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Anisotropic flow of charged hadrons, pions and (anti-)protons measured at high transverse momentum in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV ☆

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ABSTRACT

The elliptic, v_2, triangular, v_3, and quadrangular, v_4, azimuthal anisotropic flow coefficients are measured for unidentified charged particles, pions, and (anti-)protons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the Large Hadron Collider. Results obtained with the event plane and four-particle cumulant methods are reported for the pseudo-rapidity range $|\eta| < 0.8$ at different collision centralities and as a function of transverse momentum, p_T, out to $p_T = 20$ GeV/c. The observed non-zero elliptic and triangular flow depends only weakly on transverse momentum for $p_T > 8$ GeV/c. The small p_T dependence of the difference between elliptic flow results obtained from the event plane and four-particle cumulant methods suggests a common origin of flow fluctuations up to $p_T = 8$ GeV/c. The magnitude of the (anti-)proton elliptic and triangular flow is larger than that of pions out to at least $p_T = 8$ GeV/c indicating that the particle type dependence persists out to high p_T.

The goal of ultra-relativistic nucleus–nucleus collisions is to study nuclear matter under extreme conditions. For non-central collisions, in the plane perpendicular to the beam direction, the geometrical overlap region, where the highly Lorentz contracted nuclei intersect and where the initial interactions occur, is azimuthally anisotropic. This initial spatial asymmetry is converted via interactions into an anisotropy in momentum space, a phenomenon referred to as transverse anisotropic flow (for a review see [1]). Anisotropic flow has become a key observable for the characterization of the properties and the evolution of the system created in a nucleus–nucleus collision.

Identified particle anisotropic flow provides valuable information on the particle production mechanism in different transverse momentum, p_T, regions [1]. For $p_T < 2$–3 GeV/c, the flow pattern of different particle species is qualitatively described by hydrodynamic model calculations [2]. At intermediate p_T, $3 < p_T < 6$ GeV/c, the observed flow of the baryons is larger than that of the mesons [3,4]. For $p_T \gtrsim 8$ GeV/c, the fragmentation of high-energy partons, resulting from initial hard scatterings, is expected to play the dominant role. While traversing the hot and dense matter these partons experience collisional and radiative energy loss [5,6], which are strongly dependent on the thickness of the created medium [7]. In the azimuthally asymmetric system, the energy loss depends on the azimuthal emission angle of the parton, which leads to an azimuthal anisotropy in particle production at high p_T [8,9].

The magnitude of the anisotropic flow is characterized by the coefficients in the Fourier expansion of the azimuthal distribution of particles with respect to the collision symmetry plane [10,11]:

$$v_n(p_T, \eta) = \langle \cos[n(\phi - \Psi_n)] \rangle, \quad (1)$$

where p_T, η, and ϕ are the particle's transverse momentum, pseudo-rapidity, and the azimuthal angle, respectively, and Ψ_n is the n-th harmonic symmetry plane angle. For a smooth matter distribution in the colliding nuclei, the symmetry planes of all harmonics coincide with the reaction plane defined by the beam direction and the impact parameter, the vector connecting the centers of the two colliding nuclei at closest approach. In this case, for particles produced at midrapidity, all odd Fourier coefficients are zero by symmetry. Due to event-by-event fluctuations of the positions of the participating nucleons inside the nuclei, the shape of the initial energy density of the heavy-ion collision in general is not symmetric with respect to the reaction plane, and the Ψ_n may deviate from the reaction plane. This gives rise to non-zero odd harmonic coefficients [12–18], and contributes to the difference in flow coefficients calculated from two- or multi-particle azimuthal correlations, and also to the difference in v_n measured with respect to different harmonic symmetry planes.

Large elliptic flow, v_2, and significant triangular flow, v_3, were observed at the Relativistic Heavy Ion Collider (RHIC) [19–21] and at the Large Hadron Collider (LHC) [22–28]. In this Letter we present the measurement of unidentified charged particle anisotropic flow out to $p_T = 20$ GeV/c, and for protons and

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charged pions[1] out to $p_T = 16$ GeV/c. We also present unidentified charged particle quadrangular flow, v_4, measured with respect to the second (Ψ_2) and fourth (Ψ_4) harmonic symmetry planes.

