Centrality and collision event-plane determination in ALICE at the LHC

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Abstract. Investigation of physical phenomena in heavy-ion collisions requires knowledge about collision geometry, which is characterized by the energy distribution in the overlap region of the colliding nuclei and of the collision spectators. Both the event-by-event distributions of produced particles and the spectator nucleons can be used to estimate the collision geometry. Due to the pressure gradients, the spatial anisotropy of initial state geometry is converted during the system evolution to an anisotropy in momentum space. The event-planes of this anisotropy can be estimated via measured azimuthal distributions of particles produced in the collision. We report on the performance of the ALICE experiment at the LHC for the centrality and the event-plane determination for different harmonics using measured distribution of produced particles at central and forward rapidity, and the energy distribution of the spectator neutrons at beam rapidity.

1. Initial geometry of the collision
The initial geometry of a heavy-ion collision can be described in terms of the impact parameter vector connecting the centers of the colliding nuclei. The impact parameter magnitude is correlated with the size of the overlap region which corresponds to different number of nucleon-participants (nucleons which undergo at least one binary collision) and spectators (nucleons not participating in the collision). Since the impact parameter magnitude can not be measured directly, one has to estimate it from the number of produced particles or the energy of spectators.

The reaction plane is defined by the beam axis and the impact parameter vector. On average the overlap region of a non-central heavy ion collision is almond shaped with one of the two symmetry axes aligned with the reaction plane. Event-by-event the nucleon distribution in the overlap region fluctuates. These fluctuations introduce deformations of the initial overlap region characterised by shape components with symmetry axes directions deviating from the reaction plane orientation. The spatial anisotropy with respect to the reaction plane translates into a momentum anisotropy of the produced particles. The measurement of the anisotropy can be used to characterise the symmetry of the initial overlap volume.

2. ALICE experiment
A Large Ion Collider Experiment (ALICE) at CERN is optimized to study high-energy Pb-Pb collision mainly. It is composed of a central barrel, containing the main tracking and particle identification detectors, complemented by forward detectors for various purposes (trigger, multiplicity measurement, centrality determination, muon tracking). It covers a wide range
of pseudorapidity. Tracking of produced particles is provided by the Time Projection Chamber which is at midrapidity (its acceptance covers $2\pi$ in azimuthal angle and a pseudo-rapidity interval $[-0.9, 0.9]$). The scintillator detectors V0A and V0C at opposite sides from interaction point give the information about the multiplicity of produced particles at forward pseudorapidity range $[-3.7, -1.7]$ and $[2.8, 5.1]$. The Forward Multiplicity Detector (FMD) measures the charged particles produced in the collisions which are emitted at small angles relative to the beam line direction with $\eta$-range $[-3.4, -1.7]$ and $[1.7, 5.0]$. Zero Degree Calorimeters (ZDC) at both side measure the energy of spectators with a pseudorapidity range $[-\infty, -8.78]$ and $[8.78, \infty]$. For the detailed description of the ALICE apparatus see [1].

3. Centrality estimation at ALICE

An estimation of the centrality of colliding nucleons [2] allows one to measure the dependence of the particle production on the average number of participant nucleons calculated with the Glauber model (see figure 1 left). The mean number of participant nucleons is calculated in percentiles of the total cross-section for events with multiplicity in the forward direction above a certain threshold.

![Figure 1](image.jpg)

**Figure 1.** (left) The $\frac{2}{N_{\text{part}}} \langle dN_{\text{ch}}/d\eta \rangle$ for Pb-Pb and non-single diffractive p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with lower-energy (2.76 TeV) Pb-Pb and pp collisions (points are scaled by factors 1.2 and 1.13, respectively) in the centrality range 0% – 80%, as a function of $\langle N_{\text{part}} \rangle$ in each centrality class. Detailed description in [2] (right) Distribution of the sum of amplitudes in the VZERO scintillators [3]. The distribution is fitted with the NBD-Glauber fit, shown as a line. The centrality classes used in the analysis are indicated in the figure. The inset shows a zoom of the most peripheral region.

The degree of overlap between two colliding ions is called centrality and is characterised by the impact parameter (b). The larger the overlap the higher is the average number of nucleons participating in the collision ($N_{\text{part}}$). In Monte Carlo models, selecting ranges of $N_{\text{part}}$ allows to constrain the impact parameter.

This selection procedure works also for any measured distribution which is monotonic with $N_{\text{part}}$. Determination of centrality requires knowledge about total hadronic cross-section which is not known because of the electromagnetic contamination which can not be fully rejected. The total hadronic cross-section is estimated by fitting with a Glauber model combined with a convolution of a two-component model for particle production and a Negative Binomial
Distribution (see [3]) which allows centrality determination at ALICE up to 90% (see figure 1 right).

The centrality can be determined using different detectors from ALICE experiment. All centrality estimators except ZDC energy give good resolution \((1 - 2\%)\) in a wide centrality range. The best resolution is given by the combination of V0A and V0C summed amplitude which is used as a default for centrality determination at the ALICE experiment [4].

4. Symmetry planes estimation at ALICE

Initial asymmetry of the geometrical overlap region leads to the anisotropy of the particle production. The azimuthal distribution of particles can be expanded into Fourier series:

\[
\rho(\phi) = \frac{1}{2\pi} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos \left( n(\phi - \Psi_n) \right) \right) \quad v_n = \langle \cos[n(\phi - \Psi_n)] \rangle
\]  

\(\Psi_n\) is the opening angle of the detector for the \(n\)-th subevent.

