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Observation of flow angle and flow magnitude fluctuations in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV at the CERN Large Hadron Collider

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Abstract

This Letter reports on the first measurements of transverse momentum dependent flow angle Ψ_n and flow magnitude v_n fluctuations, determined using new four-particle correlators. The measurements are performed for various centralities in Pb–Pb collisions at a centre-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV with ALICE at the CERN Large Hadron Collider. Both flow angle and flow magnitude fluctuations are observed in the presented centrality ranges and are strongest in the most central collisions and for a transverse momentum $p_{\mathrm{T}} > 2$ GeV/c. Comparison with theoretical models, including iEBE-VISHNU, MUSIC, and AMPT, show that the measurements exhibit unique sensitivities to the initial state of heavy-ion collisions.

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*See Appendix A for the list of collaboration members

In ultrarelativistic collisions of heavy ions, such as those at the BNL Relativistic Heavy-Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC), a deconfined state of strongly interacting matter, commonly referred to as quark–gluon plasma (QGP), is predicted to be created under extreme conditions of temperature and energy densities [1, 2]. Many experimental results indicate that a strongly-coupled QGP is formed in heavy-ion collisions [3–7]. Initial anisotropies of the geometric overlap of the colliding nuclei and spatial inhomogeneities in the energy density drive the collective expansion of the QGP and are transformed through the evolution of the QGP into a momentum anisotropy in the final state [8–10]. This momentum anisotropy is characterised by a Fourier expansion of the distribution of the azimuthal angle, φ, of emitted particles [11]

$$\frac{\mathrm{d}^2N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\varphi} = \frac{\mathrm{d}N}{2\pi\mathrm{d}p_{\mathrm{T}}}\left(1+2\sum_{n=1}^{\infty} v_n(p_{\mathrm{T}})\cos[n(\varphi-\Psi_n(p_{\mathrm{T}}))]\right), \quad (1)$$

where $v_n(p_{\mathrm{T}})$ and $\Psi_n(p_{\mathrm{T}})$ correspond to the magnitude and angle, respectively, of the n^{th}-order harmonic flow vector $\vec{V}_n(p_{\mathrm{T}}) = v_n(p_{\mathrm{T}})e^{in\Psi_n(p_{\mathrm{T}})}$. Here the transverse momentum, p_{T}, dependence of both the flow magnitude and flow angle has been made explicit. The flow vector quantifies the orientation and magnitude of the anisotropic flow, and the flow angle Ψ_n is the angle of the symmetry plane of the n^{th}-order flow vector.

Typically, the largest flow coefficient is the elliptic flow v_2, since it is largely determined by the geometrical overlap of the colliding nuclei. However, fluctuations in the position of the colliding nuclei and in the position of nucleons within the nuclei can induce more complex geometrical shapes, which will give rise to non-zero flow coefficients with $n > 2$ [12–15], such as the triangular flow v_3. Both elliptic and triangular flow coefficients have been measured extensively at RHIC [16–19] and the LHC [20–31]. The comparison to hydrodynamical calculations can constrain the initial conditions of the heavy-ion collisions and the transport properties of the QGP, such as the specific shear viscosity η/s. These comparisons indicate that the system behaves as a strongly-coupled low-viscosity fluid [10, 32–35].

Fluctuations of the flow angle Ψ_n and the flow magnitude v_n have been shown to be present in hydrodynamical models [36, 37]. These fluctuations are possibly due to thermal hydrodynamic fluctuations during the QGP evolution [38]. The *flow angle fluctuations* (FAF) are the fluctuations of $\Psi_n(p_{\mathrm{T}})$ determined by a subset of particles at a specific p_{T} with respect to the symmetry plane determined by the total set of particles, Ψ_n. If such fluctuations are present, $\Psi_n(p_{\mathrm{T}}) \neq \Psi_n$. The *flow magnitude fluctuations* (FMF) of the v_n at different p_{T} can be understood as a decorrelation where $\langle v_n(p_{\mathrm{T}})v_n\rangle \neq \sqrt{\langle v_n^2(p_{\mathrm{T}})\rangle\langle v_n^2\rangle}$.

