

Investigating the transverse-momentum- and pseudorapidity-dependent flow vector decorrelation in p -Pb collisions with a multi-phase transport model*

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Abstract: Event-by-event fluctuations in the initial energy density of nuclear collisions lead to the decorrelation of second order flow vector, which is known as its transverse-momentum (p_T) and pseudorapidity (η) dependence as observed in high-energy heavy-ion collisions. Existing measurements at the CERN Large Hadron Collider showed that these decorrelations are also observed in small collision systems. In this work, a systematic study of the transverse-momentum- and pseudorapidity-dependent flow vector decorrelation is performed in p -Pb collisions at the 5.02 TeV with A Multi-Phase Transport (AMPT) model using different tunings of initial conditions and partonic and hadronic interactions. The string-melting version of the AMPT model provides a reasonable description of the measured flow vector decorrelation as a function of p_T and η . We demonstrate that hadronic scatterings do not have a significant effect on decorrelation in p -Pb collisions for different centrality selections, while both initial conditions and partonic interactions affect the magnitude of the decorrelations. In addition, we found that the subtraction of the non-flow, especially the long-range jet correlation, is crucial for the accurate extraction of flow vector decorrelation in small collision systems. The comparison of data and model presented in this paper provide further insights in understanding the fluctuations of the flow vector with p_T and η in small collision systems and has referential value for future measurements.

Keywords: fluctuations, decorrelation, flow vector, small collision systems, LHC

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I. INTRODUCTION

High-energy heavy-ion collisions such as those at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC) [1–8] offer a unique opportunity to study nuclear matter under extreme conditions of temperature and density. These collisions create quark-gluon plasma (QGP) [9, 10], which is a state of matter where quarks and gluons are no longer confined within hadrons but instead form a hot, dense medium. One of the most important observables for the formation of the QGP is the

azimuthal anisotropy of produced particles, which is typically characterized by the Fourier expansion of the hadron yield distribution as a function of azimuthal angle φ :

$$\frac{dN}{d\varphi} \propto 1 + 2 \sum_n v_n \cos[n(\varphi - \Psi_n)], \quad (1)$$

where the Fourier coefficient v_n and symmetry plane angle Ψ_n represent the magnitude and orientation of the n^{th} order flow vector $V_n \equiv v_n e^{in\Psi_n}$, respectively [11, 12].

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Several measurements focusing on the second harmonic flow v_2 (elliptic flow) have been performed at both RHIC [13–17] and LHC [18–28]. Comparisons to theoretical model calculations provided unprecedented constraints on the fundamental transport properties of the QGP medium [29–32], such as the ratio of shear viscosity to entropy density (η/s), which indicate that the QGP created in heavy-ion collisions behaves as a nearly perfect fluid.

Owing to event-by-event fluctuations in the initial energy density of the nuclear collisions [29, 33], the fluctuations of second order flow vector V_2 as well as its transverse-momentum (p_T) dependence have been shown in hydrodynamical models [34–36]. These fluctuations can result in the breakdown of the factorization of two-particle angular correlations into a product of single-particle flow coefficients in different p_T intervals [34, 37–40], which were discovered in Pb–Pb collisions by the ALICE and CMS Collaborations [41–44]. In addition, flow vector fluctuations along the pseudorapidity (η) direction was investigated by hydrodynamic and parton transport models, where the factorization breakdown in η was found to be sensitive to event-plane fluctuations at different η [45–48]. The LHC experiments measured the ratio of two-particle Fourier coefficients in rapidity bins η and $-\eta$ [42, 49, 50], and the results showed that the longitudinal fluctuations lead to a linear decrease of the ratio with η , *i.e.*, longitudinal flow decorrelations. These studies provide further constraint on initial conditions and new insights to the longitudinal evolution of the medium formed in heavy ion collisions.

In recent years, the observation of non-zero v_2 in p –Pb and pp collisions [51–59] raised the question of whether hydrodynamic flow exists in these small collision systems. The extracted flow harmonics in p –Pb collisions have been studied in detail as a function of p_T , η , and event multiplicity [54, 60]. On the other hand, the fluctuations of flow vector as a function of p_T and η in small collision systems are measured by the LHC experiments [41, 42, 50, 57]. The effect of factorization breakdown was observed in p –Pb collisions and considerably smaller than that in Pb–Pb collisions. The measurements of longitudinal flow decorrelations were extended to even the smaller pp collisions by the ATLAS Collaboration [57], and the results reveal significant sensitivity to non-flow correlations. Since the origin of collective flow in small collision systems remains unclear [61], there are significant uncertainties in the study of p_T and η -dependent flow vector decorrelations in these systems. The study based on event-by-event hydrodynamic calculations demonstrated the important role of longitudinal decorrelations in small collision systems and predicted rapidity-asymmetric flow decorrelations across different colliding energies [62–66]. On the other hand, the transport model has been successfully applied to describe collective phenomena in small collision systems, including charged-

particle elliptic flow (v_2), triangular flow (v_3) [67], and flavor-dependent p_T -differential flow [68–73]. Building on these successful applications, we present the first systematic study of the p_T - and η -dependent flow vector decorrelation in p –Pb collisions using A Multi-Phase Transport (AMPT) model.

This paper is organized as follows. A brief introduction about the AMPT and its various configurations is given in Sec. II. The observables to characterize the flow vector decorrelation as a function of p_T and η , respectively, are introduced in Sec. III. The two-particle correlation method and advanced nonflow subtraction strategy are also presented. The results and related discussions are provided in Sec. IV. Finally, a summary of this work is given in Sec. V.

