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Letter

Anisotropic flow of light (anti-)(hyper-)nuclei in Pb + Pb collision at $\sqrt{s_{NN}} = 5.36$ TeV

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ABSTRACT

Using the coalescence model with nucleon and Lambda phase-space distributions generated by the hybrid MUSIC framework, we study the elliptic flow (v_2) and triangular flow (v_3) of (anti-)protons, (anti-)deuterons, (anti-) ^3He , and $^3_\Lambda\text{H}$ in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV. We find that the simple v_2 scaling with the number of constituent nucleons A breaks down at high transverse momentum $p_T/A > 1.5$ GeV/c, while an improved scaling relation holds well up to $p_T/A \approx 3$ GeV/c. In contrast, v_3 exhibits similar behavior under both scaling prescriptions, with no significant difference. We also make predictions for v_2 and v_3 of the hypertriton and find these flows are insensitive to the Lambda-deuteron ($\Lambda - d$) distance inside the hypertriton. Our results are compared with preliminary experimental measurements by the ALICE Collaboration and offer insight into the production mechanisms of light (anti-)(hyper-)nuclei in high-energy heavy-ion collisions.

1. Introduction

Light nuclei, such as the deuteron (d), helium-3 (^3He) and helium-4 (^4He), as well as their antiparticles, have been measured in high-energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) [1–10]. These bound-state nuclei have small binding energies and relatively large sizes compared with the temperature and spatial extent of the fireball produced in high-energy nuclear collisions. Their production mechanism remains a topic of active debate [11–17]. In the statistical hadronization model (SHM), light nuclei are produced at a common chemical freeze-out temperature following hadronization of the quark-gluon plasma (QGP) [18–20]. In contrast, in the nucleon coalescence model [21–23], light nuclei are formed at the kinetic freeze-out stage, when the temperature and density of the hadronic matter are much lower. More recently, dynamical kinetic and transport approaches have been developed to describe light-cluster and hypernucleus production during the hadronic evolution by includ-

ing their dissociation and regeneration through hadronic reactions as well as cluster recognition or coalescence in microscopic transport simulations [15,24–32].

In heavy-ion collisions, the large pressure gradients generated in the early stages convert the spatial anisotropies of the initial collision geometry into anisotropic momentum distributions of the produced particles. These azimuthal distributions are conventionally characterized by a Fourier series [33]:

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)], \quad (1)$$

where ϕ is the azimuthal angle of the particle in momentum space, Ψ_n is the azimuthal angle of the n th order event plane, and v_n is the n th order anisotropic flow coefficient, with v_2 and v_3 referred to as elliptic and triangular flow, respectively. Significant anisotropic flow signals have been observed not only in heavy-ion collisions but also in smaller collision systems, including proton-proton (pp) [34–37] and

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proton-nucleus [38–45] collisions. Anisotropic flow provides a powerful tool for probing particle production mechanisms through coalescence scaling relations. In the coalescence picture, nucleons (or quarks) that are close in phase space have a higher probability to combine to form light nuclei (or hadrons), and the resulting composite particles inherit the flow of their constituents. Specifically, if a nucleus is produced from the coalescence of A nucleons with similar momenta, its azimuthal distribution then follows the relation [46–49]:

$$\frac{dN_A}{d\phi} \propto \left(\frac{dN_p}{d\phi} \right)^A. \quad (2)$$

In the limit of small anisotropies ($v_n \ll 1$), this yields the approximate scaling relation

$$v_n(p_T) \approx A v_n^{(p)}(p_T/A), \quad (3)$$

known as the number-of-constituent nucleon (NCN) scaling, which is a key prediction of the nucleon coalescence model for light nuclei production as first proposed by Yan and Ma et al. [48,49] and confirmed by STAR and BM@N experimental data [50–52]. An earlier example is the number-of-constituent-quark (NCQ) scaling of the elliptic flow v_2 , which has been experimentally confirmed for hadrons produced in heavy ion collisions at both RHIC [53,54] and the LHC [43,55,56], as well as in p +Pb collisions by the CMS and ALICE experiments [43,57,58]. These observations validate the quark coalescence mechanism for hadron production, particularly at intermediate p_T [59,60]. Extending this approach to light nuclei, a systematic study of the NCN scaling behavior of their anisotropic flow coefficients with respect to those of their constituent nucleons can provide direct insight into the production mechanisms of light nuclei [48,49,61–64].

Recently, the ALICE collaboration measured the v_2 of deuterons and ${}^3\text{He}$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [56,65,66]. The measured (anti-) ${}^3\text{He}$ v_2 across all centrality bins lies between the predictions of the Blast-Wave model and those of a simple coalescence model. A more realistic coalescence approach, which combines hydrodynamics evolution with the hadronic afterburner UrQMD, provides an improved description of the data in the transverse momentum range $2 < p_T < 6$ GeV/ c for the 0–20% and 20–40% centrality classes [67–70].

