

## FLOW PHENOMENA IN CMS

Quan Wang for the CMS Collaboration  
*Department of Physics & Astronomy,  
Lawrence, KS 66045-7582, USA*



Measurements by the CMS experiment of azimuthal angle correlations of charged hadrons in  $\sqrt{s_{NN}} = 2.76$  TeV Pb+Pb collisions are presented. The second-order elliptic flow harmonic  $v_2$  is shown as a function of transverse momentum ( $p_T$ ) and centrality in a broad kinematic range. Various techniques are employed to extract the signal strength of the harmonics: the event-plane method, cumulant, Lee-Yang Zeros and di-hadron correlation methods. Higher-order harmonic results,  $v_3$  from the event-plane method and  $v_3, v_4, v_5$  and  $v_6$  from di-hadron correlation methods are also shown. The results indicate that higher-order, odd harmonics are mainly dominated by initial-state fluctuations. Neutral particle  $\pi^0$   $v_2$  results and high- $p_T$  particle (up to 60 GeV/c)  $v_2$  results are also shown. The di-hadron correlation results of  $v_2$  and  $v_3$  in  $\sqrt{s_{NN}} = 5.02$  TeV p+Pb collisions are presented and compared to p+p results.

### 1 Introduction

In non-central, heavy-ion collisions, the initial nuclear overlap region is spatially anisotropic and is usually characterized with an “almond-like” shape. The initial spatial anisotropy leads to a final-state momentum azimuthal anisotropy resulting from the pressure gradients developed in collision. The azimuthal anisotropy, characterized by Fourier expansion coefficients, is an important feature of the hot, dense medium produced in heavy-ion collisions. The distribution of charged particles with respect to the participant plane can be written as,

$$\frac{dN}{d\Delta\phi} \sim 1 + 2v_2 \cos 2(\phi - \psi_2) + 2v_3 \cos 3(\phi - \psi_3) + \dots \quad (1)$$

where  $v_n$  is the  $n$ -th order Fourier coefficient, and  $\phi$  is the azimuthal angle of each particle.  $\psi_n$  is the  $n$ -th harmonic participant plane of each event. The second harmonic  $v_2$  is often called elliptic flow, which is one of the most important measurements providing information of the strongly couple quark-gluon plasma (sQGP)<sup>1</sup>. The third harmonic coefficient  $v_3$  is referred to as triangular flow, which is the largest coefficient next to  $v_2$ . Higher order terms,  $v_n$  where  $n > 2$ , can provide information of the initial-state fluctuations, whose magnitude can be sizable compare to  $v_2$ .<sup>2</sup>

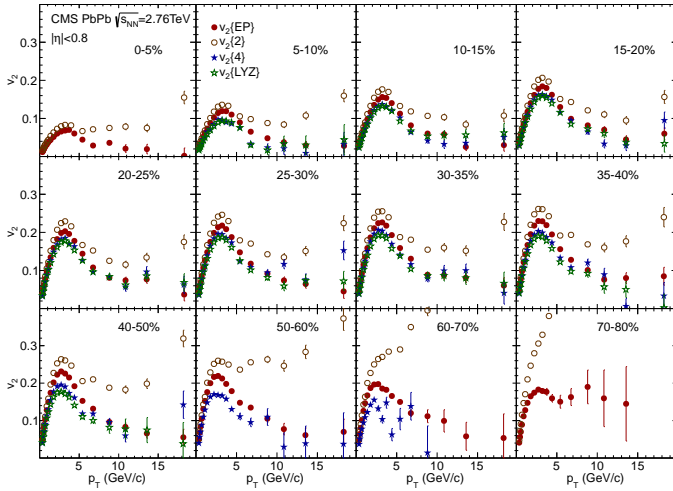


Figure 1: Elliptic flow of Pb+Pb at 2.76 TeV based on four methods.

