DIRECTED FLOW IN 158 A·GeV ^{208}Pb + ^{208}Pb COLLISIONS

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Collective flow has been studied in heavy-ion collisions since first observed at the Bevalac by the Plastic Ball experiment [1]. Collective flow development follows the time evolution of pressure gradients in the hot, dense matter. Thus, collective flow can serve as a hadronic "penetrating probe" to provide information on the initial state. In particular, the formation of a quark-gluon plasma (QGP) during the early stages of the collision is expected to result in reduced pressure gradients due to a softening of the EOS, with a corresponding reduction of collective flow [2, 3, 4].

The present analysis makes use of a subset of the detector systems of the WA98 experiment. This subset consists of the trigger detectors, the Plastic Ball detector, and the tracking spectrometers. The Plastic Ball detector provides full azimuthal coverage in the target fragment region (pseudorapidity $-1.7 < \eta < 0.5$) with 655 detector modules. It provides identification of pions, protons, deuterons, and tritons (π, p, d, and t) with kinetic energies of 50 to 250 MeV by the $\Delta\mathrm{E} - \mathrm{E}$ method. In addition, stopped π^+ are identified by detection of the delayed e^+ from the decay $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$ in the Plastic Ball. For the present analysis the rapidity region $-0.5 < y(\mathrm{proton}) < 0.2$ has been used.

Azimuthal anisotropies of the particle emission are evaluated by means of a Fourier expansion [5, 6]. The Fourier coefficients $v_n (n = 1, 2)$ are extracted from the azimuthal distribution of identified particles with respect to the reaction plane, Φ_0, which is determined using all other fragments in the Plastic Ball.

$$\frac{1}{N}\frac{dN}{d(\phi - \Phi_0)} = 1 + 2v_1' \cos(\phi - \Phi_0) + 2v_2' \cos[2(\phi - \Phi_0)] \ , \tag{1}$$

where ϕ is the measured azimuthal angle. The Fourier coefficient v_1' quantifies the directed flow, whereas v_2' quantifies the elliptic flow. The coefficients must be corrected for the event plane resolution as $v_n = v_n'/\langle\cos(n(\Phi_0 - \Phi_r))\rangle$ where $\Phi_0 - \Phi_r$ is the deviation of the measured reaction plane from the true reaction plane. The event plane resolution may be extracted from the correlation between subevents. For weak correlations one expects $\langle\cos(\Phi_0 - \Phi_r)\rangle \simeq \sqrt{2\langle\cos(\Phi_a - \Phi_b)\rangle}$. Using the more accurate procedure and interpolation formula of Ref. [6] one obtains $\langle\cos(\Phi_0 - \Phi_r)\rangle = 0.366 \pm 0.029$ for the semi-central (100 $< E_T <$ 200 GeV) event selection.

The dependence of the v_1 parameter on centrality, as determined by the measured transverse energy (E_T), is shown for protons in Fig. 1. For convenience, an impact parameter scale is also shown. The E_T scale has been converted to an impact parameter scale assuming a monotonic relationship between the two quantities, and equating $d\sigma/dE_T$ with $d\sigma/db$. As seen in Fig. 1, the strength of the correlation between the flow directions of the two subevents increases with centrality and reaches a maximum value for semi-central collisions with $b \approx 8$ fm. It is interesting to note that the strongest flow effect occurs at larger impact parameters than observed at lower incident energy for similar systems

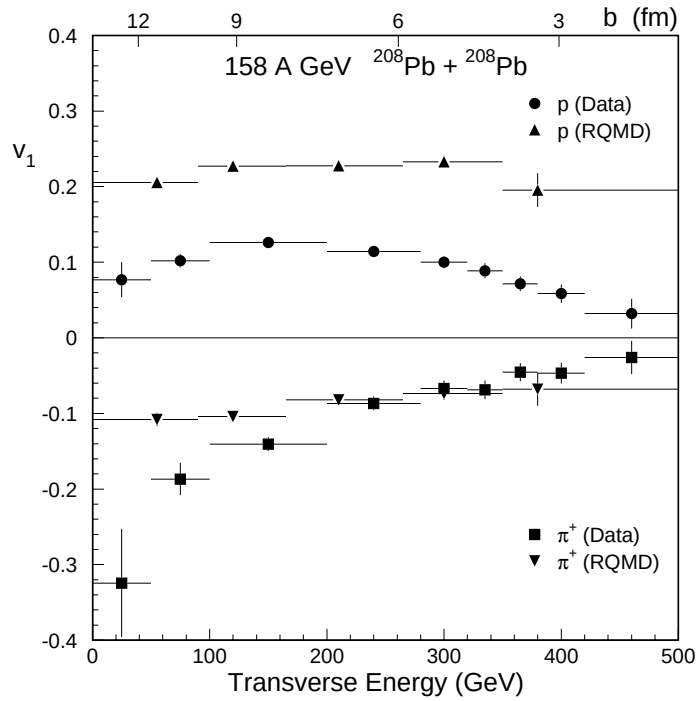

Figure 1: The centrality dependence of the directed flow coefficient v_1 for protons (circles) and π^+ (squares). Triangles are results from RQMD model calculations. The data and RQMD results have been corrected for the event-plane resolution. The vertical bars indicate the uncertainty of the fit and resolution correction. The horizontal bars indicate the E_T bin intervals (or impact parameter intervals for RQMD).

