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Elliptic flow studies using the CMS detector

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Abstract

The azimuthal anisotropy of charged particles in heavy ion collisions is an important probe of quark-gluon plasma evolution at early stages. The nuclear reaction plane can be determined independently by different detector subsystems and using different analysis methods. This paper reports the capability of the CMS detector at the LHC to reconstruct the reaction plane of the collision and to me asure elliptic flow with calorimetry and a tracking system. The analysis is based on a full CMS detector simulation of Pb+Pb events with the HYDJET event generator.

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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. The magnitude, the p_T and hadron mass dependencies of the radial and elliptic flows below $p_T \approx 2$ GeV/c are well described by ideal hydrodynamic models whose space-time evolution starts with a realistic QGP equation of state (EoS) with initial energy densities $\varepsilon_0 \approx 30$ GeV/fm^3 at thermalization times $\tau_0 \approx 0.6$ fm/c.

This report is dedicated to studying the capability of the CMS detector at the LHC to reconstruct the reaction plane and to measure elliptic flow, using calorimetry (HCAL, Hadron CALorimeter; and ECAL, Electromagnetic CALorimeter) and the tracking system. The high tracking efficiency and low rate of fake tracks, together with a large calorimetric coverage, provide a precise measurement of global event characteristics, event by event.

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:

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

where Ψ_R is the true reaction plane angle and N_0 stands for full multiplicity. Then v_2 is the average over particles of $\cos(2(\varphi - \Psi_R))$.
There exists a wealth of anisotropic flow measurement methods, each of which has its advantages and limitations. Here we apply two wide-spread methods to calculate the v_2 coefficient. The first one uses the event plane angle determination, and the second one does not involve the event plane angle determination. The basic idea of the latter method is that the v_2 coefficient can be expressed in terms of particle azimuthal correlations. 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 [1], which accounts for the event plane resolution:

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

Here event plane angle Ψ_2 is the estimate of the true reaction plane angle Ψ_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 Ψ_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 may be selected, for instance, in two distinct regions of pseudorapidity, such as $\eta < 0$ and $\eta > 0$.

The second method is based on two particle correlations [2, 3]. It is free from the need to determine the event plane angle. The procedure involves constructing the two-particle correlator, or cumulant,

$$v_2\{2\}^2 = \langle\cos 2(\varphi_i - \varphi_j)\rangle \simeq \langle\cos 2((\varphi_i - \Psi_R)\rangle\langle(\varphi_j - \Psi_R))\rangle. \quad (3)$$

The event plane angle, Ψ_n, can be determined from the measured n-th harmonics via the standard method [1, 4]:

$$\tan n\Psi_n = \frac{\sum\limits_i w_i \sin(n\varphi_i)}{\sum\limits_i w_i \cos(n\varphi_i)}, \qquad n \geq 1, \quad 0 \leq \Psi_n < 2\pi/n, \quad (4)$$

where φ_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.

3 Analysis and discussion

For the estimation of the azimuthal anisotropy of particles in heavy ion collisions, the HYDJET event generator was used. The final state in nuclear collisions from HYDJET is obtained as a combination of soft hydro-type particle production and hard (mini)jet fragmentation [5].

The accuracy of the event plane determination is mainly sensitive to two model factors: the strength of the elliptic flow signal and the particle multiplicity of the event, N_0. To illustrate the dependence of the accuracy of the event plane determination on the event centrality, sets of 1000 HYDJET Pb+Pb events were created at the generator level for each of twelve centrality bins, covering the range of impact parameters from $b = 0$ to $b = 2R_A$ (R_A is the nuclear radius, $R_A^{\rm Pb} \approx 6.7$ fm). The mean total multiplicity of the soft part of central Pb+Pb events was 26000, corresponding to a mean total multiplicity N_0 (b = 0 fm) ≈ 58000 and a mean charged particle density at $\eta = 0$ of $dN_{\rm ch}/d\eta(b = 0$ fm) = 3000. Stable charged particles within the pseudorapidity window $|\eta| < 2.4$ were considered for the event plane analysis, using $n = 2$ and $w_i = 1$. An additional cut of $p_T^{\rm ch} > 0.9$ GeV/c on charged particle transverse momentum was applied, to take into account that these particles do not generally reach the calorimeter, since they curl up in the 4 T magnetic field and are absorbed in the material in front of the calorimeter.

Figure 1-left shows the calculated resolution $\sigma(\triangle\Psi)$, defined here as the width of a Gaussian fit of the distribution of the difference between the generated, Ψ_R, and the calculated, Ψ_2, azimuthal angles of the event plane (Eq. 4), as a function of the impact parameter of the Pb+Pb collisions.

The elliptic flow coefficient $v_2^{\rm gen}$ of charged particles is presented in Fig. 1-right, as a function of the impact parameter, b. The coefficient $v_2^{\rm gen}$ is defined in the standard way: the cosine of twice the azimuthal angle of a particle relative to the reaction plane angle (which is known in each simulated event), and averaged over all charged particles in each event. As expected, the elliptic flow coefficient grows with increasing impact parameter (i.e. with

