RESULTS ON FLOW AND CORRELATIONS WITH THE CMS DETECTOR*

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We present an overview of collective flow phenomena and dihadron correlations measurements from the CMS experiment at the LHC. Fourier components of the anisotropic azimuthal distribution, ranging from the second to the sixth component, are obtained using different analysis techniques, which have different sensitivities to non-flow and flow fluctuation effects. Utilizing a novel and unique high-$p_{\rm T}$ single-track high-level trigger, the results are presented over a broad $p_{\rm T}$ range up to approximately 60 GeV/c, as a function of pseudorapidity and collision centrality. These new data will provide essential information on both the hydrodynamic properties of the medium at low $p_{\rm T}$ and path length dependence of in-medium parton energy loss at high $p_{\rm T}$. Dihadron correlations are measured over a wide acceptance and $p_{\rm T}$ range. Long-range near-side ("ridge") correlation structures are observed from low $p_{\rm T}$ (1 GeV/c) to very high $p_{\rm T}$ (at least 20 GeV/c).

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1. Introduction

The study of the strong interaction in extreme conditions of temperature and density has been the driving force for heavy-ion experiments from the Bevalac to the Large Hadron Collider. A measurement of the azimuthal anisotropy of particle production and dihadron correlations is one of the important tools for studying the properties of the dense matter created in ultrarelativistic heavy-ion collisions.

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2. The CMS detector

As it was shown before, the Compact Muon Solenoid (CMS) experiment [1] at the LHC is well suited to provide a precise measurement of the global event characteristics of the heavy-ion collisions [2].

The central feature of the CMS apparatus is a 3.8 T superconducting solenoid. Located within the field volume are a silicon pixel and strip tracker (pseudorapidity $|\eta| < 2.4$), crystal electromagnetic calorimeter ECAL and brass-scintillator hadronic calorimeter HCAL ($|\eta| < 3$). Muons are measured in gas chambers embedded in the iron return yoke. Hadronic forward calorimeter HF ($3 < |\eta| < 5.2$) is used for centrality and event plane determination in PbPb collisions.

3. Elliptic flow

The elliptic flow parameter, v_2, is defined as the second harmonic coefficient in the Fourier expansion of the particle azimuthal distribution with respect to the event plane

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}[1 + 2v_1 \cos(\phi - \Psi) + 2v_2 \cos 2(\phi - \Psi) + \ldots] , \tag{1}$$

where Ψ is the event plane angle and N_0 stands for full multiplicity. Then, v_2 is the average over particles of $\cos(2(\phi - \Psi))$. Here, we have used the methods of v_2 measurement: based on the measurement of the event plane (EP), 2- and 4-particle cumulants (2, 4), and the Lee–Yang zeros (LYZ).

The results of v_2 as the function of transverse momentum p_{T} for PbPb collisions at the energy in c.m.s. per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV obtained by the four methods at mid-rapidity are presented in Fig. 1, for 12 centrality classes [3]. The value of v_2 increases from central to peripheral collisions as expected if the anisotropy is driven by the spatial anisotropy in the initial state. The transverse momentum dependence shows a rise of v_2 up to $p_{\mathrm{T}} \sim 3$ GeV/c and then a decrease. This behavior is expected if hydrodynamic flow dominates up to $p_{\mathrm{T}} = 2 \div 3$ GeV/c.

The pseudorapidity dependence of the anisotropy parameter is of interest because it provides constraints on the description of the system evolution in the longitudinal direction. Only a weak η dependence is observed, except in the most peripheral events [3].

The CMS detector has been used to perform the first measurements of the azimuthal anisotropy of neutral pions in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [4]. The π^0 mesons in CMS are measured by reconstructing their decay photons ($\pi^0 \to \gamma\gamma$) in the central part of ECAL. Figure 2 presents a comparison between CMS π^0 meson v_2 results, and CMS inclusive charged particle v_2 as a function of p_{T} using the event plane method. The π^0 meson v_2 is systematically lower than that for inclusive charged particles v_2 between