II. MODEL

The string-melting version of the AMPT model [74, 75] is employed in this work to study flow vector decorrelation in p –Pb collisions at 5.02 TeV. The AMPT model includes four stages: initial conditions, partonic scattering, hadronization, and hadronic rescattering. The heavy ion jet interaction generator (HIJING) [76] is incorporated in the model to generate initial conditions, where minijet partons and soft-excited strings are produced and then converted to primordial hadrons based on Lund fragmentation. The strength of Lund fragmentation is controlled by two key parameter, namely, Lund string parameters a and b , which are approximately related to the string tension by $\kappa \propto \frac{1}{b(2+a)}$. With the string melting mechanism, primordial hadrons are converted into partons, which are determined by their flavor and spin structures. Subsequent parton interactions are treated with the Zhang's parton cascade (ZPC) model [77]. Only elastic scattering between the partons is considered in the model, and the cross-section of the two-body scattering is described by the simplified equation

$$\sigma = \frac{9\pi\alpha_s^2}{2\mu^2}, \quad (2)$$

where α_s and μ represent strong coupling and the Debye screening mass, respectively. Once the partons stop scattering, the nearest two or three quarks are combined into mesons or baryons using a quark coalescence model. The generated hadrons then enter the hadronic rescatterings process, which is described by an extended relativistic transport (ART) model [78], including both elastic and inelastic scatterings for baryon-baryon, baryon-meson, and meson-meson interactions. Finally, hadronic scatterings are terminated at a cutoff time ($t_{\max}$) when the observables of interest are stable; a default cutoff time of $t_{\max} = 30 \text{ fm}/c$ is used.

In order to separate the effect from different physical processes on the flow vector decorrelation, we varied the key parameters of the model in the calculations of the flow vector. The effect of the partonic phase is investigated by varying the partonic scattering cross section σ from 0 mb and 0.5 mb to 3 mb. A smaller cross section corresponds to a higher shear viscosity to entropy density ratio (η/s) in viscous hydrodynamics in the AMPT model, and 0 mb of the cross section represents the exclusion of the parton scattering effect. Following the previous studies about the elliptic flow in p -Pb collisions [70–72], the default settings of Lund string parameters are $a = 0.3$ and $b = 0.15$. In this work, we studied the initial conditions by varying $a = 0.5$ and $b = 0.9$, which correspond to a smaller string tension, when the partonic scattering cross section σ is set to 0.5 mb. In addition, the cutoff time $t_{\max}$ is set to 0.6 fm/c to turn off hadronic rescatterings, whereas resonance decays are still included. Further, we analyzed hadrons obtained right after the quark coalescence in the AMPT evolution (*i.e.*, $t_{\max} = 0$ fm/c), where both hadronic rescatterings and resonance decays are disabled. All configurations are summarized in Table 1.

III. OBSERVABLES AND METHOD

Flow vector decorrelation is studied using the two-particle correlation method, which has been widely applied in previous v_2 measurements in p -Pb collisions [52, 79]. For simplicity, the azimuthal correlation between two emission particles can be represented by N^{pair} particle pairs as a function of the relative azimuthal angle $\Delta\varphi = \varphi_a - \varphi_b$ between particles a and b and expanded in the Fourier series as

$$C(\Delta\varphi) = \frac{dN^{\text{pair}}}{d\Delta\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} V_{n\Delta}(p_T^a, p_T^b) \cos[n(\Delta\varphi)], \quad (3)$$

where $V_{n\Delta}$ refers to the two-particle n -th order harmonic. The traditional approach to calculate the p_T -differential flow of particle a (*i.e.*, the particle of interest, POIs) is to determine the flow coefficient of reference particles (RPs, labeled as "ref") over a wide kinematic range, called reference flow, and then, the flow coefficient from p_T^a interval can be expressed as

$$\begin{aligned} v_n\{2\}(p_T^a) &= \frac{V_{n\Delta}(p_T^a, \text{ref})}{\sqrt{V_{n\Delta}(\text{ref}, \text{ref})}} \\ &= \frac{\langle v_n(p_T^a) v_n^{\text{ref}} \cos[n(\Psi_n(p_T^a) - \Psi_n)] \rangle}{\sqrt{\langle v_n^{\text{ref}2} \rangle}}, \end{aligned} \quad (4)$$

where $V_{n\Delta}(p_T^a, \text{ref})$ and $V_{n\Delta}(\text{ref}, \text{ref})$ are obtained by constructing the two particle correlation function $C(\Delta\varphi)$ as Eq.

Table 1. Different configurations of AMPT parameters used in this work

	Lund a	Lund b	Partonic cross section /mb	$t_{\max}$ fm/c
Par1	0.3	0.15	0.5	30
Par2	0.3	0.15	3	30
Par3	0.3	0.15	0	30
Par4	0.5	0.9	0.5	30
Par5	0.3	0.15	0.5	0
Par6	0.3	0.15	0.5	0.6

(3) between the POIs and RPs, and the RPs, respectively. $\Psi_n(p_T^a)$ represents the p_T -differential symmetry plane angles at a specific p_T range, which may fluctuate around the reference symmetry plane angles Ψ_n . The effect of the difference between $\Psi_n(p_T^a)$ and Ψ_n is quantified by the cosine term $\cos[n(\Psi_n(p_T^a) - \Psi_n)]$, which is called p_T -dependent flow angle fluctuations. On the other hand, the fluctuations of the flow magnitude are observed when the factorization hypothesis is broken [43, 44], *i.e.*, $\langle v_n(p_T^a) v_n^{\text{ref}} \rangle$ cannot be factorized into the product of $\sqrt{\langle v_n(p_T^a)^2 \rangle}$ and $\sqrt{\langle v_n^{\text{ref}2} \rangle}$. Another p_T differential flow observable, denoted as $v_n[2](p_T^2)$, is proposed in [80], which is not affected by fluctuations in the flow angle or flow magnitude:

$$v_n[2](p_T^a) = \sqrt{V_{n\Delta}(p_T^a, p_T^a)} = \sqrt{\langle v_n(p_T^a)^2 \rangle}. \quad (5)$$

The ratio of $v_n[2](p_T^a)$ and $v_n[2](p_T^a)$ is proposed to probe p_T -dependent flow vector fluctuations:

$$\frac{v_n\{2\}(p_T^a)}{v_n[2](p_T^a)} = \frac{\langle v_n(p_T^a) v_n^{\text{ref}} \cos[n(\Psi_n(p_T^a) - \Psi_n)] \rangle}{\sqrt{\langle v_n(p_T^a)^2 \rangle} \sqrt{\langle v_n^{\text{ref}2} \rangle}}. \quad (6)$$

One can see that, if p_T -dependent flow vector fluctuations are present, the ratio value is smaller than unity. Similarly, another observable to probe the p_T -differential factorization ratio r_n has been proposed in [80, 81],

$$\begin{aligned} r_n &= \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) V_{n\Delta}(p_T^b, p_T^b)}} \\ &= \frac{\langle v_n(p_T^a) v_n(p_T^b) \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \rangle}{\sqrt{\langle v_n(p_T^a)^2 \rangle \langle v_n(p_T^b)^2 \rangle}}. \end{aligned} \quad (7)$$

$r_n < 1$ indicates the breaking of factorization, which suggests the presence of p_T -dependent flow vector fluctuations.

