Directed and Elliptic Flow in 158 GeV/Nucleon Pb + Pb Collisions

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The directed and elliptic flow of protons and charged pions has been observed from the semicentral collisions of a 158 GeV/nucleon Pb beam with a Pb target. The rapidity and transverse momentum dependence of the flow has been measured. The directed flow of the pions is opposite to that of the protons but both exhibit negative flow at low p_t. The elliptic flow of both is fairly independent of rapidity but rises with p_t. [S0031-9007(98)06090-6]

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The study of the early stages of relativistic nuclear collisions is of crucial importance for understanding the possibility of producing new phases of nuclear matter. It is thought that angular correlations generated by collective flow in noncentral collisions retain some signature of the effective pressure achieved at maximum compression in the interaction [1,2]. Such studies have proven to be valuable at lower beam energies for the study of the equation of state of nuclear matter. To address these questions, the azimuthal anisotropy of charged particle emission from the interaction of a 158 GeV/nucleon Pb beam with a Pb target has been studied in the two main Time Projection Chambers (TPCs) of CERN SPS experiment NA49 [3]. The large phase-space acceptance of these TPCs allows event-by-event study of the angular correlations of the particles from the interaction, essential for the study of collective flow. This is the first study of directed and elliptic flow as a function of rapidity and transverse momentum for collisions of the heaviest nuclei at the highest bombarding energy presently available.

Usually three kinds of flow in the plane transverse to the beam are considered: radial transverse flow, directed flow, and elliptic flow. For central collisions which are azimuthally isotropic, only radial transverse flow is allowed. For noncentral collisions, a plane can be determined for each event describing the azimuthal anisotropy of the event, and directed and elliptic flow can be identified from the azimuthal anisotropy of the particles with respect to this plane. In a Fourier expansion [4–6] of the azimuthal distribution of the particles with respect to this plane the amplitude of the first harmonic of the distribution corresponds to the directed flow which was discovered at the Bevalac [7]. One of the measures of directed flow, the mean momentum in the flow direction, appears to peak at beam energies of about 1 GeV/nucleon and then decreases at higher energies. Except at the very lowest beam energies, the directed flow of the protons in the forward hemisphere is thought to be on the side of the beam away from the target nucleus. On the other hand, the directed flow of the produced pions is often opposite to that of the protons because of shadowing effects. For a recent review of flow, see Ref. [8]. The amplitude of the second harmonic of the azimuthal distribution of particles with respect to the event plane measures the elliptic flow, the importance of which at high energies was first emphasized by Ollitrault [9]. At Bevalac energies elliptic flow was found to be oriented perpendicular to the directed flow and was called squeeze-out, but at high energies elliptic flow is expected to be in the plane of the directed flow [2,9,10]. This has been found at the AGS [11].

The data presented here consist of 50×10^3 events taken with a medium bias trigger as determined by the NA49 veto calorimeter which measures the energy within 0.3° of the beam. This trigger selected events with veto calorimeter energy from 0.45 to 0.6 of the beam energy. It corresponds to an impact parameter selection of about 6.5 to 8.0 fm, as estimated from VENUS [12] simulations.

The NA49 main TPCs, situated downstream of two large dipole magnets, cover a large region of phase space forward of midrapidity. Particle identification was performed in the TPCs by measuring the specific energy loss in the gas and was used to identify highly enriched samples of protons and charged pions. The identified proton sample used in this analysis had laboratory momenta greater than 30 GeV/c. It had an observed rapidity distribution peaked around 4.5 and an observed mean multiplicity of 20. By comparison with the yield of negative particles in the same energy-loss window it was estimated that this sample was enriched to about 85% in protons. After removing this proton sample, the other positive and negative charged particles formed a sample of unidentified charged particles. (However, the particles in the proton energy-loss window between 10 and 30 GeV/c were not included in either the proton sample or this charged particle sample.) From this charged particle sample, those particles with rapidity (assuming the pion mass) from 4 to 6, and transverse momenta from 0.05 to 1.0 GeV/c were used to determine the orientation of the event plane. They had a mean observed multiplicity of 170. They were also used for the results integrated over rapidity and p_t. The sample of pions identified by their energy loss had momenta between 3 and 50 GeV/c and was estimated to be at least 85% pions based on fits of four Gaussian distributions (p, K, π, e) to the energy-loss spectra. This pion sample had an observed rapidity distribution peaked around 4 and an observed mean multiplicity of 120. This identified pion sample was used for the results to be presented as a function of rapidity and p_t.