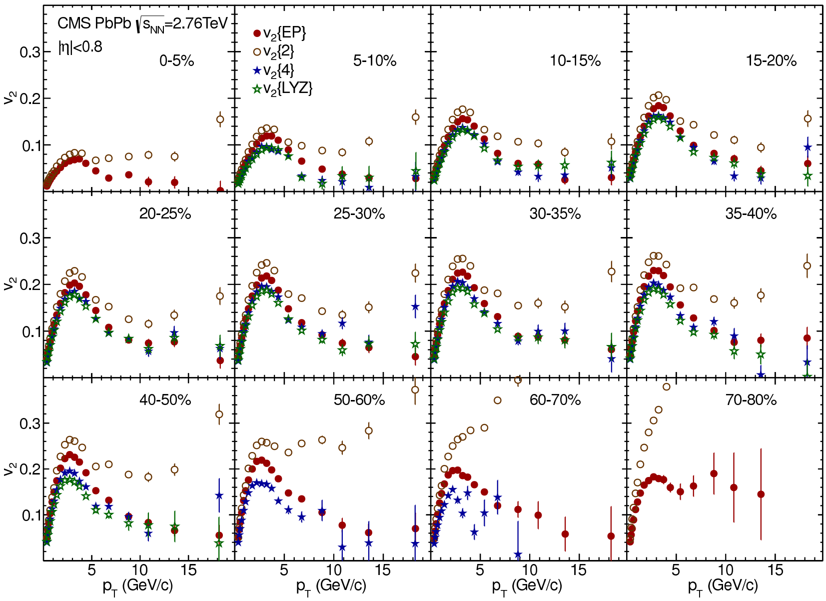

Fig. 1. (Color online) Comparison of the four different methods for determining v_2 as a function of p_{T} at mid-rapidity ($|\eta| < 0.8$) for the 12 centrality classes given in the figures. The error bars show the statistical uncertainties only.

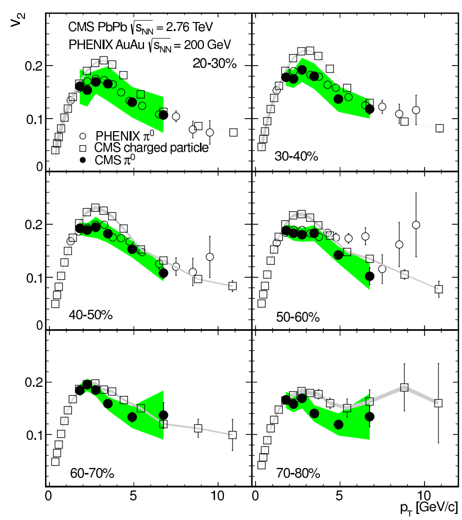

Fig. 2. (Color online) CMS π^0 v_2 (solid circles) as a function of p_{T} compared to CMS charged particles (open squares) and PHENIX [5] (open circles). The results are presented as a function of p_{T} for six centralities (20–30%–70–80%). Shaded bands represent systematic errors.

$2.5 < p_T < 5.0$ GeV$/c$ for mid-central collisions (20–60%). Also it was found that the values of $v_2(p_T)$ for neutral pions measured at RHIC [5] and the LHC were of comparable magnitude. This suggest that there may be a particle-species dependence in the anisotropic flow at LHC, similarly to the baryon/meson differences previously observed at RHIC energies [6, 7].

The investigation of the elliptic anisotropy parameter v_2 was significantly extended by the CMS [8]. Figure 3 shows $v_2(p_T)$ from 1 to 60 GeV$/c$ in six centrality ranges. A comparison to results from ATLAS [9], ALICE [10] and the CMS [3] obtained base on data collected in 2010 are also shown. All results show good agreement in their common kinematic range. Their behavior can be described as a rapid increase of the v_2 up to $p_T = 3$ GeV$/c$ followed by an abrupt decrease up to $p_T \approx 10$ 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 $p_T \approx 40$ GeV$/c$.

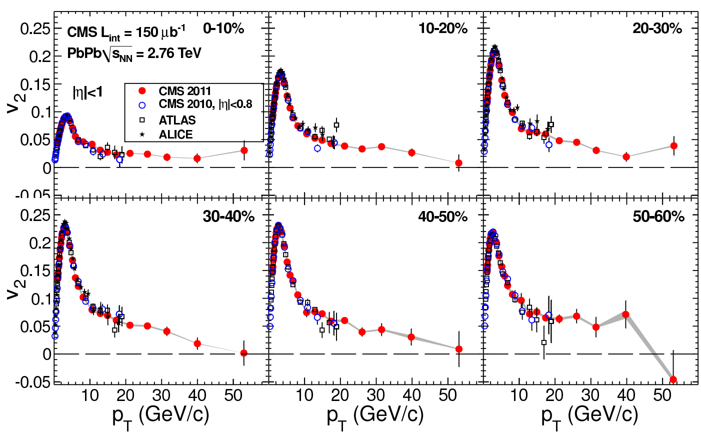

Fig. 3. (Color online) v_2 as a function of p_T up to 60 GeV$/c$ with $|\eta| < 1$ for six centrality ranges, measured by the CMS experiment (solid markers). Error bars denote the statistical uncertainties, while the shaded bands correspond to the systematic uncertainties. Comparison to results from the ATLAS (open squares), ALICE (solid triangles) and CMS (open circles) experiments using 2010 year data is also shown.

