PROCEEDINGS OF SCIENCE

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

Sandra S. Padula*
On behalf of the CMS Collaboration
Instituto de Física Teórica - UNESP, São Paulo, SP, Brazil
E-mail: padula@ift.unesp.br

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 and cover a broad kinematic range. These results can provide constraints on the theoretical description of the early dynamics in the hot and dense medium created at the LHC and the transport properties through this medium.

36th International Conference on High Energy Physics,
July 4-11, 2012
Melbourne, Australia

*Speaker.

Azimuthal anisotropies observed in the momentum distribution of particles produced in high energy heavy ion collisions are an important characteristic of the produced hot and dense medium. At their origin are spatial asymmetries reflecting the eccentricities in the overlapping region of the two nuclei in non-central collisions, which drive a collective anisotropic expansion after the local thermal equilibrium have been attained following the strong rescattering of the partons in the initial state. Such expansion is fastest along the short axis of the almond shaped initial overlapping region, corresponding to the largest pressure gradient.

The azimuthal anisotropies can be quantified by an expansion in Fourier harmonics, i.e., $dN/d\phi \sim 1 + 2v_2 \cos 2(\phi - \psi_R) + 2v_3 \cos 3(\phi - \psi_3) + ...$, where ϕ is the azimuthal angle and ψ_R is the reaction plane angle. If the initial conditions can be described by nucleons uniformly distributed in both nuclei in a rotationally symmetric way, the odd harmonics are identically zero, by symmetry. However, odd Fourier harmonics can appear if the initial conditions are fluctuating. Finite results on v_3 and v_5 were obtained by CMS, extracted from the long-range azimuthal dihadron correlations, for twelve centrality intervals in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [1]. Such non-null results are indicative of fluctuating initial conditions at this energy at the LHC. In this proceedings, however, we will focus our discussion on the elliptic anisotropy parameter v_2.

Besides inferring information about the initial conditions and the role of fluctuations, there are several other physics reasons of great interest for measuring azimuthal anisotropy of charged particles: they also allow for confronting different equations of state, to test the opacity of the system formed in high-energy heavy-ion collisions, to investigate the viscosity of the medium, etc. The azimuthal anisotropies observed experimentally in hadron transverse momentum distributions may have their origin in different physical processes, depending on the p_T range probed in high energy heavy ion collisions. In the low transverse-momentum range ($p_T \leq 2-3$ GeV/c) such measurements usually reflect the hydrodynamic flow driven by asymmetric pressure gradients and spatial anisotropies in the early stages of the system formed in such collisions. On the other hand, in the high-p_T region ($p_T \geq 8-10$ GeV/c), they are not expected to be driven by collective flow. In this case, the anisotropic azimuthal distribution of hadrons may be originated in different path-length dependences of the jet energy loss (jet quenching) when traversing the hot and dense medium probed in such collisions. In the intermediate region ($2-3 \leq p_T \leq 8$ GeVc) the experimental observations may reflect hadron production from both thermally produced partons (flow) and partons from jet fragments. All these p_T regions are being investigated in the CMS detector.

The CMS detector has an extended coverage of more than ten units in pseudorapidity ($\eta = -\log[\tan(\theta/2)]$, with θ being the polar angle) along the beam direction and nearly 4π solid angle acceptance. Its main characteristic is a large superconducting solenoid of 6 m internal diameter with 3.8 T axial magnetic field, surrounding the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to these detectors, CMS has extensive forward calorimetry, in particular two steel/quartz-fiber Cerenkov forward hadronic calorimeters (HF, $2.9 < |\eta| < 5.2$), whose signal is used for PbPb collisions as the primary minimum-bias trigger (alternatively, the beam scintillator counters - BSC - with $3.23 < |\eta| < 4.65$, can be used for this purpose). Coincident signals from detectors located at both ends (i.e., a pair of BSC or a pair of HF modules) are required. A complete description of the CMS detector can be found in Ref.[2].

The elliptic anisotropy parameter v_2 is discussed here for several collision centralities and in a broad range of transverse momentum p_T. There are several methods for performing such measurements, four of which will be discussed in what follows. One of the measurements was performed adopting the Event Plane (EP) method, in which the two-particle positive and negative event planes, ψ^+_{EP} and ψ^-_{EP}, are determined by correlating the signals in the HF^+ $(3 < \eta < 5)$ and HF^- $(-5 < \eta < -3)$, respectively. After that, the elliptical anisotropies are measured by correlating particles from the negative (positive) η range of the tracker, i.e., $-2.4 < \eta < 0$ $(0 < \eta < 2.4)$ to $\psi^+_{2_{EP}}$ $(\psi^-_{2_{EP}})$, according to $v_{2_{EP}} = \langle v_2[\cos 2(\phi - \psi_{2_{EP}})]\rangle/R$. The factor R corresponds to a resolution correction, which needs to be applied to the event plane. A gap of three units in η is kept in this measurement for reducing contamination of non-flow effects. The two-particle cumulant method estimates the elliptic flow by $v_2\{2\} = \sqrt{\langle[\cos 2(\phi_1 - \phi_2)]\rangle}$, considering all two-particle correlations in the event. Similarly, the four-particle cumulant estimates it by $v_2\{4\} = (2\langle[\cos 2(\phi_1 - \phi_2)]\rangle^2 - \langle\cos(\phi_1 + \phi_2 - \phi_3 - \phi_4)\rangle)^{1/4}$, involving all four-particle correlations. Finally, the Lee-Yang zeros method considers the correlations among all particles in the event.

