Azimuthal Anisotropy of Charged Particles at High Transverse Momenta in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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The azimuthal anisotropy of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is measured with the CMS detector at the LHC over an extended transverse momentum (p_T) range up to approximately 60 GeV/c. The data cover both the low-p_T region associated with hydrodynamic flow phenomena and the high-p_T region where the anisotropies may reflect the path-length dependence of parton energy loss in the created medium. The anisotropy parameter (v_2) of the particles is extracted by correlating charged tracks with respect to the event-plane reconstructed by using the energy deposited in forward-angle calorimeters. For the six bins of collision centrality studied, spanning the range of 0–60% most-central events, the observed v_2 values are found to first increase with p_T, reaching a maximum around $p_T = 3$ GeV/c, and then to gradually decrease to almost zero, with the decline persisting up to at least $p_T = 40$ GeV/c over the full centrality range measured.

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The experiments at the Relativistic Heavy Ion Collider have provided evidence for the formation of a strongly coupled quantum chromodynamics (QCD) state of matter in ultrarelativistic nucleus-nucleus interactions [1–4]. The opaqueness of this matter to high-energy partons leads to a "jet-quenching" phenomenon where the final-state particle yield at high transverse momentum (p_T) is found to be suppressed compared to that expected from the scaling of pp collision yields [1–6]. A large energy loss for partons traversing the dense QCD medium is also suggested by the recent observation of a large momentum imbalance of reconstructed back-to-back jets [7–9] in Pb-Pb collisions at the Large Hadron Collider (LHC).

Despite the progress made on the theoretical description of jet quenching in the past decade [10], some of its key properties, such as the detailed path-length dependence of parton energy loss, remain unknown. In addition to measurements of hadron-yield suppression, observables such as the azimuthal anisotropy of high-p_T hadrons are needed to differentiate between the theoretical approaches [11–16]. The anisotropy can be characterized by the second-order Fourier harmonic coefficient (v_2) in the azimuthal angle (ϕ) distribution of the hadron yield, $dN/d\phi \propto 1 + 2v_2 \cos[2(\phi - \Psi_{PP})]$, where Ψ_{PP} is the event-by-event azimuthal angle of the "participant plane." In a noncentral heavy-ion collision, the overlap region of the two colliding nuclei has a lenticular shape, and the interacting nucleons in this region are known as "participants." The participant plane is defined by the beam direction and the short direction of the lenticular region. In general, the participant plane will not contain the reaction impact parameter vector because of fluctuations that arise from having a finite number of nucleons. For high-p_T particles, an azimuthal anisotropy can be induced if there is stronger suppression of the hadron yield along the long axis than the short axis of the overlap region. The importance of jet-quenching measurements taking into account the jet orientation relative to the geometry of the interaction region was first demonstrated by the PHENIX experiment [17], where the azimuthal anisotropy of high-p_T neutral pions (π^0) was studied up to $p_T \approx$ 18 GeV/c in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV.

This Letter presents a study of the azimuthal anisotropy extended to very high p_T (up to $p_T \approx 60$ GeV/c) for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC using the Compact Muon Solenoid (CMS) detector. The v_2 coefficient is determined as a function of charged particle p_T and overlap of the colliding nuclei (centrality) in the pseudorapidity regions of $|\eta| < 1$ and $1 < |\eta| < 2$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the counterclockwise beam direction. In the low momentum region (below a few GeV/c), v_2 is generally associated with hydrodynamic flow [18], as distinct from the jet energy-loss mechanism believed to dominate at high p_T (e.g., above 10 GeV/c). By using a single-track high-level trigger, a significantly larger event sample of high-p_T tracks than previously available is obtained, providing the first precise measurement of the v_2 coefficient above 20 GeV/c in heavy-ion collisions. Our results may impose quantitative constraints on models of the in-medium energy loss of high-p_T partons, particularly the influence of the path length and the shape of the interaction region on the energy loss.

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The data used in this analysis correspond to an integrated luminosity of 150 μb^{-1} and were recorded during the 2011 LHC heavy-ion running period. A detailed description of the CMS detector can be found in Ref. [19]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter. In Pb-Pb collisions, trajectories of charged particles with $p_T > 200$ MeV/c are reconstructed in the silicon tracker covering the pseudorapidity region $|\eta| < 2.5$, with a track momentum resolution of about 1% at $p_T = 100$ GeV/c. In addition, CMS has extensive forward calorimetry, in particular, two steel and quartz-fiber Čerenkov hadronic forward (HF) calorimeters, which cover the pseudorapidity range $2.9 < |\eta| < 5.2$. The HF calorimeters are segmented into towers, each of which is a two-dimensional cell with a granularity of 0.5 unit in η and 0.349 rad in ϕ.

