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Collective flow and charged hadron correlations in 2.76 TeV PbPb collisions at CMS

S.J. Sanders* **for the CMS Collaboration**
University of Kansas, Lawrence, KS, 66045 USA
E-mail: `ssanders@ku.edu`

We report on the CMS measurements of charged-hadron anisotropic azimuthal distributions from PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The results are presented as a function of transverse momentum, centrality and pseudorapidity over a wide kinematic region. For low transverse momentum particles ($p_{\mathrm{T}} < 3$ GeV/c) the azimuthal behavior is believed to be dominated by the hydrodynamic flow of the expanding medium created in the reaction. We characterize this behavior in terms of the first-order term of a Fourier expansion of the azimuthal angular distribution as determined using the event-plane, cumulant, and Lee-Yang zeros methods. For high transverse momentum particles ($p_{\mathrm{T}} > 8$ GeV/c) the azimuthal asymmetry reflects the energy loss of high-energy partons moving through the medium. This is studied using the event-plane method. In both cases the azimuthal asymmetry can be related to the initial geometry of the hot and dense matter created in the reaction. These results provide constraints on theoretical descriptions of the early dynamics of heavy-ion reactions at the LHC and the transport properties through the medium created by these reactions.

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*Speaker.

We present results of the CMS collaboration on the azimuthal anisotropy of charged particles emitted in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV at the LHC. In relativistic heavy-ion reactions, the overlap region of the two ions for non-central collisions takes on a lenticular shape. Measurements of AuAu collisions at $\sqrt{s_{NN}}$= 200 GeV at RHIC show behavior consistent with the formation of a strongly coupled quark-gluon plasma (sQGP) where asymmetric pressure gradients in the produced fluid-like medium lead to the preferential emission of particles in the directon of the short axis of the overlap region [1, 2, 3]. In addition, the RHIC experiments have shown that the matter formed in the heavy-ion collisions is significantly opaque to high-energy partons. This leads to a "jet quenching" phenomenon where the particle yield at high transverse momenta is "suppressed" compared to that expected from scaling the observed pp collision yield by the number of binary collisions [1, 2, 3, 4]. Jet quenching can also leads to an azimuthal asymmetry related to the initial state geometry as shown by the PHENIX experiment [5] in a study of high-p_{T} π° particles in AuAu collisions at $\sqrt{s_{NN}}$= 200 GeV. CMS has now determined the azimuthal asymmetry of charged particles over the range $0.3 < p_{\mathrm{T}} < 60$ GeV/c, thus covering both the hydrodynamic flow and parton energy-loss, high-p_{T} regions [6, 7]. These data should provide stringent constraints on model calculations that depend on the properties of the initial state and the subsequent energy loss of partons moving through the created medium.

The azimuthal asymmetry of the particle yield can be expressed in terms of Fourier components, with

$$\frac{d^3N}{p_{\mathrm{T}}dp_{\mathrm{T}}dyd\phi} = \frac{1}{2\pi}\frac{d^2N}{p_{\mathrm{T}}dp_{\mathrm{T}}dy}\left(1+\sum_{n=1}^{\infty}2v_n\left(p_{\mathrm{T}},y\right)\cos\left[n\left(\phi-\Psi_{\mathrm{PP}}\right)\right]\right),$$

where Ψ_{PP} is event-by-event azimuthal angle of the "participant-plane" as determined by the short axis of the lenticular region defined by the participant nucleons and the beam direction. This presentation will focus on the lowest order, and dominant, v_2 component of this expansion which is commonly referred to as the "elliptic" flow coefficient. Four complementary techniques are employed to determine the v_2 coefficient. In the event-plane (EP) method [8], the direction of maximum particle density, which is related to Ψ_{PP}, is established for one range of pseudorapidity, with the $v_2\{\mathrm{EP}\}$ coefficient then determined in a non-overlapping region of pseudorapidity. A pseudorapidity "gap" prevents autocorrelations from occurring between the particles used to determine the event plane and those for which the $v_2\{\mathrm{EP}\}$ asymmetry is being determined. The two-particle cumulant method [9] (with coefficients denoted $v_2\{2\}$) considers all two-particle correlations among the emitted particles. Since the particles have an overall correlation with the event-plane, they are also correlated with each other. The four-particle cumulant method ($v_2\{4\}$) [9] considers all four-particle correlations among the emitted particles. Finally, the Lee-Yang zeros method ($v_2\{\mathrm{LYZ}\}$) considers all particle correlations [10, 11]. Each of these methods has a different sensitivity to non-flow effects such as statistical fluctuations of the participant nucleon distributions and final-state resonance decays. A comparison of v_2 results using the various methods can therefore give insight into these non-flow behaviors.