Both first harmonic and second harmonic event planes, called here, respectively, the plane and the ellipse, were determined event by event. The azimuthal laboratory angles of these planes were calculated with the following equation:

$$\phi_n = \left(\tan^{-1} \frac{\Sigma \mathrm{wgt}(\phi_i) \sin(n\phi_i)}{\Sigma \mathrm{wgt}(\phi_i) \cos(n\phi_i)} \right) \bigg/ n \,, \qquad (1)$$

where $n = 1$ for the plane, $n = 2$ for the ellipse. The sum goes over i for the charged particles used in the event plane determinations, ϕ_i is the azimuthal laboratory angle of particle i, and the weighting function, wgt, will be described below. The angle $\phi_1 = \phi_{\mathrm{plane}}$ covers 0 to 2π and $\phi_2 = \phi_{\mathrm{ellipse}}$ covers 0 to π, using the signs of the sums to determine the quadrant. Notice that the angle of the ellipse is calculated by summing over 2ϕ instead of ϕ. Notice also that p_t is not used in these equations, so that they represent the number weighted angles, not the momentum weighted angles.

To remove the biases due to acceptance correlations we have used two methods: event plane flattening by weighting, and event plane flattening by shifting. Flattening of the event plane laboratory angular distribution by weighting involved using the inverse of the laboratory azimuthal distributions of the particles, summed over all events, as a 36 channel histogram for wgt(ϕ_i) in the above equation. Flattening the distribution of the event planes by shifting involved setting wgt(ϕ_i) in the above equation to one and then fitting the resultant azimuthal distributions of the event planes, summed over all events, to a Fourier expansion. Harmonics up to fourth order were used for the plane, but of these only the even harmonics entered into the fit for the ellipse. From the resultant coefficients of the fit one can derive an equation for shifting the event plane angles, event by event, to obtain flat distributions [13]. With this method the distributions of ϕ_{plane} and ϕ_{ellipse} are flat in the laboratory. All the results presented here used this shifting method of flattening even though the flow values and the resolution corrections were exactly the same using the weighting method.

The correlations of the selected particles with respect to the above defined event-by-event planes were found by evaluating the coefficients in the Fourier expansions of the azimuthal distributions (normalized to an average value of

1) with respect to the two planes:

$$1 + 2v_1^{\mathrm{obs}} \cos(\phi - \phi_{\mathrm{plane}}) + 2v_2^{\mathrm{obs}} \cos[2(\phi - \phi_{\mathrm{plane}})], \quad (2)$$

$$1 + 2v_2^{\mathrm{obs}} \cos[2(\phi - \phi_{\mathrm{ellipse}})]. \quad (3)$$

The coefficient v_1^{obs} is evaluated by $\langle \cos(\phi - \phi_{\mathrm{plane}}) \rangle$, where $\langle\, \rangle$ indicates the mean value summed over the particles of interest for all events. The v_1^{obs} is $\langle p_x/p_t \rangle$, whereas v_2^{obs} is related to the eccentricity of the ellipse by $\langle (p_x/p_t)^2 - (p_y/p_t)^2 \rangle$, with x and y being the directions perpendicular to the beam with x in the event plane. The quantity v_2^{obs} can be evaluated from $\langle \cos[2(\phi - \phi_{\mathrm{plane}})] \rangle$, and, in fact, its sign gives the relative orientation of the plane and the ellipse. However, higher accuracy for the value of v_2^{obs} was obtained by evaluating $\langle \cos[2(\phi - \phi_{\mathrm{ellipse}})] \rangle$. Of course, when a particle had been used to calculate the direction of a plane, the autocorrelation effect in its distribution with respect to this plane was removed in the usual way by recalculating that plane's orientation without this particle [14].