Minimum bias Pb-Pb events were triggered by coincident signals from both ends of the detector in either the beam scintillator counters at $3.23 < |\eta| < 4.65$ or in the HF calorimeters. Events due to noise, cosmic rays, out-of-time triggers, and beam backgrounds were suppressed by requiring a coincidence of the minimum bias trigger with bunches colliding in the interaction region. The trigger has an acceptance of $(97 \pm 3)\%$ for hadronic inelastic Pb-Pb collisions. Because of hardware limits on the data acquisition rate, only a small fraction of all minimum bias triggered events were recorded. To maximize the event sample with high-p_T particles emitted in the Pb-Pb collisions, a dedicated high-p_T single-track trigger was implemented by using the CMS level-1 (L1) and high-level trigger system. The trajectories of charged particles from the silicon tracker were found online by using a tracking algorithm identical to those employed in the offline track reconstruction, starting with a candidate from the three-layer silicon pixel tracker having $p_T > 11$ GeV/c. For Pb-Pb events with total transverse energy at L1 (L1_ETT) above 100 GeV, a trigger efficiency of above 95% relative to offline reconstructed tracks was achieved for track p_T greater than 12 GeV/c. For the events with L1_ETT less than 100 GeV, an additional requirement of a calorimeter jet at L1 with $p_T > 16$ GeV/c [8] was imposed in order to reduce the detector readout rate. This resulted in an efficiency of about 75% starting at $p_T \approx 12$ GeV/c but increasing to almost 100% above $p_T \approx 20$ GeV/c. In this analysis, the minimum bias data sample is used for the v_2 measurement of tracks with $1 < p_T < 12$ GeV/c (also $12 < p_T < 20$ GeV/c for cross-check purposes), while the high-p_T track triggered sample is used in the range of $p_T > 12$ GeV/c.

Events are further selected offline by requiring energy deposits in at least three towers in each of the HF calorimeters, with at least 3 GeV of energy in each tower, and the presence of a reconstructed primary vertex containing at least two tracks. These criteria further reduce the background from single-beam interactions (e.g., beam-gas and beam-halo), cosmic muons, and large impact parameter, ultraperipheral collisions that lead to the electromagnetic breakup of one or both Pb nuclei [20]. The reconstructed primary vertex is required to be located within ± 15 cm of the average vertex position along the beam axis and within a radius of 0.02 cm in the transverse plane. The centrality of the Pb-Pb reaction is determined by taking fractions of the total hadronic inelastic cross section, according to percentiles of the distribution of the total energy deposited in the HF calorimeters [8]. The centrality classes used in this analysis are 0–10% (most central), 10%–20%, 20%–30%, 30%–40%, 40%–50%, and 50%–60%, ordered from the highest to the lowest HF energy deposited.

The reconstruction of the primary event vertex and the trajectories of charged particles in Pb-Pb collisions is based on signals in the silicon pixel and strip detectors and described in detail in Ref. [6]. In selecting the charged primary tracks, a set of tight quality selections were imposed to minimize the contamination from misidentified tracks. These include requirements of a relative momentum uncertainty of less than 5%, at least 13 hits on the track, a normalized χ^2 for the track fit of less than 0.15 times the number of hits, and transverse and longitudinal track displacements from the primary vertex position less than 3 times the sum in quadrature of the measurement uncertainties. From studies based on Pb-Pb events simulated by using HYDJET [21] (version 1.6), the combined geometrical acceptance and reconstruction efficiency of the primary tracks reaches about 66% (50%) at $|\eta| < 1.0$ ($1.0 < |\eta| < 2.0$) for the 5% most-central Pb-Pb events, with little dependence on p_T. For the peripheral Pb-Pb events, the efficiency is improved by up to 5%, again largely independent of p_T. The fraction of misidentified tracks is kept at the 1%–2% level at $p_T > 2$ GeV/c over almost the entire η and centrality ranges. It increases up to 10% for very low p_T (≈ 1 GeV/c) particles in the forward ($|\eta| \approx 2$) region for the 5% most-central Pb-Pb events.