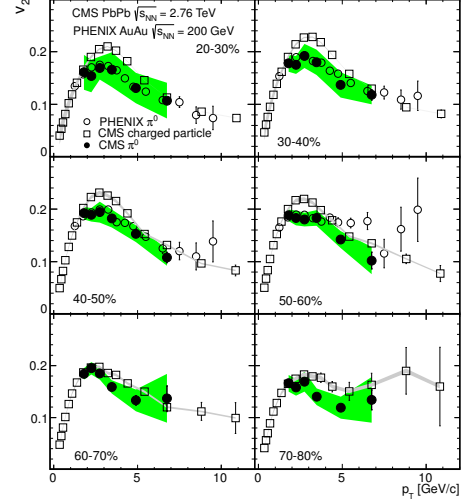


Figure 2:  $\pi^0$  elliptic flow compared to lower energy PHENIX<sup>8</sup> and CMS charged particle results<sup>3</sup>.

## 2 Data Analysis and Results

Figure 1 shows the  $v_2$  differential results, obtained from Pb+Pb collision at a center-of-mass energy of  $\sqrt{s_{NN}} = 2.76$  TeV, for the event-plane<sup>4</sup>, two- and four-particle cumulant<sup>5</sup> and Lee-Yang Zeros<sup>6</sup> methods with  $0.3 < p_T < 20$  GeV/ $c$  and for twelve centrality classes<sup>3</sup>. The differences between methods are understood by their different sensitivities to non-flow and fluctuation effects. Two-particle cumulant method is very sensitive to non-flow, especially at high  $p_T$ . The four-particle cumulant method and Lee-Yang Zeros method are less sensitive to non-flow due to the nature of multi-particle correlations. There is no pseudo-rapidity gap required in two- and four-particle cumulant methods, while a gap of three units of pseudo-rapidity is applied in the event-plane method between the particles used for the flow analysis and particles used for the event-plane reconstruction. Hence the event-plane method can largely suppress non-flow.

The CMS  $\pi^0$  elliptic anisotropy for Pb+Pb 2.76 TeV results<sup>7</sup> are shown in Fig. 2, and compared to CMS charged particle event-plane  $v_2$ <sup>3</sup> and PHENIX  $\pi^0$  results for Au+Au at 200 GeV<sup>8</sup>. The CMS  $\pi^0$  results are comparable to the lower energy PHENIX results, while lower than the CMS charged particle results. This is consistent with the higher elliptic anisotropy seen for baryons as previously found at RHIC.

For higher  $p_T$  particles, the lenticular-shape of the overlap region in heavy-ion collisions can lead to azimuthal asymmetry as a result of the path length dependence of parton energy loss. Figure 3 shows the  $v_2$  coefficients for six centrality classes<sup>9</sup> with an extended  $p_T$  range up to 60 GeV/ $c$  obtained from data selected by a dedicated high- $p_T$  trigger in the 2011 Pb+Pb run, along with previous ATLAS<sup>10</sup> and CMS results from 2010 data<sup>3</sup>. The  $v_2$  coefficient results remain finite up to at least  $p_T = 40$  GeV/ $c$ , and become consistent with zero above that for mid-central collisions (above 30%). These results shed light on the path length dependent energy loss of high  $p_T$  partons in the medium.

In Fig. 4 the integrated  $v_2$  values<sup>9</sup> for different  $p_T$  ranges are shown as a function of the number of participant nucleons ( $N_{part}$ ) for two different pseudo rapidity ranges. These results demonstrate that the higher  $p_T$  asymmetries are influenced by the initial-state geometry. Below 4 GeV/ $c$ , the  $v_2$  values are consistent with the hydrodynamic flow behavior of a hot dense medium. Above 14 GeV/ $c$ , the flow component is expected to be negligible. For these higher  $p_T$  ranges, the increase in  $v_2$  as the collisions become more peripheral (decreasing  $N_{part}$ ) reflects the corresponding increase in the eccentricity of the lenticular overlap region as  $N_{part}$  decreases.

