Flow Phenomena in Pb-Pb Collisions at CMS

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This proceeding reports the results from azimuthal angle correlations of charged hadrons measured in $\sqrt{s}_{NN}$ = 2.76 TeV PbPb collisions by the CMS experiment. The azimuthal distributions exhibit anisotropies that are correlated with the event-by-event orientation of the participant plane (the plane that contains the beam axis and the short direction of the lenticular overlap region). In general, the participant plane will not contain the reaction impact parameter vector because of fluctuations that arise from having a finite number of nucleons. The second Fourier coefficient of the charged hadron azimuthal distributions was measured as a function of transverse momentum, pseudorapidity, and centrality in a broad kinematic range. In addition, results on higher-order Fourier components are presented and their connection to the hydrodynamic medium will be discussed.

1 Introduction

In non-central heavy ion collisions, the interaction region is spatially anisotropic, often characterized as an "almond shape". This anisotropy in the initial collision geometry leads to a final-state momentum azimuthal anisotropy with respect to the participant plane. This anisotropy can be characterized with a Fourier expansion of the azimuthal distribution of charged particles. The resulting Fourier coefficients are known as anisotropy or flow parameters and provide information about the collective behavior of the medium. The second coefficient, v_2, is referred to as elliptic flow and is one of the most important measurements we have that can probe the hydrodynamic properties of the quark-gluon plasma. v_2 can also be used to constrain parton energy-loss models. In particular, the path-length of a jet traversing the medium will be correlated with its angle with respect to the participant plane, since the short-axis of the "almond" will be in the participant plane. It is expected that there will be more high-p_T particles emitted closer to the participant plane giving a non-zero value for v_2, the actual value of which will depend on the exact path-length dependence of the energy loss mechanism.

2 The Event Plane Method

Since the participant plane is not experimentally observable, we have to estimate with the event plane, which is the plane that contains the beam axis and the direction of maximum transverse energy [1]. Once the event plane has been calculated for each event and corrected for detector inefficiencies the average correlation of the particles in each event is calculated and gives us an estimate of v_2 as a function of p_T, η, and centrality. Finally, due to the finite resolution of the detector, the measurements must be corrected by a resolution factor to give the actual elliptic flow values.

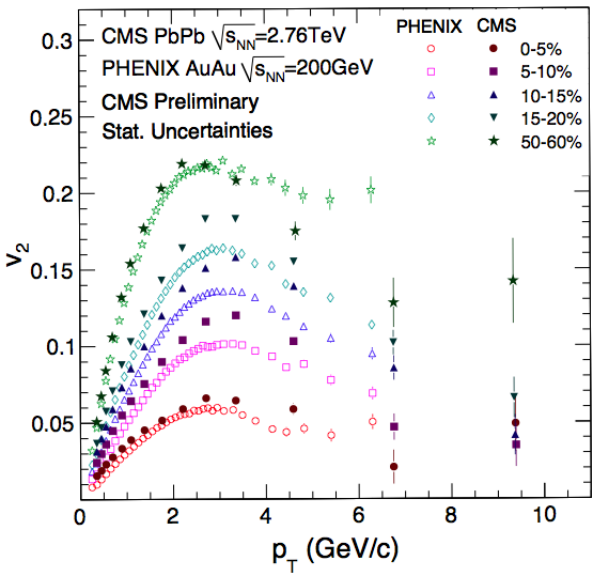


Figure 1: The single-particle azimuthal anisotropy, v_2, as a function of p_T at mid-rapidity ($|\eta| < 0.8$ for five different centrality classes measured with the event plane (EP) method. CMS data from PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is shown with the solid markers and PHENIX data from AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV is shown with the open markers. Only statistical uncertainties are shown.

Fig. 2 shows a direct comparison between CMS and PHENIX results for v_2 as a function of p_T in five different centrality classes at mid-rapidity ($|\eta| < 0.8$) using the event plane method. Even though there is an increase in center-of-mass energy by a factor of 14 from RHIC (PHENIX) to the LHC (CMS), there is only a slight increase in the observed differential v_2 values. In both cases we see v_2 reach a maximum at 3 GeV/c. This is expected since at higher momentum hard processes begin to dominate and hydrodynamic effects become less significant [1].