Similarly, the η -dependent flow harmonics $V_{n\Delta}(\eta^a, \eta^b)$ are calculated by constructing two-particle correlations between pseudorapidity bins η^a and η^b , following the same method as Eq. (3) but replacing p_T^a and p_T^b with η^a

and η^b . In order to investigate the longitudinal fluctuations of the flow vector, the decorrelation ratio $r_n(\eta^a, \eta^b)$ was proposed in Ref. [42], which is defined as

$$r_n(\eta^a, \eta^b) = \frac{V_{n\Delta}(-\eta^a, \eta^b)}{V_{n\Delta}(\eta^a, \eta^b)} = \frac{\langle v_n(-\eta^a) v_n(\eta^b) \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle v_n(\eta^a) v_n(\eta^b) \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle}, \quad (8)$$

where $\cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))]$ represents the impact of the variation in symmetry plane angles between η^a and η^b bins, resulting from η -dependent flow angle fluctuations. In addition, flow magnitude decorrelation introduces additional η -dependent fluctuations, breaking the factorization of flow coefficient products: $\langle v_n(-\eta^a) v_n(\eta^b) \rangle \neq \sqrt{\langle v_n^2(-\eta^a) \rangle} \sqrt{\langle v_n^2(\eta^b) \rangle}$. For symmetric collision systems such as Pb–Pb collisions, v_n obtained from the symmetric positive [$v_n(\eta_a)$] and negative [$v_n(-\eta_a)$] η regions are identical after averaging over all events. Therefore, the $r_n(\eta^a, \eta^b)$ is expected to converge to unity if neither flow magnitude nor flow angle fluctuate along the longitudinal direction. If either of these effects, or both, are present, the $r_n(\eta^a, \eta^b)$ will be less than unity [50]. However, in an asymmetric collision system, such as p –Pb collisions, $v_n(\eta_a)$ and $v_n(-\eta_a)$ are generally not identical. Consequently, it is not possible to isolate the η -dependent effects of symmetry-plane fluctuations in Eq. (8). The CMS collaboration proposed a method [42] to take the product of $r_n(\eta^a, \eta^b)$ and $r_n(-\eta^a, -\eta^b)$:

$$\begin{aligned} & \sqrt{r_n(\eta^a, \eta^b) r_n(-\eta^a, -\eta^b)} \\ &= \sqrt{\frac{\langle v_n(-\eta^a) v_n(\eta^b) \rangle \langle v_n(\eta^a) v_n(-\eta^b) \rangle}{\langle v_n(\eta^a) v_n(\eta^b) \rangle \langle v_n(-\eta^a) v_n(-\eta^b) \rangle}} \\ &= \sqrt{\frac{\langle \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle \langle \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^b))] \rangle}{\langle \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle \langle \cos[n(\Psi_n(-\eta^a) - \Psi_n(-\eta^b))] \rangle}}. \end{aligned} \quad (9)$$

In this case, the v_n terms can be canceled if there is no flow vector magnitude fluctuations, and then, the η -dependent flow vector decorrelation in p –Pb collisions can also be studied.

In small collision systems, the main contributions of the nonflow is from the jets, including both the short-range and long-range (also called "recoil") jet correlations [82]. The former can be effectively removed by introducing a large rapidity gap between the trigger and associated particles during the construction of the correlations, and the latter can be suppressed by many methods in measurements based on different assumptions. In this work, the template fit method developed by the ATLAS collaboration [60] is applied, which has been proven effective for nonflow subtraction in our previous studies

[70] in the AMPT. For the given p_T and η integral, the correlation function distribution obtained in high-multiplicity events is assumed to result from the superposition of the distribution obtained in low-multiplicity events scaled up by a multiplicative factor F and a constant modulated by $\cos(n\Delta\varphi)$ for $n > 1$, as shown in

$$C(\Delta\varphi) = FC^{\text{LM}}(\Delta\varphi) + G(1 + 2 \sum_{n=1}^3 V_{n\Delta} \cos(n\Delta\varphi)), \quad (10)$$

where G denotes the normalization factor and $V_{n\Delta}$ represents the two-particle n -th order harmonic after the non-flow subtraction. The C^{LM} represents correlation distributions obtained from the low-multiplicity events, and in this work, collisions with 60%–100% centrality are selected. By replacing Eq. (3) with Eq. (10), the flow vector fluctuations after the long-range nonflow subtraction can be calculated.

IV. RESULTS AND DISCUSSION

A. Transverse-momentum dependence of decorrelation

We first examine the p_T -differential v_2 of charged hadrons in the pseudorapidity region $|\eta| < 0.8$ using the AMPT model with the default configuration (Par1) described in Table 1. $v_2\{2\}$ and $v_2\{2\}$ are calculated according to Eq. (4) and Eq. (5). Figure 1 shows the p_T -differential $v_2\{2\}$ and $v_2\{2\}$ for 0–20%, 20%–40%, and 40%–60% centrality bins obtained from the AMPT calculations, compared with those obtained through ALICE measurements [41]. To suppress contributions from short-range jet correlations, $|\Delta\eta| > 0.8$ is applied. The calculations reasonably reproduce v_2 data from central to semi-central collisions, and the ratio $v_2\{2\}/v_2\{2\}$ shows deviations from unity above $p_T \approx 2$ GeV/c. These deviations increase with p_T , which is similar to the findings in Pb–Pb collisions, indicating p_T -dependent flow vector fluctuations in p –Pb collisions from the AMPT model. Unlike Pb–Pb collisions, these deviations do not significantly depend on centrality selections. To determine if these deviations are caused by non-flow effects from long-range jet correlations, we apply the template fit subtraction method described in Eq. (10). As expected, the v_2 after subtraction, shown in Fig. 1 (dashed line), is lower than that of the results without subtraction, especially at high $p_T > 2$ GeV/c. The ratio $v_2\{2\}/v_2\{2\}$ after subtraction is consistent with that before subtraction within uncertainties. This indicates that the long-range jet contribution to the decorrelations is negligible here, and the observed p_T -dependent flow vector fluctuations in p –Pb collisions are caused by real flow signals.