The analysis follows closely the event-plane method described in Ref. [22]. The observed v_2 value for a given centrality and p_T range is defined by $v_2^{\text{obs}} = \langle \cos 2(\phi - \Psi_2) \rangle$, where the average is taken over all particles in all events within a centrality and p_T bin. The second-order "event-plane" angle Ψ_2 corresponds to the event-by-event azimuthal angle of maximum particle density in Pb-Pb collisions. It is an approximation of the participant-plane angle Ψ_{PP}, which is not directly observable. The determination of Ψ_2 uses the energy deposited in the HF calorimeters with $\Psi_2 = \frac{1}{2}\tan^{-1}\frac{\sum_i w_i \sin(2\phi_i)}{\sum_i w_i \cos(2\phi_i)}$, where the weight factor w_i for the ith tower at azimuthal angle ϕ_i is taken as the corresponding transverse energy. The sums are taken over all the towers within a slightly truncated η range of each HF calorimeter coverage. For the v_2 study in this analysis, charged particles detected in the tracker with $\eta > 0$ (<0) are correlated with an event plane found by using energy deposited in a region of the HF spanning $-5 < \eta < -3$ ($3 < \eta < 5$). In this manner, a minimum η gap of 3 units is guaranteed between particles used in the event-plane determination and those for which the v_2 value is being measured, thereby significantly reducing the effect of other correlations that might exist, such as that from dijets. This η gap is particularly important for the high-p_T particle studies.

The resolution of the event plane depends on the centrality and is limited by the finite number of particles used in its determination. The final v_2 coefficient in the event-plane method is evaluated by dividing the observed value v_2^{obs} by a "resolution-correction" factor R, with $v_2 = v_2^{\mathrm{obs}}/R$ and where R can range from 0 to 1 [23], with a better resolution corresponding to a larger value of R. An event-averaged resolution-correction factor can be found experimentally by extracting separate event-plane angles using particles emitted into three nonoverlapping η regions. In this "three-subevent" technique, which is described in more detail in Ref. [23], the resolution-correction factor for a given η region (denoted A, with B and C used for the other two η ranges) is found by using

$$R_A = \sqrt{\frac{\langle\cos[2(\Psi_2^A - \Psi_2^B)]\rangle\langle\cos[2(\Psi_2^A - \Psi_2^C)]\rangle}{\langle\cos[2(\Psi_2^B - \Psi_2^C)]\rangle}}.$$

The averages are over all events corresponding to a given centrality bin. Reconstructed tracks with $|\eta| < 0.8$ and $p_T > 1$ GeV$/c$ are used for the "third" η range (denoted C) introduced to determine the resolution of the event planes found by using the HF detectors at $-5 < \eta < -3$ (denoted A) and $3 < \eta < 5$ (denoted B). In the calculation of Ψ_2^C, the weight factor w_i of the ith track at angle ϕ_i is taken as the corresponding transverse momentum. The extracted R values for the HF event planes are found to vary between 0.55 and 0.84, reaching a maximum value for events in the 20%–30% centrality bin. The difference in the resolution-correction factors found for the two HF event planes is less than 1%.

The sensitivity of the deduced v_2 values to the size of the minimum η gap is explored by defining additional event planes with different pseudorapidity ranges. Varying the gap size from 3 to 4 units, the v_2 values are found to be consistent within $\pm 2.5\%$ (central) or $\pm 10\%$ (peripheral). For all systematic studies, relative uncertainties to v_2 are quoted. The influence of misidentified tracks is another source of systematic uncertainty at high p_T. The v_2 of misidentified tracks in data is estimated by using a very loose track selection. By taking the misidentified-track v_2 signal, together with the probability of reconstructing a fake track as determined from simulated events, the systematic uncertainty on the observed v_2 values is estimated to be $\pm 1\%$–3%, depending on p_T and centrality. Potential biases of the events triggered by the high-p_T track algorithm are investigated. A comparison of v_2 results for $12 < p_T < 20$ GeV$/c$ obtained from minimum bias and high-p_T track triggered samples shows a variation of less than $\pm 1\%$. To account for nonuniformities in the detector acceptance that can lead to artificial asymmetries in the event-plane angle distribution and thereby also affect the deduced v_2 values, a Fourier-analysis-based "flattening" procedure is used [23] where each calculated event-plane angle is shifted slightly to recover a uniform azimuthal distribution of angles [22]. Monte Carlo studies have shown that this flattening procedure fully corrects for nonuniformities in the CMS detector response. The overall systematic uncertainties associated with the event-plane flattening procedure and the resolution-correction determination are found to be less than $\pm 1\%$. Additional uncertainties due to track-quality requirements are examined by loosening or tightening the selection criteria described previously and are found to be less than $\pm 0.5\%$. The different systematic sources are added in quadrature to obtain the overall systematic uncertainty in v_2.