In the present study, we investigate the elliptic and triangular flows of (anti-)protons, (anti-)deuterons, and (anti-) ${}^3\text{He}$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV using the nucleon coalescence model with nucleon phase-space distributions generated by the hybrid MUSIC framework. We examine the NCN scaling of both v_2 and v_3 for deuterons and ${}^3\text{He}$ over the transverse momentum range $p_T/A \approx 3$ GeV/ c , where $A = 1$ for nucleons, $A = 2$ for deuterons, and $A = 3$ for ${}^3\text{He}$. We show that the simple scaling with the mass number A breaks down for v_2 at high transverse momentum ($p_T/A > 1.5$ GeV/ c), whereas an improved scaling relation remains valid up to $p_T/A \approx 3$ GeV/ c . In addition, we study the elliptic and triangular flows of the (anti-)hypertriton (${}^3_\Lambda\text{H}$) in the same collision system and investigate the sensitivity of its anisotropic flow coefficients to the spatial separation between the Λ hyperon and the deuteron core in the ${}^3_\Lambda\text{H}$ wave function.

2. Methods

In this study, we employ the hybrid MUSIC+UrQMD+COAL framework to generate the phase-space distributions of nucleons and Lambda hyperons at kinetic freeze-out for coalescence model calculations of light (hyper-)nucleus production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV. The quark-gluon plasma (QGP) formed in these collisions is evolved using the (2+1)-dimensional viscous hydrodynamic model MUSIC [71–73], initialized with the IP-Glasma model [74,75], which incorporates event-by-event fluctuations of the initial geometry and gluon saturation in the framework of the Color Glass Condensate (CGC). The equation of state is NEOS-BQS [76], which implements a crossover transition at finite baryon density. Hadrons are particlized on a constant energy-density hypersurface using the Cooper-Frye prescription [77],

and their subsequent rescatterings and resonance decays are simulated with the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) transport model [78]. The resulting freeze-out phase-space distributions of nucleons and Λ hyperons are then used as input to the coalescence model [79–81] to describe the production of light (hyper-)nuclei.

The present analysis is based on 10^4 fluctuating IP-Glasma initial conditions. For each hydrodynamic event, 100 oversampled UrQMD events are generated, resulting in approximately 10^6 minimum-bias UrQMD events. Centrality classes are determined from percentiles of the charged-particle multiplicity N_{ch} , calculated from charged pions, charged kaons, protons, and antiprotons within $|y| < 0.5$. Each centrality class contains approximately 2×10^5 UrQMD events.

To improve the statistical precision for the production of rare light nuclei and hypernuclei, the coalescence calculation is performed using mixed-event sampling within each fixed centrality class. Specifically, constituent particles are randomly selected from the UrQMD event pool belonging to the same centrality class and are not required to originate from the same hydrodynamic event. In each mixing loop, $N_{mix} = 300$ events are independently sampled for each constituent, resulting in N_{mix}^A event combinations for a cluster with A constituents. The procedure is repeated $N_{loop} = 300$ times, and the mixed-event yields are normalized by the sampling amplification factor $N_{samp} = N_{loop} N_{mix}^A$. This corresponds to $N_{samp} = 300 \times 300^2$ for deuterons and $N_{samp} = 300 \times 300^3$ for ${}^3\text{He}$ and hypertritons.

For anisotropic-flow analysis, particles from each event are first rotated by their corresponding event-plane angle Ψ_n into a common event-plane frame before event mixing. The coalescence histograms and the resulting flow-scaling distributions are then constructed as functions of $\phi - \Psi_n$.

In the nucleon coalescence model, the invariant momentum spectra of a light nucleus is obtained from the overlap of its Wigner function with the phase-space distributions $f(\mathbf{r}_i, \mathbf{p}_i, t)$ of kinetically frozen-out nucleons and hyperons:

$$E_A \frac{d^3 N_A}{d\mathbf{p}_A^3} = g_c E_A \int \prod_{i=1}^A \left(p_i^\mu d^3 \sigma_{i\mu} \frac{d^3 p_i}{E_i} f(\mathbf{r}_i, \mathbf{p}_i, t) \right) \times W_A(\mathbf{r}'_1, \mathbf{r}'_2, \dots, \mathbf{r}'_A, \mathbf{p}'_1, \mathbf{p}'_2, \dots, \mathbf{p}'_A, t') \times \delta^{(3)}\left(\mathbf{P}_A - \sum_{i=1}^A \mathbf{p}_i\right), \quad (4)$$

where $g_c = (2J_A + 1)/[\prod_{i=1}^A (2J_i + 1)]$ is the statistical factor for the coalescence of A nucleons with individual spins J_i into a nucleus with total angular momentum J_A . The coordinate $\mathbf{r}_i$ and momentum $\mathbf{p}_i$ of the i th nucleon or hyperon in the distribution function $f(\mathbf{r}_i, \mathbf{p}_i, t)$ are defined on the freeze-out hypersurface and integrated over it, while the primed variables $\mathbf{r}'_i$ and $\mathbf{p}'_i$ entering the Wigner function are obtained via Lorentz transformation from the laboratory frame to the rest frame of the nucleus.