Figure 2 shows the p_T -dependent $v_2\{2\}/v_2\{2\}$ ratio in 0–20%, 20%–40%, and 40%–60% centrality classes ob-

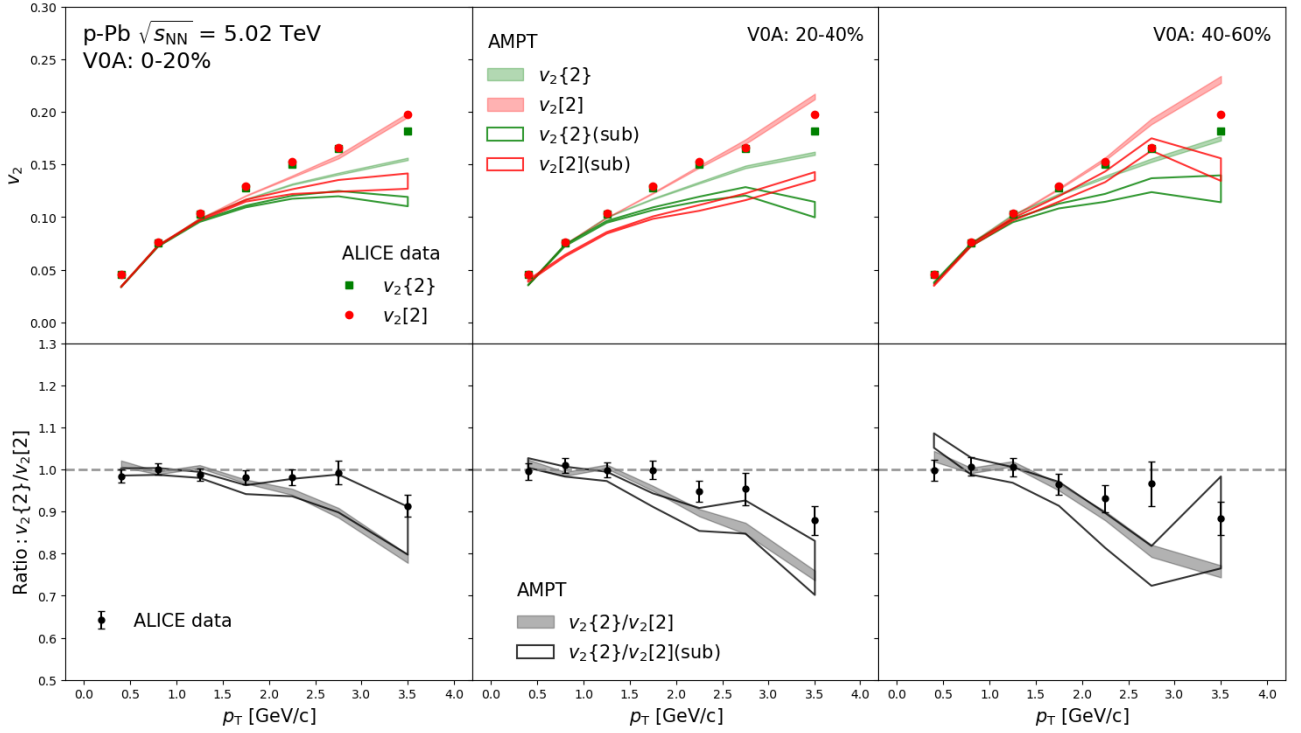


Fig. 1. (color online) $v_2\{2\}$ and $v_2[2]$ as a function of p_T and their ratio obtained from the AMPT model in 0–20%, 20%–40%, and 40%–60% p -Pb collisions at 5.02 TeV, in comparison of those obtained via ALICE measurements [41]. Results with the nonflow subtraction obtained from the AMPT model are also shown.

