



## Article

# Data-Driven Methods for Spectator Symmetry Plane Estimation in CBM Experiment at FAIR

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**Abstract:** The Compressed Baryonic Matter experiment (CBM) at FAIR aims to study the area of the QCD phase diagram at high net baryon densities and moderate temperatures with collisions of heavy ions at  $\sqrt{s_{NN}} = 2.8\text{--}4.9$  GeV. The anisotropic transverse flow is one of the most important observable phenomena in a study of the properties of matter created in such collisions. Flow measurements require the knowledge of the collision symmetry plane, which can be determined from the deflection of the collision spectators in the plane transverse to the direction of the moving ions. The CBM performance for projectile spectator symmetry plane estimation is studied with GEANT4 Monte Carlo simulations using collisions of gold ions with beam momentum of 12A GeV/c generated with the DCM-QGSM-SMM model. Different data-driven methods to extract the correction factor in flow analysis for the resolution of the spectator symmetry plane estimated with the CBM Projectile Spectator Detector are investigated.

**Keywords:** heavy-ion collisions; CBM experiment at FAIR; anisotropic transverse flow; event plane resolution



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## 1. Introduction

The Compressed Baryonic Matter (CBM) is a future experiment at the currently constructed Facility for Antiproton and Ion Research (FAIR). The CBM will study the area of the QCD phase diagram at high net baryon densities and moderate temperatures with collisions of heavy ions at beam momentum 3.3–12A GeV/c. Anisotropic transverse flow is one of the most important observable to probe the equation of state and transport properties of matter created in heavy-ion collisions. It is quantified with the anisotropic flow coefficients  $v_n$  [1] in a Fourier decomposition of azimuthal probability density  $\rho$  of produced particles relative to the collision symmetry plane given by the angle  $\Psi_s$ :

$$\rho(\varphi - \Psi_s) = \frac{1}{2\pi} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos [n(\varphi - \Psi_s)] \right), \quad (1)$$

The most common example of the collision symmetry plane is the reaction plane defined by the impact parameter and beam direction. Due to the fluctuating position of the nucleons inside the colliding nuclei, different collision symmetry planes can be identified that are connected to the orientation of the matter in the nuclei overlap area and deflection of the spectator fragments in the plane transverse to the moving ions ( $\Psi_{SP}$ ).  $v_n$  can be calculated using the following formula

$$v_n = \left\langle \cos n(\varphi - \Psi_s) \right\rangle, \quad (2)$$

where the angle brackets indicate averaging over all particles in all events. In the case of fixed-target experiments, usually, only projectile spectators can be measured. In the CBM experiment, the projectile spectator plane can be estimated using the transverse energy distribution in the Projectile Spectator Detector (PSD), from which a corresponding angle  $\Psi_{PSD}$  can be calculated. Taking into account the finite resolution of the  $\Psi_{PSD}$  angle with respect to the projectile spectator plane angle  $\Psi_{SP}^p$ , Equation (2) is modified as:

$$v_n = \frac{\langle \cos n(\varphi - \Psi_{PSD}) \rangle}{R_{PSD}}, \quad (3)$$

where  $R_{PSD}$  is the PSD event plane resolution:

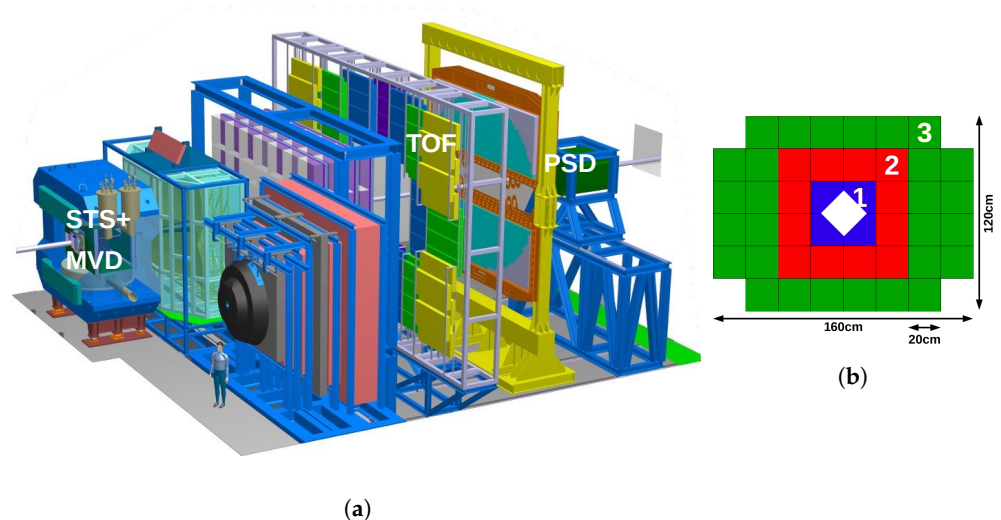
$$R_{PSD} = \langle \cos (\Psi_{SP}^p - \Psi_{PSD}) \rangle. \quad (4)$$