The results of v_2, as a function of p_T from 1 to 60 GeV$/c$ for events with centralities ranging from 0–10% (central) to 50%–60% (peripheral), are presented in Fig. 1 for $|\eta| < 1$. The highest p_T bin covers a range from 48.0 to 60.8 GeV$/c$. The new CMS results in this Letter significantly extend the p_T reach of v_2 measurements previously achieved by the ALICE [24], ATLAS [25], and CMS [22] Collaborations. The CMS and ATLAS results based on event-plane analyses using forward calorimeters for the event-plane determination show agreement within 2%–3% up to $p_T \approx 20$ GeV$/c$.

The p_T dependence of v_2 shows a trend of rapid rise, reaching a maximum at ≈ 3 GeV$/c$, followed by a dramatic decrease for p_T values up to about 10 GeV$/c$. Beyond $p_T \approx 10$ GeV$/c$, the v_2 values show a much weaker dependence on p_T and gradually decrease but remain larger than zero up to at least $p_T \approx 40$ GeV$/c$. The magnitude of v_2 at high p_T can probe the path-length (l) dependence of parton energy loss (ΔE), $\Delta E \sim l^\alpha$ [11–16]. At Relativistic Heavy Ion Collider energies, the π^0 v_2 data for $p_T \sim 6$–10 GeV$/c$ support a scenario of $\alpha = 3$ based on AdS/CFT gravity-gauge dual modeling, while the perturbative QCD calculations ($\alpha = 1$ for collisional energy loss and $\alpha = 2$ for radiative energy loss) seem to underpredict the data [17]. The v_2 results reported in this Letter extend to a significantly wider p_T regime, where particle production is unambiguously dominated by parton fragmentation and energy-loss models are expected to be more applicable. The clear p_T dependence of v_2 observed at the LHC energy suggests that additional dynamical modeling of parton modification, particularly by incorporating the proper initial parton energy dependence, is required in order to further examine the path-length dependence of energy loss (i.e., α parameter).

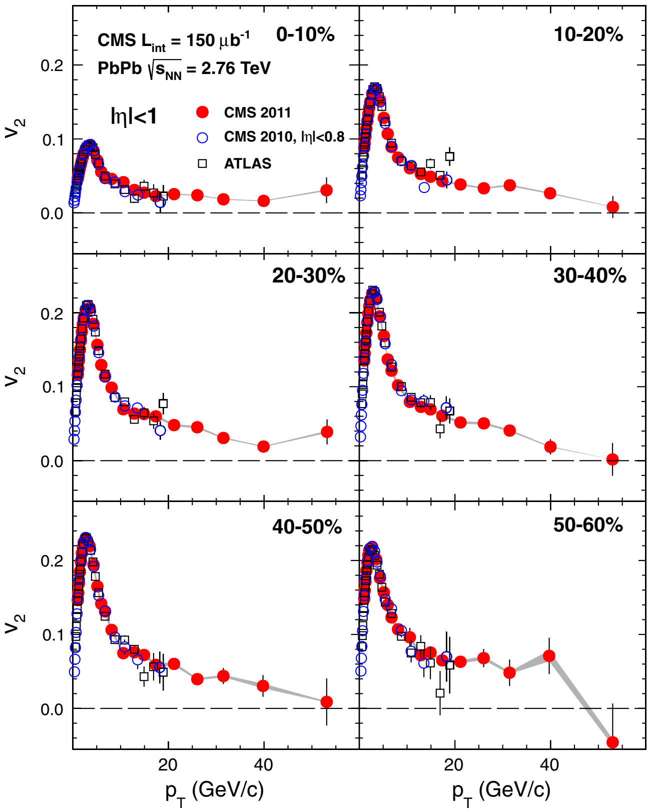

FIG. 1 (color online). The single-particle azimuthal anisotropy v_2 as a function of the charged particle transverse momentum from 1 to 60 GeV/c with $|\eta| < 1$ for six centrality ranges in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, measured by the CMS experiment (solid markers). Error bars denote the statistical uncertainties, while the gray bands correspond to the small systematic uncertainties. Comparison to results from the ATLAS (open squares) and CMS (open circles) experiments using data collected in 2010 is also shown.