The determination of QGP properties, such as η/s, rely on the comparison of theoretical model calculations to experimental data. In order to provide an unbiased extraction of the QGP properties, the models should account for the fluctuations in the flow angle and flow magnitude. Measurements at the LHC have reported the existence of p_{T}-dependent flow vector fluctuations [39–42]. However, those measurements rely on observables constructed from two-particle correlations, which intrinsically contain contributions from both the FAF and FMF with no way to separate the two experimentally.

In this Letter the FAF and FMF are measured with two new four-particle correlation functions to separate the components of the p_{T}-dependent fluctuations of the flow vector.

The FAF is quantified by

$$A_n^{\mathrm{f}} = \frac{\langle\langle\cos n[\varphi_1^{\mathrm{POI}}+\varphi_2^{\mathrm{POI}}-\varphi_3-\varphi_4]\rangle\rangle}{\langle\langle\cos n[\varphi_1^{\mathrm{POI}}+\varphi_2-\varphi_3^{\mathrm{POI}}-\varphi_4]\rangle\rangle} = \frac{\langle v_n^2(p_{\mathrm{T}})\, v_n^2\cos 2n[\Psi_n(p_{\mathrm{T}})-\Psi_n]\rangle}{\langle v_n^2(p_{\mathrm{T}})v_n^2\rangle}$$
$$\simeq \langle\cos 2n\,[\Psi_n(p_{\mathrm{T}})-\Psi_n]\rangle_{\mathrm{w}}, \quad (2)$$

where the POI superscript refers to particles of interest selected from a narrow transverse momentum range and the w subscript means that A_n^{f} is averaged over the event ensemble with each event having a weight equal to the fourth power of v_n [43]. The double brackets refer to an average over all particles and all events, and the single brackets refer to an average over all events. A value of $A_n^{\rm f} < 1$ indicates the presence of $p_{\rm T}$-dependent FAF. A large deviation from unity suggests that the symmetry plane at a specific $p_{\rm T}^{\rm POI}$ deviates from the common symmetry plane.

The FMF are studied with

$$M_n^{\rm f} = \frac{\langle\langle \cos n[\varphi_1^{\rm POI} + \varphi_2 - \varphi_3^{\rm POI} - \varphi_4]\rangle\rangle / \left(\langle\langle \cos n[\varphi_1^{\rm POI} - \varphi_3^{\rm a}]\rangle\rangle \langle\langle \cos n[\varphi_2 - \varphi_4]\rangle\rangle\right)}{\langle\langle \cos n[\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4]\rangle\rangle / \langle\langle \cos n[\varphi_1 - \varphi_2]\rangle\rangle^2} = \frac{\langle v_n^2(p_{\rm T}) v_n^2\rangle / \langle v_n^2(p_{\rm T})\rangle\langle v_n^2\rangle}{\langle v_n^4\rangle / \langle v_n^2\rangle^2}. \quad (3)$$

A deviation of $M_n^{\rm f}$ from unity indicates the presence of $p_{\rm T}$-dependent FMF. The magnitude of the deviation will show how strongly the flow magnitude in a specific $p_{\rm T}$ range, v_n ($p_{\rm T}$), is decorrelated with respect to the integrated flow, v_n. The correlators $A_n^{\rm f}$ and $M_n^{\rm f}$ probe higher moments of the distribution of flow fluctuations compared to correlators traditionally used previously with two-particle techniques [39–41]. The lower-order moments of the FAF and FMF cannot be measured separately in experiments [36, 44] but can be approximated by constructing the lower and upper limits of the first moment of flow angle and magnitude fluctuations, respectively. The lower limit of the first-moment FAF $\langle \cos n\,[\Psi_n(p_{\rm T}) - \Psi_n]\rangle$ is calculated with a double angle formula as

$$\sqrt{\frac{A_n^{\rm f} + 1}{2}} \geq \langle \cos n[\Psi_n(p_{\rm T}) - \Psi_n]\rangle. \quad (4)$$