(where $b \approx 4$ fm) [7]. For comparison, RQMD 2.3 [8] model predictions are shown subjected to the same analysis after applying the Plastic Ball detector acceptance. RQMD predicts a significantly stronger correlation for protons than observed.

Also shown in Fig. 1 is the strength of the directed flow of π^+, identified in the Plastic Ball. A clear anticorrelation, or antiflow, is observed between the fragment and π^+ flow directions. This behavior has been observed at incident energies from 1 A GeV to SPS energies and has been explained as resulting from preferential absorption of the pions emitted in the target spectator direction.

A conventional directed flow analysis has been performed [9], in which the average transverse momentum with respect to the reaction plane $\langle p_x \rangle$ is evaluated as a function of rapidity. This is done for semi-central collisions (100 $< E_T <$ 200 GeV) where the largest azimuthal asymmetry is observed (see Fig. 1). The distribution $d^3N/dp'_x dp'_y dy$ is constructed for protons and π^+ in the Plastic Ball and in the tracking arm, where the new axis p'_x corresponds to the reaction plane determined event-by-event using all remaining fragments measured in the Plastic Ball (then reflected, $p'_x \rightarrow -p'_x$, to correspond to the projectile fragment direction, according to convention). At each rapidity the average transverse momentum in the reaction plane, $\langle p'_x \rangle$, is calculated from fits to the experimental distributions.

Since the particle momenta are not projected onto the true reaction plane, the average projected momenta are reduced by $\langle p'_x \rangle = \langle p_x \rangle \cdot \langle \cos(\Phi_0 - \Phi_r) \rangle$ where ϕ is the deviation of the azimuthal angle of the estimated reaction plane from the true reaction plane. After correction for the event-plane resolution, the $\langle p_x \rangle$ for protons and π^+ are plotted as a function of rapidity in Fig. 2. As expected from Fig. 1, the π^+ show an anti-flow relative to the proton flow.

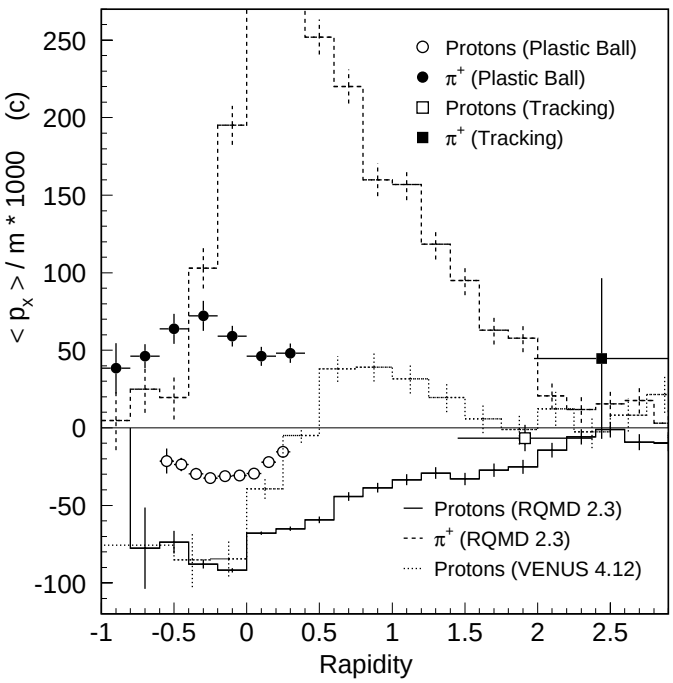

Figure 2: The average transverse momentum projected onto the reaction-plane for semi-central 158 A·GeV ^{208}Pb + ^{208}Pb collisions (Note $y_{cm} = 2.9$). The vertical errors indicate the statistical errors of the fit only. The horizontal bars on the tracking points indicate the width of the rapidity bin. RQMD model calculations (b=8-10 fm) and VENUS model calculations (b=8-10 fm) are also shown. The VENUS prediction for π^+ (not shown) is similar to that of RQMD.

In Fig. 2 the measured results are compared to RQMD 2.3 [8] and VENUS 4.12 [10] predictions for similar impact parameter range. The RQMD calculation, in cascade mode, overpredicts the observed proton flow by about a factor of three. On the other hand, at AGS energies cascade mode RQMD calculations underpredict the observed directed flow by about a factor of two, but reasonable agreement is obtained when mean field effects are included [11]. At SPS energies mean field effects are expected to be smaller, but would worsen the observed disagreement. The VENUS predictions show a similar disagreement in the target rapidity region. The results suggest a significant softness in the nuclear response. It is interesting to note that VENUS predicts a complicated proton flow behavior with protons having an anti-flow direction (similar to the RQMD pion prediction) near midrapidity. However, this prediction disagrees with the results of Ref. [12].

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