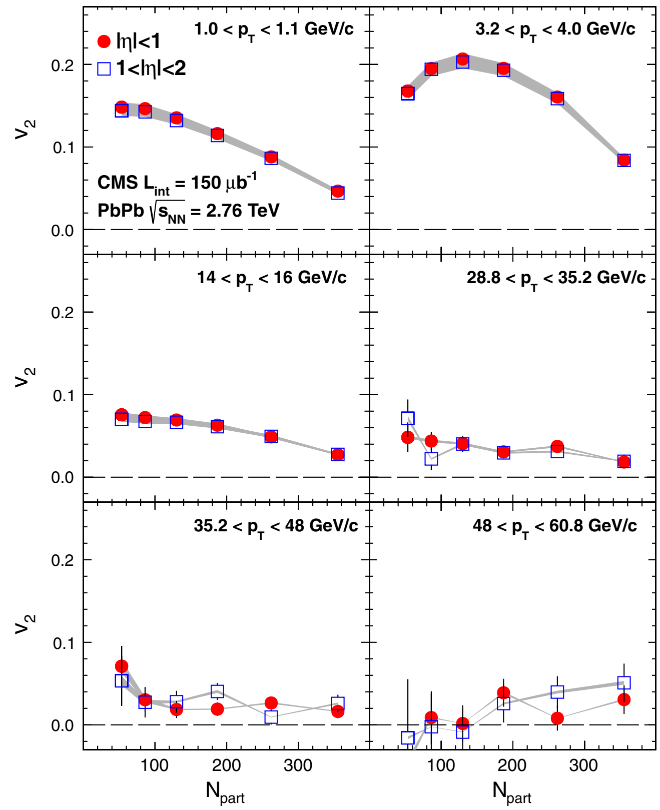

FIG. 2 (color online). The single-particle azimuthal anisotropy v_2 as a function of the number of participating nucleons with $|\eta| < 1$ (solid circles) and $1 < |\eta| < 2$ (open squares) for six selected p_T ranges in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, measured by the CMS experiment. Error bars denote the statistical uncertainties, while the gray bands correspond to the systematic uncertainties.

Figure 2 shows the v_2 dependences on the number of participant nucleons (N_{part}) associated with each centrality bin through a Glauber model calculation. The corresponding participant eccentricities of the overlap region vary from 0.46 to 0.093. Different p_T bins are shown for two pseudorapidity ranges: $|\eta| < 1$ and $1 < |\eta| < 2$. The results appear to be independent of η in all p_T bins within the statistical uncertainties. Also, the v_2 values tend to decrease with increasing collision centrality (i.e., larger N_{part}) over a wide p_T range (although this trend appears to be reversed for $3.2 < p_T < 4.0$ GeV/c toward very peripheral events). This behavior is expected for low-p_T (below a few GeV/c) particles in the context of the relationship between hydrodynamic flow phenomena and the eccentricity of the initial-state collision geometry. The similar trend observed for very high-p_T particles, at least up to $p_T \approx 48$ GeV/c, reflects how the v_2 results at high p_T are also sensitive to the initial geometry. This indicates that the initial conditions of the hot QCD medium can be further constrained by simultaneously comparing data with theoretical calculations from both hydrodynamics at low p_T and in-medium parton energy loss at high p_T.

In summary, the azimuthal anisotropy of charged particles with respect to the event plane has been studied in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the CMS detector. The v_2 coefficient was determined over a wide range in p_T up to approximately 60 GeV/c, as a function of collision centrality. The results reported in this Letter significantly improve the statistical precision of previous v_2 measurements for $12 < p_T < 20$ GeV/c and explore for the first time the very high-p_T region beyond 20 GeV/c. The $v_2(p_T)$ behavior shows a trend of rapid rise to a maximum at $p_T \approx 3$ GeV/c and a subsequent fall for all centrality and $|\eta|$ ranges. Beyond $p_T \approx 10$ GeV/c, the observed v_2 values still show a clear p_T dependence but with a more moderate decrease with p_T, remaining finite up to at least $p_T \approx 40$ GeV/c. A common trend in the centrality dependence of v_2 is observed for particles over a wide range of p_T up to approximately 48 GeV/c, suggesting a potential connection to the initial-state geometry. The precision data over a wide kinematic range presented here will provide important constraints on models of parton energy loss, particularly in terms of its dependence on the initial conditions, parton energy, and path length through the medium.

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