The data being presented were obtained during the 2010 and 2011 PbPb runs at the LHC using the CMS detector. The inner pixel and strip detector arrays were used to determine the tracks of charged particles with $|\eta| < 2.4$ moving in the 3.8 T magnetic field of the CMS solenoid. For the event-plane method, two steel/quartz-fiber Čerenkov hadronic forward (HF) calorimeters were used to establish the event-plane angle based on energy deposited in the range $3 < |\eta| < 5$. Minimum bias PbPb events were triggered by coincident signals from both ends of the detector. The coincidence was either between two beam scintillator counters at $3.23 < |\eta| < 4.65$ or the HF calorimeters. The study of the azimuthal behavior of lower p_{T} particles ($p_T < 20$ GeV/c) based on the different methods (event-plane, two- and four-particle cumulant, and Lee-Yang zeros) uses 22.6 million minimum-bias events from the 2010 run, corresponding to an integrated luminosity of $3\ \mu\mathrm{b}^{-1}$ after a selection of tracks within 10 cm of the geometric center of the detector. A dedicated high-p_{T} trigger was implemented for the 2011 run using the CMS Level-1 (L1) and high-level trigger system. This trigger has an efficiency of about 75% starting at $p_{\mathrm{T}} \approx 12$ GeV/c increasing to almost 100% above $p_{\mathrm{T}} = 20$ GeV/c. The data used in this high-p_{T} analysis corresponds to an integrated luminosity of $150\ \mu\mathrm{b}^{-1}$, with 20 times more high-p_{T} tracks than in the 2010 minimum-bias dataset.

Figure 1 shows the v_2 results [6] for the four different methods with $0.3 < p_{\mathrm{T}} < 20$ GeV/c. Twelve different centrality classes are shown, ranging from the most central 0-5% events to peripheral 70-80% events. At low p_{T} the v_2 values increase with increasing momentum, as expected for a hydrodynamic flow behavior. Above 3 GeV/c the elliptic flow coefficient is found to decrease for all but the peripheral collision, second-order cumulant results. In this higher p_{T} region hard collision processes dominate the observed behavior.

