Directed flow measurement in Pb+Pb collisions at $p_{\text{lab}} = 13A \text{ GeV/c}$ collected with NA61/SHINE at SPS

E Kashirin$^{1,4}$, I Selyuzhenkov$^{1,2}$, O Golosov$^1$ and V Klochkov$^{3,5}$ for the NA61/Shine Collaboration

$^1$ National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)
Moscow, Russia
$^2$ GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
$^3$ Eberhard Karls University of Tübingen, Tübingen, Germany
$^4$ Institute for Nuclear Research RAS, Moscow, Russia
$^5$ Goethe Universität Frankfurt, Frankfurt, Germany

E-mail: evgeny.kashirin@cern.ch, ilya.selyuzhenkov@gmail.com

Abstract. We present results of directed flow measurements in Pb+Pb collisions at beam momentum $p_{\text{beam}} = 13A \text{ GeV/c}$ recorded at NA61/Shine in 2016. Directed flow is measured relative to the symmetry plane of projectile spectators. Measurements are performed differentially relative to transverse momentum, rapidity and collision centrality. We present $v_1(p_T)$ and $v_1(y)$ for protons and negatively charged pions in different centrality classes. The analysis techniques developed as a part of this work will be used for measurements at the future CBM experiment at FAIR and the MPD experiment at NICA.

1. Introduction

Spatial asymmetry of initial energy density in the overlap region of the colliding relativistic nuclei is converted via interaction between produced particles to the asymmetry of particles momentum distribution in the final state. The resulting asymmetry encodes important information about the transport properties of the QCD matter created during the collision. 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]:

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

The energy dependence of flow coefficients is of particular importance. At the energies of SPS it is expected that the slope of proton directed flow at midrapidity, $dv_1/dy$, changes its sign [2].

Fixed-target setup of the NA61/Shine experiment allows to perform measurements up to the forward rapidity where the projectile spectators appear. The reaction plane angle $\Psi_{RP}$ is estimated using the transverse energy distribution of projectile spectators which is measured by forward calorimeter.
Figure 1. (a): The scheme of the NA61/Shine setup. (b): Photo of the Projectile Spectator Detector (PSD). Three groups of PSD modules are overlaid with different colors.

2. Data sample and analysis configuration
Tracking system of NA61/Shine consists of four large time-projection chambers (TPCs) (figure 1 (a)). Two vertex TPCs (VTPC1 and VTPC2) are emplaced into magnetic field to measure momentum of charged particles. Another two (MTPC Left/Right) are placed outside the magnetic field to additionally perform precise $dE/dx$ measurements crucial for particle identification. Tracking system covered forward hemisphere and allowed to identify charged particles down to zero $p_T$. The Projectile Spectator Detector (PSD) is installed 18 meters downstream the target. Transverse layout of PSD modules is shown in figure 1 (b).

Below we describe results of the analysis of the Pb+Pb collisions at 13 $A$ GeV/$c$ recorded by NA61/Shine in 2016.

Figure 2. (a): Distributions of energy deposited to PSD for the central (red) and minimum bias (blue) triggers. Vertical lines demarkate event (centrality) classes. (b): Resolution correction factors $R_{1,0}^A$ obtained for PSD subevents using the 3+1-subevent method.

For the analysis we selected only events with reconstructed vertex position close to the actual position of Pb target. To avoid overlapping events we accept only events with one beam particle passed through S1 trigger scintillator in 4 $\mu$s time interval. After event selection, the available statistics is 580k events for the minimum bias trigger (T4) and 480k events for the central trigger (T2) which was fully efficient in the 0–15% centrality class.
Table 1. List of track selection criteria used in the present analysis.

| Criterion | Condition |
|-----------|-----------|
| $N_{\text{clusters}}$ in all TPCs | $> 30$ |
| $N_{\text{clusters}}$ in VTPC1/2 | $> 15$ |
| $N_{\text{clusters}}/N_{\text{max.clusters}}$ | $> 55\%$ |
| $|b_X|$ | $< 2 \text{ cm}$ |
| $|b_Y|$ | $< 1 \text{ cm}$ |

In the analysis we used only tracks associated with primary vertex of event. List of selection criteria is given in table 1. Ratio of clusters associated with track to maximum possible amount of clusters for a given track’s trajectory was used to suppress contribution from split tracks. Primary tracks were selected based on the distance of closest approach (DCA) to the primary vertex in the plane transverse to the beam direction. Distribution of DCA ($b_X$) is smeared horizontally by the magnetic field, so the acceptable window for $b_X$ is selected twice as big as for vertical component of DCA ($b_Y$).

Event centrality classification was performed following the procedure described in Ref. [3]. Forward energy in the PSD is used as a centrality estimator. The result of the centrality classification procedure is shown in figure 2 (a).

3. Analysis technique

Directed flow coefficient $v_1$ was measured using scalar-product method [4] from correlations of two-dimensional flow vectors $q_1$ and $Q_1$. The $q_1$ is calculated event-by-event from azimuthal angles $\phi_i$ of the i-th particle’s momentum:

$$q_1 = \frac{1}{M} \sum_{i=1}^{M} u_{1,i},$$

(2)

where $u_{n,i} = (\cos n\phi_i, \sin n\phi_i)$ and $M$ is selected particle’ multiplicity in a given $p_T$ and rapidity range. Symmetry plane of spectators is estimated using azimuthal anisotropy of the PSD energy distribution. The PSD modules are divided into three subevents. For each PSD subevent $Q_1$ vector is determined as

$$Q_1^A = \frac{1}{E_A} \sum_{i=1}^{N_A} E_i n_i,$$

(3)

where $E_A = \sum_{i=1}^{N_A} E_i$ is the total energy of the PSD subevent $A$. Unit vector $n_i$ points in the direction of the center of i-th PSD module and $E_i$ is its measured energy.