The flow vector fluctuations are calculated as the ratio of the $p_{\rm T}$-differential flow coefficient, defined as

$$v_n\{2\} = \frac{\langle\langle \cos n[\varphi_1^{\rm POI} - \varphi_2]\rangle\rangle}{\langle\langle \cos n[\varphi_1 - \varphi_2]\rangle\rangle} = \frac{\langle v_n(p_{\rm T}) v_n \cos n[\Psi_n(p_{\rm T}) - \Psi_n]\rangle}{\sqrt{\langle v_n^2\rangle}} \quad (5)$$

and the $p_{\rm T}$-integrated flow coefficient in a narrow $p_{\rm T}$ interval [36], i.e.

$$v_n[2] = \langle\langle \cos n[\varphi_1^{\rm POI} - \varphi_2^{\rm POI}]\rangle\rangle = \sqrt{\langle v_n^2(p_{\rm T})\rangle}. \quad (6)$$

The flow vector fluctuations is then given by

$$v_n\{2\}/v_n[2] = \frac{\langle v_n(p_{\rm T})\; v_n \cos n\,[\Psi_n(p_{\rm T}) - \Psi_n]\rangle}{\sqrt{\langle v_n^2(p_{\rm T})\rangle}\sqrt{\langle v_n^2\rangle}}, \quad (7)$$

which satisfies the Cauchy-Schwartz inequality for two observables X and Y, $\langle XY\rangle \leq \sqrt{\langle X^2\rangle\langle Y^2\rangle}$, as $\cos n(\Psi_n(p_{\rm T}) - \Psi_n) \leq 1$. The ratio of Eq. (4) and (7) determines the upper limit of the first-order FMF

$$\frac{v_n\{2\}/v_n[2]}{\sqrt{(A_n^{\rm f}+1)/2}} \leq \frac{\langle v_n(p_{\rm T})\; v_n\rangle}{\sqrt{\langle v_n^2(p_{\rm T})\rangle}\sqrt{\langle v_n^2\rangle}}. \quad (8)$$

The limits on the first-moment flow angle and magnitude fluctuations connect the study of the separated fluctuations with prior studies of flow vector fluctuations based on two-particle correlations [39–41]. All the above correlators are calculated with the generic framework [45, 46], which corrects the non-uniformities in the acceptance of the detector. The statistical uncertainties of these two correlators in Eqs. (2) and (3) are estimated with the bootstrap method of random sampling with replacement.