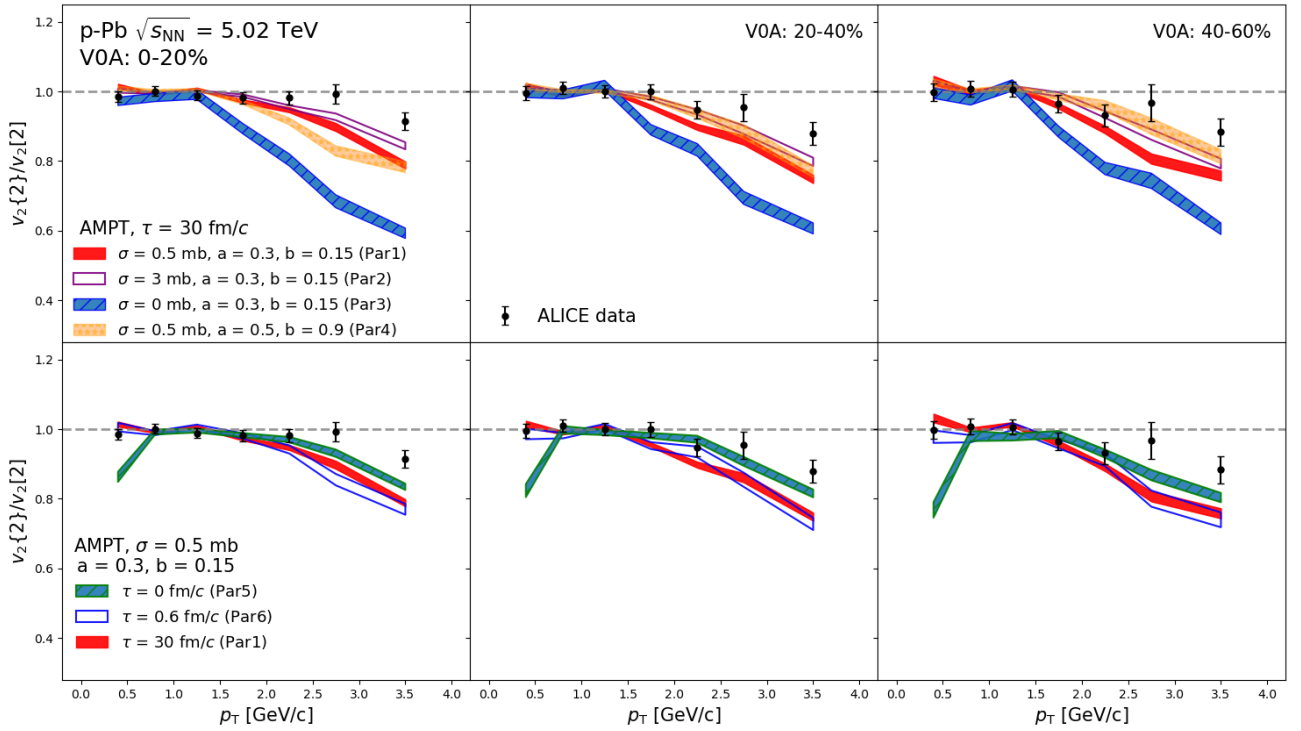


Fig. 2. (color online) p_T -dependent $v_2\{2\}/v_2[2]$ ratio in 0–20%, 20%–40%, and 40%–60% centrality classes from the AMPT model with different configurations. ALICE data points [41] are shown as black open circles for comparison.

tained from AMPT model with different configurations, compared to ALICE data points [41]. For direct comparison with the data, nonflow subtraction is not applied here. The impact of partonic scattering on the ratio can be seen by comparing the results from Par1, Par2, and Par3, as shown in Fig. 2(top). The ratio obtained from larger parton scattering cross section (Par2) is slightly higher than the results from Par1. On the other hand, a large deviation to unity is observed when the cross section is set to $\sigma = 0$ mb (Par3). It may attribute to the break of factorization from the nonflow because the parton scattering process proved to be the main contribution to the flow in small collision systems [70]. The effect from varying initial conditions via the Lund string parameters, namely, a and b , can be seen by comparing the results from Par4 and Par1, as shown in Fig. 2 (top). One can see that the $v_2\{2\}/v_2\{2\}$ ratio obtained with larger Lund a and b (Par4) is lower in most 0–20% collisions. With the increasing of centralities, the results from Par4 are enhanced, and finally, they are higher than the results from Par1. The effects from hadronic scatterings are studied by varying the cutoff time of hadronic rescatterings, which can be seen

in the comparison of the results of Par1, Par5, and Par6, as shown in Fig. 2 (bottom). The $v_2\{2\}/v_2\{2\}$ ratio from Par1 and Par6 are consistent within uncertainties from the central to peripheral collisions, indicating that the impact from hadronic scatterings on the flow vector fluctuations are negligible. It is consistent with previous findings that hadronic scatterings have almost no effects on the p_T -differential v_2 in p -Pb collisions [70]. For the case of Par5, where both the resonance decay and hadronic scatterings are turned off, the $v_2\{2\}/v_2\{2\}$ ratio is lower at $p_T < 0.8$ GeV/c but higher at $p_T > 1.4$ GeV/c compared to the results of Par1 and Par6. It is expected that, the decay processes convert high- p_T hadrons into low- p_T particles, and therefore, it shifts the overall ratio toward the low- p_T region. One can see that the results of all configurations underestimate the data, suggesting that the model needs further tuning.

The factorization ratio r_2 defined in Eq. (7) is calculated in different centrality and p_T^b ranges and compared with the ALICE data points [41] in Fig. 3. The results from the AMPT model with different configurations are shown in Fig. 3(a) (Par1, Par2 vs. Par3) and Fig. 3(b)

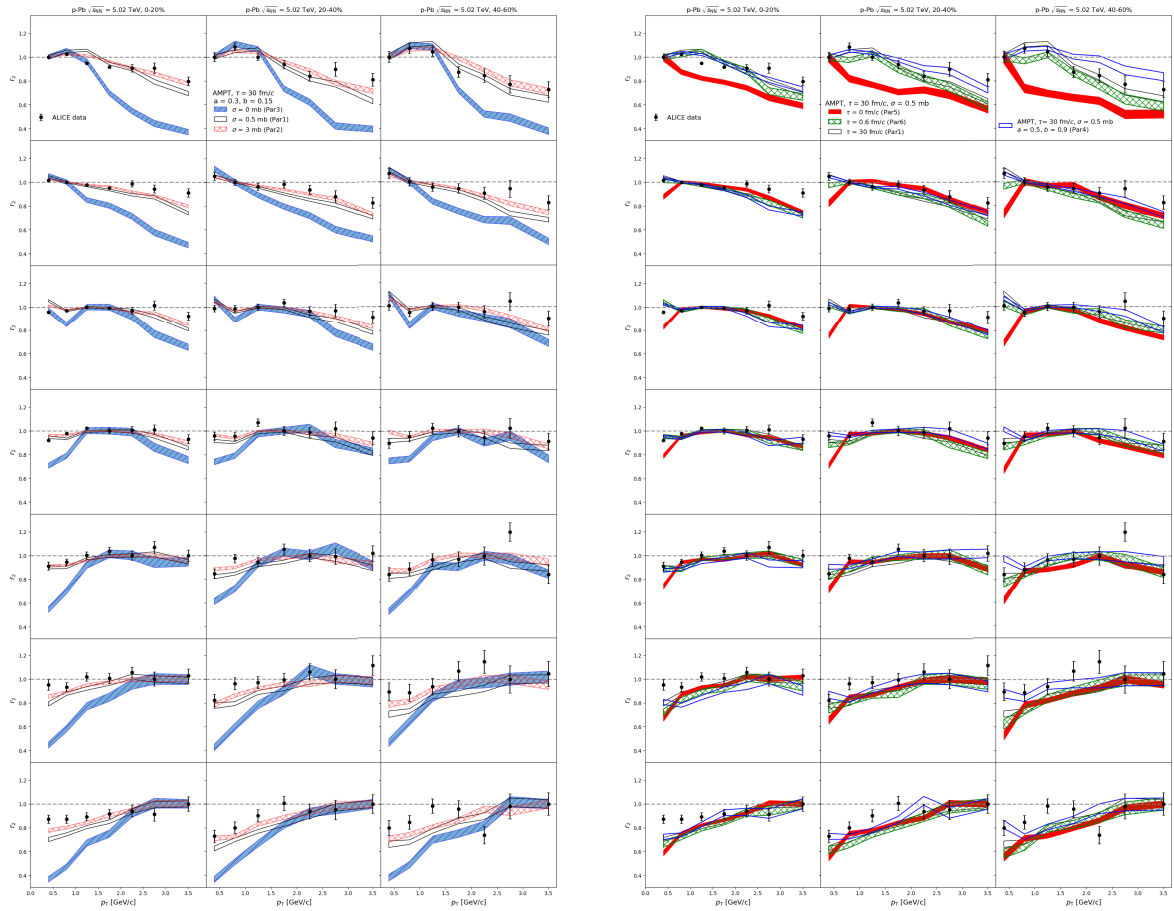


Fig. 3. (color online) Factorization ratio r_2 as a function of p_T^a obtained from AMPT calculations in different centrality and p_T^b ranges is compared to those of ALICE data points [41].