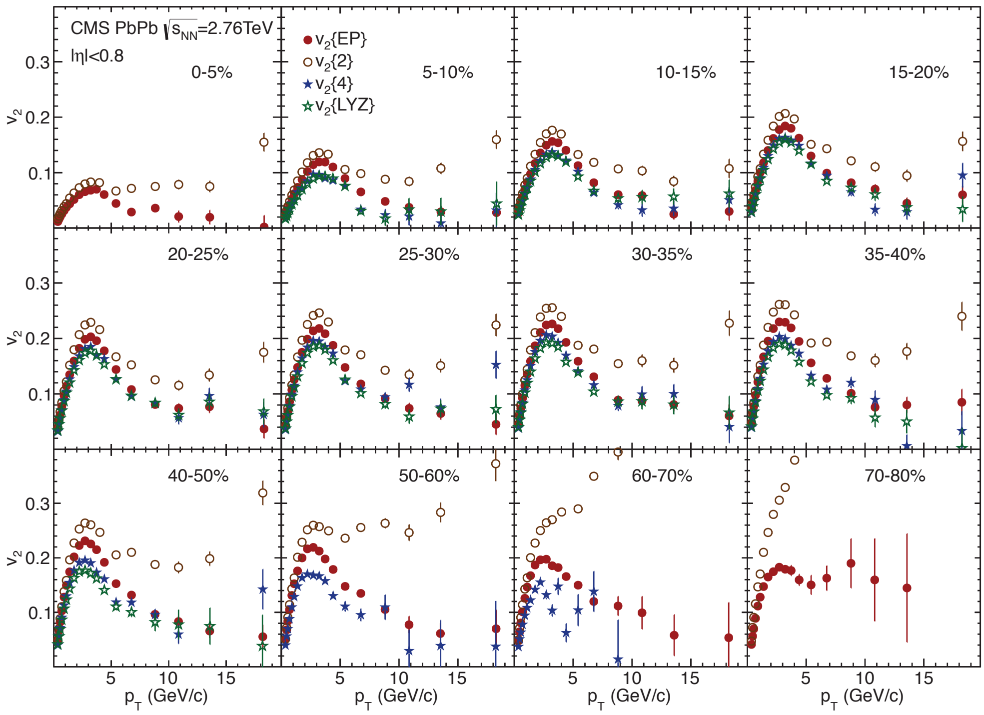

Figure 1: $v_2(p_{\mathrm{T}})$ distributions for the four analysis methods and for twelve different centrality classes.

The different methods show expected differences that can be attributed to their respective sensitivity to non-flow effects. The relatively high values observed for the $v_2\{2\}$ results can be

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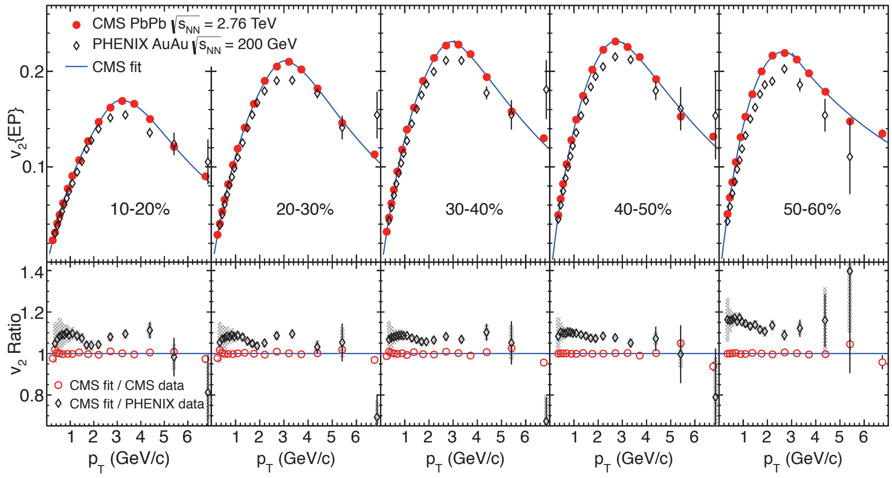

Figure 2: TOP. Comparison of CMS [6] and PHENIX [12] results ($|\eta| < 0.8$ and $|\eta| < 0.35$, respectively) for the indicated systems and energies at mid-rapidity. BOTTOM. Fraction of a fit to the CMS data with respect to the individual CMS and PHENIX data points.

understood by the absence of a pseudorapidity gap in the analysis of the two particle correlations. In the cumulant analyses, a “reference flow” plays a similar role to the event-plane determination in the event-plane method. For the current analysis, a pseudorapidity gap was not required between the particles used to determine the reference flow and those used to establish the differential flow. Thus, short range correlations can have a significant influence. The event-plane analysis avoids such correlations by requiring a pseudorapidity gap of at least three units between the particles used to determine the event plane (using one or the other of the HF detectors) and the particles used to find v_2 (using the tracker detector). In a collision with event multiplicity M, the sensitivity to correlations of order k typically scales as $1/M^{k-1}$. Consequently, the fourth-order cumulant and Lee-Yang zeros methods are inherently less sensitive to such correlations.

Figure 2 compares the CMS mid-rapidity event-plane results for PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV to results obtained by the PHENIX collaboration [12] for AuAu collisions with $\sqrt{s_{NN}}$ = 200 GeV. Only a small increase is observed in the elliptic-flow coefficients despite a large increase in the center-of-mass energy. This is emphasized in the bottom panels where a fit to the CMS results is divided the the corresponding CMS and PHENIX data points. The CMS results are typically around 10% higher than found by PHENIX at the lower energy, and are only found to be around 15% higher for the most peripheral centrality bin shown.