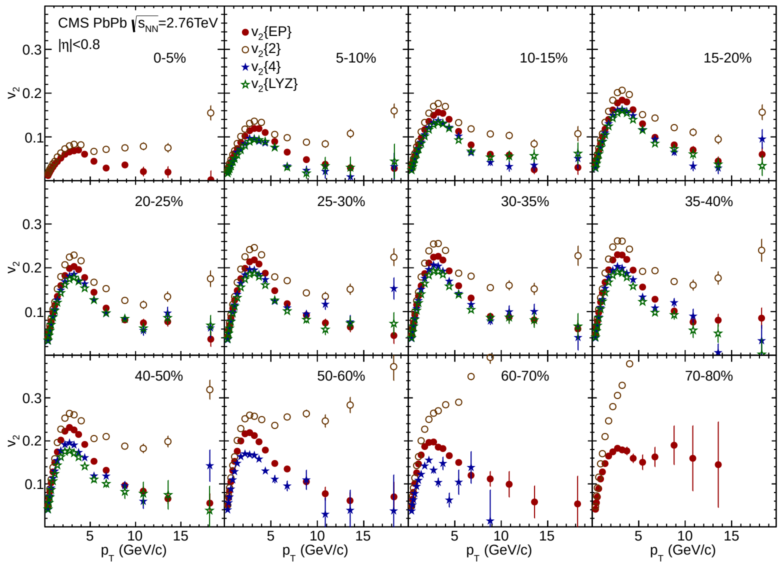

Figure 1: Results from four methods (EP, $v_2\{2\}$, $v_2\{4\}$, LYZ) measured in the central rapidity region ($|\eta < 0.8|$) are shown in several centrality windows as a function of the transverse momentum p_T [3].

Results of the differential elliptic flow measurements performed at the CMS detector using the four methods described above [3] are shown in Figure 1 as a function of p_T, for several centrality windows. In all results $v_2(p_T)$ grows up to 40-50% centrality and then decreases. The general behavior with p_T shows that v_2 rises up to $p_T \sim 3$ GeV/c, then gradually decreases, except for $v_2\{2\}$ in collisions with centrality above 50%. The $v_2\{2\}$ is more sensitive to non-flow effects, since the reference and the differential flow signals are determined in the same pseudorapidity range in this case. Generally, non-flow effects refer, for instance, to resonance decays, jets and quantum-statistical effects, such as Bose-Eintein correlations. Although the event-plane method is expected to be similarly affected by non-flow, in our analysis the particles used in the event-plane determination and the particles used to measure the flow are at least three units of pseudorapidity apart, which suppresses most non-flow correlations. The differences between the two-particle cumulant and the event-plane methods are most pronounced at high p_T and in peripheral collisions, where jet-induced correlations dominate over the collective flow. In a collision where M particles are produced, direct k-particle correlations are of order $1/M^{k-1}$, so that they become smaller as k increases. Therefore, the fourth-order cumulant and the Lee-Yang zeros methods are expected to be much less affected by nonflow contributions than the second-order cumulant method, a trend observed in Figure 1.

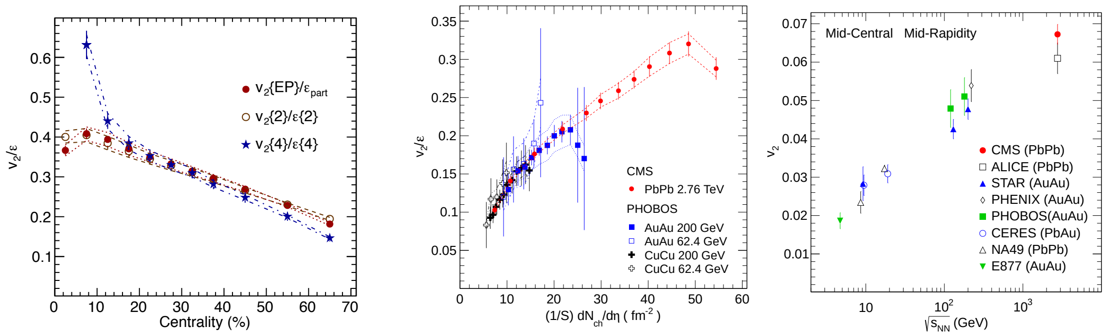

Figure 2: CMS results for integrated v_2 from three methods (EP, $v_2\{2\}$, $v_2\{4\}$) are shown on the left panel [3], scaled by the corresponding eccentricities. The middle panel shows comparison with results from PHOBOS [4], demonstrating similarities in spite of nearly 14 times increase in the center-of-mass energy. The panel on the right shows approximately logarithmic rise of the elliptic anisotropic flow with energy [3].

