^+/\Omega^-$ ratios with available experimental data and other Krakow and HIJING/ $B\bar{B}$ [5,36–38] model results. Section III D evaluates the elliptic flow (v_2) as a function of p_T , $\langle p_T \rangle$, and $\langle v_2 \rangle$ as a function of N_{part} . The measured mean $\langle p_T \rangle$ also shows the variation with energies and heavier mass/quark content, which provides more information about the thermal and/or chemical equilibrium and strong radial flow. Section III E discusses charged particles mass ordering phenomena at (10–20%) centrality interval. Finally, Sec. IV summarizes our findings.

II. MODEL FORMALISM

HYDJET++ model is a widely used hybrid Monte Carlo event generator that successfully simulates a large number of observables measured in relativistic heavy-ion collisions [28,29] at RHIC as well as LHC energies. The HYDJET++ simulation is comprised of two independent processes: one simulating soft, hydroprocess (low momentum regime) which is based on preset relativistic hydrodynamics parametrization of the freeze-out hypersurfaces by the FAST MC [45] generator and the other simulates hard component where energetic partons lose energy in the medium.

The soft component simulates a thermalized hadronic system generated on freeze-out hypersurfaces defined by parametrized relativistic hydrodynamics with specified freeze-out conditions [45,46]. The thermal hadrons are emitted from a freeze-out hypersurface defined by parameters such as the thermal freeze-out temperature (T_{th}), maximum transverse flow rapidity (ρ_{max}), spatial and temporal dimensions (R_f , τ_f , $\Delta\tau_f$), and chemical potentials in Ref. [45]. The freeze-out hypersurface is constructed event by event, but with fixed global parameters (i.e., no event-by-event fluctuations of the surface geometry are implemented by default). The model assumes longitudinal boost invariance and cylindrical symmetry in the transverse plane. Based on these assumptions, the particle momenta are generated according to the generalized Cooper-Frye prescription [47]. Further, the effective thermal volume of the fireball, calculated for each event, determines the average hadron multiplicities at freeze-out and is proportional to the number of wounded nucleons at a given collision centrality, as provided by the Glauber model [48]. Following this, final-state interactions are limited to two- and three-body decays of resonances, which are taken from an extensive table containing over 360 mesons and baryons states [49], including charmed particles, and contribute significantly to the final particle spectra observed.

In contrast, the hard component of the event involves the production of multijets, modelled using a binomial distribution based on the PYQUEN (PYthia QUENched) energy loss model [50]. In this framework, the initial parton spectra are generated using PYTHIA6.4 [51], with jet production vertices determined by nuclear geometry that depends on the collision's impact parameter. As the hard partons propagate through the QGP, they experience energy loss influenced by the density and geometry of the soft component, which serves

as a static background medium. The collisional energy loss per unit length, dE^{coll}/dl , is calculated in the high-momentum transfer limit, representing the incoherent sum of individual scattering events [27,29]. Low-momentum transfer contributions are negligible and effectively absorbed by setting $t_{\text{min}} \approx \mu_D^2$, where μ_D is the Debye screening mass. Meanwhile, the radiative energy loss per unit length, dE^{rad}/dl , is evaluated using the Baier-Dokshitzer-Mueller-Schiff (BDMS) framework [27,52], which quantifies the strength of multiple scatterings through the transport coefficient $\hat{q}$. This parameter, primarily governed by the initial QGP temperature T_0 , is used to compute the energy spectrum of coherent, medium-induced gluon radiation [29]. The final hadronization of hard partons and in-medium emitted gluons according to the Lund string model [40] takes place. The number of jets produced in HYDJET++ is directly related to the number of binary NN collisions at a given impact parameter and the integral cross section of the hard process in NN collisions with the minimum transverse momentum transfer (p_T^{min}) [5].

The calculation of transverse momentum spectra, anisotropic flow, jet-quenching effect, and particle ratios observables for charged particle production in heavy-ion collisions have been successfully done by HYDJET++ [28,53] under the soft and hard component processes.

Anisotropic flow is generated from the corresponding spatial eccentricities of the overlap zone of the fireball, which is characterized by the azimuthal spatial anisotropy $\langle \epsilon(b) \rangle$ and momentum anisotropy $\langle \delta(b) \rangle$ parameters [22,46,53]. These parameters can either be treated independently for each centrality interval or connected through their influence on the elliptic flow coefficient v_2 , whose relationship has been predicted using the hydrodynamical approach [22,28]. In recent studies [17,22], the HYDJET++ model has simulated multi-strange particle production under a single thermal freeze-out scenario, where all charged particles freeze at the same thermal temperature and γ_s ($\gamma_s = 1$ shows no strangeness suppression and $\gamma_s \neq 1$ shows the strangeness suppression). However, other studies [1–5,13] have concluded that thermal and/or chemical freeze-out is hadron species-dependent, with multi-strange hadrons experiencing earlier thermal freeze-out due to their smaller hadronic interaction cross sections.

In this article, we have tuned the model on the basis of hadron-species dependent freeze-out parameters like T_{th} , T_{ch} , and γ_s . We have tuned γ_s by matching independently strange/nonstrange hadrons particle yield to the experimental data for each centrality interval [54]. In thermal model calculations, γ_s is used as a parameter that indicates the strangeness equilibration as a function of system size and collision energy in $p + p$ and $A + A$ collisions [17,41,42,54–56]. γ_s increases with increasing the collision energies $\sqrt{s_{NN}}$ (SPS to LHC then remain constant at LHC) [54]. In Tables I and II, we have shown the values of γ_s given as input; $\langle N_{\text{part}} \rangle$, and $\langle N_{\text{coll}} \rangle$ for various centrality classes obtained from HYDJET model. By comparing the p_T spectra with ALICE experiment data, we have optimized the value of γ_s for both $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV LHC energies. The geometrical parameters obtained from the HYDJET++ model, as calculated using the 2pF (two-parameter Fermi form) MC Glauber model [48], are consistent with the experimental data reported by the ALICE

TABLE I. Centrality-dependent values of the number of participants ($\langle N_{\text{part}} \rangle$), number of binary collisions ($\langle N_{\text{coll}} \rangle$), and suppression factor (γ_s) used in HYDJET++ simulations for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Centrality (%)	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$	γ_s
0–5	374.5	1590	1.00
5–10	315.5	1238	0.99
0–10	345.0	1414	–
10–20	242.5	857.7	0.975
20–30	167.6	511.0	0.95
30–40	111.7	287.5	0.94
40–50	70.19	147.8	0.93
50–60	40.31	67.2	0.925
60–80	14.23	17.15	0.91

collaborations. The input parameters such as T_{ch} and T_{th} , are tuned in such a way that the geometrical quantities remain consistent with the default HYDJET++ model [5,13].

III. RESULTS

A. p_T spectra

Figures 1–4 show the p_T -spectra results of the ϕ meson and Ω baryon. In particular, Fig. 1 presents the transverse momentum spectra of ϕ and Ω hadrons for central and peripheral collisions, highlighting the separate contributions from soft and hard components, along with their combined spectra as calculated by HYDJET++. For ϕ and Ω , the bulk of the p_T yield have a significant contribution from hydro and jet production at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV. Moreover, from intermediate to high p_T , the particle production is dominated solely by the jet part with a minor contribution from the hydro part. For Ω^- and Ω^+ , the bulk of the p_T yield have a major contribution from hydro (soft) production of hadrons and a minor contribution from hard production in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV. It is due to the fact that the Ω baryon, is less likely to be formed from direct fragmentation, and more likely to result from coalescence [24] (that mechanism

is absent in the HYDJET++ model [5] and fragmentation dominates at higher energies) within the QGP.