The different sensitivities of the methods to fluctuations in the locations of the participant nucleons is demonstrated in Fig. 3. The left side of this figure shows the yield-weighted average v_2 values for $0.3 < p_T < 3.0$ GeV/c scaled by the participant eccentricity ε_{part} [13] as a function of collision centrality. There is a clear separation of the methods. The right-hand panel shows the same results for $v_2\{\mathrm{EP}\}/\varepsilon_{\mathrm{part}}$, but now the cumulant results are scaled by their respective cumulant moments, with $\varepsilon\{2\} \equiv \sqrt{\langle\varepsilon^2_{\mathrm{part}}\rangle}$ and $\varepsilon\{4\} \equiv \sqrt[4]{2\langle\varepsilon^2_{\mathrm{part}}\rangle^2 - \langle\varepsilon^4_{\mathrm{part}}\rangle}$. The curves for the different methods are found to collapse to a common behavior except for the most central events.

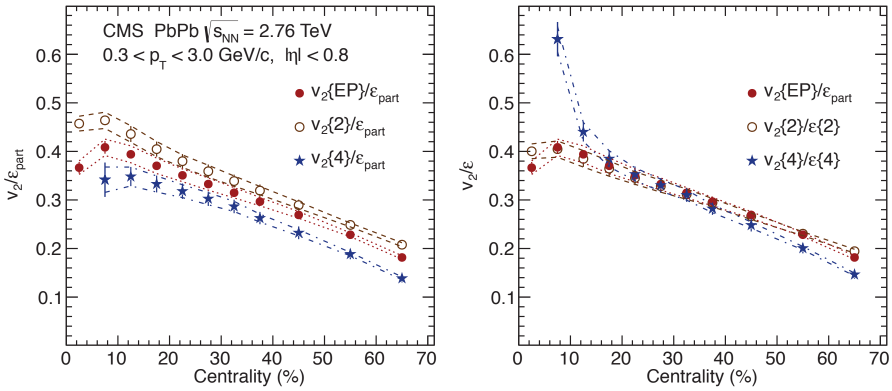

Figure 3: LEFT. v_2 results scaled by the participant eccentricity as a function of collision centrality. RIGHT. Same, but with the cumulant v_2 values scaled by the their respective cumulant moments, as defined in the text.

Figure 4 shows the pseudorapidity dependence of the yield-weighted average v_2 values with $0.3 < p_T < 3$ GeV/c for the four different methods and for twelve different centrality classes. The results clearly divide into two classes corresponding to their relative sensitivities to non-flow effects: $v_2\{EP\}$ and $v_2\{2\}$ have similar behavior and the $v_2\{4\}$ and $v_2\{LYZ\}$ form a separate grouping. Only a modest pseudorapidity dependence is found, with the greatest change with pseudorapidity observed for the more peripheral centrality classes. It should be noted that the yield-weighted average v_2 values are dominated by the low-p_T range where the event-plane and two-particle cumulant methods also show similar values in Fig.1.

Charged-particle densities are significantly higher at LHC energies as compared to those found at RHIC. Also, the excellent azimuthal coverage of the CMS detector allows for the v_2 coefficients to be determined over a wide range of collision centrality, as shown in Fig. 1. Together, these features allow the study of the elliptic flow behavior over a very wide range of transverse charged-particle density, defined as the charged-particle density $dN_{ch}/d\eta$ per transverse area S, as determined through Glauber-model calculations [14]. Figure 5 shows the CMS results for v_2/ε_{part} as a function of the transverse charge-particle density[6], using extrapolated yield-weighted average v_2 values ($0 < p_T < 3$ GeV/c). Also included are the results from the PHOBOS collaboration obtained for lower energy CuCu and AuAu collisions [15]. There appears to be a very good scaling of the participant eccentricity scaled v_2 results with transverse charged-particle density.