(Par1, Par4, Par5, and Par6). Similar to Fig. 2, nonflow subtraction is not applied here. The model with a 0.5 mb cross section, $a = 0.3$, $b = 0.15$, and $\tau = 30$ fm/c (Par1), provides a fair description of the data in all centrality and p_T bins. The deviation of r_2 from unity has no dependence on centrality selections, and it is more pronounced with an increasing $|p_T^a - p_T^b|$. The r_2 obtained with a larger Lund a and b (Par4) are higher in more peripheral collisions, which reflects effects from the initial conditions. Changing the partonic scattering cross section from 0.5 mb to 3 mb (Par1 vs. Par3) slightly enhances r_2 , while the results obtained with $\sigma = 0$ mb show a significant breakdown of the factorization at large $|p_T^a - p_T^b|$. The impacts from hadronic scatterings are negligible for all centralities and p_T bins (Par1 vs. Par6); however, the resonance decay process still has large impacts on the r_2 at low- p_T region (Par1 vs. Par5). One can see that the calculations of r_2 and $v_2\{2\}/v_2[2]$ ratio have a generally similar dependence on the initial conditions, parton scattering cross section, and hadron scattering process. It is expected since r_2 is basically a double-differential $v_2\{2\}/v_2[2]$ ratio [59].

B. Pseudorapidity-dependence of decorrelation

The η -dependent v_2 is first calculated before studying the decorrelation. We follow the two-particle correlation method and nonflow subtraction strategy used by the ALICE experiment [54]. The correlation between three groups of particles is constructed based on Eq. (10), and then, the flow coefficients are extracted for three combinations:

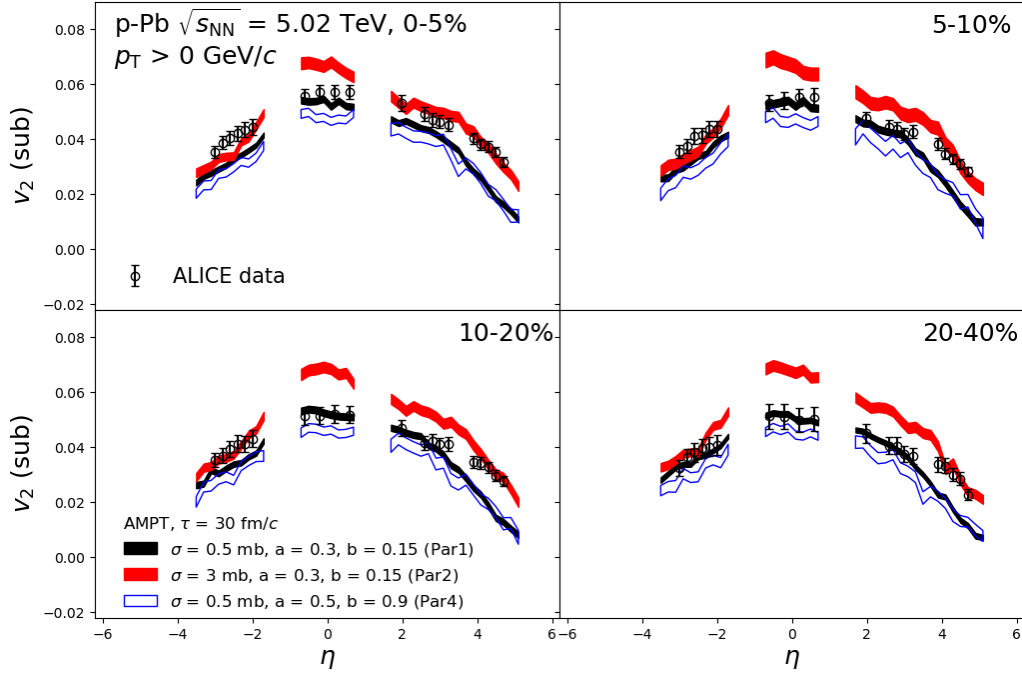
$$v_n(\eta^a) = \sqrt{\frac{V_{n\Delta}(\eta^a, \eta^b)V_{n\Delta}(\eta^a, \eta^c)}{V_{n\Delta}(\eta^b, \eta^c)}}, \quad (11)$$

where a , b , and c represent hadrons with $p_T > 0$ GeV/c at different rapidity bins. Similarly, $v_n(\eta^a)$ and $v_n(\eta^b)$ can be obtained by alternating indices a , b , and c in Eq. (11). Figure 4 shows the v_2 of charged hadrons for $p_T > 0$ GeV/c as a function of η in 0–5%, 5%–10%, 10%–20%, and 20%–40% centrality ranges, and the comparison to the ALICE data [54]. Results obtained from different configurations of the AMPT model are shown in Fig. 4(a) and Fig. 4(b). Calculations obtained with a 0.5 mb cross section, $a = 0.3$, $b = 0.15$, and $\tau = 30$ fm/c (Par1) provide a good description of the data at mid-rapidity but slightly underestimate v_2 at forward and backward rapidity. On the other hand, the Par2 calculations with a larger cross section ($\sigma = 3$ mb) describe the data at forward and backward rapidity but significantly overestimate the v_2 at mid-rapidity. The calculations without hadron rescatterings (Par6) are lower compared to those of the Par1 results, especially at mid-rapidity, whereas the deviation is negligible at forward and backward rapidity. A similar behavior is observed in results obtained with larger Lund a and