In Figs. 2–4, we compared the p_T spectra produced by HYDJET++ with the available ALICE experiment [18,57–59] and other models, namely VISHNU, EPOS, and AMPT predictions [44]. For better visualization, the p_T spectra for different centralities are scaled appropriately with scaling factors mentioned in the legends of the figures. We can see that the HYDJET++ results match quite well with experimental data in central and semicentral collisions for the ϕ meson, Ω^- and Ω^+ baryons.

For improved visualization of our results, we have shown the model-to-data ratios in the lower panels of Figs. 2–4. HYDJET++ substantially overestimates the experimental data in the mid- p_T region for peripheral collisions, particularly for Ω^- and Ω^+ baryons at both energies and by a factor of 2.5 for the ϕ meson at $\sqrt{s_{NN}} = 5.02$ TeV. This suggests that thermal equilibrium is not achieved for pure strange hadrons in peripheral collisions, mainly due to the absence of coalescence mechanism in the HYDJET model or because of the absence of minijet production in the model [60]. Furthermore, the comparison of Ω^- baryon p_T spectra with VISHNU and EPOS models in central and peripheral collisions, as well as with the AMPT model in the most central collisions, provides valuable insights. The AMPT model accurately describes the K^+ spectra but underestimates the Λ , Ξ^- , and Ω spectra, likely due to the absence of strangeness production and annihilation processes in the parton cascade part of the AMPT model [31]. The EPOS and VISHNU models overestimate the experimental data at peripheral collisions due to less contribution from feed-down of higher mass resonances as described in Ref. [5].

Figures 5(a) and 5(b) show a comparison in the yields of ϕ and Ω hadrons at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. Experimentally, particle yield should increase with increasing energies and p_T but after a certain p_T value, it should be constant with increasing energies [18]. Similarly, HYDJET++ results exhibit an increasing trend with increasing energies at a certain p_T , however, because of large statistical uncertainties towards high p_T , proper physical interpretation cannot be made for the model calculations. This behavior gives the information to understand the nuclear modification factors [18].

B. Nuclear modification factors (R_{AA} and R_{CP})

Figures 6 and 7 show the results of R_{AA} and R_{CP} for ϕ meson and Ω baryon productions in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV energies, respectively at $|y| < 0.5$. R_{AA} is the ratio of particle yield in A + A collisions with scaling by binary collisions $\langle N_{\text{coll}} \rangle$ to particle yield in $p + p$ collisions at the same energies. It gives information about medium effects in heavy-ion collisions relative to $p + p$ collisions. On the other hand, R_{CP} , which is basically used by theoretical models to understand medium effects, is defined as the ratio of particle yield in central to peripheral collisions with scaling by $\langle N_{\text{coll}} \rangle$ at the same energies, collision systems under the same time and conditions [61–64] which reduces other nuclear effects like shadowing, anti-shadowing, etc unlike R_{AA} . Due to HYDJET++ model limitations, we can not

TABLE II. Centrality-dependent values of the number of participants ($\langle N_{\text{part}} \rangle$), number of binary collisions ($\langle N_{\text{coll}} \rangle$), and suppression factor (γ_s) used in HYDJET++ simulations for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Centrality (%)	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$	γ_s
0–10	346.2	1540	1.00
10–20	245.3	938.7	0.99
20–30	170.1	558.9	0.98
30–40	114.0	314.8	0.95
40–50	71.97	161.6	0.92
50–60	41.64	73.57	0.9
60–70	21.85	29.89	0.89
70–80	9.263	9.811	0.87

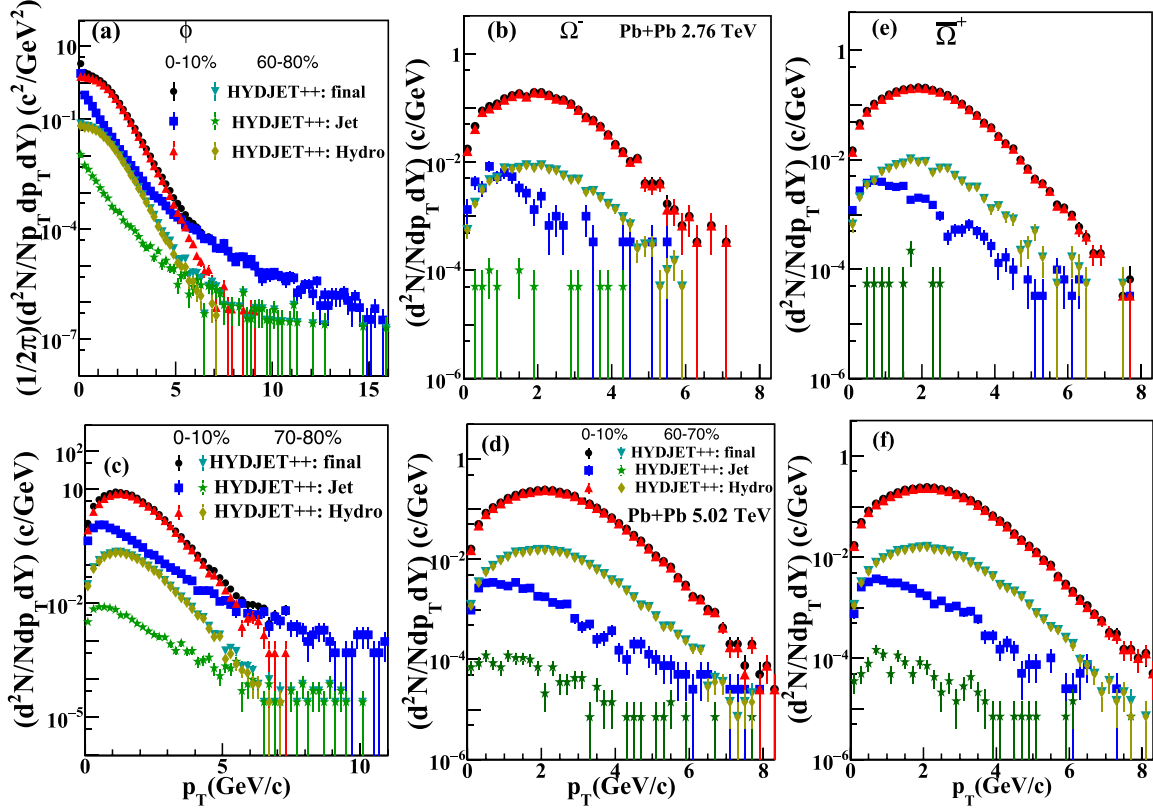


FIG. 1. Transverse momentum (p_T) spectra of (a), (c) ϕ , (b), (d) Ω^- , and (e), (f) Ω^+ in central and peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV. The spectra obtained from HYDJET++ simulations are shown for the final output, as well as separate contributions from the soft (hydrodynamic) and hard (jet).