The v_1^{obs} and v_2^{obs} values are the flow values relative to the observed event planes. To obtain the values relative to the true reaction plane one has to divide these values by a factor which corrects for the limited resolution of the measurement of the angle of the event plane [4,6,15]. To accomplish this the events were randomly divided into two subevents and the correlations of the planes of the subevents were evaluated. The square roots of $\langle \cos(\phi_{\mathrm{sub1}} - \phi_{\mathrm{sub2}}) \rangle$ and of $\langle \cos[2(\phi_{\mathrm{sub1}} - \phi_{\mathrm{sub2}})] \rangle$ are the resolution corrections of the observed subevent planes. The resolution corrections of the observed event planes of the full events were determined by correcting for the fact that the full events have twice the multiplicity of the subevents. When the resolution corrections are small compared to 1 this can be done by multiplying the resolution corrections by $\sqrt{2}$. Instead we used the more general multiplicity dependence of the resolution correction given by Eq. (13) and Fig. 4 of Ref. [4] to do this extrapolation. The resolution correction factors for the full events are shown in the last line of Table I.

To evaluate our methods and, in particular, our ability to remove the acceptance correlations, we generated 50×10^3 events with a simple Monte Carlo event generator which had no azimuthal correlations but reproduced the charged particle and proton multiplicities and p_t spectra within our acceptance. These events were filtered through a GEANT model of the NA49 detector. In the GEANT simulation, all physics processes including decays were turned off so that these events should not have any correlations beyond those due to the acceptance geometry. In a separate study not shown, VENUS [12] calculations were filtered through the GEANT model of the detector with all physics processes turned on. This gave the same results as analyzing the raw VENUS events, showing that acceptance correlations are removed in our method and that other sources of correlations are small.

The experimental azimuthal distributions of the charged particles are plotted with respect to the charged particle plane and ellipse in Fig. 1. Also shown are the results from the simple Monte Carlo filtered for the NA49 acceptance. The graphs clearly show both directed flow in the forward hemisphere (which is defined to have symmetry about 180°) and elliptic flow (which is defined to have symmetry about 90°). In the left graph, in addition to a first harmonic, the fit contains a small second harmonic with positive amplitude which shows that the ellipse is aligned with the plane. This means that the elliptic flow is in-plane, not out-of-plane squeeze-out. This was verified by observing a positive correlation between the plane of one charged particle subevent and the ellipse of the other.

Data not shown indicate that the ellipses of the protons and the other charged particles are aligned, and that the directed flow of the protons appears to be small and opposite to that of the other charged particles. It was assumed that the proton directed flow is in the positive (direction of the impact parameter from the target nucleus) side of the event plane in the forward hemisphere. In Table I is given a summary of the results which have been divided by the resolution corrections shown in the last line. The units of percent for v_1 and v_2 mean that the numbers have been multiplied by a factor of 100.

The rapidity and p_t dependence of the flow of the protons and pions identified by their energy loss are now evaluated relative to the same charged particle event planes used above. Again, all flow values are corrected for the resolutions of these planes. The rapidity dependence of the flow is shown in Fig. 2 with reflection about midrapidity. In reflection, the signs of the v_1 values have been reversed in the backward hemisphere, but not the v_2 values. The directed flow (v_1) values exhibit characteristic S-shaped curves. The elliptic flow (v_2) values for the pions appear to be slightly peaked at medium-high rapidity and for the protons somewhat peaked near midrapidity. Here one can see that our choice of the sign of the event plane is plausible

TABLE I. Flow values integrated over the indicated y and p_t ranges.