The magnitude of this correction factor may vary with the detector acceptance, collision energy, collision centrality, etc. To calculate the resolution correction factor  $R_{PSD}$  in real-data analysis, different data-driven methods are used. All of them are based on the analysis of correlations between azimuthal angles of different non-overlapping subsets of produced particles or spectator fragments, which are called subevents.

In this report, we present methods for the resolution correction factor extraction and the CBM performance for the projectile spectator symmetry plane estimation as a function of centrality for collisions of gold ions with a beam momentum of 12A GeV/c generated with the hybrid model combining the Dubna Cascade, Quark-Gluon String and the Statistical Multifragmentation Models (DCM-QGSM-SMM).

## 2. The CBM Experiment and Simulation Setup

The CBM detector subsystems are shown in Figure 1a and include [2] the Superconducting Dipole Magnet, Micro-Vertex Detector (MVD), Silicon Tracking System (STS), Ring Imaging Cherenkov Detector (RICH), Transition Radiation Detector (TRD), Time-of-Flight (TOF) detector and the Projectile Spectator Detector (PSD).



**Figure 1.** (a) The layout of the CBM experiment. (b) The layout of the PSD modules in the plane transverse to the beam direction. Colors show module groups (subevents) used for the projectile spectator symmetry plane angle  $\Psi_{SP}^p$  estimation: PSD1 (central), PSD2 (middle) and PSD3 (outer).

The charged particle tracking system represented by MVD and STS detectors covers the acceptance of the polar angle  $2.5^\circ < \theta < 25^\circ$ . Protons and charged pions can be identified based using the time-of-flight information from the TOF detector. In the presented

analysis, these CBM subsystems were used to determine the centrality based on the number of reconstructed charged tracks and to define auxiliary subevents for the extraction of the PSD resolution correction factors.

PSD is a hadron calorimeter that consists of 44 modules (Figure 1b) and registers hadrons emitted at polar angles of  $0.21^\circ < \theta < 5.7^\circ$  ( $4.3^\circ$ ) in x (y) directions. A 20 cm square-shaped hole in its center is needed to avoid radiation damage at high beam intensities expected during the CBM operation at the  $10^6$ – $10^7$  /s interaction rate. In this analysis, the transverse distribution of energy deposition in the PSD modules was used to estimate the projectile spectator symmetry plane angle  $\Psi_{SP}^p$ .

A sample of 5M collisions of gold ions with a beam momentum of 12A GeV/c generated with the DCM-QGSM-SMM model was used for this performance study. The DCM-QGSM-SMM generator is characteristic for realistic modeling of spectator fragments which is crucial for the simulation of the PSD signals close to the one expected in the real experiment (see [3,4] and references therein). The particles generated with the DCM-QGSM-SMM were passed through the GEANT4 simulation of the CBM detector response, and CBMROOT event and track reconstruction chain.

### 3. Methods of Spectator Symmetry Plane Estimation

It is convenient to represent different estimates of the collision symmetry plane orientations in terms of two-dimensional flow ( $\mathbf{Q}_n$ ) vectors defined in the plane transverse to the beam direction:

$$\mathbf{Q}_n = \frac{\sum_{i=1}^N w_i \mathbf{u}_{n,i}}{\sum_{i=1}^N w_i} \quad (5)$$

where  $\mathbf{u}_{n,i} = (\cos n\phi_i, \sin n\phi_i)$ .  $\mathbf{Q}_n$ -vectors are calculated for the group of tracks reconstructed with MVD + STS or the groups of PSD modules with azimuthal angles  $\phi_i$ . In Equation (5),  $N$  is the total number of tracks (modules) in a subevent,  $i$  is the index of the track (module), and  $w_i$  is its weight equal to unity for tracks and to the energy deposition for PSD modules.

The rectangular shape of the detector subsystems and horizontal bending of charged particles' trajectories by the field of the CBM magnet introduce substantial biases in the azimuthal distributions used for the symmetry plane estimation. These biases were corrected for using the data-driven procedure described in [5] and implemented in the QnTools framework [6]. A recentering correction was applied for all  $\mathbf{Q}_n$ -vectors. Additionally, twist and rescaling corrections were used for the  $\mathbf{Q}_n$ -vectors determined from the MVD+STS tracks. All corrections were applied as a function of the collision centrality.