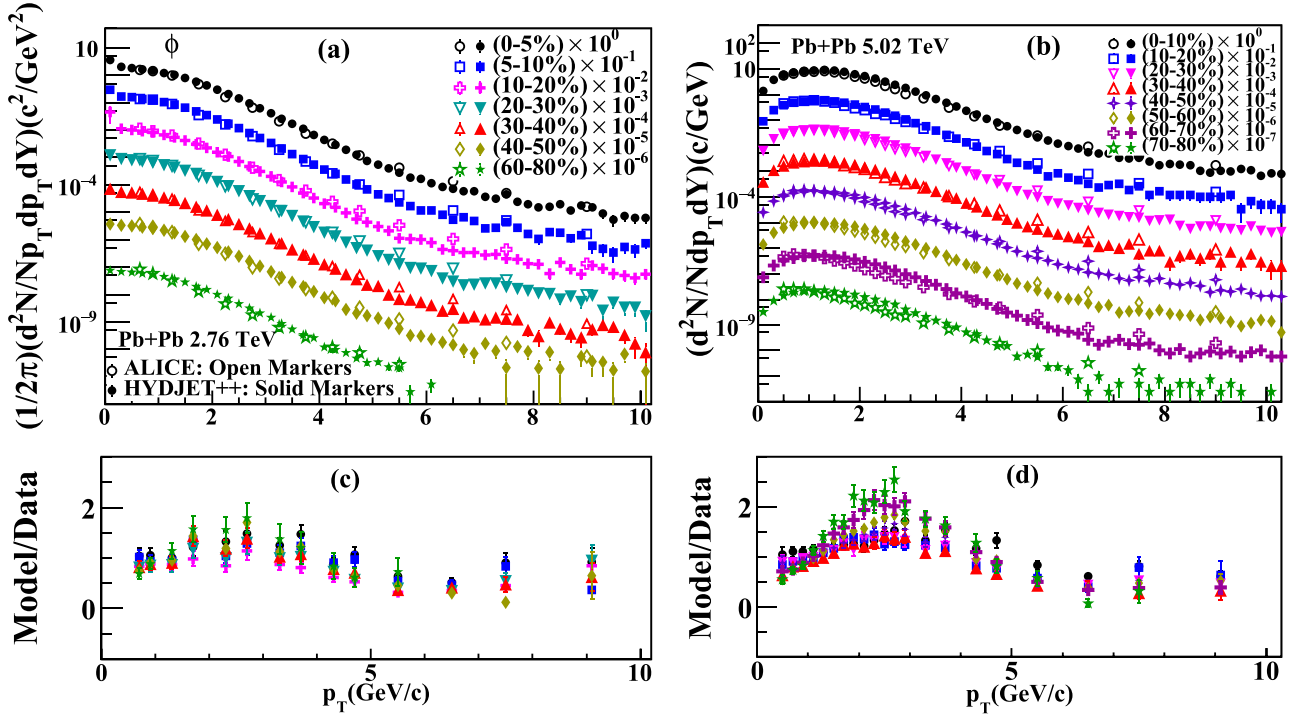


FIG. 2. Transverse momentum (p_T) spectra of ϕ at (a) $\sqrt{s_{NN}} = 2.76$ TeV, (b) $\sqrt{s_{NN}} = 5.02$ TeV in Pb+Pb collisions. Different open and solid markers show ALICE experimental results [18,57] and HYDJET++ model results. (c) and (d) show the ratios of model predictions to experimental results.

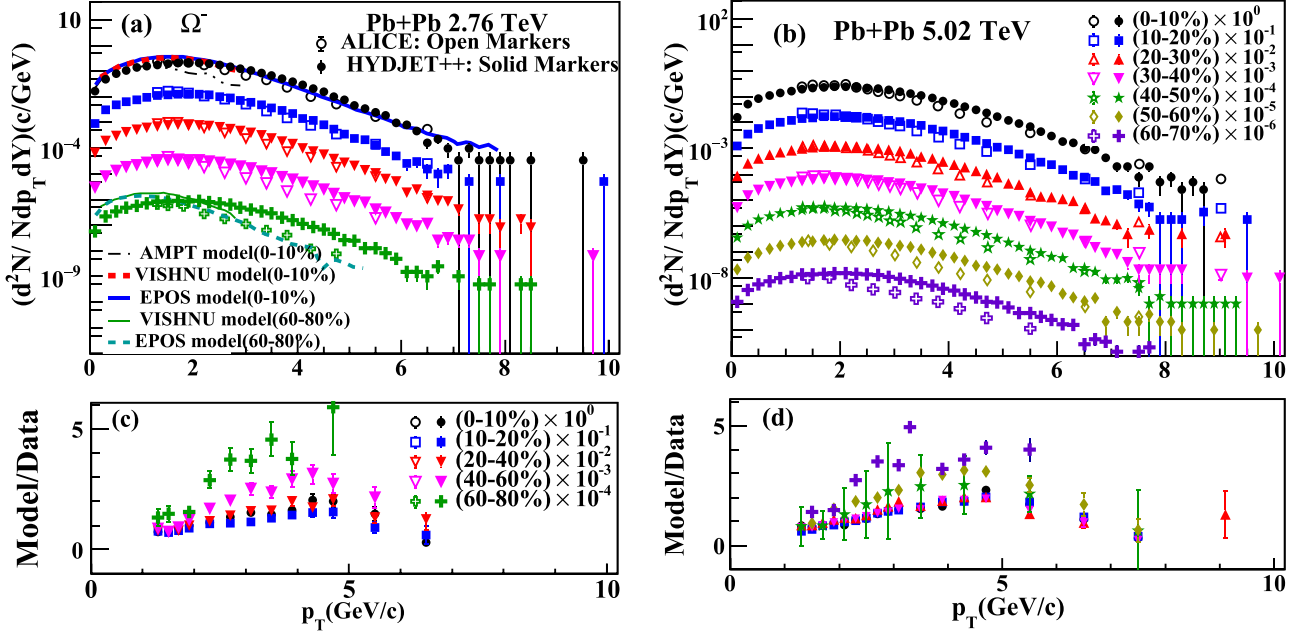


FIG. 3. Transverse momentum (p_T) spectra of Ω^- at (a) $\sqrt{s_{NN}} = 2.76$ TeV, (b) $\sqrt{s_{NN}} = 5.02$ TeV in Pb+Pb collisions. Different open and solid markers show ALICE experimental data [57], preliminary results [59], and HYDJET++ model results. Different lines show the AMPT [31], VISHNU, and EPOS model results [44]. Panels (c) and (d) show the ratios of model predictions to experimental data.

simulate $p + p/p + A$ collisions results. So, we have used the available ALICE experimental results in $p + p$ collisions [18] for R_{AA} calculations in both energies.

Figures 6(a) and 6(c) show that the HYDJET++ model results for ϕ -meson follow the same trend as experimental results [18,57,65] at the entire p_T range for 2.76 TeV and

deviate from the experimental results for non-central collisions at 5.02 TeV. The possible explanation for this behavior in R_{AA} is possibly due to the inability of the model in reproducing the particle spectra in peripheral collisions at 5.02 TeV. Figure 6(b) shows that the HYDJET++ results for $\Omega^- + \Omega^+$ baryons follow the general trend of the experimental data in

