NEW MEASUREMENT OF PION DIRECTED FLOW RELATIVE TO THE SPECTATOR PLANE BY THE NA49 EXPERIMENT AT CERN*

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This article reports on a new measurement of negatively charged pion directed flow v_1 relative to the spectator plane for Pb+Pb collisions at the beam energy of $40A$ GeV/c recorded by the NA49 experiment at CERN. v_1 is shown as a function of rapidity and transverse momentum in different classes of collision centrality. The projectile spectator plane is estimated using the transverse segmentation of the NA49 forward hadron calorimeter. The new results extend the NA49 data for v_1, which was previously measured only relative to the participant plane, and complement recent preliminary data by the NA61/SHINE Collaboration and published results of STAR from the RHIC beam energy scan program.

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1. The NA49 experiment and data sample

The NA49 experiment at the CERN SPS is the predecessor of the currently operating fixed target NA61/SHINE experiment which has recently extended its program with a Pb-ion beam momentum scan at $13A$, $30A$ and $150A$ GeV/c. NA49 collected data for Pb+Pb collisions at beam energies of $20A$, $30A$, $40A$, $80A$ and $158A$ GeV [1]. The NA49 and NA61/SHINE data complement the measurement of flow harmonics available from the Beam

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Energy Scan (BES) program of STAR at RHIC [2] and extend the measurement towards forward rapidity up to the region where projectile spectators appear. The new results are also relevant for studies in the few GeV collision energy range, in particular, for the preparation of the Compressed Baryonic Matter (CBM) heavy-ion experiment at the future FAIR facility in Darmstadt.

A sample of Pb+Pb collisions at $40A$ GeV recorded in 2000 with minimum bias and central trigger was used in the present analysis. About 340k (440k) minimum bias (central) events with fitted vertex position close to the target were selected.

The layout of the NA49 experiment is shown in Fig. 1. The NA49 experiment [3] employs four large-volume time-projection chambers (TPC). The two vertex TPCs (VTPC-1 and VTPC-2) are positioned inside the magnets and used for momentum reconstruction. The two main TPCs (MTPC-L and MTPC-R) are used for particle identification via measurement of the specific energy loss ($\mathrm{d}E/\mathrm{d}x$).

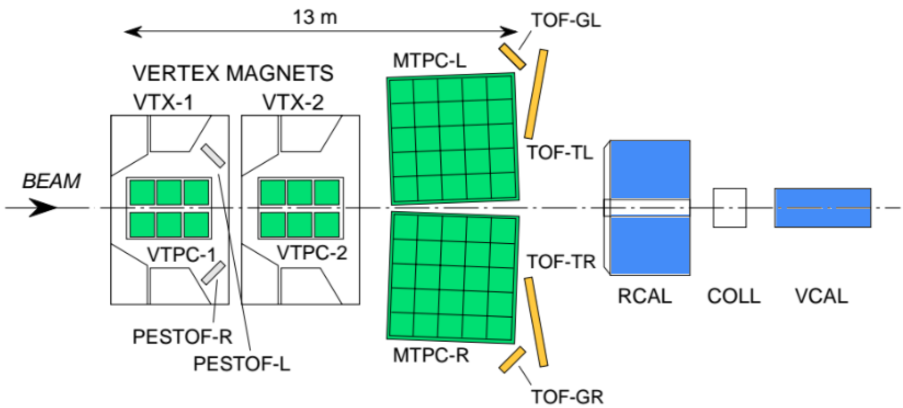

Fig. 1. (Colour on-line) Schematic layout of the NA49 experiment. The four large volume time-projection chambers (TPC) are shown in grey/green, while the Ring (RCAL) and Veto (VCAL) calorimeters are marked in light grey/blue.