The data sample recorded by ALICE during the 2010 heavy-ion run at the LHC is used for this analysis. Detailed descriptions of the ALICE detector can be found in [29–31]. The Time Projection Chamber (TPC) was used to reconstruct charged particle tracks and measure their momenta with full azimuthal coverage in the pseudo-rapidity range $|\eta| < 0.8$, and for particle identification via the specific ionization energy loss, dE/dx, in the transverse momentum region $p_T > 3$ GeV/c. Two scintillator arrays (VZERO) which cover the pseudo-rapidity ranges $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$ were used for triggering, and the determination of centrality [32] and symmetry planes. The trigger conditions and the event selection criteria are identical to those described in [22,23,32]. Approximately 10^7 minimum-bias Pb–Pb events with a reconstructed primary vertex within ± 10 cm from the nominal interaction point in the beam direction are used for this analysis. Charged particles reconstructed in the TPC in $|\eta| < 0.8$ and $0.2 < p_T < 20$ GeV/c were selected. The charged track quality cuts described in [22] were applied to minimize contamination from secondary charged particles and fake tracks. The charged particle track reconstruction efficiency and contamination were estimated from HIJING Monte Carlo simulations [33] combined with a GEANT3 [34] detector model, and found to be independent of the collision centrality. The reconstruction efficiency, which may bias the determination of the p_T averaged flow, increases from 70% to 80% for particles with $0.2 < p_T < 1$ GeV/c and remains constant at 80 ± 5% for $p_T > 1$ GeV/c. The estimated contamination by secondary charged particles from weak decays and photon conversions is less than 6% at $p_T = 0.2$ GeV/c and falls below 1% for $p_T > 1$ GeV/c.

The selection of pions and protons at $p_T > 3$ GeV/c is based on the measurement of the dE/dx in the TPC, following the procedure described in [35]. Enriched pion (proton) samples are obtained by selecting tracks from the upper (lower) part of the expected pion (proton) dE/dx distribution. For example, protons were typically selected, depending on their momentum, in the range from 0 to -3σ or from -1.5σ to -4.5σ around their nominal value in dE/dx, where σ is the energy loss resolution. Note that dE/dx of pions is larger than that of protons in the p_T range used for this study. The track selection criteria have been adjusted to keep the contamination by other particle species below 1% for pions and below 15% for protons. The pion and proton v_2 and v_3 are not corrected for this contamination. The systematic uncertainties in v_2 and v_3 related to the purity of the pion and proton samples are 2% for $p_T < 8$ GeV/c and 10% for $p_T \geqslant 8$ GeV/c.

The flow coefficients v_n are measured using the event plane method ($v_n\{\mathrm{EP}\}$ [1]) and the four-particle cumulant technique ($v_n\{4\}$ [36]), which have different sensitivity to flow fluctuations and correlations unrelated to the azimuthal asymmetry in the initial geometry ("non-flow"). The non-flow contribution to $v_n\{4\}$ is estimated to be negligible from analytic calculations and Monte Carlo simulations [37–39]. The contribution from flow fluctuations was shown to be negative for $v_n\{4\}$ and positive for $v_n\{\mathrm{EP}\}$ [1].

The orientation of the symmetry planes Ψ_n is estimated with the event plane angle determined from the azimuthal distribution of hits measured by the VZERO scintillators. The corresponding event plane resolution is estimated from correlations between event planes determined in the TPC and the two VZERO detectors. The large gap in pseudo-rapidity between the charged particles in the TPC and those in the VZERO detectors greatly suppresses non-flow contributions, which largely come from the inter-jet correlations and resonance decays and are narrow in rapidity. An estimate of the remaining non-flow contributions is obtained by rescaling the correlation measured in pp collisions under the assumption that it scales inversely proportional to the total multiplicity. It was observed that the two-particle azimuthal correlations in pp and the most peripheral Au–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV are very similar [40], which suggests that non-flow dominates correlations in the centrality range 80–90%. The systematic uncertainty from the remaining non-flow, δ_n^{cent}, in the measured $v_n\{\mathrm{EP}\}$ coefficients was estimated based on the equation:

$$\delta_n^{\mathrm{cent}} = v_n^{80\text{–}90\%} \sqrt{\frac{M^{80\text{–}90\%}}{M^{\mathrm{cent}}}}, \tag{2}$$

where $v_n^{80\text{–}90\%}$ and $M^{80\text{–}90\%}$ are the magnitude of v_n and average multiplicity for the centrality range 80–90%, respectively, and M^{cent} is the average multiplicity in a given centrality class. The non-flow increases with p_T and from central to peripheral collisions. For example, the non-flow contributions to v_2 in 5–10% (40–50%) most central collisions are about 1% (2%) at $p_T = 1$ GeV/c and reach up to 10% (12%) for $p_T > 10$ GeV/c. Other sources of systematic uncertainties were evaluated from the variation of the results with different cuts on the reconstructed collision vertex and the centrality estimated from the charged particle multiplicity measured in the TPC and VZERO detectors. Changes due to variations of the track selection criteria and the difference of the results obtained using only positively or negatively charged particles were considered as a part of the systematic error. The difference in the extracted coefficients using one or the other of the two VZERO detectors was found to be below 1% for v_2 and v_3, and below 5% for v_4 over the measured region of transverse momentum. The combined results from correlations with both VZERO detectors are denoted as $v_n\{\mathrm{EP}, |\Delta\eta| > 2.0\}$ in the following. The contributions from all sources were added in quadrature as an estimate of the total systematic uncertainty. The resulting systematic uncertainties in v_2 are 3% for $0.9 < p_T < 1$ GeV/c and $^{+3}_{-11}$% ($^{+3}_{-12}$%) for $9 < p_T < 10$ GeV/c in the 5–10% (40–50%) centrality class. The resulting systematic uncertainties in v_3 are 3% for $0.9 < p_T < 1$ GeV/c and increase to 6% (10%) for $7 < p_T < 9$ GeV/c for centrality 5–10% (40–50%). We assign an 8% (16%) systematic uncertainty to v_4 for $0.9 < p_T < 1$ GeV/c in the 5–10% (40–50%) centrality class, while for $p_T > 6$ GeV/c the systematic uncertainty is dominated by non-flow contributions.

Fig. 1 shows unidentified charged particle v_2, v_3, and v_4 as a function of transverse momentum for different centrality classes. The difference between $v_2\{\mathrm{EP}\}$ and $v_2\{4\}$ for $p_T < 7$ GeV/c is predominantly due to flow fluctuations. The measured v_2 at $p_T > 8$ GeV/c is non-zero, positive and approximately constant, while its value increases from central to mid-peripheral collisions. In the 20–50% centrality range, the observed $v_2\{\mathrm{EP}\}$ at $p_T > 10$ GeV/c is fairly well described by extrapolation to the LHC energy [41] of the WHDG model calculations [42] for v_2 of neutral pions including collisional and radiative energy loss of partons in a Bjorken-expanding medium [43]. The coefficient v_3 exhibits a weak centrality dependence with a magnitude significantly smaller than that of v_2, except for the most central collisions. Unlike v_3, which originates entirely from fluctuations of the initial geometry of the system, v_4 has two contributions, which are probed by correlations with the Ψ_2 and Ψ_4 symmetry planes. The measured $v_{4/\Psi_4}\{\mathrm{EP}\}$ does not depend strongly on the collision centrality which points to a strong contribution from flow fluctuations. In contrast, $v_{4/\Psi_2}\{\mathrm{EP}\}$ shows a strong centrality dependence which is typical for correlations with respect to the true reaction

[1] In this analysis we do not differentiate between particle and antiparticle.