The correlators $A_2^{\rm f}$ and $M_2^{\rm f}$ are measured based on 54 million Pb–Pb collisions recorded with the ALICE experiment [47] in 2015 at a centre-of-mass energy per nucleon pair of $\sqrt{s_{\rm NN}}$ = 5.02 TeV. Experimentally, events are selected based on a minimum bias trigger achieved by requiring a coincidence of signals in the two V0 scintillator arrays, V0A with a pseudorapidity range $2.8 < \eta < 5.1$, and V0C with a pseudorapidity range $-3.7 < \eta < -1.7$. Additionally, a reconstructed primary vertex within ± 10 cm of the nominal interaction point along the beam axis is required. Events with significant pileup from out-of-bunch collisions within the Time Projection Chamber (TPC) readout time will have incorrect multiplicity and cannot be used to assess the collision properties of a given centrality class. Such pileup events are rejected based on cuts of the correlation between the number of tracks measured with different detectors. A variation of the criteria for pileup rejection is considered for the systematic uncertainties [48]. The centrality of the events is measured using information from the V0A and V0C detectors [49]. Charged particle tracks, hereafter simply called tracks, are reconstructed using the Inner Tracking System (ITS) [50] and the TPC [51]. Tracks are selected with at least 70 TPC space points out of 159 points and a χ^2 per TPC cluster less than 4 [52]. To reduce contamination from secondary particles, tracks are selected with a distance of closest approach to the primary vertex of less than 2 cm in the longitudinal direction and a p_{T}-dependent selection ranging from 0.2 cm at p_{T} = 0.2 GeV/c to 0.016 cm at p_{T} = 5 GeV/c in the transverse direction. Tracks are selected within the full TPC and ITS acceptance of $|\eta| < 0.8$. Additionally, as the regime of hard processes is not of interest in this work, the kinematic range of the tracks is restricted to $0.2 < p_{\mathrm{T}} < 5$ GeV/c, where most of the tracks originate from the thermalised medium. In order to suppress non-flow correlation contributions, such as resonance decays and jets, which are not related to collective behaviour, the subevent method is utilised to calculate the correlators. In this method the event is divided into subevents separated by a gap in pseudorapidity denoted $|\Delta\eta|$. This ensures that short-range non-flow correlations between particles from the same subevent, mostly originating from resonances, are not introduced. An η-gap of $|\Delta\eta| > 0.8$ is used for two-particle correlations and $|\Delta\eta| > 0$ for four-particle correlations in order to ensure optimal balance between the statistical precision and non-flow suppression. To further investigate the non-flow suppression, the analysis is also performed with the so-called like-sign method, where only positively or negatively charged particle tracks are considered for analysis. The difference is less than 1% compared to the measurements of A_2^{f} andM_2^{f} using all tracks. Furthermore, the analysis is repeated with increasing pseudorapidity gaps between the subevents. Pseudorapidity gaps of $|\Delta\eta| > 0$, $|\Delta\eta| > 0.4$, and $\Delta\eta| > 0.8$ are tested, and it is found that the measurements of A_2^{f} and M_2^{f} differ by less than 1%, when measured with different pseudorapidity gaps. Additional Monte Carlo studies using HIJING [53], a model that does not feature collective effects, but involves particle correlations arising from other sources, indicate that non-flow is sufficiently suppressed with the applied pseudorapidity gaps. The HIJING calculations of the four-particle correlation functions defined in Eqs. (2) and (3) show no statistically significant difference from zero. Based on the model studies, the like-sign method, and the variations of the pseudorapidity gaps, the non-flow correlation contributions are less than 1% of the measured values of A_2^{f} and M_2^{f}.

Systematic uncertainties are evaluated by varying the event and track selection criteria. The systematic uncertainty is presented for A_2^{f}, as the uncertainties are of a similar size for both observables. Since the systematic uncertainty may depend on the collision centrality and the p_{T} bin, only the largest contribution from each source is mentioned below. The systematic uncertainty associated with the event selection criteria is evaluated by varying the selection on the vertex position along the beam direction (from 10 cm to 7, 8, or 9 cm), the magnetic field polarity, and the criteria for rejecting pileup events, and is below 1%. The robustness of the centrality determination is investigated by repeating the analysis using the centrality estimated at midrapidity from hits in the Silicon Pixel Detector (SPD) instead of the V0, resulting in a negligible difference. Uncertainties related to track selection are estimated by considering different track reconstructions and track quality selection criteria. Changing the track reconstruction to include tracks without hits in the SPD leads to a variation of, at most, 1.7%. The quality of the reconstructed tracks is varied by changing the minimum number of TPC space points to 80 and 90, which leads to a difference of 1.5% on the measured correlators. Uncertainties related to the variations in the distance of closest approach in both longitudinal and transverse directions are negligible, indicating that the effect of contaminations from secondary particles on the measurements is insignificant. Finally, tightening the