The veto (VCAL) calorimeter is installed 20 meters downstream of the target behind the collimator and has a 2×2 transverse module granularity. The opening of the collimator is adjusted such that beam particles, projectile fragments, and spectator neutrons and protons can reach the calorimeter. The energy deposited in the VCAL modules comes mostly from projectile spectators and is used for centrality and spectator plane estimation. Figure 2 (left) shows the distribution of energy in VCAL for different centrality triggers. The ring (RCAL) calorimeter is positioned at 18 meters from the target and its transverse granularity of 10 rings with 24 modules each is used to estimate the spectator plane resolution of VCAL. Figure 2 (right) shows the extracted spectator plane resolution correction factor of VCAL from the correlation with RCAL signals (more details in Sec. 2 below).

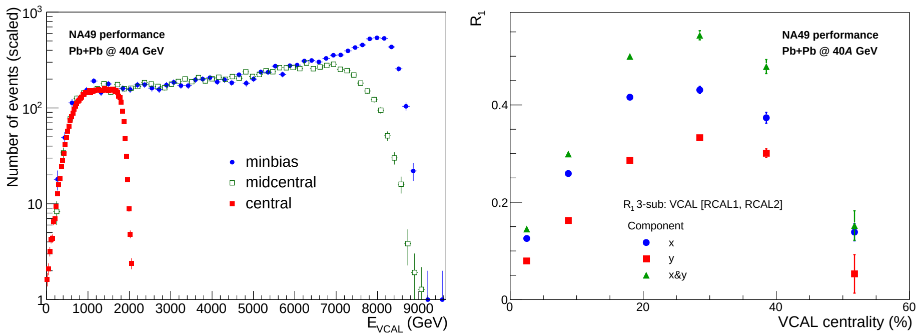

Fig. 2. Left: VCAL energy ($E_{\rm VCAL}$) distribution for different triggers. Right: Spectator plane resolution correction factor (R_1) for VCAL *vs.* collision centrality. Calculations for x and y Q-vector components separately and combined are shown.

Only tracks with at least 20 points in the VTPCs and at least 30 points in all TPCs were considered. To avoid using split tracks, the number of hits associated with a track was required to be more than 55% of total hits possible. Primary tracks were selected using the distance of closest approach (DCA) to the fitted primary vertex. Only tracks with DCA less than 2 cm in the magnetic field bending (x) direction and less than 1 cm in the perpendicular (y) direction were considered.

2. Flow analysis details

Directed flow v_1 is measured from the correlation of two-dimensional flow vectors $\boldsymbol{q_1}$ and $\boldsymbol{Q_1}$. The vector $\boldsymbol{q_1}$ is calculated event-by-event from the azimuthal angle ϕ_i of the $i^{\rm th}$ particle's momentum

$$\boldsymbol{q_1} = \frac{1}{M_{\pi^-}} \sum_{i=1}^{M_{\pi^-}} \boldsymbol{u_{1,i}}\,, \tag{1}$$

where $\boldsymbol{u_{1,i}} = (\cos\phi_i, \sin\phi_i)$ and M_{π^-} is the negatively charged pion multiplicity in a given $p_{\rm T}$ and rapidity (y) range. The symmetry plane of spectators is estimated with the $\boldsymbol{Q_1}$ direction determined from the azimuthal asymmetry of the energy deposition in VCAL

$$\boldsymbol{Q_1^{\rm VCAL}} = \frac{1}{E_{\rm VCAL}} \sum_{i=1}^{4} E_i \boldsymbol{n_i}\,, \tag{2}$$

where $E_{\mathrm{VCAL}} = \sum_{i=1}^{4} E_i$ is the total energy deposited in VCAL. The unit vector $\boldsymbol{n_i}$ points in the direction of the center of i^{th} VCAL module and E_i is the energy deposited in it. An equation similar to Eq. (2) is used to define Q_1^{RCAL} from the RCAL modules. For this, the RCAL module rings are divided into two subgroups: 5 inner (RCAL1) and 5 outer (RCAL2) rings.