Three different methods to calculate the first harmonic PSD resolution correction factor have been assessed in the study. 3-subevent method is given by equation:

$$R_{1,i}^A\{B,C\} = \sqrt{2 \frac{\langle Q_{1,i}^A Q_{1,i}^B \rangle \langle Q_{1,i}^A Q_{1,i}^C \rangle}{\langle Q_{1,i}^B Q_{1,i}^C \rangle}}, \quad (6)$$

where  $A$ ,  $B$  and  $C$  mark different PSD subevents, while index  $i$  indicates the  $x$  and  $y$  components of the  $\mathbf{Q}_n$ -vector.

The mixed-harmonic method is an extension of the 3-subevent method with an additional projection on the 2-nd harmonic  $\mathbf{Q}_2^D$ -vector calculated from the MVD+STS subevents:

$$R_{1,i}^A\{B,C;D\} = \sqrt{2 \frac{\langle Q_{1,i}^A Q_{1,i}^B \rangle \langle Q_{1,i}^A Q_{1,j}^C Q_{2,k}^D \rangle}{\langle Q_{1,i}^B Q_{1,j}^C Q_{2,k}^D \rangle}}. \quad (7)$$

Non-zero correlations are possible for the following combinations:  $(i,j,k) = (x,x,x)$ ,  $(x,x,y)$ ,  $(y,x,y)$  and  $(y,y,x)$ .

In the 4-subevent method, a fourth subevent is added that allows having a separation in rapidity between all correlated subevent pairs:

$$R_{1,i}^A = \sqrt{\frac{\langle Q_{1,i}^A Q_{1,i}^C \rangle R_{1,i}^D \{A, C\}}{\langle Q_{1,i}^C Q_{1,i}^D \rangle}}, \quad R_{1,i}^B = \frac{\langle Q_{1,i}^B Q_{1,i}^D \rangle}{R_{1,i}^D \{A, C\}}, \quad (8)$$

where a combination of  $(A, B, C, D)$  subevents can be either  $(PSD1, PSD2, PSD3, STS)$  or  $(PSD3, PSD2, PSD1, STS)$ .

For each of the three methods, the results for  $x$  and  $y$  components of  $\mathbf{Q}$ -vectors were compared with the resolution correction factors obtained using the reaction plane angle from the output of the DCM-QGSM-SMM event generator. These are given by equations analogous to Equation (4) decomposed in a sum of cosine and sine products:

$$R_{1,x}^A = \langle \cos \Psi_{RP} Q_{1,x}^A \rangle, \quad R_{1,y}^A = \langle \sin \Psi_{RP} Q_{1,y}^A \rangle. \quad (9)$$

The different methods listed above were implemented using the following set of five subevents. Three subevents were defined from signals in groups of the PSD modules (Figure 1b): PSD1 (central modules), PSD2 (middle ring) and PSD3 (outer ring). Two additional subevents were defined from MVD + STS tracks identified as protons or positively charged pions using TOF information and the Bayesian approach described in [7]:

- protons with  $y \in [-0.6, -0.2]$  and  $p_T \in [0, 3]$  GeV/ $c$ ,
- positively charged pions with  $y \in [0.8, 1.2]$  and  $p_T \in [0, 1.4]$  GeV/ $c$ .

The negatively charged pions, which together with positive pions and protons constitute most of the produced hadrons, were excluded from consideration to avoid non-flow correlations with protons in the PSD acceptance due to secondary decays. The kinematic regions (see Figure 2) were chosen such that MVD + STS subevents contain particles with the larger magnitude of  $v_1$  (to provide stronger subevent correlations) but are not in the acceptance of the PSD (to avoid self-correlations).