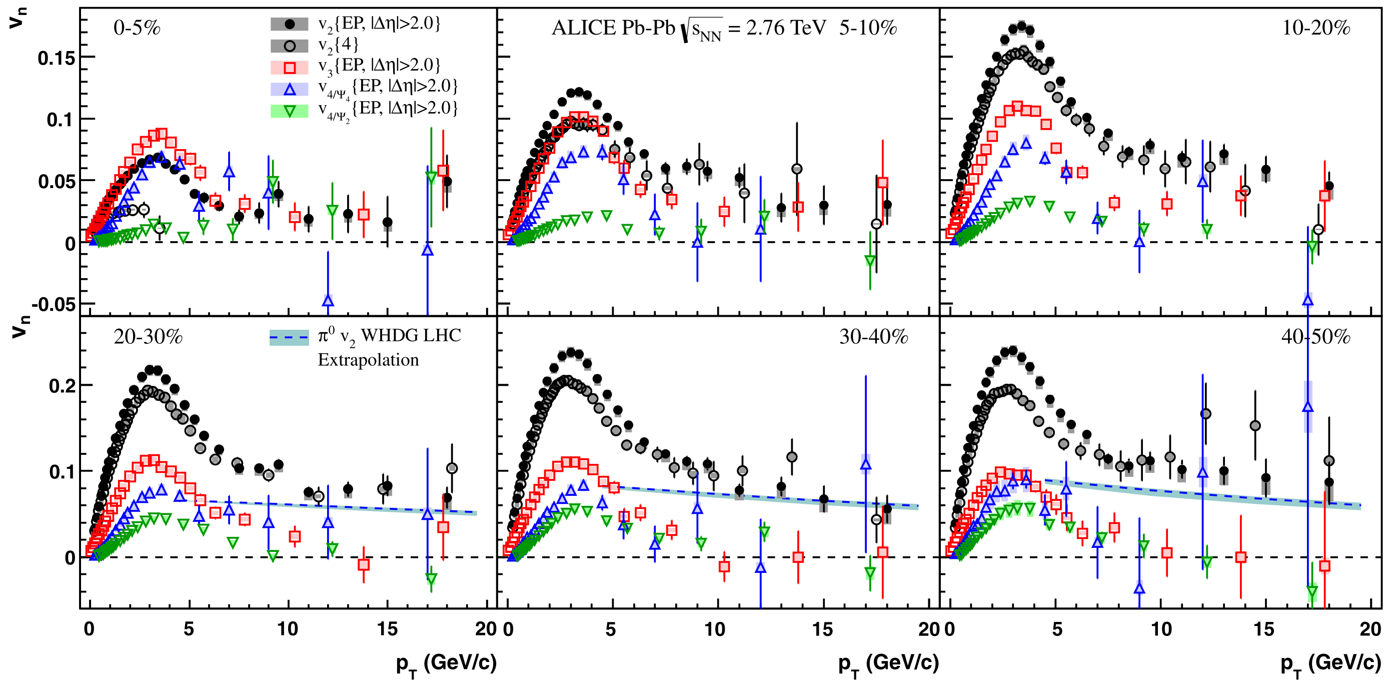

Fig. 1. (Color online.) v_2, v_3, and v_4 measured for unidentified charged particles as a function of transverse momentum for various centrality classes. The dashed line represents the WHDG model calculations for neutral pions v_2 [43] extrapolated to the LHC collision energy. For clarity, the markers for v_3 and v_{4/Ψ_2} results are slightly shifted along the horizontal axis. Note that the highest p_T data point for v_{4/Ψ_4} in 5–10% centrality is out of the plotting range. Error bars (shaded boxes) represent the statistical (systematic) uncertainties.

