Directed flow of protons with the event plane and scalar product methods in the HADES experiment at SIS18

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Abstract. Differential measurements of the directed flow of protons of Au+Au collisions at the beam energy of 1.23 A GeV collected by the HADES experiment at SIS18 are presented. Measurements are performed with respect to the spectator symmetry plane estimated using the Forward Wall hodoscope. Corrections for the detector azimuthal non-uniformity are applied. Event plane and scalar product methods are used to evaluate the systematic uncertainty.

1. Introduction

Anisotropic transverse flow is one of the most important observables in the study of strongly interacting matter. Spatial asymmetry of the initial energy distribution in the overlap region of colliding nuclei transforms into momentum anisotropy of emitted particles due to interaction among them. Comparison of measured azimuthal anisotropies with theoretical calculations allows to extract properties of the created matter such as its equation of state.

Asymmetry is usually quantified with the coefficients \(v_n\) in a Fourier decomposition of the azimuthal distribution of produced particles relative to the reaction plane spanned by the impact parameter and the beam direction [1]:

\[
\rho(\phi - \Psi_{RP}) = \frac{1}{2\pi} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos(\phi - \Psi_{RP}) \right],
\]

where \(\Psi_{RP}\) is a reaction plane azimuthal angle. The first coefficient of the expansion \(v_1\) is called directed flow. \(v_n\) coefficients can be calculated as \(v_n = \langle \cos n(\phi - \Psi_{RP}) \rangle\), where angle brackets denote an average over all particles and events.

The event plane method was originally developed with the assumption that fluctuations of energy distribution in the overlap region of colliding nuclei are negligible [2], though later there were observed significant fluctuations at top RHIC and the LHC energies [3, 4]. The values for \(v_n\) obtained with the event plane technique ranges between \(\langle v_n \rangle\) and \(\sqrt{\langle v_n^2 \rangle}\) [5], the exact value depends on the event plane resolution. At the same time the scalar product method [6] does not suffer from such an ambiguity and consistently yields the rms value \(\sqrt{\langle v_n^2 \rangle}\) [2]. In this paper...

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directed flow of protons is measured with both methods and results are compared to quantify systematic uncertainty.

2. The HADES experiment and analyzed data sample

The High Acceptance Di-Electron Spectrometer (HADES) is a fixed target experiment at SIS18 accelerator in GSI, Darmstadt [7]. Its layout is shown in figure 1.

![Figure 1. Schematic layout of the HADES experiment.](image)

In the present analysis the following detector subsystems were used: (a) Tracking system consisting of four stations of multiwire drift chambers (MDC), (b) Time Of Flight (TOF) detector and Resistive Plane Chambers (RPC) for charged particles identification (c) Forward Wall (FW) hodoscope registering the charge of spectator fragments for symmetry plane estimation.

Around one billion Au+Au collisions at beam energy 1.23 AGeV were recorded by HADES in the year 2012. A subset of 10M Au+Au collisions with minbias (PT2) trigger was used in this analysis. Centrality estimation was performed based on total amount of hits in TOF and RPC detectors according to procedure described in [8]. The minbias (PT2) trigger was found to be efficient for the centrality up to 60%. Events with reconstructed vertex position $(x_v, y_v, z_v)$ within target region, $\sqrt{x_v^2 + y_v^2} < 3$ mm and $z_v \in (-60,0)$ mm were selected. Contamination from pileup events was suppressed by selecting events with single collision vertex inside the target region. Only tracks with fit quality $\chi^2 < 100$ were used. Tracks associated with primary particles were selected by requiring their distance of the closest approach to collision vertex, $DCA$, to be within $(-10,10)$ mm. Uncorrected differential yields of selected protons normalized to their total number as a function of rapidity in center of mass, $y_{cm}$, azimuthal angle, $\phi$, and transverse momentum, $p_T$, are presented in figure 2.

3. Flow observables and analysis methods

Two methods, Event Plane (EP) and Scalar Product (SP), were used for $v_1$ measurements. Observables for $v_1$ coefficient can be written in terms of flow vectors. For each particle in the event a vector in transverse plane $u_1$ is calculated:

$$u_1 = e^{i\phi},$$ (2)
where $\phi$ is azimuthal angle of particle’s momentum. A $Q_1$-vector is defined as a sum of $u$-vectors over a group of particles:

$$Q_1 = \sum_{k=1}^{M} u_{1,k} = X + iY = |Q_1|e^{i\Psi_{EP,1}},$$

(3)

In case of the event plane method the normalization factor equals to magnitude of $Q_1$ vector, $v_1\{|Q|\} = v_1\{|Q|\}$. This normalization introduces a nonlinear dependence on a number of particles used in $Q_1$. In particular $v_1\{|EP\} \rightarrow \langle v_1 \rangle$ when $v_1\sqrt{M} \gg 1$, while for $v_1\sqrt{M} \ll 1$ $v_1\{|EP\}$ gives $v_1\{|EP\} \rightarrow \sqrt{\langle v_1^2 \rangle}$. For this reason the values of $v_1\{|EP\}$ measured in experiment ranges between these two limits [5]. In case of the scalar product method, $v_1\{|SP\}$, the normalization factor is equal to multiplicity $N_Q = M$. This method yields $v_1\{|SP\} \rightarrow \sqrt{\langle v_1^2 \rangle}$ regardless of the measured multiplicity.