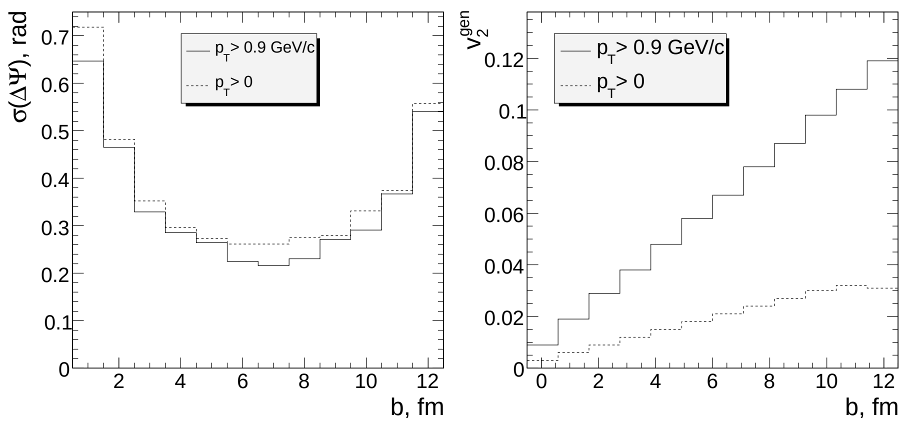

Figure 1: Left: Reaction plane resolution $\sigma(\triangle\Psi)$ as a function of impact parameter in Pb+Pb collisions at the "generator level". Right: v_2 values as a function of impact parameter in Pb+Pb collisions by HYDJET generator.

increasing azimuthal anisotropy of the initial nuclear overlap region). Since in HYDJET $v_2(p_T)$ increases with transverse momentum up to $p_T \sim 1.5$ GeV/c (the kinematic region where hydro-type behaviour of particle spectra dominates over the contribution from jet production), introducing the cut $p_T > 0.9$ GeV/c (solid histograms) results in a much stronger elliptic flow, compared with the case without such a cut (dashed histograms). The following results were obtained for one fixed impact parameter, $b = 9$ fm, in Pb+Pb collisions.

Study of event plane resolution with CMS Calorimeters (ECAL, HCAL). Table 1 shows the resolutions obtained with the calorimetric system of CMS [6]. Stable particles (charged pions and kaons, protons, neutrons, photons and electrons), within the pseudorapidity window $|\eta| < 3$ (CMS barrel+endcap calorimetry acceptance), were considered for the event plane analysis, using $\omega_i = p_{Ti}$ in Eq. 4. An additional cut $p_T > 0.8$ GeV/c on the charged particle transverse momentum was applied. Although the anisotropic flow is maximal at midrapidity, the much larger total energy deposition in the endcaps 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. The ECAL is more suitable than the HCAL for event plane determination. This is primarily due to the better energy resolution of the ECAL for low and moderate p_T particles, along with a larger distorting influence of the magnetic field on the HCAL energy flow.

Study of v_2 reconstruction with the CMS Tracker. A sample of 100 thousand Pb+Pb events at impact parameter $b = 9$ fm 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 % [7]). A cut on $p_T > 0.9$ GeV/c was set in both simulated and reconstructed events. At this centrality, the number of reconstructed tracks per event is about 170.

The differential p_T and η dependencies of the elliptic flow in Pb+Pb collisions for impact parameter $b = 9$ fm are shown in Fig. 2. Here we have calculated the dependencies using the event plane angle determination from Eq. (4).

Table 1: Event plane resolution, $\sigma(\triangle\Psi)$ in rad, for Pb+Pb collisions at $b = 9$ fm.

Calorimeter	Barrel	Endcaps	Barrel+ Endcaps
ECAL	0.53	0.39	0.37
HCAL	1.11	0.62	0.58
ECAL+HCAL	0.58	0.41	0.39

For the p_T dependence, two sub-event sets were used, with $\eta > 0$ and $\eta < 0$. For the η dependence, the factor R in each histogram bin was calculated using particles from other bins (excluding neighboring bins).

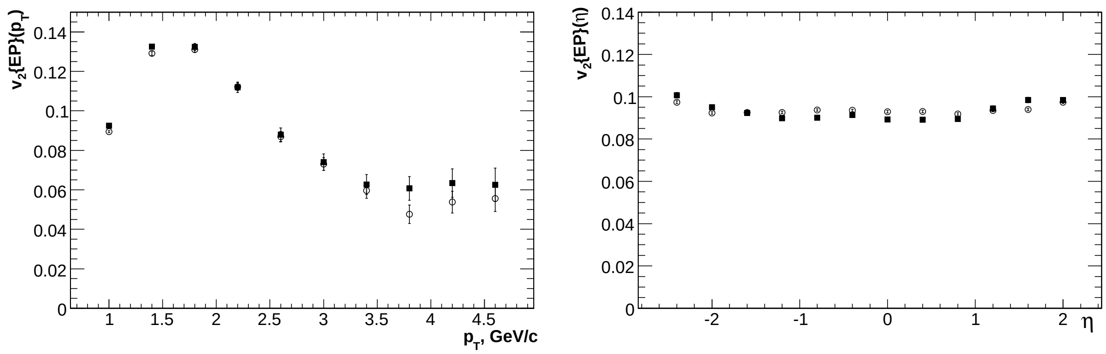

Figure 2: The p_T (left) and η (right) dependencies of $v_2\{EP\}$, in Pb+Pb collisions for impact parameter $b = 9$ fm, calculated with the simulated events (open circles) and reconstructed events (closed squares). Statistical errors are shown for 100k events. Non-flow systematic uncertainties not included.

4 Summary

We have shown that, at central rapidities ($|\eta| < 2.4$), CMS will be able to determine the reaction plane for a very wide range of particle multiplicities and elliptic flow magnitudes, using the calorimeters and the tracker. The CMS electromagnetic calorimeter is found to be more suitable than the hadron calorimeter for event plane determination. Using the endcaps for the event plane reconstruction and the barrel for reconstructing the jets should provide a more robust analysis of elliptic flow.
The transverse momentum and rapidity dependencies of the elliptic flow coefficient v_2 can be reconstructed in the CMS Tracker with high accuracy using the event plane or the cumulant methods. The CMS track reconstruction performance induces a systematic error estimated to be about 3% on the v_2 determination.

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