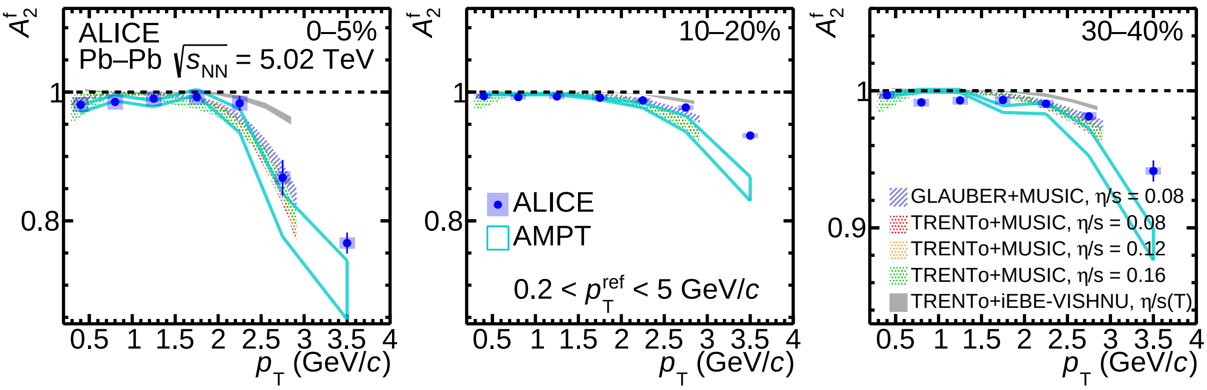

Figure 1: The flow angle fluctuation A_2^{f} in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV as a function of the transverse momentum, p_{T}, in centrality classes 0–5% (left), 10–20% (middle), and 30–40% (right). Comparison with iEBE-VISHNU with T$_{\mathrm{R}}$ENTo initial conditions and $\eta/s(T)$ [55], MUSIC with Glauber initial conditions and $\eta/s =$ 0.08 [56], MUSIC with T$_{\mathrm{R}}$ENTo initial conditions and $\eta/s = 0.08, 0.12, 0.16$ [56], and AMPT [57] are shown as coloured bands.

χ^2 per number of TPC clusters from 4 to 2.5 gives an uncertainty of, at most, 3%. The total systematic uncertainty is calculated as the quadratic sum of the individual sources that have a statistically significant contribution according to a statistical test [54].

Measured values of A_2^{f} are present in Fig. 1 as a function of the transverse momentum p_{T} in selected collision centrality classes. The results are presented from 0.2 GeV/c up to 4 GeV/c since the requirement of two particles at high p_{T} for the four-particle correlations limits the available data sample. In the 0–5% most central collisions, finite and increasing large deviations from unity are observed starting from p_{T} $\approx$ 2.5 GeV/c. As previously mentioned, this deviation cannot be attributed to non-flow effects, whose contributions are negligible. With more than 5σ significance of the deviation at $p_{\mathrm{T}} > 3$ GeV/c across the presented centralities, these measurements provide the first observation of p_{T}-dependent FAF. In centralities 10–20% and 30–40%, the fluctuation weakens in comparison to 0–5% most central collisions and reaches around 5–7% deviation from unity at $3 < p_{\mathrm{T}} < 4$ GeV/c. The increasing deviation from unity with $p_{\mathrm{T}} > 2.5$ GeV/c observed in data suggests that the elliptic flow at large transverse momentum ($p_{\mathrm{T}} > 2.5$ GeV/c) may not be correlated with the reference flow and a common symmetry plane. This will affect the comparison of measurements relying on a common symmetry plane between particles at high and low p_{T} with theoretical models that do not feature FAF.

Theoretical calculations with AMPT [57, 58], MUSIC [59, 60], and iEBE-VISHNU [61] models are, when available, compared to the data in Fig. 1. The AMPT transport model uses partonic interactions within the string melting tune, while a quark coalescence model is utilised to form hadrons, which are then transported through a hadronic cascade model [62]. The input parameters of the AMPT model are tuned to measurements of dN/dη, p_{T}-spectra and elliptic flow of charged pions, kaons and protons from ALICE [57, 63]. On the other hand, the MUSIC model is an event-by-event (3+1D) viscous hydrodynamic model and is used with both Glauber [64] and T$_{\mathrm{R}}$ENTo [65] initial conditions. Different values of η/s of 0.08, 0.12, and 0.16 are used with T$_{\mathrm{R}}$ENTo initial conditions [56]. Finally, the iEBE-VISHNU model is an event-by-event (2+1)D viscous hydrodynamical model coupled to the hadronic cascade model UrQMD [66]. This model has been successful in describing collective phenomena, as well as event-by-event fluctuations, in several collision systems and energies [55, 67]. The iEBE-VISHNU model calculations with T$_{\mathrm{R}}$ENTo initial conditions and a temperature-dependent specific shear viscosity $\eta/s(T)$ [68] are also shown. The iEBE-VISHNU model calculations are available at p_{T} ranges below 3 GeV/c.