4. Higher order harmonic flow

The higher-order coefficients of interest in Eq. (1) are v_3 (triangular flow), v_4 (quadrangular flow), v_5 (pentagonal flow), and v_6 (hexagonal flow). The flow harmonics have been extended to higher harmonics at the CMS [11, 12] using multiple methods, including the dihadron-correlation technique. In general, significant contributions are found up to at least the

5th-order harmonic, with little centrality dependence found for harmonics $n > 2$. These results are consistent with the higher harmonic anisotropies being dominated by fluctuations in the initial participant locations.

The results of v_3 and v_4, as a function of p_T from 0.3 to 50 GeV/c for events with centralities ranging from 0–10% to 50–60%, are presented in Figs. 4 and 5, for $|\eta| < 1$ and $1 < |\eta| < 2$. The p_T dependence of v_3 and v_4 shows a trend of first rapid rise, reaching a maximum at $p_T \approx$ 3 GeV/c, followed by a decrease for p_T values up to about 10 GeV/c. Beyond

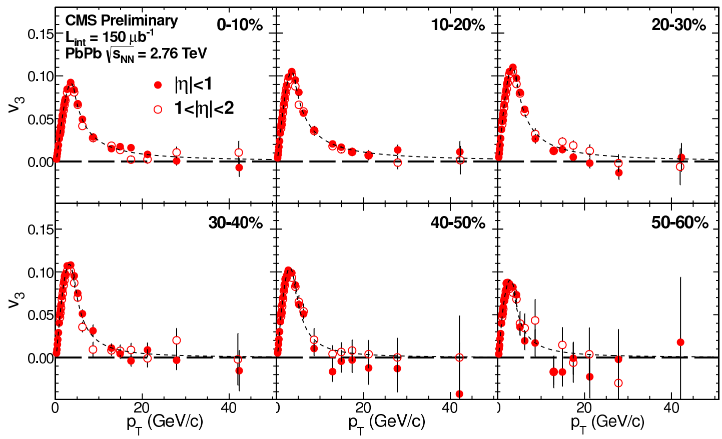

Fig. 4. (Color online) $v_3(p_T)$ for 0.3 to 50 GeV/c with $|\eta| < 1$ (solid markers) and $1 < |\eta| < 2$ (open markers) for six centrality ranges. Error bars denote the statistical uncertainties.

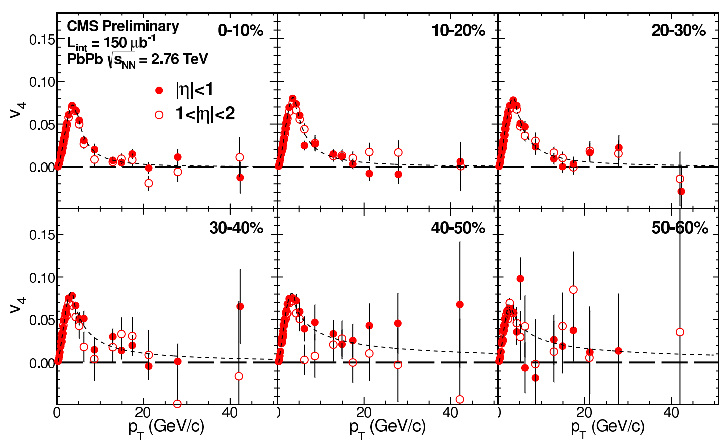

Fig. 5. (Color online) $v_4(p_T)$ for 0.3 to 50 GeV/c with $|\eta| < 1$ (solid markers) and $1 < |\eta| < 2$ (open markers) for six centrality ranges. Error bars denote the statistical uncertainties.

$p_T \approx 10$ GeV/c, the v_3 and v_4 values show a much weaker dependence on p_T and gradually decrease, but remain larger than zero up to at least $p_T \approx 20$ GeV/c. The magnitude of v_3 and v_4 at high p_T can provide further detailed information on the path length dependence of parton energy loss.

5. Dihadron correlations

The "ridge" was discovered in long-range pseudorapidity correlations in central AuAu collisions at the RHIC [13, 14], where particles are found to be correlated in small relative azimuthal angle $|\Delta\phi| \approx 0$ but extending out to very large relative pseudorapidity $|\Delta\eta|$. A striking ridge-like structure has also been observed in very high multiplicity pp collisions at $\sqrt{s} = 7$ TeV by the CMS Collaboration, posing new challenges to the theoretical understanding of the phenomenon [15]. The angular correlations between two charged particles up to $|\Delta\eta| \approx 4$ and over the full range of $\Delta\phi$ in the 0–5% most central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV were measured [16]. The extracted 2D correlation functions show a variety of characteristic features in heavy ion collisions that are not present in minimum bias pp interactions. Short- and long-range azimuthal correlations have been studied as a function of transverse momentum for the trigger particles $p_T^{\rm trig}$. The observed long-range ridge-like structure on the near-side $|\Delta\phi| \approx 0$ is most evident in the intermediate transverse momentum range, $2 < p_T^{\rm trig} < 6$ GeV/c but decreases to zero for $p_T^{\rm trig}$ above 8–10 GeV/c.