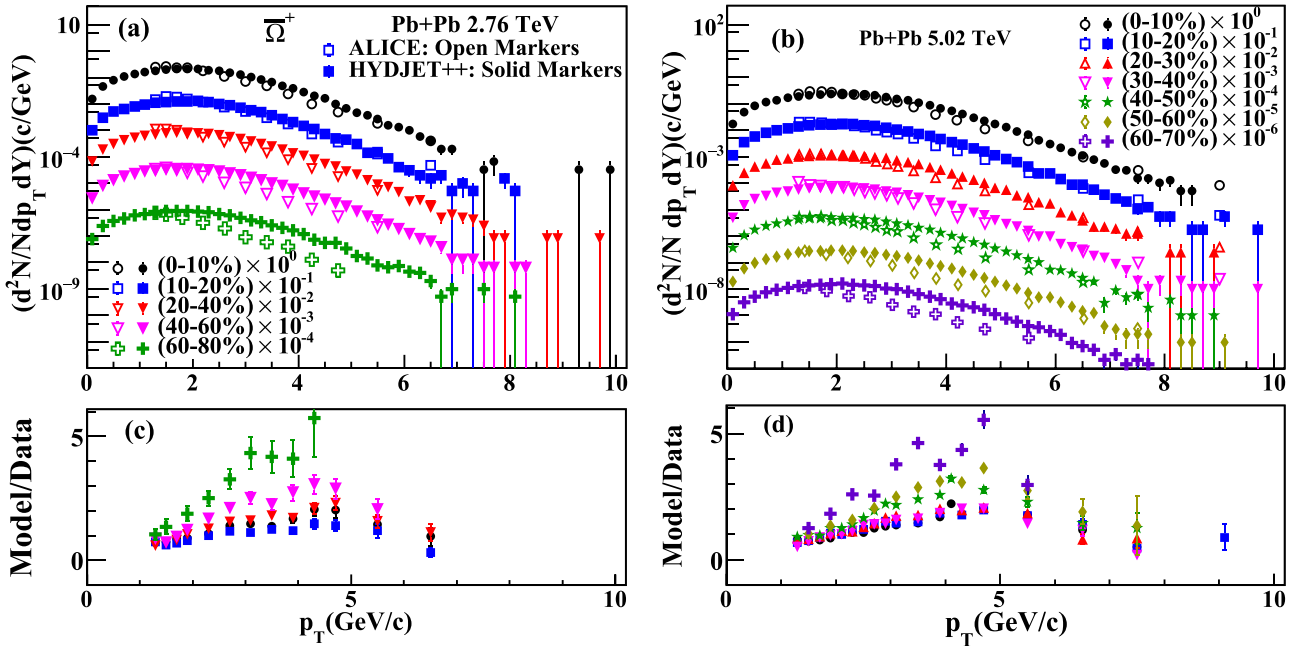


FIG. 4. Transverse momentum (p_T) spectra of Ω^+ at (a) $\sqrt{s_{NN}} = 2.76$ TeV, (b) $\sqrt{s_{NN}} = 5.02$ TeV in Pb+Pb collisions. Different open and solid markers represent ALICE experimental data [57], preliminary results [59], and HYDJET++ model results. (c) and (d) show the ratios of model predictions to experimental data.

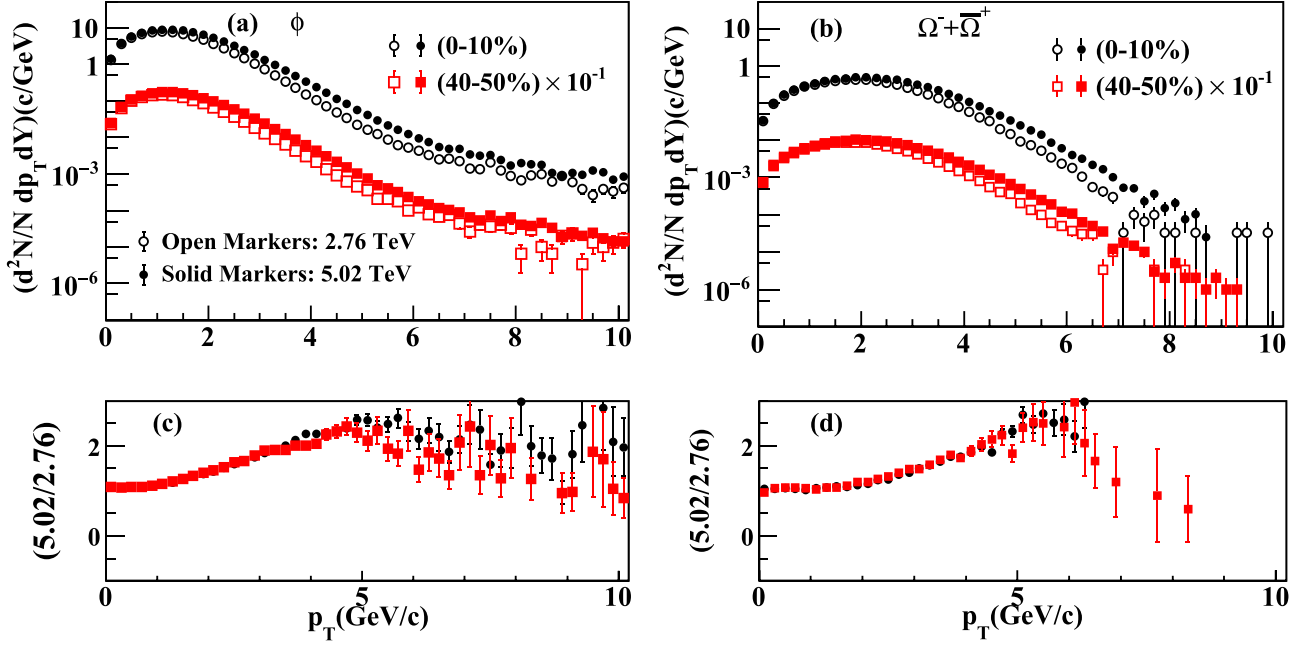


FIG. 5. Transverse momentum (p_T) spectra of (a) ϕ and (b) Ω in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV energy and $\sqrt{s_{NN}} = 5.02$ TeV energy depicted in the upper panels using different markers for each energy. The corresponding yield ratios between the two energies are shown in the lower panels (c) and (d).