In the numerical implementation, the continuous phase-space distributions in Eq. (4) are represented by the discrete freeze-out coordinates and momenta of nucleons and Λ hyperons generated by UrQMD. Candidate nucleon or hyperon combinations are constructed event by event, or via mixed events for rare light nuclei and hypernuclei. Each candidate is boosted to the rest frame of the corresponding nucleus, where the Jacobi coordinates and relative momenta are evaluated and inserted into the Wigner function, providing the coalescence weight used to compute the final momentum spectra and flow observables.

The phase-space integral in Eq. (4) is evaluated as a weighted Monte Carlo sum over sampled candidate combinations. For a selected p_T bin, all candidates in the sampled phase-space ensemble contribute to the same Monte Carlo estimator through their Wigner-overlap weights. Denoting by w_α the product of the statistical factor and the Wigner function for a sampled combination α , the yield in a fixed p_T bin B is given by

$$N_A(B) = \frac{1}{N_{samp}} \sum_{\alpha \in B} w_\alpha, \quad (5)$$

Table 1

Statistical factors (g) and width parameters (σ_r, σ_λ) for the deuteron, ^3He and $^3_\Lambda\text{H}$.

Nucleus	g	σ_r (fm)	σ_λ (fm)
$p + n \rightarrow d$	3/4	2.26	/
$p + p + n \rightarrow ^3\text{He}$	1/4	1.76	1.76
$p + n + \Lambda \rightarrow ^3_\Lambda\text{H}$	1/4	2.26	5.45/6.52/7.96

where N_{samp} is the sampling amplification factor introduced by the mixed-event procedure. The corresponding weighted estimator for the anisotropic flow is given below in Eq. (10).

Following Ref. [80], we employ harmonic oscillator wave functions for nuclei and obtain their Wigner functions in Eq. (4) via the Wigner transformation. For the deuteron, the resulting Wigner function reads

$$W_d(\mathbf{r}, \mathbf{p}) = 8 \exp\left(-\frac{\mathbf{r}^2}{\sigma_d^2} - \sigma_d^2 \mathbf{p}^2\right), \quad (6)$$

With m_i denoting the mass of nucleon i , the relative coordinate $\mathbf{r}$ and relative momentum $\mathbf{p}$ are

$$\begin{aligned} \mathbf{r} &= \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2) \\ \mathbf{p} &= \sqrt{2} \frac{m_2 \mathbf{p}_1 - m_1 \mathbf{p}_2}{m_1 + m_2}. \end{aligned} \quad (7)$$

The size parameter σ_d is related to the root-mean-square radius $r_d \approx 1.96$ fm of the deuteron [82,83] via $\sigma_d = \sqrt{4/3} r_d = 2.26$ fm.

Similarly, the Wigner function of helium-3 (hypertriton) is given by

$$W_3(\mathbf{r}, \mathbf{p}) = 8^2 \exp\left(-\frac{\mathbf{r}^2}{\sigma_r^2} - \frac{\lambda^2}{\sigma_\lambda^2} - \sigma_r^2 \mathbf{p}_r^2 - \sigma_\lambda^2 \mathbf{p}_\lambda^2\right), \quad (8)$$

where $\mathbf{r}$ and $\mathbf{p}_r$ are defined as in Eq. (7), and the relative coordinate λ and momentum $\mathbf{p}_\lambda$ are defined as

$$\begin{aligned} \lambda &= \sqrt{\frac{2}{3}} \left(\frac{m_1 \mathbf{r}_1 + m_2 \mathbf{r}_2}{m_1 + m_2} - \mathbf{r}_3 \right), \\ \mathbf{p}_\lambda &= \sqrt{\frac{3}{2}} \frac{m_3(\mathbf{p}_1 + \mathbf{p}_2) - (m_1 + m_2)\mathbf{p}_3}{m_1 + m_2 + m_3}, \end{aligned} \quad (9)$$

The width parameters σ_r and σ_λ in Eq. (8) are determined by the root-mean-square radii of ^3He and $^3_\Lambda\text{H}$, as in the deuteron case. For ^3He , with $r_{^3\text{He}} = 1.76$ fm [83], we take $\sigma_r = \sigma_\lambda = r_{^3\text{He}} = 1.76$ fm, following Ref. [82].

The lightest known hypernucleus, the hypertriton ($^3_\Lambda\text{H}$), and its antiparticle were first observed in 2010 by the STAR Collaboration at RHIC [2]. They are characterized by a lifetime close to that of a free Λ and a very small Λ separation energy of $B_\Lambda = 0.17 \pm 0.06$ MeV [84–86]. This results in a halo-like structure in which the weakly bound Λ is spatially extended and loosely correlated with a deuteron-like nucleon core [87]. Accordingly, we adopt $\sigma_r = 2.26$ fm, the same value as for the deuteron, while considering three different values of σ_λ corresponding to different root-mean-square $\Lambda - d$ separation distance $r_{\Lambda d}$. Using the relation $\sigma_\lambda = \frac{2}{3} r_{\Lambda d}$ together with the connection between $r_{\Lambda d}$ and the Λ separation energy B_Λ in $^3_\Lambda\text{H}$, we obtain the approximate expression $\sigma_\lambda \approx (2.15(B_\Lambda/\text{MeV})^{-1/2} + 1.23)$ fm. Based on B_Λ values measured by the STAR and ALICE collaborations, we use $\sigma_\lambda = 5.45$ fm, 6.52 fm, and 7.96 fm for the hypertriton in this study [88]. The corresponding parameters and statistical factors for the nuclei considered are summarized in Table 1.