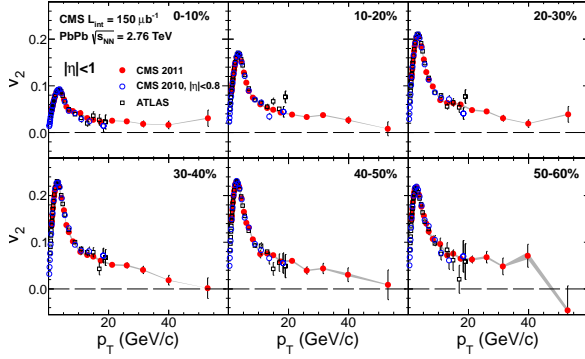


Figure 3: Extended  $v_2(p_T)$  distribution up to 60 GeV/c for six centrality bins. Lower  $p_T$  results from both CMS<sup>3</sup> and ATLAS<sup>10</sup> are shown.

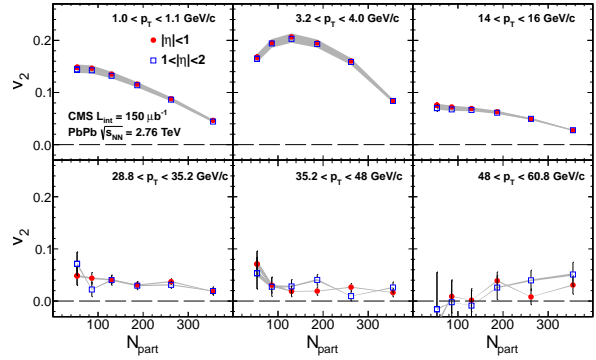


Figure 4:  $v_2$  values as a function of the number of participant nucleons for given  $p_T$  ranges.

Higher-order harmonics have been measured at CMS for Pb+Pb at 2.76 GeV using various methods, including the event-plane method and di-hadron correlation methods<sup>11</sup>. Significant contributions are found up to at least the 5-th order harmonics ( $v_5$ ), with little centrality dependence seen for the odd harmonics  $n=3$  and  $n=5$ . These results suggest that these higher odd harmonic anisotropies are dominated by initial-state fluctuation of the collisions.

The initial-state geometry of the produced medium in relativistic heavy-ion collisions results in a large uncertainty for the deduced value of the shear viscosity to entropy ratio ( $\eta/s$ ) of the medium. It has been suggested that the initial condition has less an influence on very central events where the geometry is determined only by the extent of the colliding nuclei<sup>12 13</sup>. Using a dedicated ultra-central collision trigger, CMS selects the most central 0-0.2% events in Pb+Pb collisions at 2.76 GeV<sup>14</sup>. The flow coefficients  $v_2$  through  $v_6$  are measured using the di-hadron correlation method. The  $p_T$  dependence of  $v_n$  is shown in Fig. 5, where higher order harmonics ( $n > 2$ ) are strongly excited.  $v_3$ ,  $v_4$  and  $v_5$  even rise above  $v_2$  at higher  $p_T$  values, suggesting the strong influence of the initial-state fluctuations in these ultra-central collisions.

The recent p+Pb di-hadron correlation results of high-multiplicity triggered events at 5.03 TeV reveal a long-range, near-side ridge like structure, suggesting a flow-like behavior<sup>15</sup>. In Fig. 6 di-hadron correlation yield, after applying ZYAM procedure are shown for various selections of  $p_T$  and multiplicity, along with corresponding results obtained from p+p collision at 7 TeV using the same procedure. The data were recorded using a high multiplicity trigger implemented to select ultra-central events. The HIJING simulation results<sup>16</sup>, shown as dashed curves, qualitatively reproduce the shape of the correlation yield at low multiplicity, but fail at high multiplicity. Long-range, near-side particle correlations in p+Pb collisions have been predicted using models that assume collective hydrodynamic expansion with fluctuating initial-conditions. The correlation results<sup>17</sup> from the predicted elliptic and triangular flow components for p+Pb collision at 4.4 TeV are shown as solid curves for  $1.0 < p_T < 2.0$  GeV/c. The correlation yields in high multiplicity events are strongly enhanced compared to p+p collisions. Further analysis is needed to investigate the origin of the ridge like correlations and the collective behavior.

