Directed and Elliptic Flow in $158A$GeV Pb+Pb Collisions

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Directed and elliptic flow of protons and positively charged pions has been studied in the target fragmentation region using the Plastic Ball detector in the WA98 experiment. The results exhibit a strong dependence on centrality, rapidity, and transverse momentum. The rapidity dependence can be described by a Gaussian distribution. The model comparisons reveal a large discrepancy of the flow strength obtained from the data and the simulations.

1. Introduction

In high energy collisions it is expected that a high density interaction zone is formed. If this system thermalizes, the thermal pressure will necessarily generate collective transverse expansion[1, 2]. If the initial state is azimuthally asymmetric, as in semi-central collisions, this property may be reflected in the azimuthal asymmetry of the final state particle distributions. The strength of collective flow will yield information on the nuclear equation of state during the expansion. Especially the in-plane or out-of-plane character of the elliptic flow should give important hints on the underlying mechanisms.

2. Method

Two independent methods are used to determine the strength of the collective flow. To be able to compare the result to previous data the average transverse momentum $\langle p_x \rangle$ method is used. In this method the transverse momentum p_T of each identified particle is decomposed into components with respect to the measured reaction plane. In order to perform systematic studies the p_x versus p_y distributions are evaluated for different centrality and rapidity bins and for all identified particle species. The second method is based on the Fourier decomposition[3, 4]. The azimuthal distributions of identified particles with respect to the reaction plane for all events are constructed. These distributions are fitted with the function:

$$\frac{1}{N}\frac{dN}{d\Delta\Phi} = 1 + 2v_1 \cos(\Delta\Phi) + 2v_2 \cos(2\Delta\Phi)$$

Where $\Delta\Phi$ is the azimuthal angle of the single particle with respect to the reaction plane. The strength of the collective flow is then given by v_1 (v_2) for the directed (elliptic) flow.

The flow measurements with respect to the reaction plane assume a perfect event plane determination, i.e. that the reaction plane angle could be obtained from the data exactly.

In reality, the limited detector resolution and effects like the finite number of detected particles produces a limited resolution in the measurement of the reaction plane angle. All observables that refer to the reaction plane must be corrected up to what they would be relative to the true event plane[5]. This correction is done by dividing the observable by the event plane resolution[6, 7].

Another effect which has to be taken into account, is the auto correlation effect. Naturally, there is a correlation between the azimuthal angle of a particle with respect to the reaction plane, if this particle is included in the evaluation of the reaction plane angle. This auto correlation is avoided by calculating for each particle the event plane angle of the remaining particles.

3. Results

A systematic study of the dependence of the flow signal on centrality for protons and pions in terms of $\langle p_x \rangle$ is displayed in figure 1. The proton absolute momentum transfer in the reaction plane increases with the number of participants to a maximum $|\langle p_x \rangle|$ for semi-central collisions at an impact parameter of $b \approx 8\,\text{fm}$[8, 9] which is twice as large as that found for Au + Au collisions at AGS energies[10]. For more head-on collisions the $|\langle p_x \rangle|$ decreases again. In the limit of impact parameter zero the sideward flow vanishes due to symmetry.
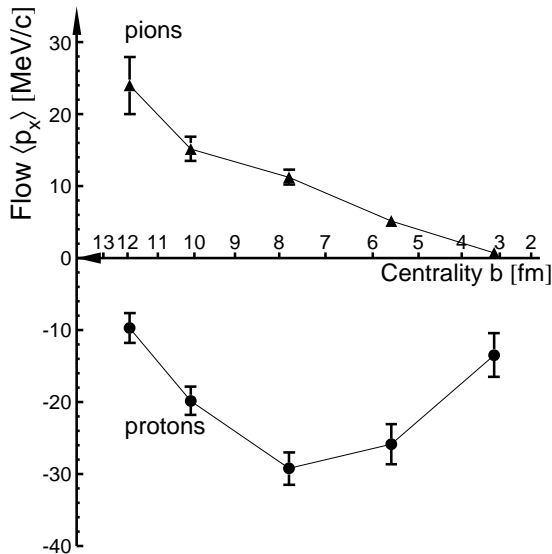

Figure 1. The average transverse momentum for protons (circles) and pions (triangles) as function of centrality in terms of the impact parameter b.
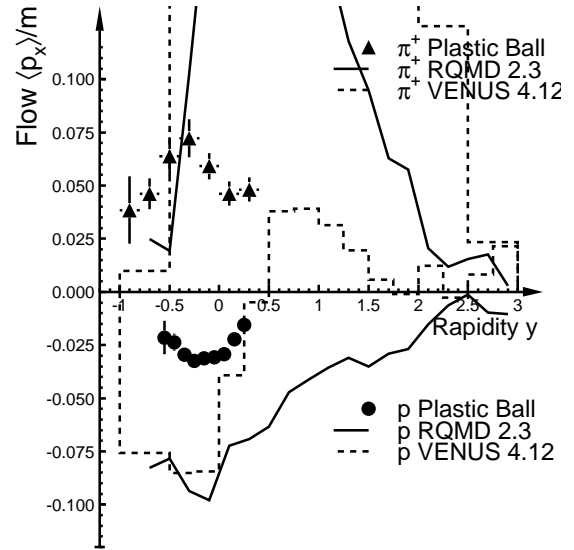
Figure 2. The average transverse momentum for protons (circles) and pions (triangles) as function of rapidity y compared to model predictions.