We note that, within the coalescence model for hypernucleus production, the halo structure of the hypertriton, characterized by a large $\Lambda - d$ separation distance of approximately 10 fm, leads not only to a suppression of the $^3_\Lambda\text{H}$ yield [23,89] but also to a softening of its transverse-momentum (p_T) spectrum, with only a weak centrality dependence [88].

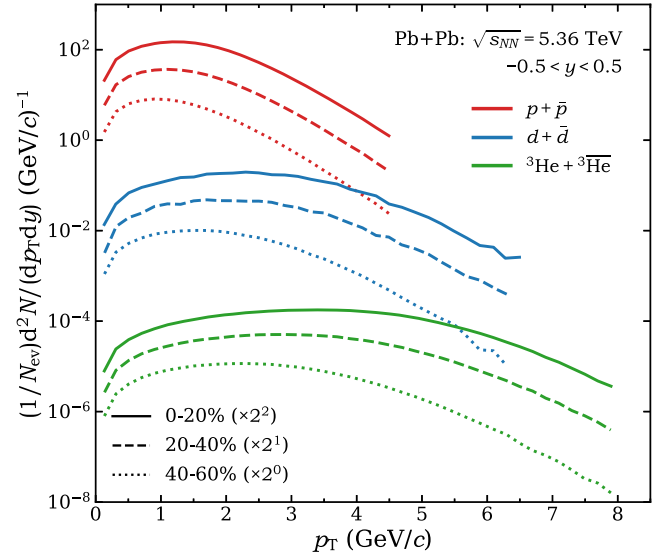


Fig. 1. Invariant transverse momentum (p_T) spectra of protons ($p + \bar{p}$), deuterons ($d + \bar{d}$), and helium-3 ($^3\text{He} + ^3\bar{\text{He}}$) at midrapidity ($-0.5 < y < 0.5$) in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV. The theoretical predictions from the hybrid dynamical approach coupled with the nucleon coalescence model are shown for three centrality classes (0–20%, 20–40%, and 40–60%). For clarity within a single panel, the spectra for different centralities are scaled by factors of 2^n ($n = 2, 1, 0$).

3. Results

Using the parameters for the hydrodynamic simulations from Ref. [90], we present in this Section our results from the MUSIC+UrQMD+COAL framework for the transverse momentum spectra of light nuclei and their anisotropic flow coefficients.

3.1. Transverse momentum spectra of light nuclei

Fig. 1 presents our theoretical predictions for the invariant transverse momentum (p_T) spectra of protons, deuterons, and ^3He in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV. The spectra are evaluated at midrapidity ($-0.5 < y < 0.5$) for three centrality classes and exhibit several characteristic features of coalescence production and collective hydrodynamic expansion.

First, the overall production yields show a strong centrality dependence. Second, the sizable radial flow developed during the QGP and hadronic evolution stages induces a mass-dependent blueshift to the spectra, efficiently pushing heavier nuclei toward higher transverse momenta. Third, a comparison of the spectral magnitudes across different species in Fig. 1 reveals a strong suppression of yields with nucleon number. This approximately exponential decrease, spanning several orders of magnitude from protons to ^3He , reflects the intrinsic coalescence penalty factor.

These predicted spectra can be directly compared with the upcoming measurements from the ALICE Collaboration in LHC Run 3.

3.2. Nucleon number scaling of light nuclei anisotropic flows

Using the MUSIC+UrQMD+COAL model, we calculate the elliptic and triangular flow coefficients v_2 and v_3 of protons, deuterons, ^3He , $^3_\Lambda\text{H}$, and their corresponding antiparticles in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV. The anisotropic flow coefficients are determined via the event plane method,

$$v_n(B) = \frac{1}{R_n} \frac{\sum_{\alpha \in B} w_\alpha \cos[n(\Phi_\alpha - \Psi_n)]}{\sum_{\alpha \in B} w_\alpha}, \quad (10)$$