In the present analysis $u_1$-vectors were built from tracks of the identified protons from MDC. Flow measurements are performed relative to event plane evaluated with charged spectator fragments registered by FW hodoscope. The $Q_1$ vector for FW is obtained as follows:

$$Q_1 = \sum_{k=1}^{N} E_k e^{i\phi_k},$$

(5)
where $\varphi$ is an azimuthal angle of k-th FW module, $E_i$ is the signal in it, $N_A$ is number of modules.

The resolution correction factor, $R_1$, in case of event plane method is evaluated with random sub-event (RND) method \[10\]. Modules of FW in each event are randomly split into two groups "a" and "b" which are called sub-events. The $Q_1$-vector is calculated for each sub-event separately. Resolution correction factor is calculated according to formula

$$R_{1\text{sub}} = \sqrt{\frac{\langle Q_1^a \rangle \langle Q_1^b \rangle}{\langle Q_1^a \rangle^2 \langle Q_1^b \rangle^2}}.$$ \hspace{1cm} (6)

Then resolution of a sub-event is extrapolated to resolution of the full event using procedure \[9\].

For the scalar product method resolution correction factor was calculated using three sub-event technique:

$$R_1^t = \sqrt{\frac{\langle Q_1^a Q_1^b \rangle^2}{\langle Q_1^a Q_1^b \rangle^2}}.$$ \hspace{1cm} (7)

Five sub-events were used in different combinations to obtain several estimates of three-subevent resolution. Two sub-events were constructed from identified proton tracks from MDC: (Mf) 0.35 < $y_{cm}$ < 0.55 and (Mf) −0.55 < $y_{cm}$ < −0.35. Modules of the FW were divided into three groups according to the ranges of pseudorapidity, $\eta_{lab}$: (W1) 3.77 < $\eta_{lab}$ < 5.38; (W2) 3.28 < $\eta_{lab}$ < 3.88 and (W3) 2.68 < $\eta_{lab}$ < 3.35. One should note that due to the rectangular shape of the FW modules there is a small overlap in pseudorapidity between the FW sub-events.

4. Corrections for detector azimuthal non-uniformity

Due to segmentation of the MDC the azimuthal angle distribution for protons is not uniform, see figure 2(b). Correlation of two $Q_n$-vectors "a" and "b" can be decomposed into the product of individual components:

$$\langle Q_n^a Q_n^b \rangle = \langle X_n^a X_n^b \rangle + \langle Y_n^a Y_n^b \rangle.$$ \hspace{1cm} (8)

In the case of ideal detector, correlations are expected to be equal:

$$\langle X_n^a X_n^b \rangle = \langle Y_n^a Y_n^b \rangle.$$ \hspace{1cm} (9)

Detector azimuthal non-uniformity may bias the $Q$-vector orientation and magnitude which manifests in the inequality of correlations of different $Q$-vector components. This bias may be corrected with data-driven corrections described in \[11\]: recentering, twist and rescaling. In the present analysis $p_T/y_{cm}$ differential acceptance corrections were applied using QnTools \[12\] framework incorporating QnCorrections framework originally developed for ALICE experiment at the LHC \[13\].

Correlations between the $u_1$ and $Q_1$ vector components are shown in figure 3(a). After the corrections for detector non-uniformity values of the $XX$ and $YY$ correlations are in agreement within statistical uncertainties. This fact allows to use the average of $xX$ and $yY$ correlations to calculate $v_1$.

5. Comparison of the EP and SP methods

In the figure 2(b) the measured flow of protons calculated using event plane and scalar product methods is presented as a function of centrality. The $R_1$ with the three sub-event method can be evaluated using different combinations of five available $Q_1$-vectors (see equation (7)). In the present analysis a combination with largest (pseudo-)rapidity separation between sub-events was chosen to suppress correlations not originating from the initial asymmetry of the collision geometry. This result obtained with scalar product method has larger statistical errors.
Figure 3. (a) Comparison of the $\langle u_1 Q_1 \rangle$ correlation for different steps of corrections for detector azimuthal non-uniformity. (b) Comparison of the directed flow measured with the event plane and scalar product methods.

compared to the event plane results. Statistical uncertainty can be reduced by merging results estimated with different combinations of five $Q_1$-vectors. The maximum variation between the two methods was found to be below 5%, although this statement is limited by the statistical precision of the data.

6. Summary
Directed flow of protons measured using event plane and scalar product methods is presented for Au+Au collisions at the beam energy of 1.23AGeV. Maximum variation between the two methods is found to be below 5%.

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