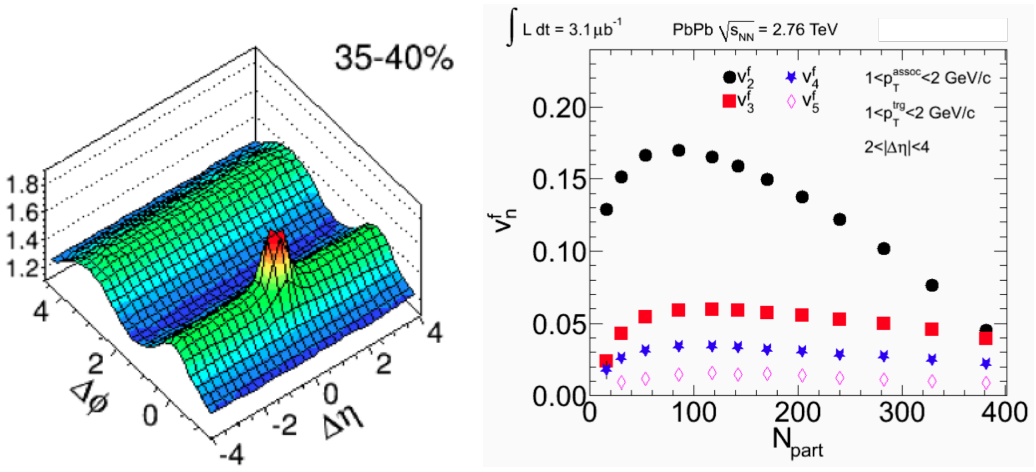
3 Dihadron Correlations

Dihadron correlations are another way of investigating flow properties of the QGP. Since these measurements do not rely on the reaction plane and the systematic uncertainties associated with finding the event plane, they are a useful alternative. The associated yield, shown in Fig. 2(a), shows the two-particle correlation plotted as a function of $\Delta\eta$ and $\Delta\phi$ between the two particles. The correlated particles are each chosen such that a "trigger" particle in a given p_T^{trig} range is paired with all of the "associated" particles in a given event that are in a specified p_T^{assoc} range [2].

By looking at the long-range region of the associated yield, $2 < |\Delta\eta| < 4$, and projecting onto the $\Delta\phi$ axis, we can again Fourier expand the 1-D associated yield and extract the coefficients, $V_{n\Delta}(p_T^{trig}, p_T^{assoc})$. It has been shown [2] that these Fourier coefficients from dihadron correlations can be factored into the product of the single-particle azimuthal anisotropy harmonics: $V_{n\Delta}(p_T^{trig}, p_T^{assoc}) = v_n(p_T^{trig}) \times v_n(p_T^{assoc})$. With this relationship we can use dihadron correlations to compare with other techniques such as the event plane method. We can also measure higher-order harmonics, which are shown as a function of N_{part} in Fig. 2(b). One can see an obvious centrality dependence of v_2. However, v_3 - v_5 are largely independent of centrality.

4 v_2 at high p_T

Flow effects are only expected to be significant up to $p_T \approx 3$ GeV/c. At higher transverse momentum, recombination effects and hard processes begin to dominate [1]. Despite the absence of hydrodynamic flow at high p_T, we can still use the anisotropy parameter v_2 to constrain the



(a) The associated yield

(b) Higher-order flow harmonics

Figure 2: Subfigure (a) shows the associated yield in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in $35-40\%$ centrality class with $4 < p_T^{trig} < 6$ GeV/c and $2 < p_T^{assoc} < 4$ GeV/c. A $\cos(2\Delta\phi)$ modulation is clearly visible away from the jet region ($2 < |\eta| < 4$), which is indicative of elliptic flow. Subfigure (b) shows the single-particle azimuthal harmonics, $v_2 - v_5$, from the long range ($2 < |\eta| < 4$) azimuthal dihadron correlations as a function of N_{part} in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $1 < p_T^{assoc} < 2$ GeV/c and $1 < p_T^{trig} < 2$ GeV/c. $v_3 - v_5$ are essentially independent of the collision centrality, as expected if they are caused by fluctuations in the initial collision geometry.