Particle	y	p_t (GeV/c)	v_1 (%)	v_2 (%)
Protons	3–6	0.0–2.0	1.1 ± 0.2	2.6 ± 0.3
Charged particles	4–6	0.05–1.0	−3.0 ± 0.1	2.3 ± 0.1
Resolution corrections			0.35 ± 0.01	0.27 ± 0.01

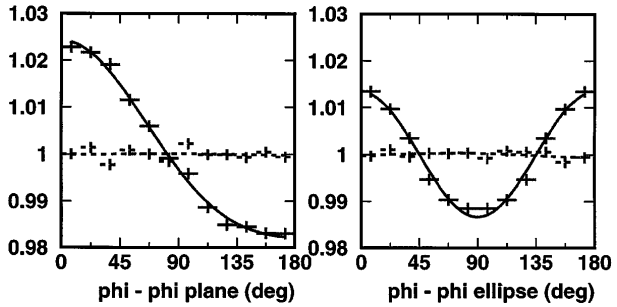

FIG. 1. Shown are the azimuthal distributions of the charged particles with respect to the plane (left) and ellipse (right) of the charged particles. Counts are plotted on the vertical axis but have been normalized to an average value of 1. The dashed points and lines near a value of 1 are for the simple Monte Carlo simulation. The curves are fits with $\cos(\phi)$ plus $\cos(2\phi)$ [Eq. (2)] (left), and $\cos(2\phi)$ [Eq. (3)] (right). On the right, the points above 90° have been reflected from those below 90°. The results are integrated for rapidity from 4.0 to 6.0 and p_t from 0.05 to 1.0 GeV/c.

from the fact that the protons at high rapidity have positive directed flow, as one would expect for the baryons in the reaction plane. Figure 3 shows the p_t dependence of the flow. These curves should go to zero at zero p_t where no transverse direction is defined.

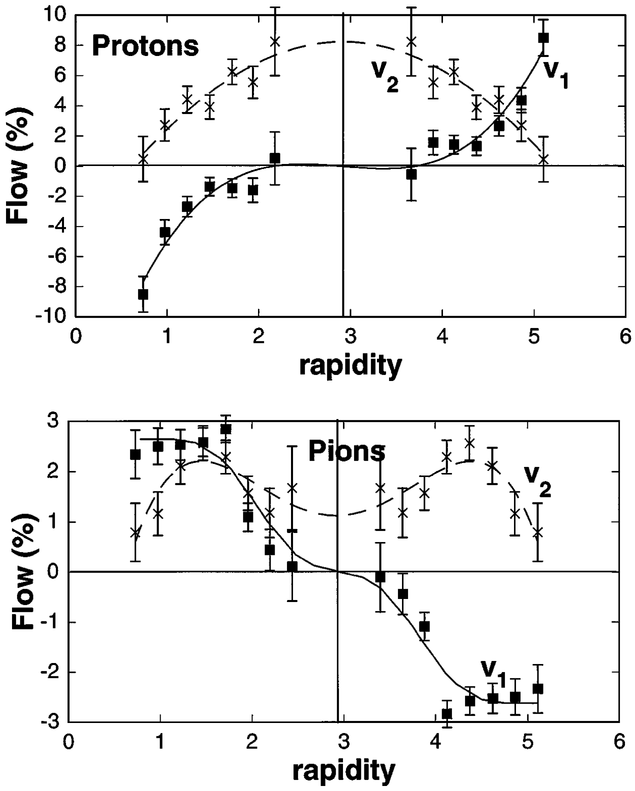

FIG. 2. The rapidity dependence of the directed (v_1) and elliptic (v_2) flow for the protons ($0.6 < p_t < 2.0$ GeV/c) and pions ($0.05 < p_t < 0.35$ GeV/c). The points below midrapidity ($y = 2.92$) have been reflected from the measurements in the forward hemisphere. The curves are to guide the eye.