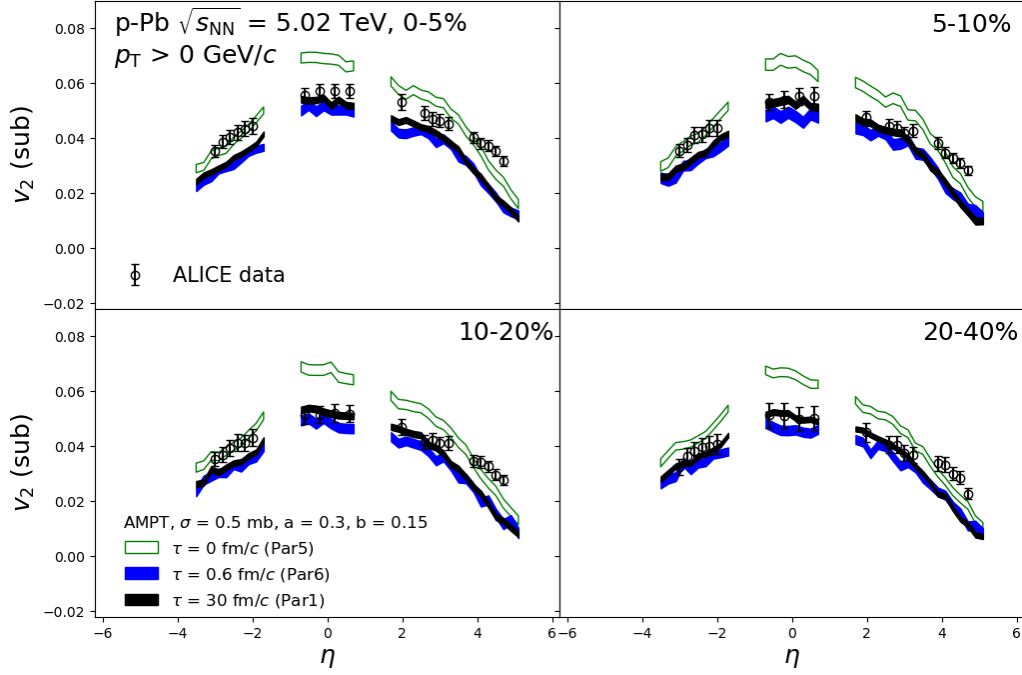
b (Par4). Furthermore, the results obtained from Par5 are significantly enhanced for all rapidity bins, indicating the effect of resonance decay on the integrated- v_2 . One can see that the results from all configurations cannot simultaneously describe the data at mid- and forward/backward-rapidity. This suggests that the rapidity dependence of parameters (*e.g.*, the initial conditions, the strength of parton interactions) must be considered in further developments of the model [75].

As defined in Eq. (9), the η -dependent $\sqrt{r_2(\eta^a, \eta^b)r_2(-\eta^a, -\eta^b)}$ in p -Pb collisions at 5.02 TeV for $3 < \eta^b < 4$ and $4.4 < \eta^b < 5.0$ are shown in Fig. 5. The results obtained from AMPT with all configurations are compared to the measurements from the CMS collaboration [42]. In order to compare with the data directly, we do not apply the nonflow subtraction here. All calculations show a larger breakdown of factorization as η^a increases, as observed in data. Similar to the findings in the p_T -dependent flow vector decorrelation, a significant breakdown of factorization is observed when the parton scattering cross section is set to 0 (Par3); however, the difference between the results of cross section $\sigma = 0.5$ mb (Par1) and $\sigma = 3$ mb (Par2) is small. Decorrelations obtained without hadronic scatterings (Par6) are consistent with Par1 calculations, suggesting that η -dependent decorrelation has no sensitivity to the hadronic scatterings. No significant effect of the resonance decay is observed for $\eta^a < 1$, whereas a slight enhancement is shown for $\eta^a > 1$ (Par1 vs Par5). On the other hand, varying the Lund parameters to $a = 0.5$ and $b = 0.9$ (Par4) lead to a smaller decorrelation for both $3 < \eta^b < 4$ and $4.4 < \eta^b < 5$ (Par4 vs Par1), which reflects the effects from initial conditions. In general, the model calculations with all tunings, except for $\sigma = 0$, provide a fair description of the data for $4.4 < \eta^b < 5.0$; however, they systematically overestimate the deviation from unity of decorrelations for $3 < \eta^b < 4$ and $\eta^a > 1$.

Figure 6 shows the $\sqrt{r_2(\eta^a, \eta^b)r_2(-\eta^a, -\eta^b)}$ as a function of η^a in 0–20%, 20%–40%, and 40%–60% centrality classes before and after nonflow subtraction. The template fit method described in Eq. (10) is applied for the calculations of Eq. (8) and Eq. (9), where the contribution from the long-range jet correlations is suppressed. After subtraction, the decorrelation decreases significantly across all three centrality classes, approaching unity. This indicates that the η -dependent flow vector decorrelation in p -Pb collisions is strongly influenced by nonflow effects (*e.g.*, dijets). This is consistent with findings in recent measurements in smaller pp collisions performed by the ATLAS collaboration [57]. On the other hand, the difference between the results before and after the nonflow subtraction becomes larger with increasing centrality. Especially in the 40%–60% centrality class, the tendency of the decorrelation completely changes after nonflow subtraction, first increasing then decreasing.



(a) The AMPT calculations are performed with different cross sections σ of parton scatterings and Lund parameters a and b .



(b) The AMPT calculations are performed with different cutoff time τ .

Fig. 4. (color online) v_2 as a function of pseudorapidity η in different centrality ranges obtained from the AMPT model with various configurations. ALICE data points [54] are shown as black open circles for comparison.

ing with an increasing η^a . It is worth noting that such an effect from the long-range jet correlations is negligible for the p_T -dependent decorrelation at mid-rapidity ($|\eta| < 0.8$), as shown in Fig. 1. This is because the contribution from long-range jet correlations to the v_2 is more

significant at forward/backward rapidity compared to mid-rapidity in small collision systems [83]. This hints at the important role of the subtraction of long-range jet correlations in the calculations of longitudinal fluctuations of the flow vector in the small collision systems. More