The azimuthal asymmetry of higher p_T particles is believed to result from jet quenching in the asymmetrically shaped overlap region created in the collision. However, it is still possible to characterize the asymmetry by a v_2 coefficient. Figure 6 shows the CMS results from the 2011 PbPb run where the p_T range now extends out to 60 GeV/c [7]. Six different centrality classes are shown. Also shown in this figure are the lower p_T results of the CMS collaboration obtained from the 2010 year PbPb run [6], and the previously published results of the ATLAS experiment [16]. Excellent agreement is found with the earlier analyses in the range of overlap. Focusing on the newer results, the v_2 coefficient is found to remain finite up to at least $p_T = 40$ GeV/c over the full centrality range measured. Above $p_T = 40$ GeV/c, the v_2 values become consistent with zero for

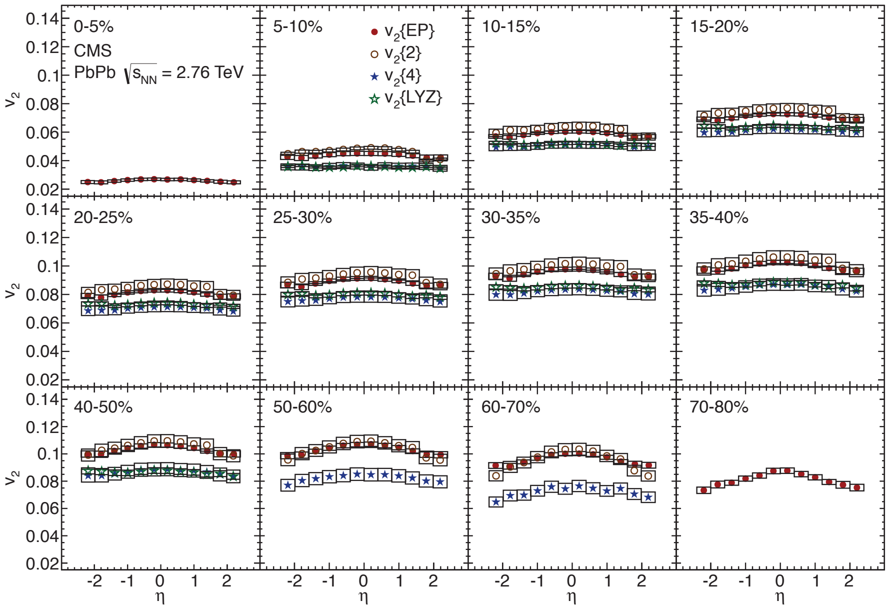

Figure 4: Pseudorapidity dependence of the yield-weighted average v_2 with $0.3 < p_T < 3$ GeV/c for the four different methods and for twelve different centrality classes.

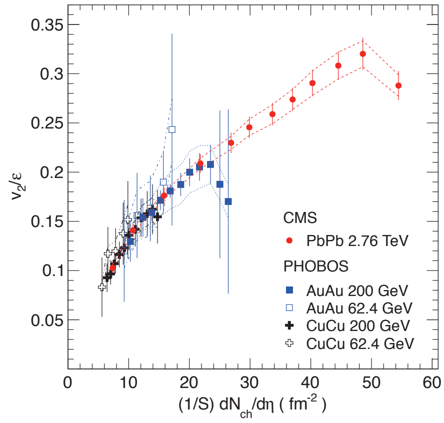

Figure 5: v_2/ε_{part} values as a function of transverse charged particle density from CMS [6] and PHOBOS [15].

mid-central (> 30%) events.

To demonstrate that the higher p_T results are influenced by the initial state geometry, in Fig. 7 the v_2 values for different p_T cuts are shown as a function of the number of participant nucleons (N_{part}) for two different pseudorapidity ranges. Up to 4 GeV/c, the results are expected to be strongly influenced by the hydrodynamic flow behavior of the created medium. Above 14 GeV/c, the flow component is expected to be negligible. For these higher p_T values, the increase in v_2 as the collisions become more peripheral (decreasing N_{part}) reflects the corresponding increase in the