The left panel of Figure 2 shows the centrality dependence of the integrated elliptic flow scaled by eccentricity for three methods obtained with the CMS detector (see [3] for details). The left panel of Figure 2 shows the centrality dependence of the integrated elliptic flow scaled by eccentricity for three methods obtained with the CMS detector (see [3] for details). The two-particle and four-particle cumulant results are divided by their corresponding moments of the participant eccentricity, ε_2 and ε_4, while $v_2\{EP\}$ is scaled by the participant eccentricity ε_{part}. The error bars show the sum in quadrature of the statistical and systematic uncertainties in the v_2 measurement, and the lines represent the systematic uncertainties in the eccentricity determination. The observed scaling for centralities in the 15-40% range demonstrates that the differences between the methods are well described by Glauber model eccentricities ε. The middle panel in Figure 2 shows that the CMS eccentricity-scaled v_2/ε results are in good agreement with results from PHOBOS[4] at much lower energies and also that they scale with the charged-particle rapidity density. The error bars include both statistical and systematic uncertainties in v_2. The dashed lines represent the systematic uncertainties in the eccentricity determination. The right panel in Figure 2 shows the $\sqrt{s_{NN}}$ dependence of the integrated v_2 from mid-central collisions spanning three orders of magnitude, from $\sqrt{s_{NN}} = 4.7$ GeV (AGS) to $\sqrt{s_{NN}} = 2.76$ TeV (LHC) [3]. The CMS measurement is obtained with the EP method in the 20-30% centrality class by extrapolating the $v_2(p_T)$ and the charged-particle spectra down to $p_T = 0$. The extrapolation assumed that $v_2(0) = 0$, and the charged-particle yield is constrained in order to match the $dN_{ch}/d\eta$ values measured by CMS [3]. The integrated v_2 values increase approximately logarithmically with $\sqrt{s_{NN}}$ over the full energy range, with a 20-30% increase from the highest RHIC energy to that of the LHC.

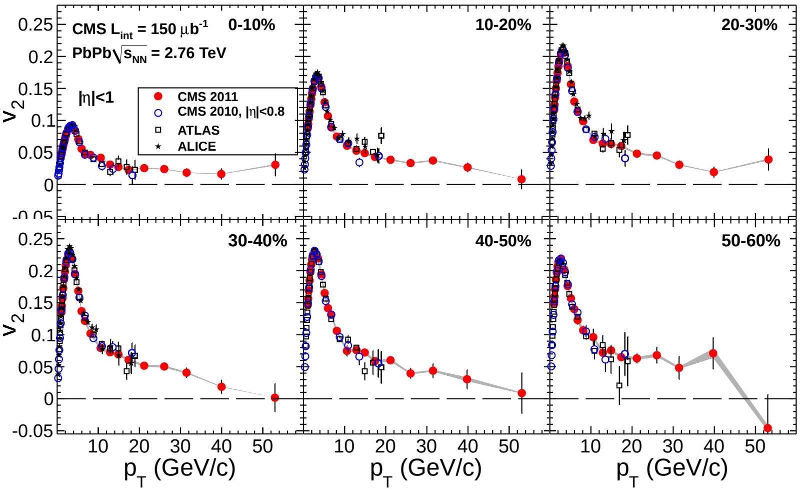

Figure 3: The single-particle azimuthal anisotropy parameter v_2 is shown as a function of the charged particle p_T with $|\eta| < 1$ as measured by the CMS experiment (solid markers) in PbPb collisions at $\sqrt{s_{NN}} =$ 2.76 TeV [5]. Error bars correspond to statistical and gray bands to the small systematic uncertainties. Comparison to results from the ATLAS (open squares) [6] (open squares), ALICE (solid stars) [7] and CMS (open circles) experiments using data collected in 2010 [3] is also shown.