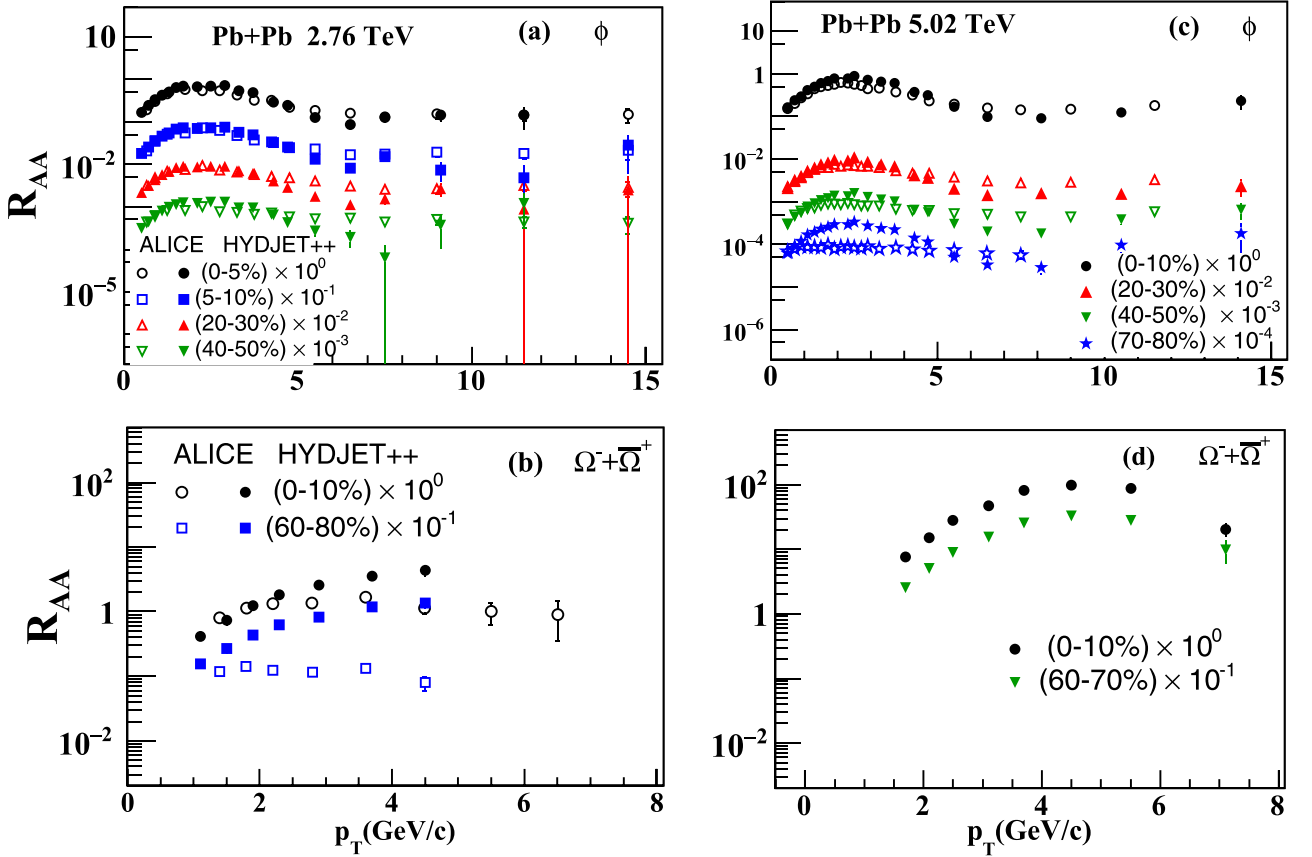


FIG. 6. Nuclear modification factor (R_{AA}) of ϕ and Ω at (a), (b) $\sqrt{s_{NN}} = 2.76$ TeV and (c), (d) $\sqrt{s_{NN}} = 5.02$ TeV as a function of transverse momentum (p_T). Different open and solid markers represent ALICE experimental results [18,57,65] and HYDJET++ model results, respectively.

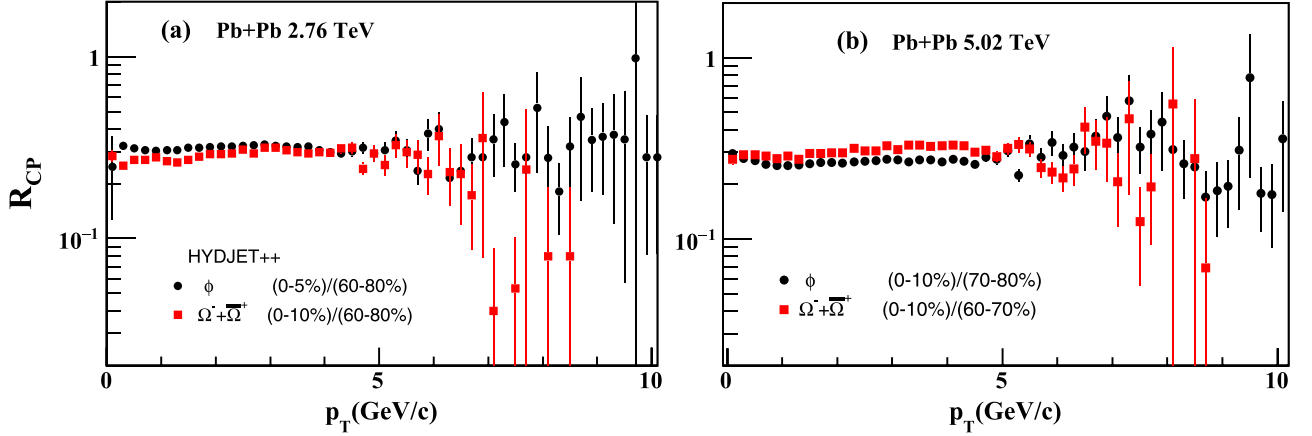


FIG. 7. Nuclear modification factor (R_{CP}) of ϕ and Ω at (a) $\sqrt{s_{NN}} = 2.76$ TeV and (b) $\sqrt{s_{NN}} = 5.02$ TeV as a function of transverse momentum (p_T). The results are obtained from the HYDJET++ model for various centrality intervals, indicated by different markers.

central collisions at $\sqrt{s_{NN}} = 2.76$ TeV but tend to overestimate the data at high p_T and in peripheral collisions. A similar pattern is observed in Fig. 6(d) for $\sqrt{s_{NN}} = 5.02$ TeV. The model qualitatively reproduces the suppression trend (R_{AA}) in central collisions and at lower p_T values but fails to provide a quantitative description at higher p_T and in more peripheral events. These discrepancies indicate limitations in the current model approach, particularly in its treatment of particle production at high transverse momentum and peripheral centralities. They also motivate further refinement of the model to better capture the underlying physics in these regimes. Furthermore, both the model and experimental results show that the ϕ mesons experience greater suppression compared to Ω baryons and exhibit comparable suppression across different energies, whereas Ω baryons exhibit significant suppression at lower energies.

Similarly, Fig. 7 shows the HYDJET++ results of R_{CP} for the ϕ meson and Ω baryon. It is observed that the R_{CP} is almost independent of the center-of-mass energy and p_T for the HYDJET model calculations. Based on previous HYDJET++ studies [13,17,22], as well as the present analysis, the HYDJET++ model demonstrates a good agreement with experimental results for both strange and nonstrange hadrons across a wide range of energies from RHIC to LHC.

C. Particle ratio

Figures 8 and 9 show the $\Omega^- + \bar{\Omega}^+/\phi$, $\bar{\Omega}^+/\Omega^-$, $\Omega^- + \bar{\Omega}^+/\pi^- + \pi^+$, and $\phi/\pi^- + \pi^+$ ratios as a function of p_T in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV energies [centrality (0–10%), (60–80%), and (60–70%)]. These ratios provide helpful information about the chemical properties, such as the chemical equilibrium of the system.

Due to small or negligible chemical potential, same-mass particle (i.e., antiparticle-to-particle) ratios are weakly dependent on chemical freeze-out temperature and give less information about the temperature. Different mass-particle ratios are more prominent to check the sensitivity of chemical freeze-out dependence. We have also calculated the different-mass particle ratios such as $\Omega^- + \bar{\Omega}^+/\phi$, $\Omega^- +$

$\bar{\Omega}^+/\pi^- + \pi^+$, and $\phi/\pi^- + \pi^+$ which serve as a thermometer to probe QGP temperature in heavy-ion collisions [42].

In Figs. 8(a) and 8(b), $\Omega^- + \bar{\Omega}^+/\phi$ ratio shows a strong dependence on p_T but it is independent of centrality and collision energy [16,43,57,66]. The observed pattern of the Ω/ϕ ratios by HYDJET++ indicate that there is no clear difference in the production of $\Omega + \bar{\Omega}^+$ and ϕ particles at various centralities at LHC energies which is similar to the observation of ϕ/K ratio at RHIC energies [16].

