FLOW PHENOMENA IN CMS

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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 π^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,

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

where v_n is the n-th order Fourier coefficient, and ϕ is the azimuthal angle of each particle. ψ_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) [1]. 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. [2]

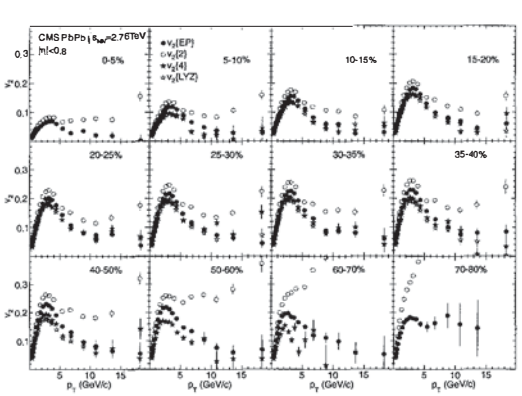

Figure 1: Elliptic flow of Pb+Pb at 2.76 TeV based on four methods.

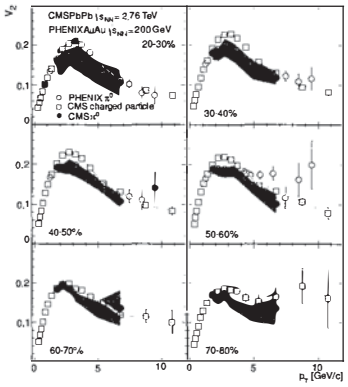

Figure 2: π^0 elliptic flow compared to lower energy PHENIX [8] and CMS charged particle results [3].

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 [4], two- and four-particle cumulant [5] and Lee-Yang Zeros [6] methods with $0.3 < p_T < 20$ GeV/c and for twelve centrality classes [3]. 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 π^0 elliptic anisotropy for Pb+Pb 2.76 TeV results [7] are shown in Fig. 2, and compared to CMS charged particle event-plane v_2 [3] and PHENIX π^0 results for Au+Au at 200 GeV [8]. The CMS π^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-on 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 [9] 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 [10] and CMS results from 2010 data [3]. 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 [9] 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.

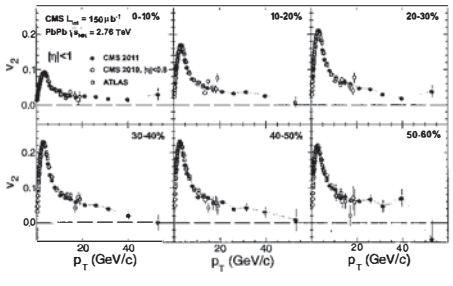

Figure 3: Extended $v_2(p_T)$ distribution up to 60 GeV/c for six centrality bins. Lower p_T results from both CMS [3] and ATLAS [10] are shown.

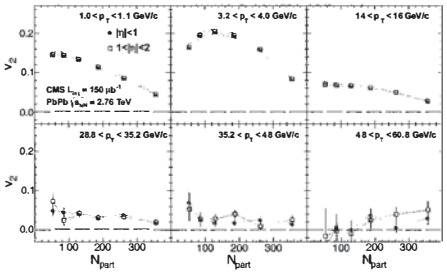

Figure 4: v_2 values as a function of the number of participant nucleons for given p_T ranges.

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 [11]. 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 (η/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 [12 13]. Using a dedicated ultra-central collision trigger, CMS selects the most central 0-0.2% events in Pb+Pb collisions at 2.76 GeV [14]. 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 [15]. 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 [16], 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 [17] 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 π^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

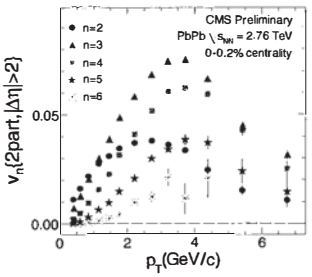

Figure 5: v_n as a function of p_T for ultra-central events.

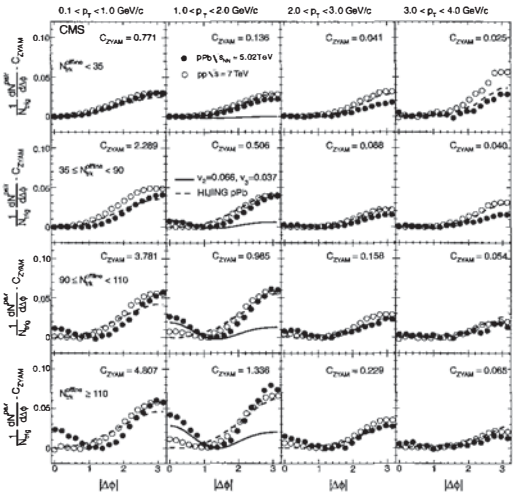

Figure 6: Di-hadron correlated yield for 5.02 TeV p+Pb and 7 TeV p+p, compared to p+Pb predictions for HIJING [16] (dashed curve) and a hydrodynamics model [17] (solid curve)

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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