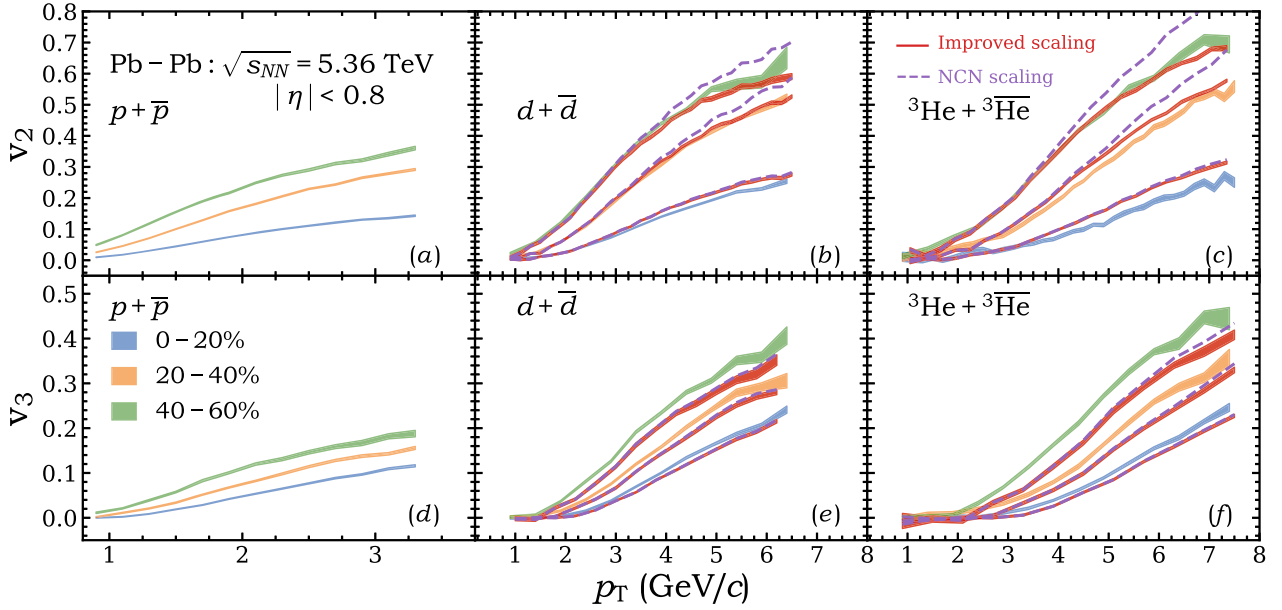


Fig. 2. Panels (a)–(f) show $v_2(p_T)$ and $v_3(p_T)$ for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV in the 0–20%, 20–40% and 40–60% centrality classes for different particles: (anti-)proton (a, d), (anti-)deuteron (b, e) and (anti-)Helium-3 (c, f). The solid lines, labeled as improved scaling in the figure, are obtained from Eq. (2) by constructing the normalized distribution $[P_p(\phi - \Psi_n)]^A$ and projecting it onto $\cos[n(\phi - \Psi_n)]$ to obtain v_n . The dashed lines, labeled as NCN scaling, correspond to Eq. (3).

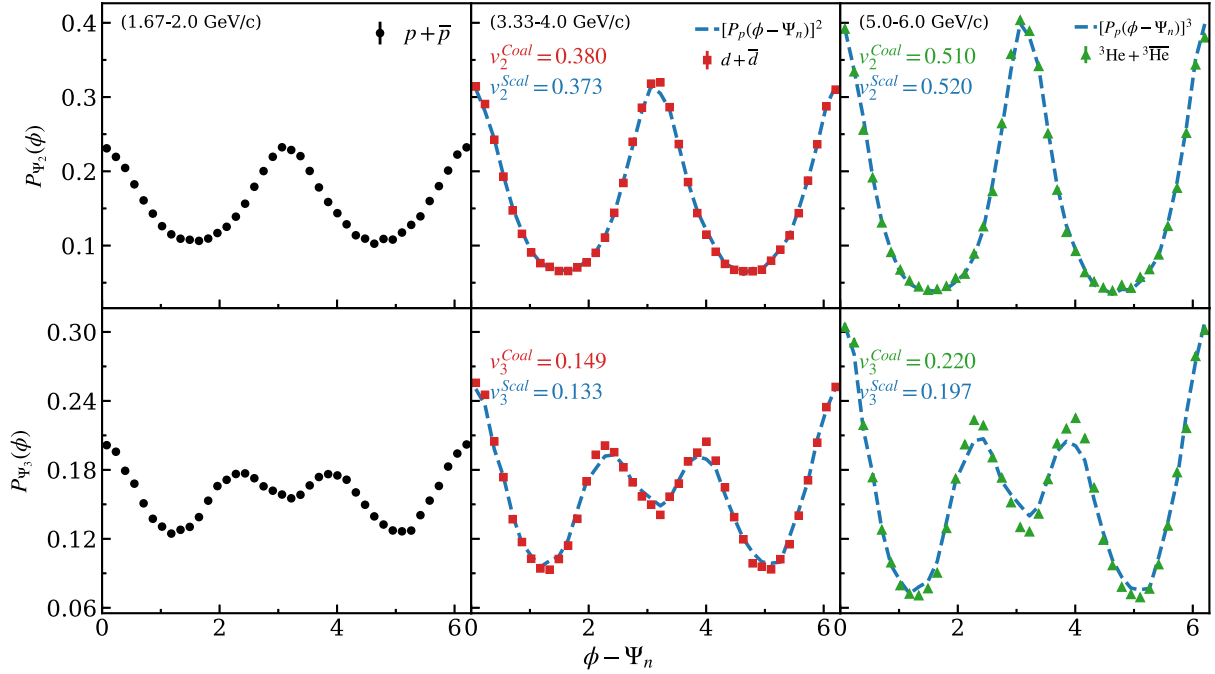


Fig. 3. Normalized azimuthal distributions of proton (left), deuteron (middle) and ^3He (right) relative to Ψ_2 (top) and Ψ_3 (bottom) in the 40%–60% centrality class. Symbols represent the results from the coalescence model (v_{Coal}), while the dashed lines, labeled in the figure as $[P_p(\phi - \Psi_n)]^2$ for deuterons and $[P_p(\phi - \Psi_n)]^3$ for ^3He , show the expectation from the normalized $[P_p(\phi - \Psi_n)]^A$ distribution (v_{Scal}). The event-plane angle Ψ_n is subtracted event by event, so all distributions are shown as functions of the relative azimuthal angle $\phi - \Psi_n$. The transverse momentum ranges are $1.67 < p_T < 2.0$ GeV/c (proton), $3.33 < p_T < 4.0$ GeV/c (deuteron), and $5.00 < p_T < 6.0$ GeV/c (^3He). The extracted flow coefficients are shown in each panel.