The AMPT calculation presented here describes the data well in the 0–5% most central collisions and

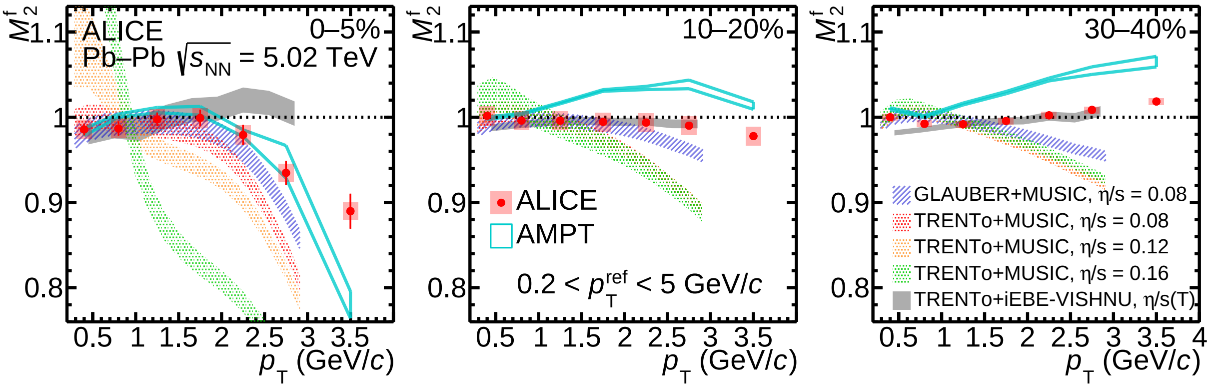

Figure 2: The flow magnitude fluctuation M_2^f in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the transverse momentum, p_T, in centrality classes 0–5% (left), 10–20% (middle), and 30–40% (right). Comparison with iEBE-VISHNU with T$_R$ENTo initial conditions and $\eta/s(T)$ [55], MUSIC with Glauber initial conditions and $\eta/s = 0.08$ [56], MUSIC with T$_R$ENTo initial conditions and $\eta/s = 0.08, 0.12, 0.16$ [56], and AMPT [57] are shown as coloured bands.

captures the deviation from unity in the highest p_T bin. At higher centralities, the AMPT calculation overestimates the deviation from unity at high p_T. The comparison of the MUSIC calculations with Glauber and T$_R$ENTo initial conditions shows that A_2^f is sensitive to the fluctuations in the initial state with little to no sensitivity to the different values of specific shear viscosity. This observation is consistent with the AMPT calculations presented in [69], where AMPT with different values of specific shear viscosity and initial conditions are compared. The iEBE-VISHNU calculation underestimates the deviation of A_2^f from unity at $p_T > 2.5$ GeV/c across the presented centralities with the largest difference in the 0–5% most central collisions. The iEBE-VISHNU model with T$_R$ENTo initial conditions uses parameters extracted from a Bayesian analysis [68] in contrast to the MUSIC models, which use standard T$_R$ENTo initial conditions with p = 0 [65]. The extracted parameters from the Bayesian analysis represent the current best understanding of the initial conditions and QGP transport properties. Including additional constraints in the Bayesian analyses, such as A_2^f, should improve our understanding of the event-by-event fluctuating initial state thus allowing for a more robust and unbiased extraction of the expansion properties of the matter formed in these collisions.