### 3 Summary

The LHC Pb+Pb runs at 2.76 TeV in 2010 and 2011 have provided abundant new results that can be informative for the understanding of the properties of the medium produced in heavy-ion collisions. The CMS program has investigated the azimuthal asymmetries in a wide kinematic range, from the hydrodynamic flow behavior at low  $p_T$ , the  $\pi^0$  azimuthal anisotropies at intermediate  $p_T$ , and the asymmetric anisotropy from parton energy loss in the medium at high  $p_T$ . At low  $p_T$ ,  $p_T$  differential  $v_n$  results are sensitive to the initial-state fluctuations and

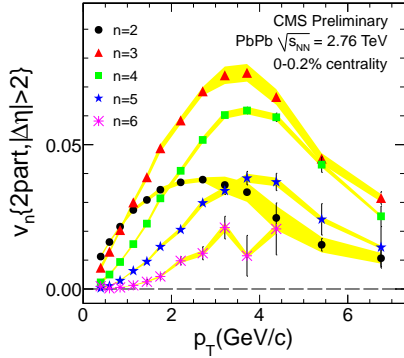


Figure 5:  $v_n$  as a function of  $p_T$  for ultra-central events.

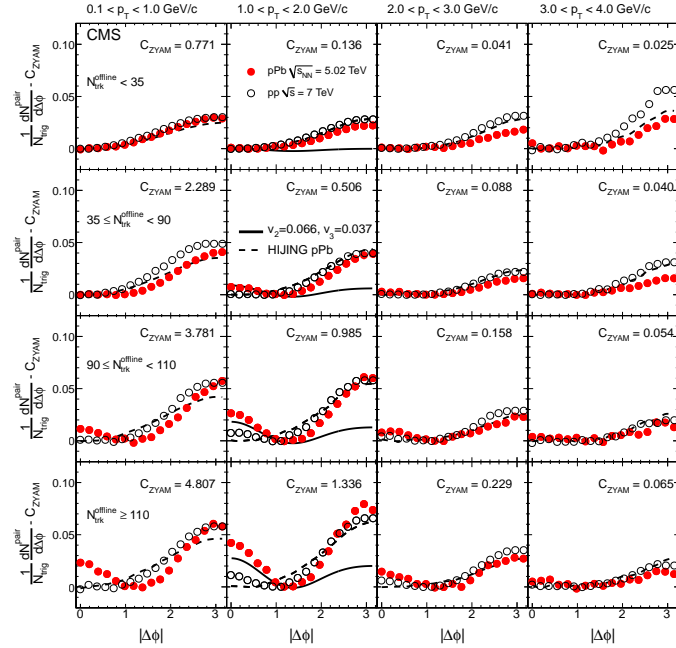


Figure 6: Di-hadron correlated yield for 5.02 TeV p+Pb and 7 TeV p+p, compared to p+Pb predictions for HIJING<sup>16</sup> (dashed curve) and a hydrodynamics model<sup>17</sup> (solid curve)

the property of the hot dense medium created in heavy-ion collisions. A single-track, high- $p_T$  trigger enables us to extend the  $v_2$  measurements up to 60 GeV/c, making it possible to explore the path length dependence of parton energy loss in the medium. An ultra-central collision trigger has allowed a measurement of  $v_n$  coefficients with  $n=2$  through 6 for the top 0.2% most central events. The recent p+Pb run at 5.03 TeV in 2012 has revealed a near-side long-range ridge like structure in di-hadron correlation analysis, which could suggest hydro-like correlations arising in a small system. Further work is needed to study the origin and behavior of the ridge structure.

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