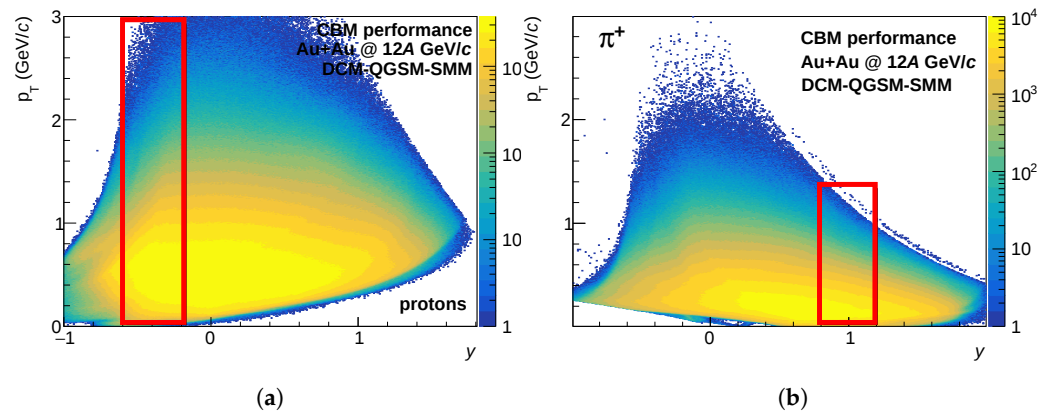
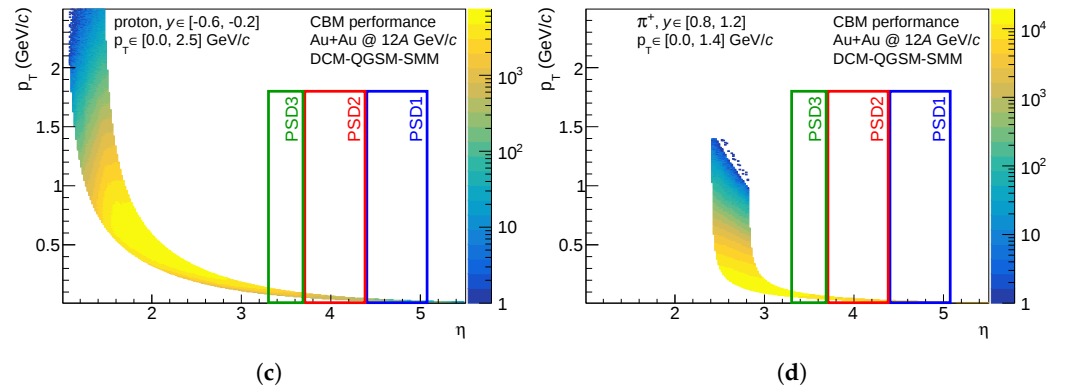


Figure 2. Cont.



**Figure 2.** The distribution of tracks identified as (a) protons and (b) positively charged pions vs.  $p_T$  and  $y$ . Red boxes mark the kinematic selection for the corresponding Q-vector subevents. (c,d): comparison of the acceptance for the five (two STS and three PSD) subevents used in the performance studies. See text for details.

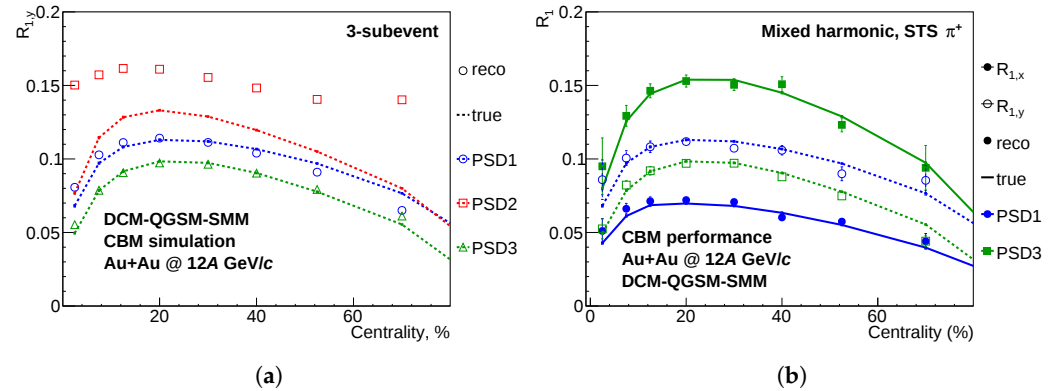
#### 4. Results and Discussion

The definition of the resolution correction factor with Equation (4) is given in terms of the so-called event plane method, which defines the flow observables via symmetry plane angles and their estimates [1]. Despite the fact that the results below are presented for the  $R_{PSD}$  calculated using the scalar product method [1], which operates in terms of the flow vectors directly without normalizing them by their magnitude as in the event plane method, all conclusions about CBM performance are independent from the choice of this method.

The centrality dependence of the resolution correction factor determined for a group of particles is driven by these particles' multiplicity and the magnitude of their directed flow. The highest value of spectator symmetry plane resolution is found in mid-central (10–40%) collisions, which corresponds to the largest asymmetry of the nuclei overlap region. In central collisions the spatial anisotropy of the nuclei overlap region becomes smaller, while in peripheral collisions the build up of flow itself is small due to the small amount of participating nucleons.