We have also compared our findings with available experimental results and Krakow, HIJING/ $B\bar{B}$ model results [43]. The Krakow model [36] provides predictions for the $\Omega^- + \bar{\Omega}^+/\phi$ ratio in the (0–10%) centrality interval. The HYDJET++ simulation shows good agreement with both the Krakow model prediction and ALICE experimental data [36] at low p_T , and an over prediction at intermediate p_T due to nonthermal equilibrium production of Ω baryons and missing an important mechanism quark coalescence in HYDJET++ which plays a significant role in intermediate p_T . Additionally, the available HIJING/ $B\bar{B}$ model [5,37,38] result for (0–20%) centrality interval has also been shown. The model results exhibit a qualitatively similar trend in central collisions at low p_T . Figure 8(c) shows the antiparticle-to-particle ratio. This ratio shows almost independent behavior with p_T and centrality. Similarly, in Fig. 9, $\Omega^- + \bar{\Omega}^+/\pi^- + \pi^+$ and $\phi/\pi^- + \pi^+$ ratio remain nearly constant with increasing collision energy [16]. Additionally, the ratio magnitude decreases from lighter to heavier particles with increasing p_T . It may be because of the high probability of light meson formation rather than heavy strange baryons at low p_T . Towards intermediate p_T , the ratio of baryons to mesons increases. This is because the particle momentum becomes comparable to or exceeds the mass of strange quarks, significantly enhancing the likelihood of strange baryon formation. At high p_T , the fragmentation function of jets is suppressed for strange particles compared to nonstrange particles. This results in producing a large number of u and d quarks compared to s quarks and hence the ratios relative to mesons start to decrease at high p_T [17,42]. The resulting particle ratios might differ from predicting

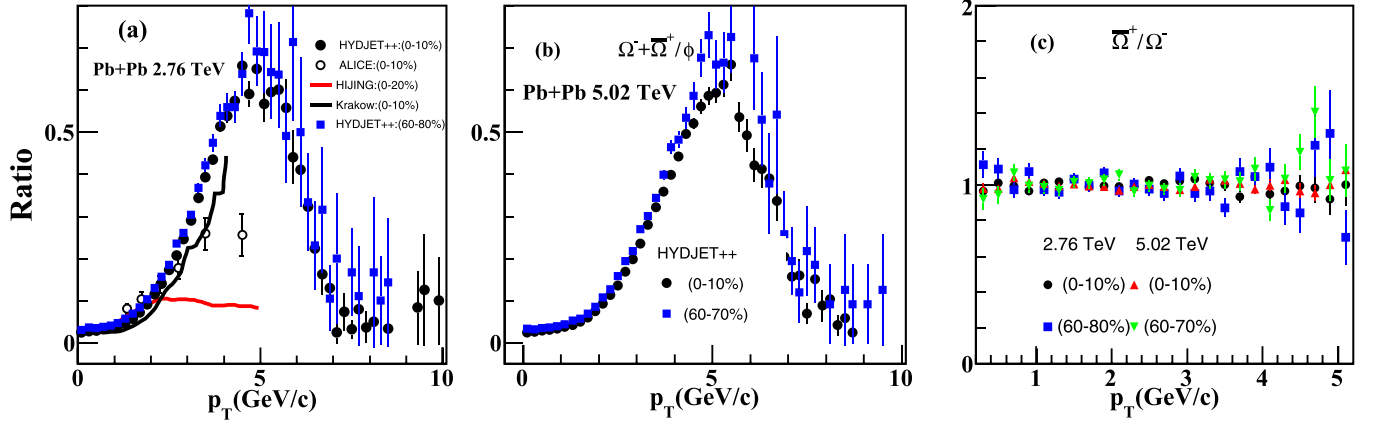


FIG. 8. Particle ratio of $\frac{\Omega}{\bar{\Omega}}$ at (a) $\sqrt{s_{NN}} = 2.76$ TeV and (b) $\sqrt{s_{NN}} = 5.02$ TeV, along with the (c) antiparticle-to-particle ratio $\frac{\bar{\Omega}}{\Omega}$, as obtained from HYDJET++ simulations. The results are compared with ALICE experimental results and predictions from the Krakow and HIJING models [43].

experimental results at intermediate to high p_T in case of $\Omega^- + \bar{\Omega}^+/\phi$ and $\phi/\pi^- + \pi^+$ [57], perhaps indicating a higher freeze-out temperature or deviating fully from the thermalization picture [42,57].

D. Elliptic flow (v_2)

Figure 10 presents the elliptic flow of ϕ -meson and Ω -baryons as a function of p_T . The elliptic flow shows dependence on p_T . The radial flow impels the heavier particles towards higher p_T which gets displayed to p_T -dependent mass ordering of elliptic flow at low p_T . This tends to decrease the elliptic flow with increased hadron mass [22]. Flow occurs

due to path-dependent energy loss at intermediate to high p_T , offering insights into jet quenching phenomena [67]. For comparison, we have also presented available experimental results in which flow is calculated using different methods such as the event plane, two-particle, and four-particle methods [21,23], along with the HYDJET++ reaction plane method. The model accurately reproduces the experimental v_2 data up to 2–3 GeV/c in central and midcentral collisions, but overpredicts it at higher p_T [22]. More fluctuations are observed in the Ω -baryon data due to lower statistics, as heavier particle multiplicities are less than those of lighter particles for a given number of events.

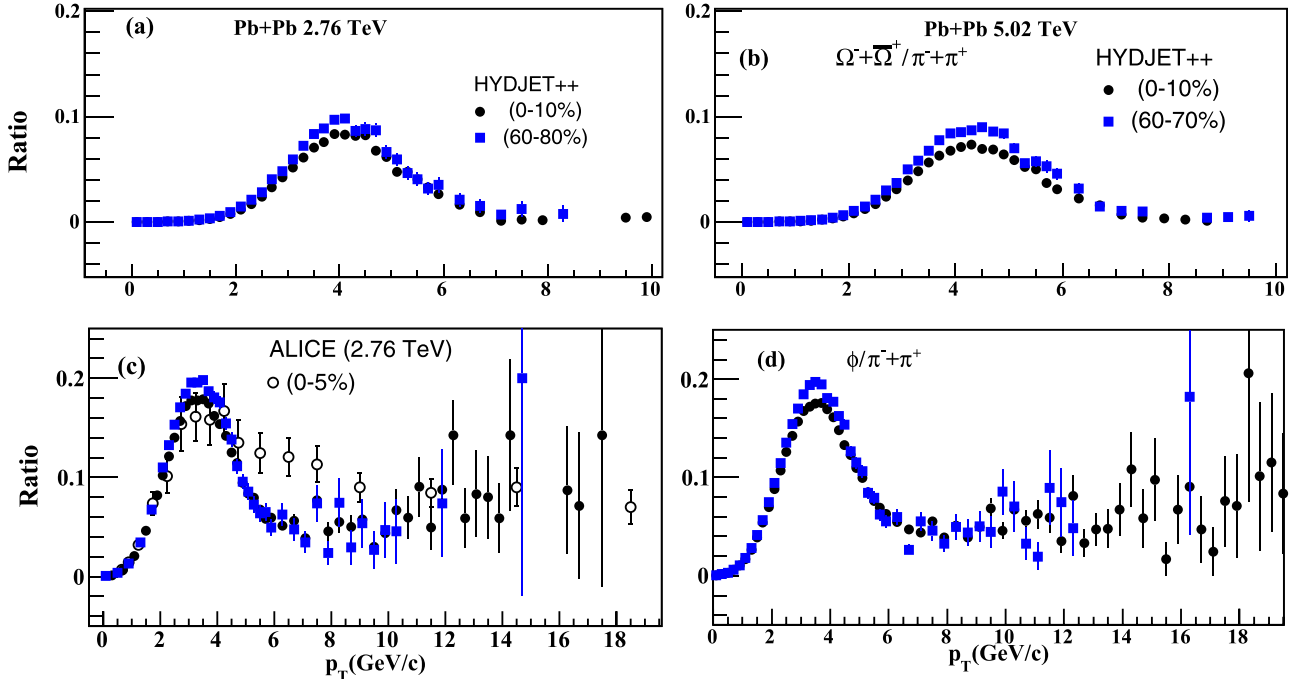


FIG. 9. Ω/π [in (a), (b)] and ϕ/π [in (c), (d)] ratios as a function of p_T for centralities (0–10%) and (60–80%) at $\sqrt{s_{NN}} = 2.76$ TeV energy, and (0–10%) and (60–70%) at $\sqrt{s_{NN}} = 5.02$ TeV energy. The Open marker shows the ALICE experimental result [57] for ϕ/π at (0–5%) [in (c)] centrality.