Independent estimates of directed flow v_1 are obtained using the scalar product method

$$v_1^{\alpha}\left\{A|B,C\right\} = \frac{2\left\langle q_{1,\alpha} Q_{1,\alpha}^{A}\right\rangle}{R_{1,\alpha}^{A}\left\{B,C\right\}}\,, \tag{3}$$

where $\alpha = x, y$ are q_1 and Q_1 components and $A =$VCAL, $B =$RCAL1, and $C =$RCAL2. Correction factors $R_{1,\alpha}^{A}\left\{B,C\right\}$ were calculated with the three-subevent method,

$$R_{1,\alpha}^{A}\left\{B,C\right\} = \sqrt{2\frac{\left\langle Q_{1,\alpha}^{A} Q_{1,\alpha}^{B}\right\rangle \left\langle Q_{1,\alpha}^{A} Q_{1,\alpha}^{C}\right\rangle}{\left\langle Q_{1,\alpha}^{B} Q_{1,\alpha}^{C}\right\rangle}}\,. \tag{4}$$

Effects of transverse momentum and rapidity-dependent tracking efficiency on the measurement of v_1 were corrected using a Monte Carlo simulation of the NA49 detector response. For this simulation, a sample of heavy-ion collisions was generated using the VENUS event generator [4]. Non-uniform azimuthal acceptance of the NA49 experiment was corrected for with the procedure described in Ref. [5] and implemented in the QnCorrections framework [6, 7]. Recentering, twist and rescale corrections were applied as a function of time and centrality.

3. Results

Results are reported for negatively charged pions (π^-) produced by strong interaction process and weak decays (within the TPC acceptance). Corrections for detector acceptance non-uniformity was applied according to the description given in Sec. 2 above. Independent v_1 estimates with x and y Q-vector components are found to be consistent within statistical uncertainties. Due to the azimuthal TPC acceptance, the correlation for x components are better defined statistically and thus are used for presenting new NA49 preliminary results.

Figure 3 (left) shows NA49 results for directed flow v_1 *vs.* transverse momentum (p_{T}) measured relative to the projectile spectator plane in Pb+Pb collisions at 40A GeV. Results are compared to previously published NA49 results for the directed flow relative to the participant plane. The observed differences are caused by the use of different event plane estimators.

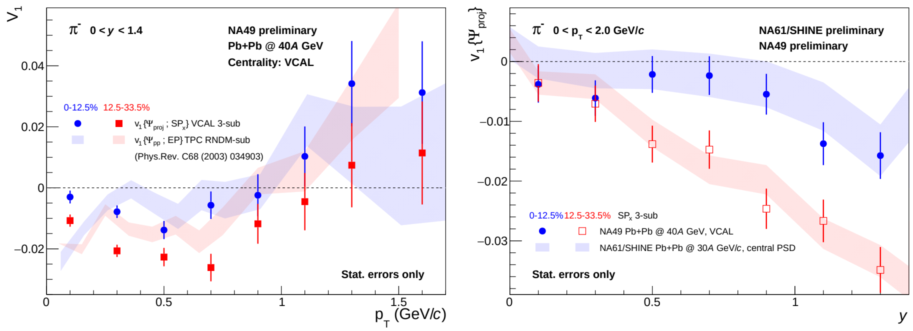

Fig. 3. Directed flow (v_1) of negatively charged pions in different centrality classes. Left: v_1 *vs.* transverse momentum (p_T). Right: v_1 *vs.* rapidity (y). Only statistical errors are shown.

Figure 3 (right) shows results for v_1 *vs.* rapidity in Pb+Pb collisions at $40A$ GeV. The results are compared to the new preliminary data [8] for directed flow relative to spectator plane in Pb+Pb collisions at $30A$ GeV/c reported recently by the NA61/SHINE Collaboration. Despite small difference in the collision energy, good agreement is observed between v_1 from NA49 and NA61/SHINE.

4. Summary and outlook

Preliminary results for directed flow of negatively charged pions relative to the projectile spectator plane in Pb+Pb collisions at $40A$ GeV are presented for different centrality classes as a function of transverse momentum and rapidity. Good agreement of directed flow estimated with the descibed new technique is shown for the energies $30A$ GeV (NA61/SHINE) and $40A$ GeV (NA49).

For Pb+Pb at $40A$ GeV, it is planned to study elliptic flow and make systematics studies. The newly developed technique of azimuthal flow measurement relative to the spectator plane will also be applied to other energies available from NA49.

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