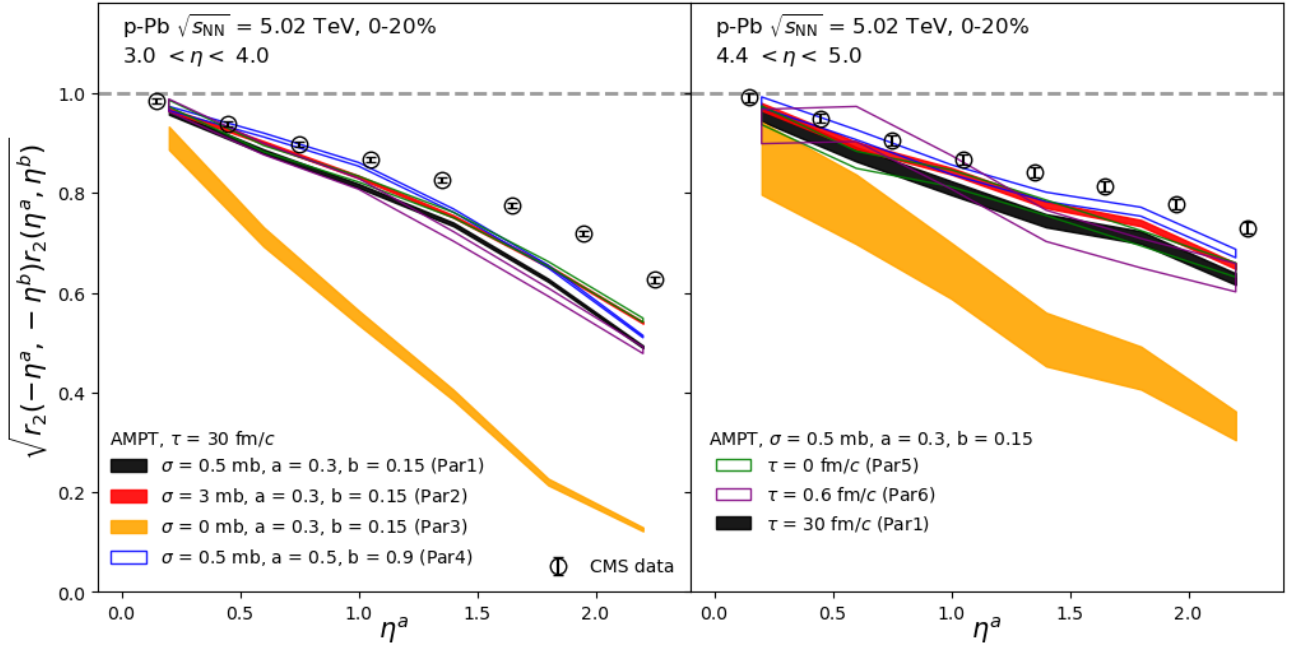


Fig. 5. (color online) Square root of the product of factorization ratios $\sqrt{r_2(\eta^a, \eta^b)r_2(-\eta^a, -\eta^b)}$ as a function of η^a for $3.0 < \eta^b < 4.0$ (left) and $4.4 < \eta^b < 5.0$ (right) in the 0–20% centrality class of p –Pb collisions at 5.02 TeV obtained from the AMPT model with various tunings. The CMS data points [42] are shown as black open circles for comparison.

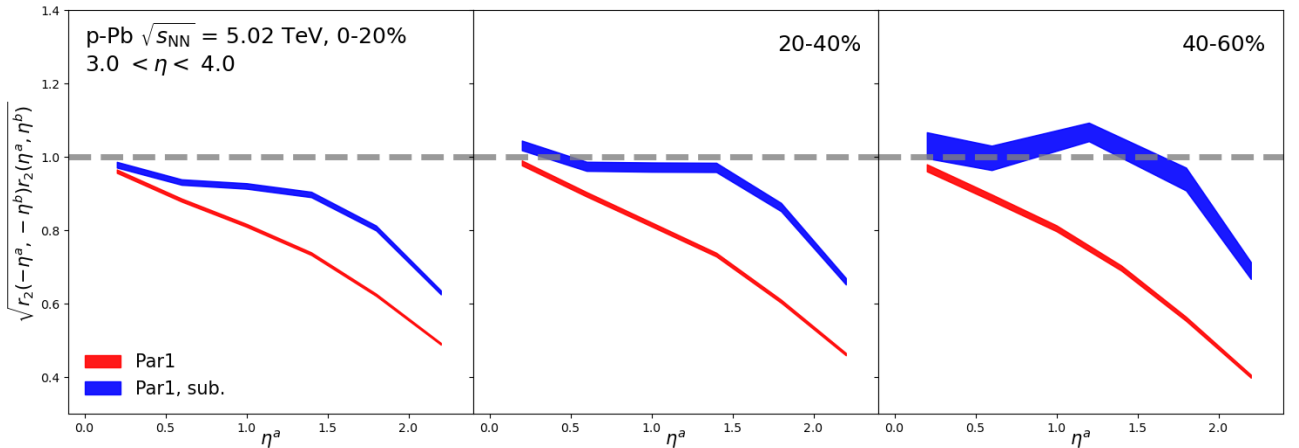


Fig. 6. (color online) Comparison of the $\sqrt{r_2(\eta^a, \eta^b)r_2(-\eta^a, -\eta^b)}$ as a function of η^a for $3.0 < \eta^b < 4.0$ in p –Pb collisions at 5.02 TeV between before and after nonflow subtraction. The results in 0–20% (left), 20–40% (middle), and 40–60% (right) centrality classes are all shown.

measurements of the flow vector decorrelation in p –Pb collisions with a proper long-range jet contribution subtraction are required in the future.

V. SUMMARY

The p_T - and η -dependent decorrelation of the flow vector in p –Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are systematically studied with the AMPT model in this paper. The sensitivity of the decorrelations to the initial conditions, partonic scatterings, and hadronic rescatterings are probed by varying the configurations of the model. It is found

that the observables are driven by the partonic scatterings and initial conditions together; however, they have a weak dependence on the hadronic rescattering. This suggests that the event-by-event fluctuations of the initial state lead to the fluctuations of the flow vector observed in the final state through the parton interactions. These results point to the possibility for employing flow vector decorrelation for investigating the transport properties of the hot and dense medium likely formed in small collision systems. Furthermore, we demonstrate that long-range jet correlations significantly affect the longitudinal decorrelation in p –Pb collisions. It provides further in-

sights in understanding the fluctuations of the flow vector in small collision systems and has referential value for future measurements.

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