The measurements of the p_T-dependent FMF, M_2^f in centrality classes 0–5%, 10–20%, and 30–40% are shown in Fig. 2. A substantial deviation of M_2^f from unity is observed in the 0–5% most central collisions. This deviation by more than 5σ significance at $p_T > 3$ GeV/c constitutes the first observation of p_T-dependent FMF. The measurements show that the p_T-differential flow coefficients decorrelate with the p_T-integrated flow coefficient as the transverse momentum increases. In centrality 0–5%, where the initial state fluctuations are most significant, the flow magnitude deviates from unity for p_T above 2 GeV/c. Deviations increase with rising p_T and are more pronounced in the 0–5% central collisions compared to those observed in the 10–20% and 30–40% centrality ranges. M_2^f is not restricted to be below unity as seen in Fig. 2 at 30–40% centrality. The observable M_n^f is not constructed to satisfy the Cauchy-Schwarz inequality as such an observable, $\langle v_n^2(p_T) v_n^2 \rangle / \sqrt{v_n^4(p_T) v_n^4}$, would require four particles from a narrow p_T range. The flow vector fluctuations measured with two-particle correlations and the FAF measured with A_2^f, however, can only be larger than unity due to non-flow effects [37]. The non-flow studies mentioned previously show that non-flow correlations are negligible for M_2^f, so the deviation from unity must be due to the FMF.

The AMPT transport model calculation succeeds in describing the FMF in the most central collisions, where it also describes the FAF (Fig. 1 left). At higher centralities, the AMPT model significantly overestimates the data even at low p_T, but it qualitatively captures the increasing trend of M_2^f in the 30–40% centrality interval. The AMPT model works well in qualitatively describing both FAF and FMF

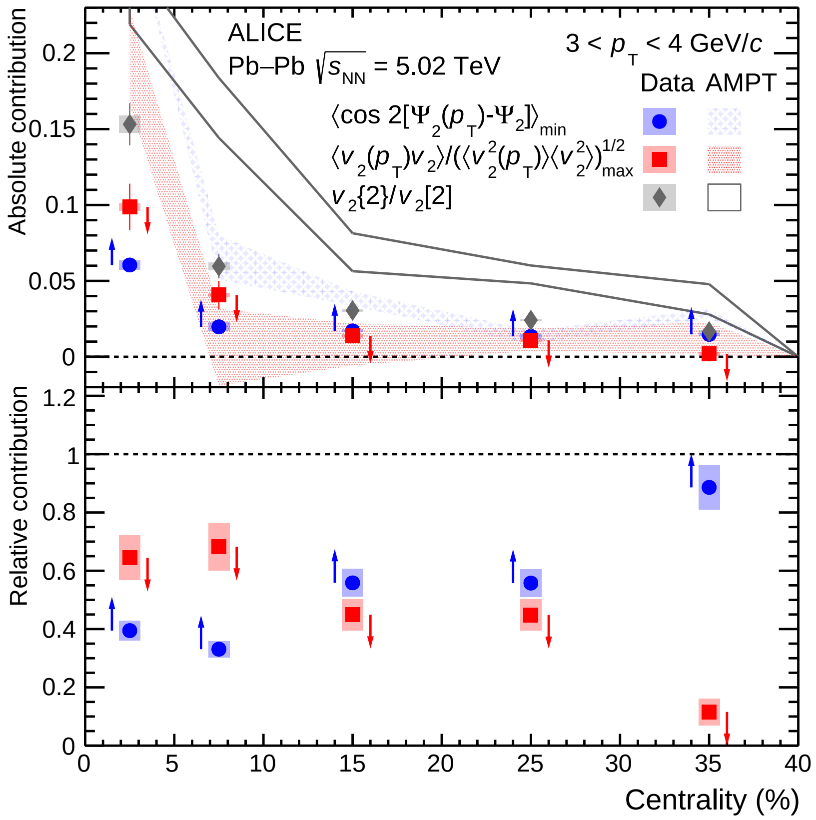

Figure 3: The lower limit of the first-order flow angle fluctuations, upper limit of the first-order flow magnitude fluctuations, and the flow vector fluctuations as a function of centrality for the $3.0 < p_T < 4.0$ GeV/c. The lower and upper limits are denoted by the arrows. The top panel shows the absolute contribution and the bottom panel the contribution relative to the overall flow vector fluctuations. Comparisons to AMPT [57] are shown as coloured bands.