At first sight the v_1 curves in Fig. 3 appear peculiar, especially for the pions, because they approach zero from the negative side. However, this behavior was predicted for protons by Voloshin [16] as a consequence of the interaction of transverse radial flow and directed flow. Simply, in the presence of large transverse radial flow, a low p_t particle can be produced only by the part of the moving source where the directed flow subtracts from the radial flow. If this is the correct explanation then the data also contain information on the transverse radial flow. However, especially for the pions, it is also possible that this behavior of the directed flow results from some kind of fireball shadowing effect, resonance decays, or Coulomb effects.

Previously, elliptic flow has been observed using the NA49 Ring Calorimeter by analyzing the azimuthal anisotropy of the transverse energy [17]. The correlation which was observed between the forward and backward event planes may not be inconsistent with that seen here considering that transverse energy flow, not number flow, was studied, that neutral particles and charged baryons were included, and that the bins were in pseudorapidity. Also the elliptic flow of photons from π^0 decay has been reported [18] by WA93 for S + Au at the SPS. They find an anisotropy of the order of 5% for semicentral collisions.

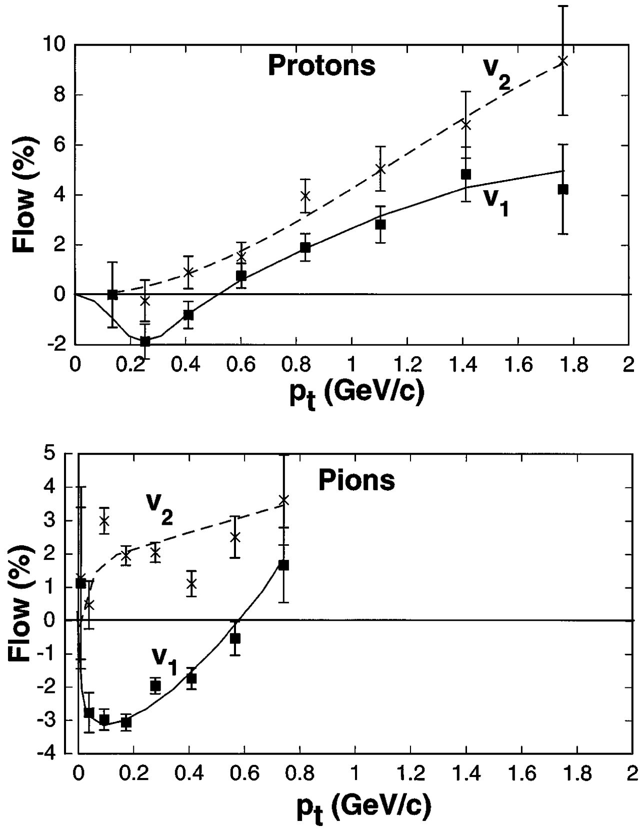

FIG. 3. The transverse momentum dependence of the directed (v_1) and elliptic (v_2) flow for the protons and pions with $4.0 < y < 5.0$. The curves are to guide the eye.

At the AGS, E877 reported [15] v_1 values of about 10% for protons and about 2% for pions. Their v_2 values [11] for charged particles are, however, at most 2%. Thus, although the directed flow is smaller at the SPS, the elliptic flow may be larger.

In summary, we have presented the first data on directed and elliptic flow for Pb + Pb collisions at 158 GeV/nucleon. Protons and pions exhibit significant, but opposite, directed flow at large rapidities. The elliptic flow was found to be slightly peaked at medium-high rapidity for the pions and peaked somewhat near midrapidity for the protons. For both sets of particles the flow axis of the elliptic flow is in the plane of the directed flow. This excludes shadowing by spectator matter as the origin of the elliptic flow. Therefore we conclude that the elliptic flow in these semicentral collisions retains some signature from the high density region created during the initial collision. This opens a new probe of the early stage of ultrarelativistic nucleus-nucleus collisions [9].

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