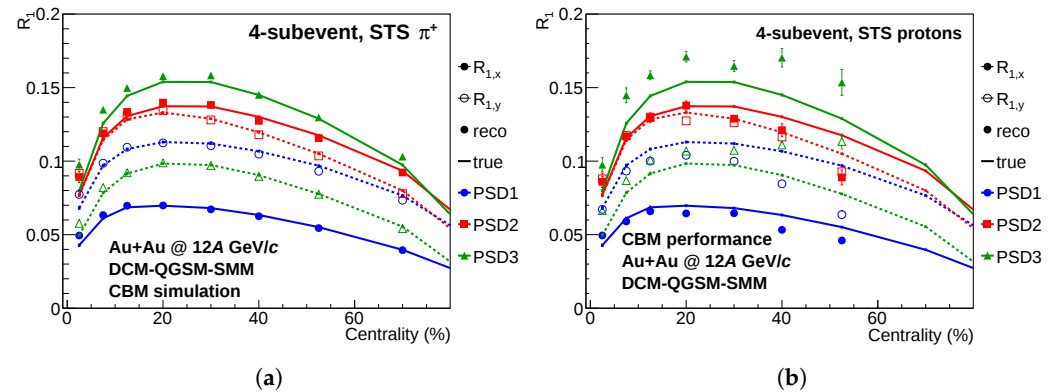
Figure 3a shows the resolution correction factors from 3-subevent method for the three PSD subevents calculated using  $y$  components of  $\mathbf{Q}_1$ -vectors. There are significant differences between the true (dashed lines) and reconstructed (colored symbols) resolution correction factors, in particular, for the PSD2 subevent that can be explained by the auto-correlations arising due sharing the hadronic shower between modules in the neighboring subevents. For the PSD2 subevent, the affected correlations in Equation (6) are  $\langle Q_1^{PSD1} Q_1^{PSD2} \rangle$  and  $\langle Q_1^{PSD2} Q_1^{PSD3} \rangle$ .

To suppress effects due to correlations between neighbouring subevents, we deployed the mixed-harmonic method, which included an additional  $\mathbf{Q}_2$ -vector from the positively charged MVD + STS tracks identified using TOF information as pions. The results are shown in Figure 3b. The mixed-harmonic method allows reproducing true resolution correction factors for PSD1 and PSD3 using both  $x$  and  $y$  components of  $\mathbf{Q}_1$ -vectors. The method still does not fully remove the correlation between neighboring subevents in the case of the calculations for the PSD2 resolution correction. It should be noted that due to the smaller magnitude of the elliptic flow  $v_2$ , the mixed-harmonic method requires much higher statistics compared to the 3-subevent method to obtain statistically stable results.



**Figure 3.** Resolution correction factors for PSD subevents calculated with (a) 3-subevent and (b) mixed-harmonic methods. The lines show the true values obtained using reaction plane angle from the event generator.

The 4-subevent method makes use of the auxiliary  $Q_1$ -vector from STS and includes correlations only between rapidity-separated subevents. As can be seen from Figure 4a, the calculated resolution correction factors are in good agreement with the true values when the auxiliary subevent is constructed from positively charged MVD + STS tracks identified with TOF as pions. Using protons at backward-rapidity to construct the auxiliary subevent from MVD + STS tracks yield a significantly worse performance and less stable results (see Figure 4b), which indicates the presence of the remaining non-flow (resonances and other short range) correlations between protons in the MVD + STS acceptance and fragments registered by the PSD.



**Figure 4.** Resolution correction factors for PSD subevents calculated with the 4-subevent method using the auxiliary STS subevent from (a) positively charged pions and (b) protons. The lines show the true values of the resolution obtained using reaction plane angle from event generator.

## 5. Conclusions

The CBM performance for projectile spectator symmetry plane estimation is studied with GEANT4 Monte Carlo simulations using collisions of gold ions with a beam momentum of 12A GeV/c generated with the DCM-QGSM-SMM model. Different data-driven methods to extract the correction factor in flow analysis for the resolution of the spectator symmetry plane estimated with the CBM Projectile Spectator Detector are investigated. Significant bias due to correlations between neighbouring subevents is observed for the calculations with the 3-subevent method. Alternative methods, such as mixed harmonic and the 4-subevent method, allow to suppress these biases and consistently reconstruct the input values of the spectator symmetry plane resolution for the CBM Projectile Spectator Detector.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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