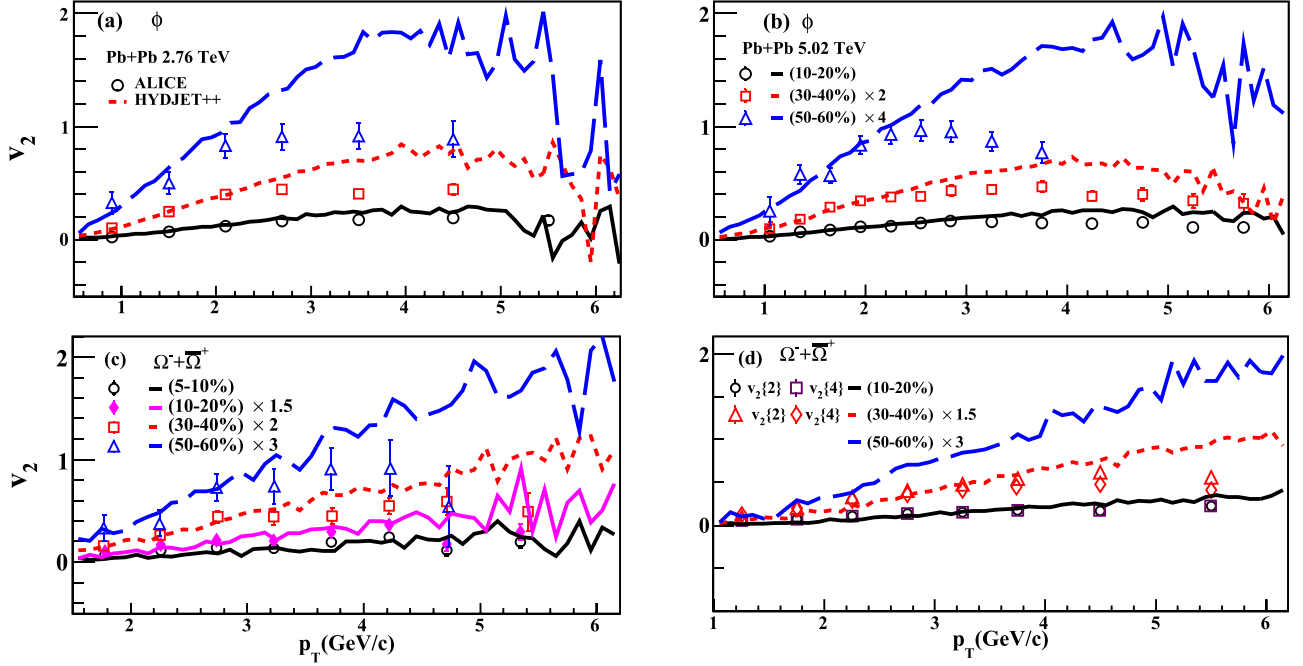


FIG. 10. Elliptic flow (v_2) of ϕ mesons (a), (b) and Ω baryons (c), (d) as a function of transverse momentum (p_T). Different Markers show ALICE experimental results [21,23] of v_2 with various techniques (two-particle, four-particle, and event plane) and lines show HYDJET++ results.

Figure 11 presents the $\langle p_T \rangle$ and $\langle v_2 \rangle$ of the ϕ meson and Ω baryon as a function of $\langle N_{part} \rangle$. The $\langle p_T \rangle$ in our results exhibits an independent behavior with respect to centrality while $\langle v_2 \rangle$ shows the strong centrality dependence in $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV, respectively. In central collisions, the $\langle p_T \rangle$ of the ϕ meson from Fig. 11(a) matches well to the experimental data with uncertainty range at both collision energies. However, toward peripheral collisions, the model overpredicts the experimental $\langle p_T \rangle$ data for the ϕ meson, indicating that thermal equilibrium might not be achieved for

the smaller fireball formed in peripheral collisions. Due to the unavailability of experimental data, we have only presented the model results for Ω 's $\langle p_T \rangle$. The HYDJET++ simulation for the Ω hadron at both $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV are consistent with the recently published results from HYDJET++ (Ref. [17]). Similarly, Fig. 11(b) presents the mean v_2 results for both energies, obtained using the HYDJET++ model, which is consistent with the findings in a recently published article on HYDJET++ [22]. The meson-baryon grouping in integrated p_T flow is absent

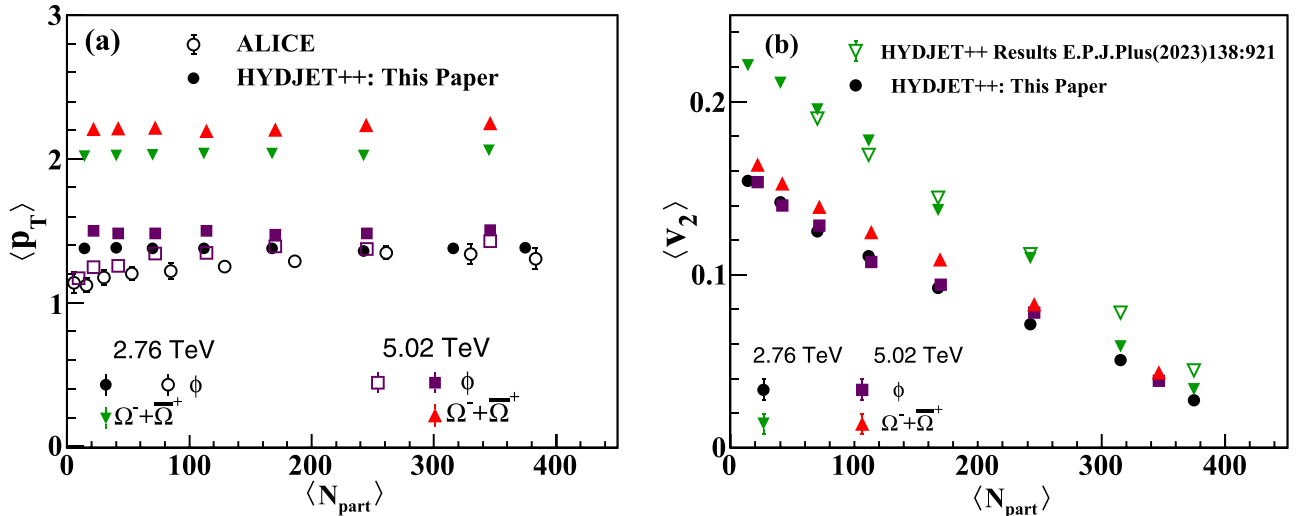


FIG. 11. (a) Mean transverse momentum ($\langle p_T \rangle$) [18] and (b) mean elliptic flow ($\langle v_2 \rangle$) [22] of ϕ and Ω as a functions of $\langle N_{part} \rangle$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV, respectively.