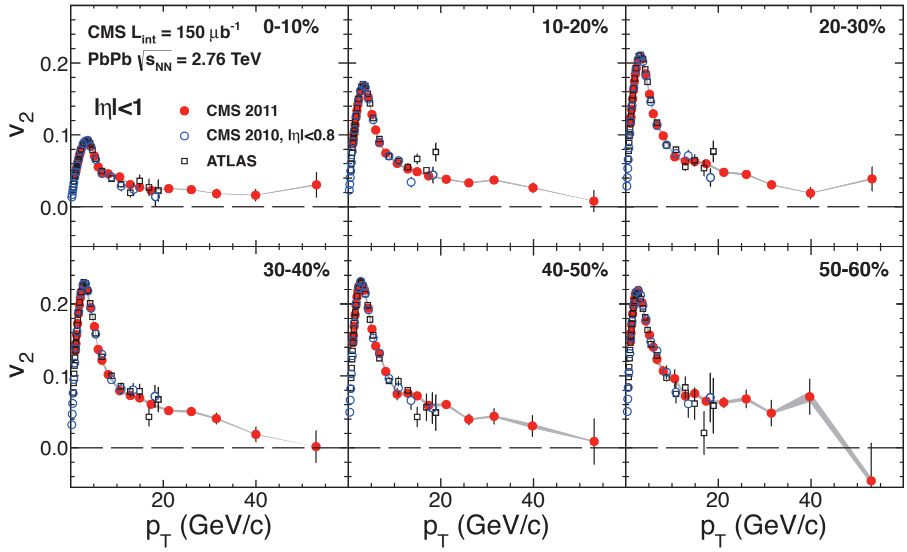

Figure 6: $v_2(p_T)$ distributions extending to 60 GeV/c for six centrality classes. Lower p_T results from both the ATLAS [16] and CMS [6] collaborations are also shown.

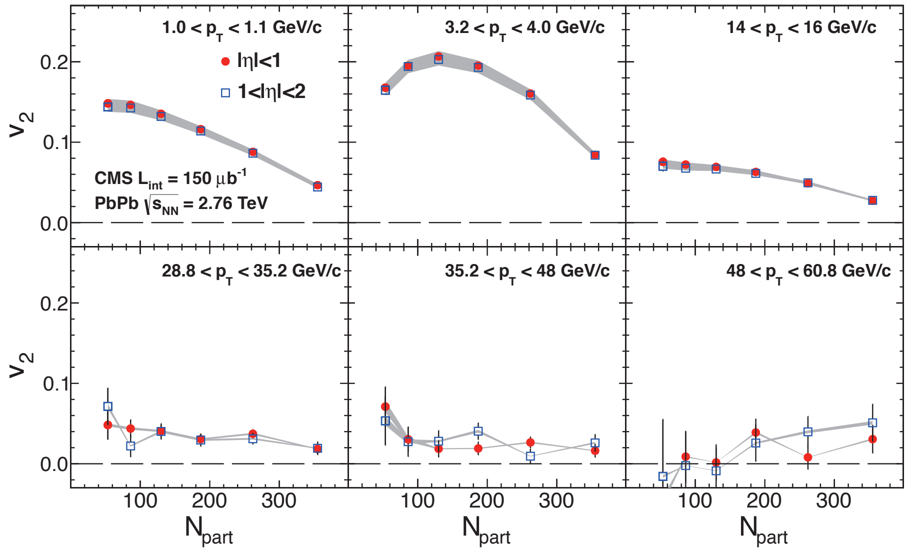

Figure 7: v_2 values for the indicated p_T ranges shown as a function of the number of participant nucleons.

eccentricity of the lenticular overlap region as N_{part} decreases.

In summary, the CMS experiment has determined the azimuthal asymmetry of charged particles emitted in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV over wide ranges of pseudorapidity, collision centrality, and transverse momentum. The data at lower p_T has been analyzed using four different methods (event plane, second- and fourth-order cumulant, and Lee-Yang zeroes). The observed differences in the v_2 values obtained by the different methods is attributed to non-flow effects and, in particular, fluctuations in the initial participant nucleon distribution. An azimuthal asymmetry related to the initial-state geometry is found to persist up to at least 40 GeV/c over an extended range of collision centrality. The high-p_T behavior is attributed to jet quenching in the medium. We expect the comprehensive data obtained for the v_2 coefficient presented here will provide stringent constraints on model calculations that are sensitive to the assumed viscosity of the created medium and the opaqueness of this medium to high-energy partons.

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