without a hydrodynamic phase. This is possibly due to the fact that these effects mainly originate in the initial state. The MUSIC models show strong sensitivity to the η/s in 0–5% most central collisions as well as a sensitivity to the different initial conditions. The dependence on η/s is unexpected and in contrast to the findings in [69], where the magnitude of the flow fluctuations is found to be independent of the value of η/s. In the 10–20% and 30–40% centrality intervals, M_2^f shows no sensitivity to η/s but is still affected by the different initial conditions. The MUSIC models overestimate the deviation of M_2^f from unity in all presented centrality classes. The iEBE-VISHNU calculations underestimate the effect in 0–5% centrality showing almost no p_T dependence. In the 10–20% and 30–40% centrality intervals, the model captures the increasing trend with p_T and, consequently, describes the data. The comparison of the measurements with the above models confirms that the FMF are driven by initial state fluctuations in non-central collisions. However, the dependence of M_2^f on η/s in the 0-5% central collisions with the MUSIC model is not well understood. The large discrepancy between the iEBE-VISHNU model and the data in central collisions suggests that the FMF could be an important observable in Bayesian analyses and could contribute further improvements of the extracted parameters used in the state-of-the-art description of the initial state and the QGP transport properties.

Equations (4) and (8) allow for the determination of the lower and upper limit for the contribution of the FAF and FMF, respectively, to the flow vector fluctuations defined in Eq. (7). Thus the lower moments of the FAF and FMF, which cannot be directly accessed in experiments, can be explored. The lower limit on the first-order FAF, the upper limit on the first-order FMF, and the total flow vector fluctuations are shown as a function of centrality for the $3 < p_{\rm T} < 4$ GeV/c range in Fig. 3. In central collisions, the upper limit on the FMF is higher than the lower limit of the FAF up to 10% centrality. For the 10–30% centrality interval, the limits are similar, and above 30% centrality, the flow magnitude upper limits are much smaller, and the FAF dominate the overall flow vector fluctuations completely. This is consistent with the measurements shown in Figs. 1 and 2, where $M_2^{\rm f}$ approaches unity faster with increasing centrality than $A_2^{\rm f}$ and even goes above unity in semicentral collisions. While $p_{\rm T}$-dependent FAF and FMF are both present in central Pb–Pb collisions, the effects of FAF are present in all centralities considered in this work compared to the much smaller FMF in non-central collisions. The AMPT transport model calculations overestimate the flow vector fluctuations $v_2\{2\}/v_2[2]$ as well as the limits of the first-order FAF and FMF in the central collisions. At higher centralities, AMPT describes the lower and upper limits well, whereas the flow vector fluctuations are still overestimated by the model, as in central collisions. Hydrodynamic calculations for the limits are not available.

In summary, the $p_{\rm T}$-dependent flow angle fluctuations and flow magnitude fluctuations of the second-order flow vector $\vec{V}_2$ are measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the correlators $A_2^{\rm f}$ and $M_2^{\rm f}$ in centrality intervals 0–5%, 10–20%, and 30–40%. Large deviations from unity of both $A_2^{\rm f}$ ($\approx$20%) and $M_2^{\rm f}$ ($\approx$10%) are observed at $p_{\rm T} > 3$ GeV/c in central collisions, where the event-by-event fluctuations of the position of the colliding nucleons dominate over the geometric response. In semicentral collisions, both flow angle and flow magnitude fluctuations decrease. The flow angle fluctuations reach 5–7%, and the flow magnitude fluctuations reach around 2% and are above unity in 30–40% centrality for the presented $p_{\rm T}$ range. The flow magnitude fluctuations decrease faster than the flow angle fluctuations up to 40% centrality, where the flow vector fluctuations are almost solely due to flow angle fluctuations. The comparison of the measurements to theoretical models shows that the observables are sensitive to the initial conditions of heavy-ion collisions. This suggests that the fluctuations originate during the early stages of the QGP evolution. The observation of flow angle and flow magnitude fluctuations thus gives additional insight into the nature of event-by-event fluctuations in the initial state of heavy-ion collisions and can be used to constrain the initial conditions and QGP properties.

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