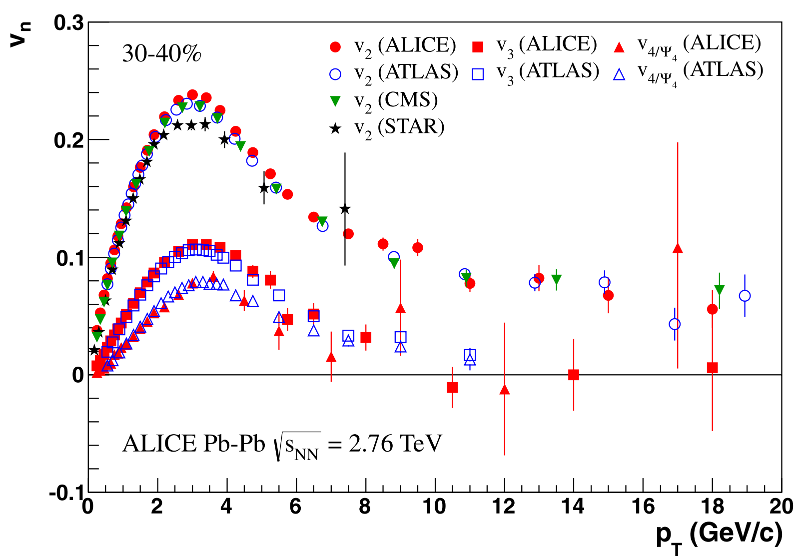

Fig. 2. (Color online.) Comparison of the ALICE results on $v_n(p_T)$ obtained with the event plane method to the analogous measurements from ATLAS [26] and CMS [27] collaborations, as well as v_2 measurements by STAR [44]. Only statistical errors are shown.

plane. The difference between the two, indicative of flow fluctuations, persists at least up to $p_T = 8$ GeV/c.

Fig. 2 compares our results obtained with the event plane method for 30–40% centrality to the analogous measurements by ATLAS [26] and CMS [27] collaborations, and results obtained at RHIC by the STAR Collaboration [44]. An excellent agreement is observed between results from all three LHC experiments. $v_2(p_T)$ at top RHIC energy has a peak value about 10% lower than at LHC although it is very similar in shape.

To investigate further the role of flow fluctuations at different transverse momenta we study the relative difference between $v_2\{\mathrm{EP}\}$ and $v_2\{4\}$, $[(v_2\{\mathrm{EP}\}^2 - v_2\{4\}^2)/(v_2\{\mathrm{EP}\}^2 + v_2\{4\}^2)]^{1/2}$, which for small non-flow is proportional to the relative flow fluctuations $\sigma_{v_2}/\langle v_2\rangle$ [1]. Fig. 3 presents this quantity as a function of transverse momentum for various centrality classes. The relative flow fluctuations are minimal for mid-central collisions and become larger for peripheral and central collisions, similar to those observed at RHIC energies [1]. It is remarkable that in the 5–30% centrality range, relative flow fluctuations are within errors independent of momentum up to $p_T \sim 8$ GeV/c, far beyond the region where the flow magnitude is well described by hydrodynamic models ($p_T < 2$–3 GeV/c). This indicates a common origin for flow fluctuations, which are usually associated with fluctuations of the initial collision geometry, at least up to the regime where hard scattering and jet energy loss are expected to dominate. The ratio develops a momentum dependence, starting to

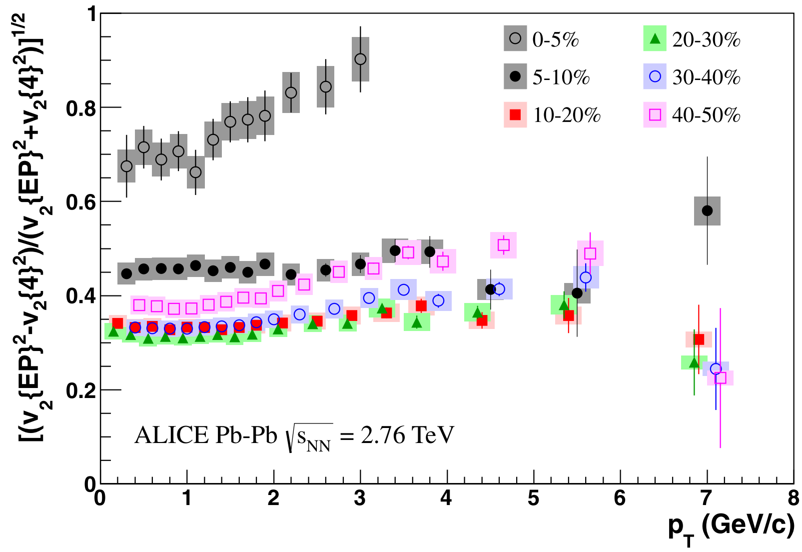

Fig. 3. (Color online.) Relative event-by-event elliptic flow fluctuations for unidentified charged particles versus transverse momentum for different centrality classes. For clarity, the markers for centrality classes $\geqslant 10\%$ are slightly shifted along the horizontal axis. Error bars (shaded boxes) represent the statistical (systematic) uncertainties.