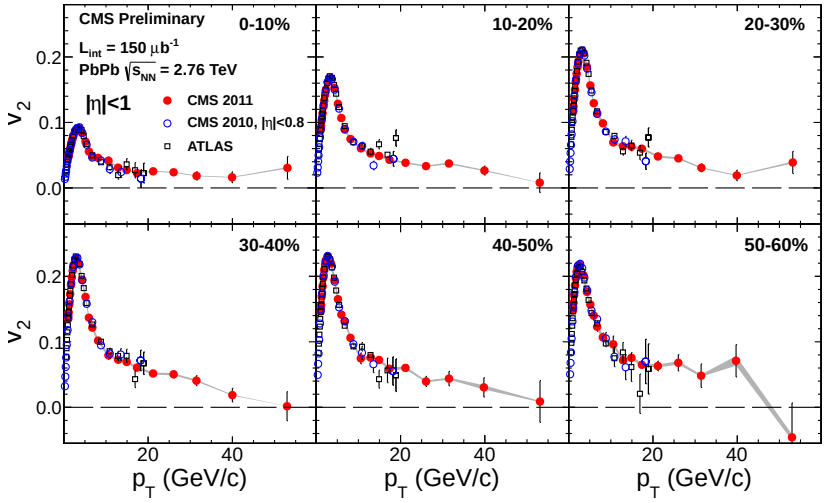
path-length dependence of parton energy-loss mechanisms in a QGP medium [3]. Fig. 3(a) shows v_2 as a function of transverse momentum up to $p_T \approx 60$ GeV/c in six different centrality classes at mid-rapidity ($|\eta| < 1$) with the event plane method. The data is also compared to 2010 CMS data (blue open circles) and ATLAS data (black open squares). This is the first accurate measurement of v_2 at such high p_T. Fig. 3(b) shows v_2 as a function of centrality in six different p_T ranges for $|\eta| < 1$ (red circles) and $1 < |\eta| < 2$ (blue open squares). You can see that in all centrality classes a non-zero v_2 persists up to $p_T \approx 40$ GeV/c.

5 Conclusions

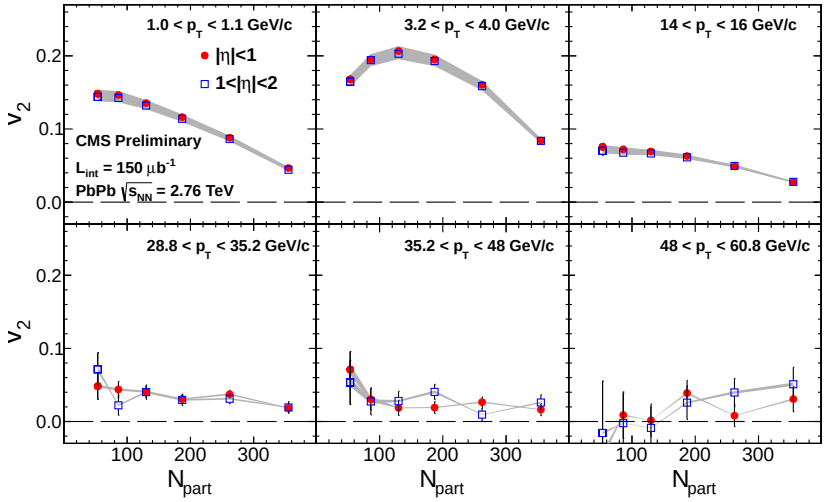
Detailed measurements of charged hadron azimuthal anisotropies in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been presented. The results cover a broad kinematic range in different centrality classes. In particular, v_2 measurements from the event plane method were shown at a p_T range much higher then any previosly published results. The data indicate that the elliptic flow at mid-rapidity at LHC energies is comparable to that at RHIC energies. It was also shown that non-zero higher-order Fourier coefficients exist and are independent of centrality. These results will be useful in comparison to hydro models and will help us to better understand the hydrodynamic properties of the QGP. The high-p_T v_2 data indicates that there is parton energy-loss occurring in the medium that is correlated with the reaction plane, thus implying a path-length dependence. Further studies will be useful for constraining this path-length dependence in energy-loss models.

References

1. CMS Collaboration, arXiv:1204.1409v1 [nucl-ex] 6 Apr 2012.
2. CMS Collaboration, arXiv:submit/0398170 [nucl-ex] 16 Jan 2012.
3. CMS Collaboration, arXiv:1204.1850v1 [nucl-ex] 9 Apr 2012



(a) v_2 as a function of p_T for six different centrality classes.



(b) v_2 as a function of N_{part} for six different p_T ranges.

Figure 3: Subfigure (a) shows the single-particle azimuthal anisotropy, v_2, as a function of the charged particle transverse momentum from $1-60$ GeV/c with $|\eta| < 1$ in six different centrality ranges in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV/c. Results from the data collected in 2011 by the CMS experiment are shown (red solid markers) as well as ATLAS (black open squares) and 2010 CMS data (blue open circles). Error bars denote the statistical uncertainty while the grey bands correspond to the systematic uncertainty. Subfigure (b) shows v_2 as a function of N_{part} in six different p_T ranges with $|\eta| < 1$ (red circles) and $1 < |\eta| < 2$ (blue open squares) in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Error bars denote the statistical uncertainty while the grey bands correspond to the systematic uncertainty.