At very high $p_T^{\rm trig}$, sizeable v_2 signals are observed, which exhibit an almost flat p_T dependence from 10 to 20 GeV/c for most of the centrality ranges [17]. This is not the case for the higher-order harmonics. The extracted v_2–v_5 are shown in Fig. 6 as a function of participant number $N_{\rm part}$, for three representative $p_T^{\rm trig}$ ranges. A strong centrality dependence of v_2 is observed for all $p_T^{\rm trig}$ ranges, while the higher-order harmonics v_3–v_5 do not

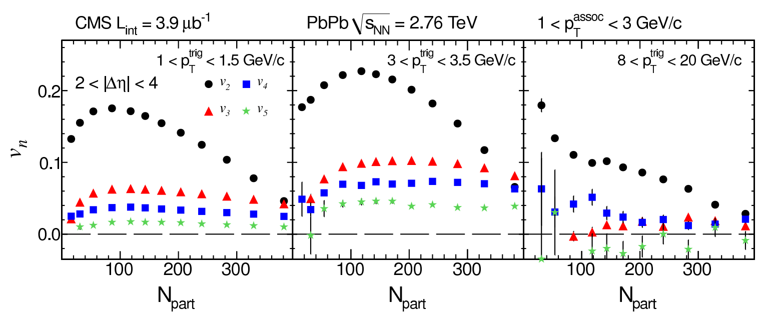

Fig. 6. (Color online) The v_2–v_5 coefficients, extracted from the long-range ($2 < |\Delta\eta| < 4$) azimuthal dihadron correlations as a function of $N_{\rm part}$ in $p_T^{\rm trig}$ ranges of 1–1.5, 3–3.5, and 8–20 GeV/c.

vary significantly with $N_{\rm part}$. This behaviour is expected in the context of hydrodynamic flow for low $p_{\rm T}$ particles and the path-length dependence of the parton energy-loss scenario for high $p_{\rm T}$ particles.

6. Flow in ultra-central collisions

Azimuthal anisotropy harmonics have been measured in the ultra-central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using data from the 2011 run [18]. 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 for very central PbPb collisions, a unique trigger on the 0–0.2% ultra-central events was implemented by requiring ranges on total transverse energy in the HF calorimeters and total multiplicity of cluster hits in the pixel tracker. A total of about 1.8 million events were recorded, corresponding to an integrated luminosity of 150 μb^{-1}. Fourier flow harmonics are extracted from long-range dihadron correlations.

Figure 7 shows the $p_{\rm T}$ dependence of the flow coefficients. The different v_n coefficients exhibits very different behavior: at $p_{\rm T} > 1$ GeV/c, v_2 becomes smaller than higher-order harmonics, even smaller than v_5 for $p_{\rm T} > 3$ GeV/c. These measurements can be compared to hydrodynamics calculations with fluctuating initial conditions and can provide important constraints on the value of the shear viscosity of the medium in a largely model-independent way.

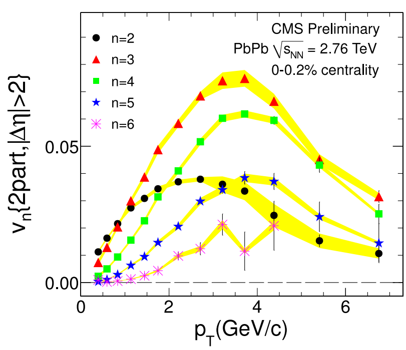

Fig. 7. (Color online) The v_2–v_6 values as a function of $p_{\rm T}$ in 0–0.2% central PbPb collisions. Error bars denote the statistical uncertainties, while the shaded bands correspond to the systematic uncertainties.

7. Summary

Using LHC PbPb runs in 2010 and 2011, the CMS Collaboration has provided a wealth of new information about the flow and correlations. At low transverse momentum, there are measurement up to 6th-order harmonic coefficients of the flow in a broad centrality, $p_{\rm T}$ and rapidity range employing a variety of methods, flow measurement for π^0 and the ultra-central PbPb collisions. For the high transverse momentum, there are the first v_2–v_4 measurements at very high $p_{\rm T}$ and also very high $p_{\rm T}$ dihadron correlations.

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