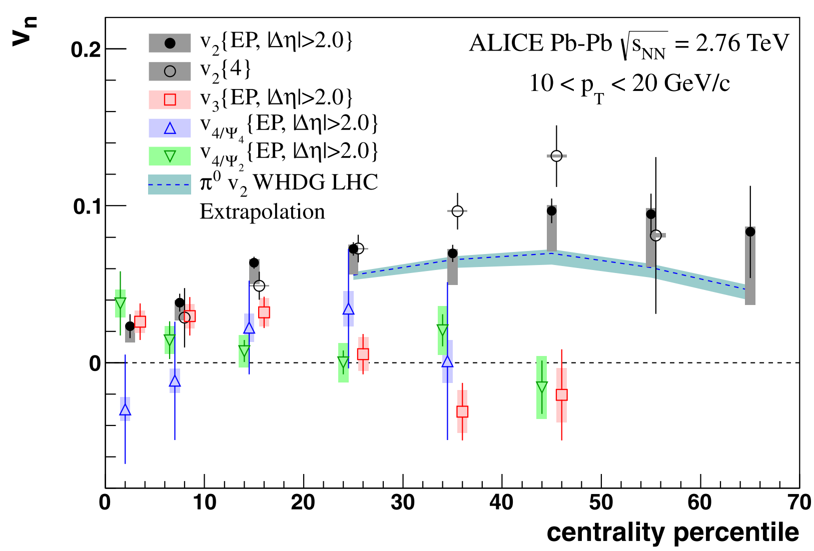

Fig. 4. (Color online.) Unidentified charged particle v_2, v_3, and v_4 integrated over the transverse momentum range $10 < p_T < 20$ GeV/c as a function of collision centrality, with the more central (peripheral) collisions shown on the left-(right-)hand side, respectively. The dashed line represents the WHDG model calculations for neutral pions [43] extrapolated to the LHC collision energy. Error bars (shaded boxes) represent the statistical (systematic) uncertainties.

increase at $p_T \sim 1.5$ GeV/c, for more peripheral collisions (30–50%), and in most central collisions (0–5%), where it is most pronounced. In both cases, the relative contribution of non-flow effects is expected to be the largest.

Fig. 4 shows unidentified charged particle v_2, v_3, and v_4 averaged over $10 < p_T < 20$ GeV/c as a function of centrality. v_2 increases from central to peripheral collisions. No significant difference between $v_2\{EP\}$ and $v_2\{4\}$ results is observed, which might indicate that the fluctuations of the initial collision geometry become unimportant for $p_T > 10$ GeV/c. The centrality dependence of v_3 differs significantly from that of v_2. v_4 measured with respect to the second and fourth harmonic symmetry planes is consistent with zero within relatively large uncertainties. All these observations indicate that for $p_T > 10$ GeV/c the effect of fluctuations of the initial collision geometry on the final momentum anisotropy might be very different compared to that at low and intermediate p_T.

Fig. 5 presents charged pion and proton v_2 and v_3 as a function of p_T in the 10–50% centrality range from the event plane method. The proton v_2 and v_3 are higher than that of pions out to $p_T = 8$ GeV/c where the uncertainties become large. This behavior is qualitatively consistent with a picture where particle production in this intermediate p_T region includes interaction of jet fragments with bulk matter, e.g. as in model [45]. The magnitude of the measured charged pion elliptic flow for $p_T > 8$ GeV/c is compatible with that for unidentified charged particles, and π^0 measured by PHENIX [46] in Au–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV, and reproduced by the WHDG model calculations for v_2 of neutral pions [43]. The unidentified charged particle, pion, and proton v_3 are the same within uncertainties for $p_T > 8$ GeV/c.