Independent estimates of directed flow $v_1$ are given by equations

$$v_{1,\alpha}(A) = \frac{2\langle q_{1,\alpha} Q_1^A \rangle}{R_{1,\alpha}^A},$$

(4)

where $\alpha = x, y$ are $q_1$ and $Q_1$ components and $A, B$ - PSD subevents.

Due to energy sharing between adjacent PSD subevents, the three-subevent method for the event plane resolution is biased. For 13A GeV/$c$ this effect gives dominant contribution to $R_{\alpha}^{PSD2}$ in centrality range 0–20%. To remove auto-correlation we introduced additional 4th subevent from TPC. In present analysis $Q_1$-vector for the TPC subevent was calculated from the identified protons in the forward rapidity region ($0.8 < y - y_{beam} < 1.2$).
For the PSD1 and PSD3 $Q_1$-vector from TPC replaces PSD2:

$$R_{1,\alpha}^{PSD1,3} = \sqrt{2 \langle Q_{1,\alpha}^{PSD1,3}Q_{1,\alpha}^{TPC} \rangle / \langle Q_{1,\alpha}^{PSD1,3}Q_{1,\alpha}^{TPC} \rangle}.$$  \tag{5}

Event plane resolution of PSD2 has different formula involving four subevents:

$$R_{1,\alpha}^{PSD2} = \langle Q_{1,\alpha}^{PSD2}Q_{1,\alpha}^{TPC} \rangle / R_{1,\alpha}^{TPC}, \quad R_{1,\alpha}^{TPC} = \sqrt{2 \langle Q_{1,\alpha}^{PSD1}Q_{1,\alpha}^{TPC} \rangle / \langle Q_{1,\alpha}^{PSD1}Q_{1,\alpha}^{TPC} \rangle}.$$  \tag{6}

Centrality dependence of $R_{1,\alpha}$ is shown in figure 2 (b).

Azimuthal acceptance of NA61/Shine has large azimuthal non-uniformity due to geometry of TPCs. $Q_1$-vectors used in the analysis were corrected following the procedure described in [3]. Recentering, twist and rescale corrections were applied $p_T/y$ differentially for $Q_1$-vectors from TPC. Only recentering procedure is applied for the $Q_1$-vectors for PSD subevents.

4. Results

Estimations of the directed flow with respect to different PSD subevents are consistent within statistical uncertainties. $v_x^1$ and $v_y^1$ are consistent for negatively charged pions, but for protons discrepancy of $x$ and $y$ component is statistically significant. This effect is possibly due to presence of the magnetic field which deflects projectile spectators and stretches energy distribution in PSD along the $x$ direction. Thus, only $x$-component was used to obtain results for the directed flow. Directed flow estimations with respect to different PSD subevents were combined to obtain the final result.

![Figure 3. Negatively charged pion (a) and proton (b) directed flow $v_1(p_T)$ for different centrality classes.](image)

In mid-central collisions the flow of negatively charged pions has minimum at $p_T \approx 0.2 - 0.6$ GeV/c. At the minimum the value $v_1$ is negative. At $p_T \approx 0.7 - 1.3$ GeV/c it changes sign to positive. The value of $v_1$ in the minimum of $v_1(p_T)$ and value of $p_T$ where $v_1$ changes sign strongly depend on the collision centrality.
Dependence of protons $v_1(p_T)$ on collision centrality is shown in figure 3 (b). The magnitude of $v_1(p_T)$ increases with transverse momentum until $p_T \approx 1.5 - 2.0 \text{ GeV}/c$.

Expanding matter in the area of nuclei overlap deflects projectile spectators in the outward direction along the impact parameter vector. Due to this the protons inherits positive $v_1$ which is reflected in the positive slope of $v_1(y)$. Negatively charged pions are emitted from the expanding matter in the overlap area. Due to momentum exchange, negatively charged pions are deflected in the opposite direction to protons, resulting in a negative sign of the pion directed flow.

These expectations are reflected in comparison of the directed flow for protons and negatively charged pions in figure 4. Shapes of $v_1(p_T)$ for protons and negatively charged pions (figure 4 (a)) are different. $v_1(p_T)$ of protons is positive in the entire $p_T$ range, while directed flow of negatively charged pions starts with negative values and than changes sign. Rapidity dependencies are also different for protons and negatively charged pions (figure 4 (b)). Slopes of $v_1(y)$ for protons and pions are of the opposite signs.

Figure 4. Directed flow $v_1$ of negatively charged pions and protons as a function of transverse momentum (a) and rapidity (b).

5. Summary
Directed flow $v_1$ is measured relative to the spectator plane in Pb–Pb collisions at 13A GeV/$c$ for protons and negatively charged pions. Measurements were performed differentially relative to transverse momentum, rapidity and collision centrality. We observe strong centrality dependence of directed flow for negatively charged pions. For negatively charged pions $v_1(p_T)$ changes its sign at $p_T \sim 1 \text{ GeV}/c$. The slope of $v_1(y)$ for pions (negative slope) have different sign compared to that for protons (positive slope). This effect is due to momentum exchange in the interaction between expanding matter and collision spectators.

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