where α labels the particle or cluster entering the sum, Φ_α denotes its azimuthal angle, and Ψ_n is the reconstructed n th-order event-plane angle. The factor R_n denotes the corresponding event-plane resolution. For particles, $w_\alpha = 1$, while for clusters w_α is the coalescence weight obtained from the Wigner function. The sums run over all particles or clusters in the selected p_T bin B within a given centrality class.

The event-plane resolution R_n is computed for each centrality class using the standard three-subevent method [33]:

$$R_n = \sqrt{\frac{\langle \cos(n(\Psi_n^A - \Psi_n^B)) \rangle \langle \cos(n(\Psi_n^A - \Psi_n^C)) \rangle}{\langle \cos(n(\Psi_n^B - \Psi_n^C)) \rangle}}, \quad (11)$$

where Ψ_n^A , Ψ_n^B and Ψ_n^C are the event plane angles reconstructed in three non-overlapping pseudorapidity (η) intervals: $-3.7 < \eta_A < -1.7$

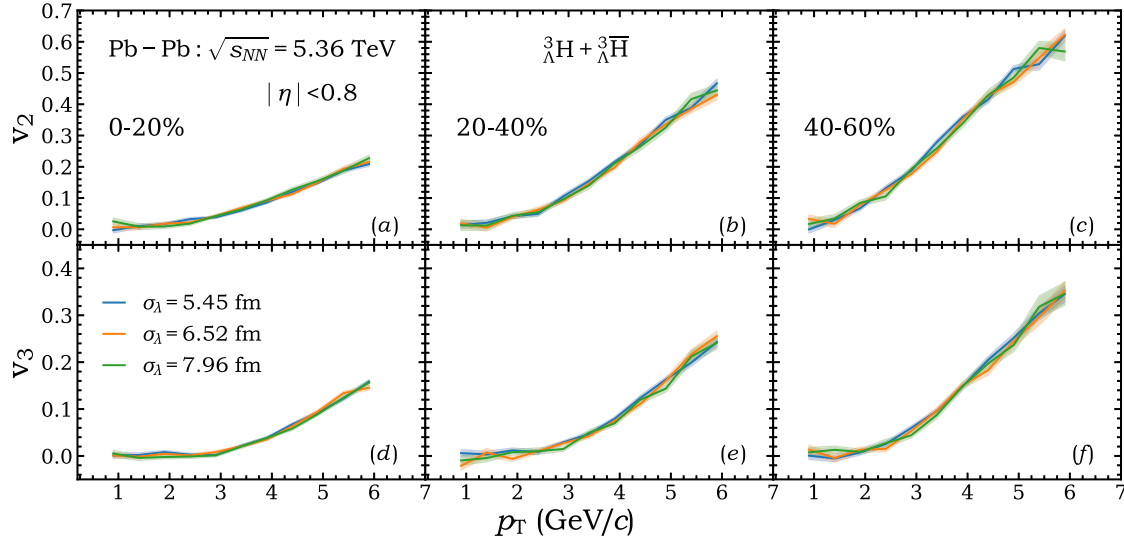


Fig. 4. $v_2(p_T)$ and $v_3(p_T)$ of (anti-)hypertriton for different values of the parameters σ_λ in the 0–20%(left), 20–40%(middle) and 40–60%(right) centrality classes in Pb+Pb collision at $\sqrt{s_{NN}} = 5.36$ TeV.

and $2.8 < \eta_A < 5.1$, $0.0 < \eta_B < 0.8$, and $-0.8 < \eta_C < 0.0$. The event-plane angle in each subevent is obtained from

$$\Psi_n = \frac{1}{n} \arctan \left(\frac{\text{Im}(Q_n)}{\text{Re}(Q_n)} \right), \quad (12)$$

where the flow vector Q_n is defined as

$$Q_n = \sum_i^M \exp(in\phi_i), \quad (13)$$

with M being the number of particles in the corresponding pseudorapidity window.

The upper panels of Fig. 2 show the p_T dependence of v_2 for (anti-)proton (a), (anti-)deuteron (b), and (anti-) ^3He (c) in the 0–20%, 20–40%, and 40–60% centrality classes. The colored bands represent results from the MUSIC+UrQMD+COAL calculation. The curves labeled as “NCN scaling” corresponding to the simple scaling relation in Eq. (3), while those labeled as “improved scaling” follow Eq. (2), where the normalized distribution $[P_p(\phi - \Psi_2)]^A$ is projected onto $\cos[2(\phi - \Psi_2)]$ to obtain v_2 .

