Elliptic flow studies in heavy-ion collisions using the CMS detector

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Abstract. The azimuthal anisotropy of charged particle emission in heavy ion collisions is a sensitive probe of the properties and the dynamical evolution of the produced matter. The systematic study of elliptic flow ($v_2$), and higher order harmonics can yield information about the equilibration timescale, the nuclear equation of state and the viscosity in the different stages of the system evolution, as well as the initial state conditions of the heavy ion collisions. Experimentally, it is important to be able to reconstruct the flow using different methods, since they have different sensitivity to non-flow correlations and fluctuations which affect the extracted signal. In CMS, the nuclear reaction plane can be determined independently using several different detector subsystems. The reconstruction of elliptic flow using calorimetry and the tracking system is presented.

1. Introduction
In non-central collisions between two nuclei the beam direction and the impact parameter vector define a reaction plane for each event. A measurement of the azimuthal anisotropy of particle production with respect to the reaction plane is one of the important tools for studying the properties of the dense matter created in ultra relativistic heavy-ion collisions [1, 2]. There is a number of predictions for elliptic flow in the heavy-ion programme at the LHC [3, 4, 5]; compared with the RHIC energies a decrease, increase or saturation is possible.

This report is dedicated to studying the capability of the CMS detector [6] at the LHC to reconstruct the reaction plane and to measure elliptic flow, using calorimetry and the tracking system. The high tracking efficiency and low rate of fake tracks at CMS, together with a large calorimetric coverage, provide a precise measurement of global event characteristics, event by event [7, 8].

The first measurements of the proton-proton collisions with the CMS detector at the LHC was begun in November 2009 [9]. The start of the heavy-ion programme at the LHC with lead-lead collisions at the energy in c.m.s. $\sqrt{s} = 2.76$ TeV per nucleon pair is planned for the end of 2010.
2. Methods

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 reaction plane:

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi} [1 + 2v_1 \cos(\phi - \Psi_R) + 2v_2 \cos 2(\phi - \Psi_R) + ...], \quad (1)$$

where $\Psi_R$ is the true reaction plane angle and $N_0$ stands for full multiplicity. Then $v_2$ is the average over particles of $\cos(2(\phi - \Psi_R))$.

There exists a wealth of anisotropic flow measurement methods, each of which has its advantages and limitations. Here we have used a $v_2$ determination method based on plane angle measurement. Usually the true elliptic flow coefficient in the event plane (EP) method is evaluated by dividing the observed $v_2$ value by a factor, $R$ [10], which accounts for the event plane resolution:

$$v_2\{EP\} = \frac{v_2^{\text{obs}}\{EP\}}{R} = \frac{\langle \cos 2(\phi - \Psi_2) \rangle}{\langle \cos 2(\Psi_2 - \Psi_R) \rangle}. \quad (2)$$

Here the event plane angle $\Psi_2$ is the estimate of the true reaction plane angle $\Psi_R$. The mean was taken over all charged particles in a given event and then over all events. In order to avoid the trivial autocorrelation of particles, the event plane angle $\Psi_2$ and, hence, $R$ are calculated from the angular distribution of a sample of events, and $v_2$ from another event sample with the same multiplicity. The samples can be selected, for instance, in two distinct regions of pseudorapidity, such as $\eta < 0$ and $\eta > 0$.

The event plane angle, $\Psi_n$, can be determined from the measured $n$-th harmonics via the standard method [10, 11]:

$$\tan n\Psi_n = \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}, \quad n \geq 1, \quad 0 \leq \Psi_n < 2\pi/n, \quad (3)$$

where $\phi_i$ is the azimuthal angle of the $i$-th particle and $w_i$ is a weight. The sum runs over all particles in each given event.

Other techniques like cumulant [12] and Lee-Yang zero’s [13] methods for elliptic flow measurement with CMS detector at the LHC also will be useful.

3. Analysis and discussion

For the estimation of the azimuthal anisotropy of particles in heavy ion collisions, the HYDJET event generator [14] was used with a full GEANT simulation of the CMS detector responses.

**Study of event plane resolution with CMS calorimeters.** It was found that the CMS calorimetric system can be used for the determination of the event plane, using the energy responses of the calorimeter towers $\omega_i = E_i$ in Eq. (3) [7]. Although the anisotropic flow has to be maximal at midrapidity, the much larger total energy deposition in the CMS calorimeter endcaps ($1.5 < |\eta| < 3$) results in reduced relative fluctuations and, accordingly, in a much better event plane resolution. Moreover, energy flow measurements in the endcaps are less sensitive to the magnetic field than in the barrel region ($|\eta| < 1.5$).

**Study of $v_2$ reconstruction with the CMS tracker.** A sample of $10^5$ Pb+Pb events at impact parameter $b = 9$ fm at $\sqrt{s} = 5.5$ TeV per nucleon pair within the pseudorapidity window $|\eta| < 2.4$ (the CMS tracker acceptance) was utilized. The standard settings were used to reconstruct tracks (i.e. more than 12 hits per track and a track fit probability above 1%). A cut on $p_T > 0.9$ GeV/c was set in both simulated and reconstructed events. The number of reconstructed tracks per event is about 170 at this centrality.
Figure 1. The $p_T$ dependence of $v_2\{EP\}$ in Pb+Pb collisions for impact parameter $b = 9$ fm, calculated with the simulated (open circles) and reconstructed events (closed squares). Statistical errors are shown for $10^5$ events. Non-flow systematic uncertainties not included.

Figure 2. The $\eta$ dependence of $v_2\{EP\}$ in Pb+Pb collisions for impact parameter $b = 9$ fm, calculated with the simulated (open circles) and reconstructed events (closed squares). Statistical errors are shown for $10^5$ events. Non-flow systematic uncertainties not included.

The differential $p_T$ and $\eta$ dependencies of the elliptic flow in Pb+Pb collisions for impact parameter $b = 9$ fm are shown in Fig. 1 and Fig. 2, respectively. The dependencies were calculated using the event plane angle determination from Eq. (3). For the $p_T$ dependence, two sub-event sets were used, with $\eta > 0$ and $\eta < 0$. For the $\eta$ dependence, the factor $R$ in each histogram bin was calculated using particles from other bins (excluding neighboring bins).
4. Summary
We have shown that the CMS detector at the LHC will be able to determine the reaction plane using the calorimeters and the tracker. The transverse momentum dependence of the elliptic flow coefficient $v_2$ can be reconstructed in the CMS tracker with high accuracy. The CMS track reconstruction performance induces a systematic error estimated to be about 3% on the $v_2$ determination.

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