In addition to the small flow effect of pions due to the thermal motion, pions are subject to absorption and rescattering mainly through the delta resonance. Thus they should show flow effects comparable to that of protons[11, 12]. Since the observed $\langle p_x \rangle$ of pions is positive it indicates that the pions are preferentially emitted away from the target

spectators. This leads to the interpretation of an absorption of the pions in the target remnant, which appears as preferred emission toward the other side. If the apparent anti-flow is due to absorption, central collisions with little or no spectator matter should show no flow effect[13] which is indeed seen for central events, where the pion flow signal is compatible with zero. The effect in semi-central collisions is weak but grows with the impact parameter nearly linearly.

Figure 2 shows the rapidity dependence of the average transverse momentum for protons and pions in comparison with model predictions. For protons a clear maximum flow at target rapidity is evident in the data as well as in the simulations, though the absolute height of the data cannot be reproduced by RQMD[14] or VENUS[15]. There is also a large discrepancy between the pion data and the model predictions, though the absolute height is approximately reproduced in the most backward rapidity regions.

The Fourier decomposition method also provides the transverse momentum dependence of the flow strength. Over a wide range of p_T the directed flow in terms of v_1 is well described by a linear function of the transverse momentum as depicted in figure 3. The second harmonic or elliptic flow in terms of v_2 is consistent with zero in the target rapidity range, hence it is not plotted in the figure.
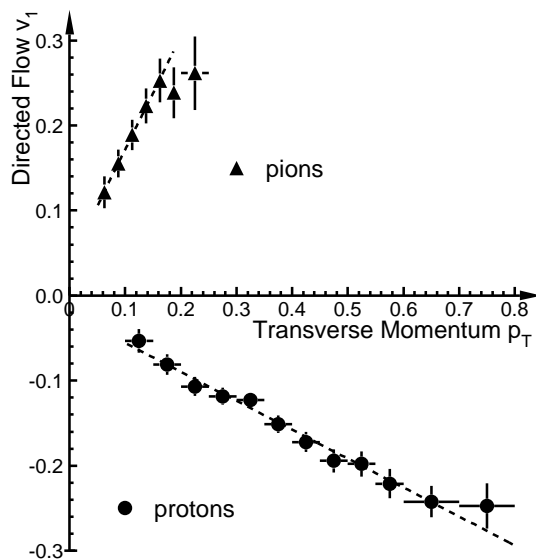

Figure 3. The directed flow in terms of v_1 for protons (circles) and pions (triangles) as function of transverse momentum p_T.
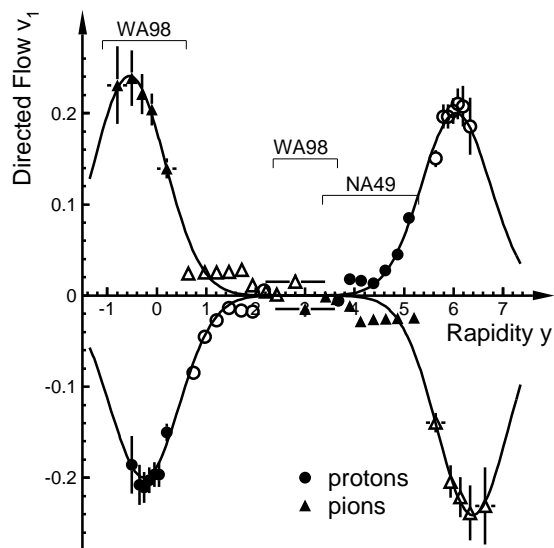
Figure 4. The flow parameter v_1 for protons (circles) and pions (triangles) as function of rapidity y in semi central collisions.

Figure 4 shows the rapidity dependence of the directed flow in terms of $v_1 = \langle \cos(\Delta\Phi) \rangle$. The filled symbols represent measured data, while the open symbols are the data reflected around midrapidity $y = 2.9$. Shown are proton (circles) and pion (triangles) data from the Plastic Ball in the target rapidity region. In addition, pion data measured with the tracking arm in the WA98 experiment[16] at midrapidity and data near midrapitiy measured by the NA49 collaboration[17] are shown. It can be noticed that the directed flow of protons as well as of pions has a maximum in the fragmentation regions.

The Plastic Ball data in the region $y < 0.5$ are fitted with Gaussian distributions.

These Gaussian distributions, shown as solid lines, are reflected around midrapidity like the data and describe the data rather well. It should be emphasized that the midrapidity data were not included in the Gaussian fit. The shape of the distribution appears different than that observed in heavy-ion collisions at lower beam momenta[18, 19], where the flow strength increases from zero at midrapidity linearly to the peaks at target and projectile rapidity. In 158 AGeV Pb + Pb collisions however, the peaks are Gaussian and only the tails extend to midrapidity. It is conceivable that the S-shape curve obtained at lower beam energies could also be obtained by a combination of two Gaussian distributions. In this case the ratio of the relative width and the gap between the Gaussian peaks would be smaller so that a linear behaviour is found at midrapidity. This suspicion was confirmed by a good agreement with a Gaussian fit for the proton data from 200 AMeV Au + Au collisions provided by the Plastic Ball collaboration[18].

Hence for a complete description of the rapidity distribution of the collective flow F the formerly used slope at midrapidity $(dF/dy|_{y=0})$ is not sufficient. It is more reasonable to use the three parameters of the Gaussian distribution to describe the data. The peak position reflects the beam momentum, the peak height gives the strength of the flow and the width of the distribution provides information on how much the participants and the spectators are involved in the collectivity.

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