Figure 2. (left) Second order event plane resolution correction factor \(R_2\) for TPC, V0 - A/C, FMD - A/C and T0 - A/C detectors estimated with the 3-subevents method [5]. (right) \(v_2\{EP\}\) with six different event plane estimators [5].

Flow coefficients \(v_n\) are the functions of transverse momentum, rapidity and global event observable. The coefficients \(v_n\) quantifies the degree of anisotropy for particle production. These have been measured by ALICE up to the 5\(\text{th}\) harmonics was done by ALICE as a function of centrality [6]. To extract \(v_n\) one has to estimate the symmetry plane orientations. Presence of the flow effect allows one to use the measured azimuthal distributions of the produced particles or spectators for the estimation. It is done with \(q_n\)-vector object determined event-by-event for several subsystems of the ALICE detectors:

\[
q_{n,x}^D = \frac{1}{S_D} \sum_i S_{D,i} \cos(n\varphi_i) \quad q_{n,y}^D = \frac{1}{S_D} \sum_i S_{D,i} \sin(n\varphi_i)
\]  

The \(q_n\)-vector is calculated (equation (2)) for TPC as a sum of cosine or sine of azimuthal angle over all selected tracks normalized by the number of tracks \(S_D\), weight for each track \(S_{D,i} = 1\) and for forward detectors as a sum of cosine or sine angle of vector from center of detector to the center of each channel weighted with the signal in a given channel \(S_{D,i}\) and normalized by the total signal \(S_D\) in all channels. The direction of the \(q_n\)-vector estimates the orientation of the corresponding event-plane event-by-event. Detector acceptance non-uniformity influences the measured azimuthal distributions therefore the measurement has to be corrected. The correction can be done using measured distributions themselves. The recentering, width equalization and detector alignment corrections were applied (for details see [7]).
Flow calculations can be done with $q_n$-vectors in different detectors with the resolution of the event-plane estimation depending on the detector acceptance (see figure 2, left). The best resolution is obtained with the TPC $q_n$-vector. After correction for resolution effects [5], the elliptic flow measurements via different ALICE subsystems are in a good agreement (within 4% for the $0 - 80\%$ centrality range, see figure 2, right).

5. **Event shape estimation at ALICE**

Calculations with the Monte-Carlo Glauber model for Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV collisions show a dependence of the participants density on the eccentricity of the overlap region for fixed centralities (see figure 3 upper left). It motivated ALICE for the measurements of the $p_T$ spectra for charged hadrons in the event classes determined both by centrality and the eccentricity of the overlap region.

![Figure 3](image)

*Figure 3.* (upper left) Participant density as a function of the participant eccentricity estimated in a Glauber Monte Carlo model for semicentral collisions. (upper right) Distributions of $q_2^{VOC}$ as a function of centrality. The solid curve shows the average $q_2$ as a function of centrality, while the dashed and the dotted curves indicate the top 10% and the bottom 10%, respectively. (lower row) Comparison between the effect of the event-shape selection obtained with the standard V0C and with the tuned TPC selections, in the centrality class $30\% - 40\%$. (lower left) Ratio of the $p_T$ distribution of charged hadrons in the large $-q_2$ or small $-q_2$ sample to the unbiased sample (lower right) $v_2\{SP\}$ and ratios $v_2\{SP\}$ to the unbiased sample. See details in [8].

The elliptic flow is correlated with the eccentricity of the overlap region therefore the
magnitude of the $q_n$-vector can be used as the event-by-event estimate for the eccentricity. Detailed selection of the events is done in several steps. First, the centrality is estimated (see Sec. 3). Then for each centrality the events are divided into classes according to the distribution of the $q_n$-vector magnitude (see figure 3, upper right). The procedure is similar to that in centrality estimation. The correlations between 2$^{nd}$ harmonics $q_n$-vector in TPC and V0 allows to estimate the eccentricity of the overlap region with either of the $q_n$-vectors. The elliptic flow (measured for the particles within TPC acceptance) in the event classes based on the 2$^{nd}$ harmonics $q_n$-vector in V0C and TPC shows good agreement for different selections (see figure 3 lower right). Such selection allows to explore effects that are sensitive to the shape of the overlap region.

The comparison of the spectra for the shapes with different eccentricity (see figure 3 lower left) showed the sensitivity of the spectra to the shape of the overlap region. It shows that the radial and elliptic flows are correlated. Comparison with hydrodynamical models leads to different values of the shear viscosity for the matter produced in different event classes based on the ellipticity and centrality [8].

6. Conclusion

Properties of the initial geometry in heavy-ion collisions are estimated via measured distributions of produced particles and spectators. The ALICE detector shows good performance for the collision centrality and initial symmetry estimation. Centrality corresponds to the size of the overlap region, which is reflected in a number of produced particles. ALICE detector provides good centrality estimation with resolution ($1 - 2\%$) in a wide centrality range. Azimuthal asymmetry and event-by-event shape fluctuations of the overlap region are reflected in anisotropic particle production relative to event-planes. Measurement of the elliptic flow from different ALICE sub-detectors corrected by the detector resolution are in a good agreement (within 4\% for the 0 – 80\% centrality range). ALICE detector subsystems are used for classification of events by the shape of the overlap region which provides a wide field of studies and investigations.

References

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