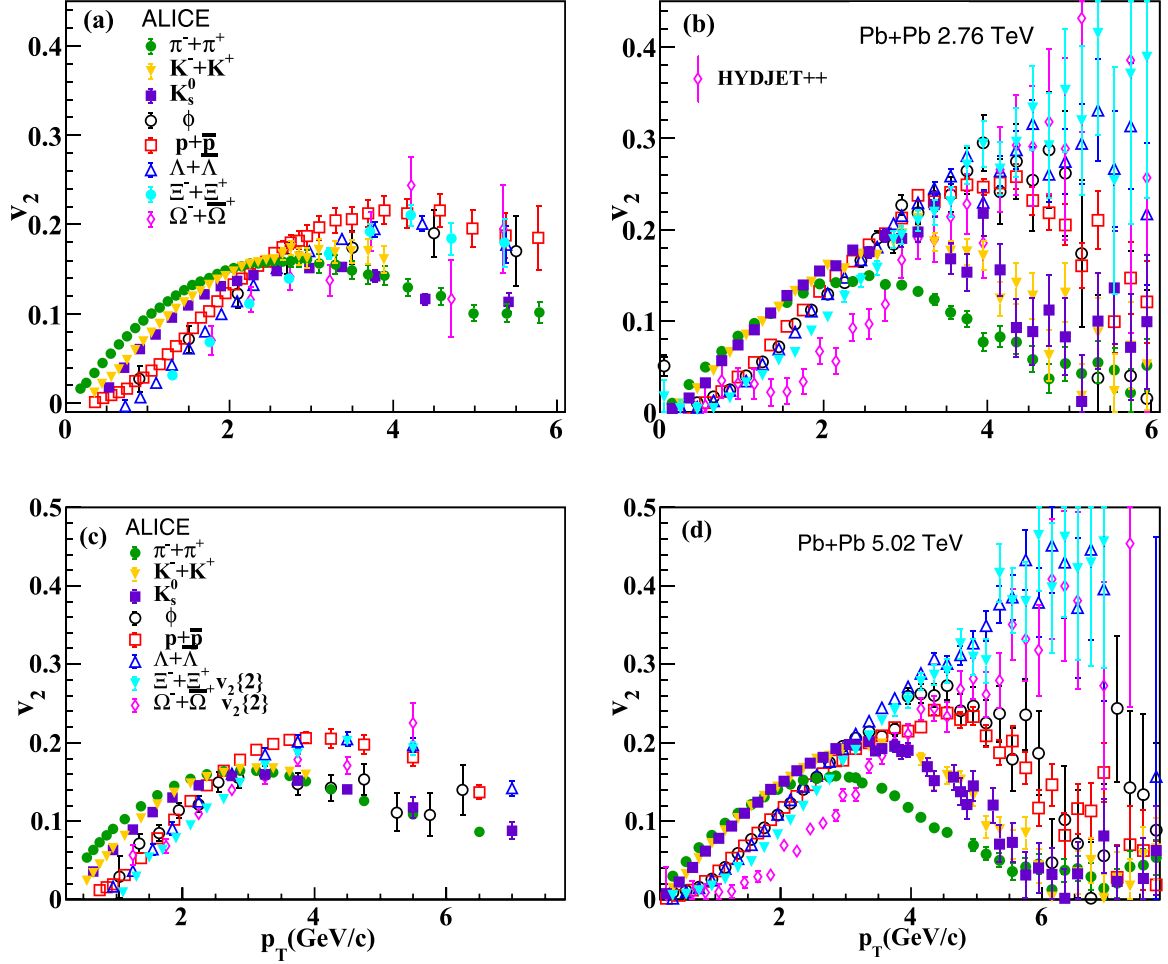


FIG. 12. v_2 of various particle species for (10–20%) centrality interval at both energies is shown in separate pads for available ALICE experimental results [21,23] and HYDJET++ results.

in Pb+Pb collisions from $\sqrt{s_{NN}} = 2.76$ TeV to $\sqrt{s_{NN}} = 5.02$ TeV.

E. Mass ordering

Figure 12 presents the mass ordering of elliptic flow among ϕ , Λ , $p + \bar{p}$, and Ω in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV energies. The available ALICE experimental data [21,23] provides the v_2 mass ordering for (10–20%) centrality interval at low p_T except for ϕ , Λ , and proton. Model results are shown as points with uncertainties to reflect statistical fluctuations in the simulations, allowing for a direct and consistent comparison with experimental data, which are also represented as points. Since these particles have the approximate same mass and different hadronic rescattering contributions (i.e., hadronic state interaction affected by heavy quark contents) that affect their v_2 values [18,68]. It is difficult to determine whether this difference is related to the particle's mass or type (whether it is a baryon or a meson). It also suggests that these v_2 play a significant role in partonic-to-hadronic dynamics and baryon-to-meson ratio. The HYDJET++ model also follows a similar trend of mass ordering among all the hadron species at both energies.

IV. CONCLUSIONS

We have studied the particle production of pure multi-strange hadrons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV energies, respectively. We have presented the p_T spectra of ϕ , Ω^- , and Ω^+ hadrons in both central and peripheral collisions, highlighting the contributions from soft and hard processes. These results provide insights into how the yield contributions from soft and hard processes vary with flavour, particle species, and energy. We have also compared the p_T spectra at various centrality intervals with available experimental data and other model results including AMPT, EPOS, and VISHNU. According to our findings, HYDJET++ provides a better description of the experimental data in central collisions at LHC energies for strange particles compared to the VISHNU, AMPT, and EPOS models. However, among these, only the EPOS model accurately describes the p_T spectra of Ω^- baryons at full range of p_T for central to peripheral collisions.

Additionally, we compared the yields in central and peripheral collisions at both energies. We observed that at low $p_T < 2$ GeV/c, the charged particle production is expected to be almost the same, while at intermediate p_T , there is

an increase in charged particle production at higher energies. This provides insights into the nuclear effects relative to $p + p$ /peripheral collisions and enhances our understanding of the behavior and evolution of the QGP with varying collision energies and system sizes. This effect also contributes to flow dynamics, i.e., elliptic flow at high p_T . The resulting particle ratios by HYDJET++ might be different from experimental predictions at intermediate to high p_T in case of $\Omega^- + \bar{\Omega}^+/\phi$ and $\phi/\pi^- + \pi^+$, which indicate a deviation from the thermalization picture and make it possible to differentiate between early and late freeze-out.

We have also presented the elliptic flow of ϕ meson and $\Omega^- + \bar{\Omega}^+$ baryons and compared our findings with the available ALICE experimental data at both LHC energies. HYDJET++ model suitably describes the experimental data at low p_T . At intermediate p_T , the model overpredicts the experimental data. The difference between the model calculations and the experimental data increases as we move towards peripheral collisions. This may be because the mechanism involved in addressing the interaction between the medium and jet partons is absent in the HYDJET++ model framework in the present scenarios, particularly with heavier particles. The meson-baryon grouping in integrated p_T flow is absent in $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV energies. This behavior shows that all hadron production is almost the same at high p_T at higher energies. Further, we have given observation of mass ordering in the v_2 of strange and nonstrange

hadrons at low p_T in Pb+Pb collisions for $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV energies. Both the experimental data and HYDJET++ results show no significant difference between v_2 of ϕ mesons and protons, which play a substantial role in partonic to hadronic dynamics and baryon-to-meson ratios. At intermediate p_T , the mass order reverses, and heavier baryons acquire higher flow than mesons.

Overall, HYDJET++ delivers deeper insights into the understanding the dynamics of anisotropic flow dynamics, radial expansion effects, and jet-quenching phenomena in high-energy heavy-ion collisions.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [18,21,23,43,44,57,59].

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