In summary, we have presented elliptic, triangular, and quadrangular flow coefficients measured by the ALICE Collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV over a broad range of

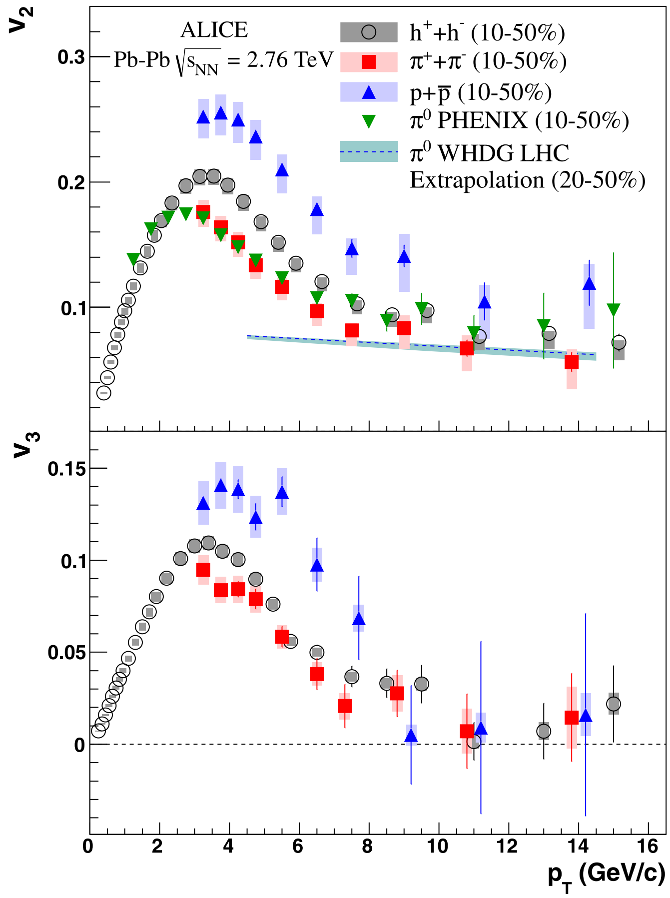

Fig. 5. (Color online.) v_2 (top) and v_3 (bottom) of charged pion and proton as a function of transverse momentum for 10–50% centrality class compared to unidentified charged particles results from the event plane method. For clarity, the markers for v_2 and v_3 at $p_T > 8$ GeV/c are slightly shifted along the horizontal axis. PHENIX π^0 v_2 measurements [46] are also shown. The dashed line represents the WHDG model calculations for neutral pions [43] extrapolated to the LHC collision energy for the 20–50% centrality range. Error bars (shaded boxes) represent the statistical (systematic) uncertainties.

transverse momentum. For $p_T > 8$ GeV/c, we find that the unidentified charged particle v_2 in 0–70% and v_3 in 0–20% centrality ranges are finite, positive and only weakly dependent on transverse momentum, while v_3 for 20–50% and v_4 for 5–50% centrality are consistent with zero within rather large statistical and systematic uncertainties. The observed difference in the centrality dependence of v_{4/Ψ_4} and v_{4/Ψ_2}, and the results on v_2 obtained with the event plane and four-particle cumulant methods indicate that the effect of flow fluctuations extends at least up to $p_T = 8$ GeV/c and does not change significantly in magnitude, except for very central collisions. It shows that the effect of fluctuations of the initial collision geometry on particle production is similar at low and intermediate p_T regions, which are considered to be dominated by hydrodynamical flow and quark coalescence, respectively. For $p_T > 10$ GeV/c, where particle production is dominated by fragmentation of hard partons, the response to fluctuations of the initial collision geometry might be different, but more data is needed to study this regime in more detail. The pion v_2 at LHC energies is very close to that measured at RHIC out to $p_T = 16$ GeV/c and is reproduced by WHDG model calculations for $p_T > 8$ GeV/c. The proton v_2 and v_3 are finite, positive, and have a larger magnitude than that of the pion for $p_T < 8$ GeV/c, indicating that the particle type dependence, which is typical at low p_T, persists out to intermediate transverse momenta. The pion and proton v_3 are consistent with zero within uncertainties for $p_T > 8$ GeV/c.

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