The investigation of the elliptic anisotropy parameter v_2 was significantly extended by CMS. Figure 3 shows v_2 results as a function of p_T from 1 to 60 GeV/c in six centrality ranges and within $|\eta| < 1$ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (CMS data in solid markers) [5]. Error bars correspond to statistical and grey bands to systematic uncertainties. Results from ATLAS (open squares) [6], ALICE (solid stars) [7] and CMS (open circles) [3] data collected in 2010 are also compared. All results show good agreement in their common kinematical region. Their behavior can be described as a rapid increase of the differential v_2 up to $p_T = 3$ GeV/c followed by an abrupt decrease up to $v_2 \sim 10$ GeV/c, beyond which the v_2 values show a much weaker dependence on p_T. In particular, we see that the elliptic anisotropic parameter measured by CMS for $p_T > 20$ GeV/c continues to slowly decrease but remains larger than zero up to at least $p_T \sim 40$ GeV/c.

The v_2 results shown here significantly extend the p_T measurements, up to ranges where particle production is dominated by parton fragmentation and where energy-loss models are expected to be more applicable [5]. The magnitude of v_2 at high p_T can probe the path-length (l) dependence of parton energy loss (ΔE), i.e., $\Delta E \sim l^{\alpha}$. Different values of α are expected in scenarios based on AdS/CFT gravity-gauge dual modeling ($\alpha = 3$) and in perturbative QCD calculations ($\alpha = 1$ for collisional energy loss and $\alpha = 2$ for radiative energy loss). A clear p_T dependence of v_2 is observed at the LHC energy, which may constrain dynamical models on parton energy loss from these different scenarios.

Figure 4 shows the dependence of v_2 on the number of participant nucleons (N_{part}) associated with each centrality bin [5] 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 $1 < |\eta| < 2$, appearing to be independent on η in all p_T bins. It also shows that the v_2 values tend to decrease with increasing collision centrality (larger N_{part}), over

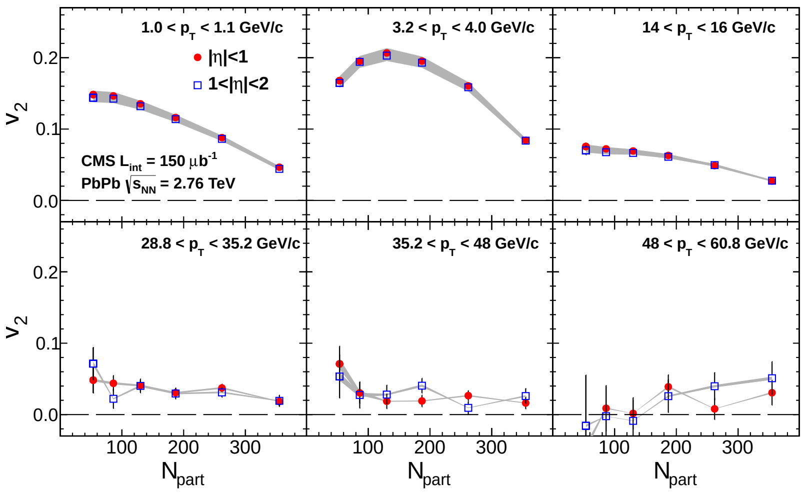

Figure 4: The single-particle azimuthal anisotropy parameter v_2 is shown as a function of the number of participating nucleons, N_{part}, in $|\eta| < 1$ (solid circles) and $1 < |\eta| < 2$ (open squares) for six p_T ranges in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, measured by the CMS experiment. Error bars correspond to statistical and gray bands to the systematic uncertainties.

a wide p_T range, at least up to $p_T \sim 48$ GeV/c. Such behavior is expected for low-p_T particles, where it reflects hydrodynamic flow phenomena and the eccentricity of the initial-state collision geometry. This similarity suggests that the v_2 results at very high p_T are also sensitive to the initial geometry. Therefore, data on the elliptic anisotropy parameter v_2 presented here over a broad range of p_T could provide information on the initial conditions of the hot QCD medium in both realms, i.e., of hydrodynamics at low p_T, and of the in-medium parton energy loss mechanisms at high p_T.

References

[1] CMS Collaboration, *Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Eur. J. Phys.* **C 72** (2012) 2012.

[2] CMS Collaboration, *The CMS experiment at the CERN LHC*, *JINST* **0803** (2008) S08004.

[3] CMS Collaboration, *Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV*, (2012) arXiv: `nucl-ex/1204.1409`

[4] PHOBOS Collaboration, *Importance of correlations and fluctuations on the initial source eccentricity in high-energy nucleus-nucleus collisions*, *Phys. Rev.* **C 77** (2008) 014906.

[5] CMS Collaboration, *Azimuthal Anisotropy of Charged Particles at High Transverse Momenta in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Phys. Rev. Lett.* **109** (2012) 022301.

[6] ATLAS Collaboration, *Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector*, *Phys. Lett.* **B 707** (2012) 330.

[7] ALICE Collaboration, *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*, (2012) arXiv: `nucl-ex/1205.5761`.