The simple scaling relation is seen to overestimate the v_2 of deuterons and ^3He at $p_T > 3$ GeV/c in the 20%-40% and 40%-60% centrality classes, whereas the improved scaling relation remains in good agreement with the full model calculations up to $p_T \approx 8$ GeV/c.

The lower panels of Fig. 2 show the corresponding results for the v_3 , obtained using the same event-plane reconstruction procedure. A non-zero (positive) v_3 is observed over the entire p_T range, with a noticeably weaker centrality dependence than v_2 . The simple scaling relation yields larger v_3 values for deuterons and ^3He than the improved scaling relation; however, the difference is small due to the relatively small magnitude of the proton v_3 . Consequently, both scaling relations agree surprisingly well with the full model calculations, as shown by the colored bands.

3.3. Angular distributions

To further investigate the validity of mass-number scaling in the anisotropic flow of light nuclei, we present in Fig. 3 the normalized azimuthal angle distributions of protons, deuterons, and ^3He . The distributions are constructed after subtracting the corresponding event-plane

angle Ψ_n on an event by event basis. The results from the coalescence calculations using the MUSIC+UrQMD+COAL model (symbols) are compared with scaling expectations obtained from the A th power of the proton distribution (dashed lines). The transverse momentum intervals are chosen to satisfy $p_T/A \approx \text{const}$, ensuring a consistent kinematic comparison across different species.

The angular distributions of light nuclei are found to approximately follow the shape of $\left(\frac{dN_p}{d\phi}\right)^A$, indicating that their production is largely driven by the collective flow of the constituent nucleons. However, a quantitative comparison of the extracted flow coefficients reveals subtle deviations between the coalescence results v_n^{Coal} and the scaling expectations v_n^{Scal} . While v_2^{Coal} agrees reasonably well with v_2^{Scal} , noticeable deviations are observed in the third-order flow, where v_3^{Coal} differs more significantly from v_3^{Scal} .

This indicates that, although the simple scaling relation captures the dominant features of the azimuthal distributions, it does not fully account for the higher-order momentum correlations and flow fluctuations inherent in the coalescence process.

3.4. Anisotropic flow of (anti-)hypertriton

Fig. 4 shows the p_T dependence of v_2 (upper panels) and v_3 (lower panels) of (anti-)hypertriton for different centrality classes. The colored bands correspond to three different Λ – d separation distances, or equivalently, three different Λ separation energies. Both the elliptic and triangular flows of the hypertriton increase from central to peripheral collisions, with magnitudes close to those of ^3He .

In contrast to its yield and p_T spectrum [88], the anisotropic flow coefficients exhibit only a weak sensitivity to the Λ – d separation distance. This feature can be understood as follows. For large σ_λ , the relative momentum between the Λ hyperon and the deuteron must be very small for hypertriton formation. In the limit of $\sigma_\lambda \gg \lambda$, the hypertriton Wigner function can be approximated as

$$W_{\Lambda\text{H}}^3 \simeq 8^2 \pi^{3/2} \sigma_\lambda^{-3} \delta^{(3)}(\mathbf{p}_\lambda) \exp\left(-\frac{\mathbf{r}^2}{\sigma_r^2} - \sigma_r^2 \mathbf{p}_r^2\right). \quad (14)$$

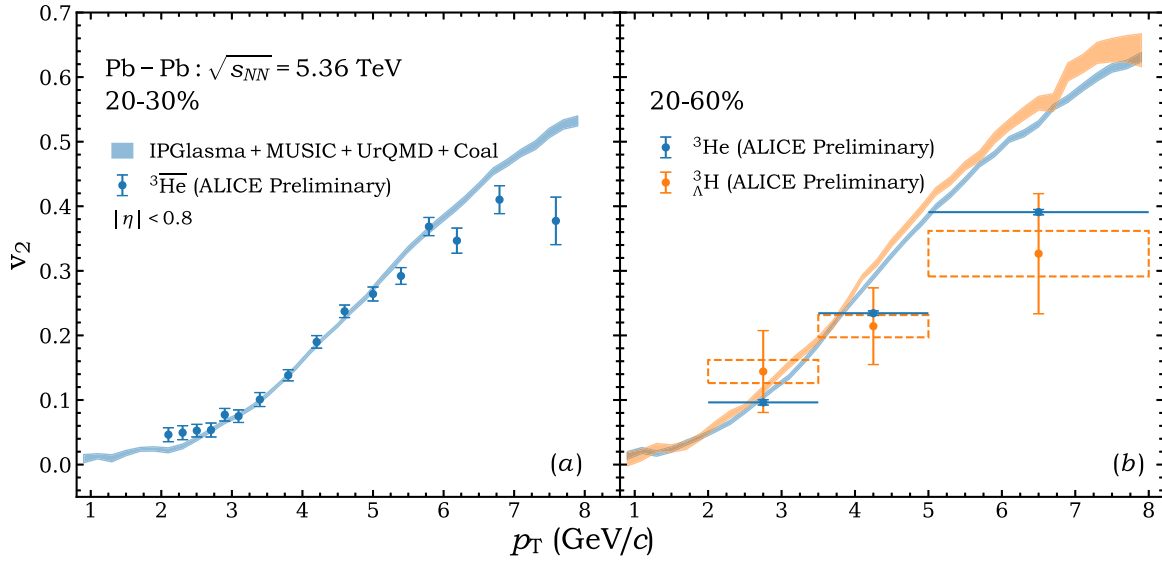


Fig. 5. Panel (a): $v_2(p_T)$ of (${}^3\text{He}$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV for the 20–30% centrality class. Panel (b): $v_2(p_T)$ of ${}^3\text{He}$ and ${}^3_\Lambda\text{H}$ in the same system for the 20–60% centrality class. The preliminary ALICE data are taken from Ref. [91].

The corresponding angular distribution at fixed P_T can then be written as

$$\begin{aligned} \frac{d^3 N_{\Lambda\text{H}}}{P_T dP_T d\Phi dy} &\approx 8^2 g_{\Lambda\text{H}}^3 \pi^{3/2} \sigma_\lambda^{-3} \int \prod_{i=p,n,\Lambda} \left(p_i^\mu d^3 \sigma_{i\mu} \frac{d^3 p_i}{E_i} f_i \right) \\ &\times \exp \left(-\frac{r^2}{\sigma_r^2} - \sigma_r^2 p_r^2 \right) \delta^{(3)}(p_\lambda) \\ &\times \delta^{(3)}(P_H - p_p - p_n - p_\Lambda), \end{aligned} \quad (15)$$

where $g_{\Lambda\text{H}} = 1/4$ the statistical factor.

The anisotropic flow coefficient is obtained from this angular distribution as

$$v_{n,\Lambda\text{H}}(P_T) = \frac{\int d\Phi \cos[n(\Phi - \Psi_n)] \frac{d^3 N_{\Lambda\text{H}}}{P_T dP_T d\Phi dy}}{\int d\Phi \frac{d^3 N_{\Lambda\text{H}}}{P_T dP_T d\Phi dy}}. \quad (16)$$

In this ratio, the factor $\pi^{3/2} \sigma_\lambda^{-3}$ cancels, rendering v_n independent of σ_λ . This explains the weak sensitivity of anisotropic flows to σ_λ observed in Fig. 4. This result is consistent with recent ALICE measurements of the elliptic flow ${}^3\text{He}$ and ${}^3_\Lambda\text{H}$, which show comparable flow magnitude despite their very different binding energies and spatial structures [91].

3.5. Comparison with preliminary experimental data

To assess the performance of the coalescence model in describing the collective flow of light (anti-)nuclei, we present in Fig. 5 the transverse momentum dependence of the elliptic flow coefficient v_2 for ${}^3\text{He}$ in the 20–30% centrality class (panel a) and for ${}^3\text{He}$ and for ${}^3_\Lambda\text{H}$ in the 20–60% class (panel b). The shaded bands represent predictions from the IP-Glasma + MUSIC + UrQMD + coalescence framework, with the band widths reflecting theoretical uncertainties.

The markers denote the preliminary ALICE measurements [91], where the vertical error bars represent statistical uncertainties for ${}^3\text{He}$ and systematic uncertainties for ${}^3_\Lambda\text{H}$, and the horizontal bars indicate the p_T bin widths. The theoretical calculations are found to be in excellent agreement with the experimental data across both species and centrality intervals, demonstrating the capability of the nucleon coalescence mechanism to describe the anisotropic flow of light nuclei.

Future high-precision measurements will provide further constraints and tests of this production mechanism.

4. Summary

In the present study, we have investigated the elliptic and triangular flows of (anti-)protons, (anti-)deuterons, (anti-) ${}^3\text{He}$, and (anti-)hypertriton (${}^3_\Lambda\text{H}$) in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV employing a nucleon coalescence model with phase-space distributions of kinetically frozen-out nucleons and Λ hyperons generated by the hybrid IP-Glasma + MUSIC + UrQMD framework.

We find that the simple NCN scaling relation for v_2 with the number of constituent nucleons A breaks down at high transverse momentum ($p_T/A > 1.5$ GeV/c), where it overestimates the v_2 of deuterons and ${}^3\text{He}$. An improved scaling relation, derived from the A th power of the proton azimuthal distribution, remains valid up to $p_T/A \approx 3$ GeV/c and provides good agreement with the full coalescence model calculations. For v_3 , both scaling relations yield similar results owing to the relatively small magnitude of the proton v_3 , and both reproduce the full model calculations across all centrality classes considered.

We also present predictions for the v_2 and v_3 of the (anti-)hypertriton. Both flow coefficients are found to increase from central to peripheral collisions, with magnitudes close to those of ${}^3\text{He}$. Notably, unlike the hypertriton yield and p_T spectrum, its anisotropic flow coefficients show little sensitivity to the Λ - d separation distance within the hypertriton wave function.

A comparison with preliminary ALICE measurements shows good agreement, demonstrating the capability of the coalescence model to describe the collective flow of light (hyper-)nuclei. These results, together with future high-precision data from LHC Run 3, will provide further insight into the production mechanisms of light (anti-)(hyper-)nuclei in high-energy heavy-ion collisions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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