

## Energy flow and particle spectra with respect to the reaction plane for Au+Au collisions at AGS energies

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Transverse energy flow is studied by exploiting the near  $4\pi$  calorimetric coverage of experiment E877. A Fourier decomposition of the azimuthal transverse energy distributions in different regions of pseudorapidity is performed as a function of the centrality in order to describe the event shape. The extracted coefficients are compared to model predictions. Using the E877 forward spectrometer, triple differential cross section for protons and  $\pi^+$  are measured with respect to the reaction plane determined by calorimeters. The variation of slope parameters at different orientations to the reaction plane is obtained by fitting to thermal Boltzmann distributions.

### 1. INTRODUCTION

Flow phenomena were first observed in intermediate energy heavy ion collisions at the Bevalac more than ten years ago [1]. According to theoretical calculations [2] flow studies can provide information on the collision dynamics as well as on the equation of state and, in particular, on a possible phase transition to soft quark matter [3]. Recently, the E877 collaboration reported the first observation of azimuthally anisotropic transverse energy flow in Au on Au collisions at the AGS at 11 A GeV/c [4]. Here, we focus on two aspects in our recent analysis of flow phenomena, comparison of the mentioned azimuthal anisotropy with model calculations, and particle spectra with respect to the reaction plane.

### 2. ENERGY FLOW AND REACTION PLANE

Transverse energy  $E_T$  is measured in the target (TCal,  $-0.5 < \eta < 0.8$ ) and participant (PCal,  $0.83 < \eta < 4.7$ ) calorimeters surrounding the target [5]. At a given centrality, characterized by the total  $E_T$  in the PCal, azimuthal distributions in different pseudorapidity intervals are analyzed by a Fourier expansion method [4,6]. The extracted anisotropy parameters  $\tilde{v}_n$  are obtained from the Fourier coefficients for a pseudorapidity bin after averaging over events of a given centrality and unfolding fluctuations. They describe the shape and amplitude of the azimuthal transverse energy anisotropy, and have the following

Work performed under the auspices of the US Dept. of Energy.

physical meaning:

$$\tilde{v}_n = \langle \varepsilon_T \cos(n\varphi) \rangle / \langle \varepsilon_T \rangle \quad (1)$$

where  $\varepsilon_T$  is the transverse energy of a single particle emitted into a given pseudorapidity interval with an azimuthal emission angle  $\phi$ . Relative to the reaction plane angle  $\psi$ , this becomes  $\varphi = \phi - \psi_r$ . For every event with a non-zero  $v_1$  the reaction plane angle  $\psi_r$  is defined by  $\psi_1$ , and the dispersion of  $\psi = \psi_1 - \psi_r$  can be determined (see eq.(16) in [6]).

For  $n = 1$ ,  $\tilde{v}_1 = \langle \varepsilon_x \rangle / \langle \varepsilon_T \rangle$  is a measure for the well known sideward flow signal, where  $\langle \varepsilon_x \rangle$  is the mean transverse energy into the reaction plane. Figure 1 shows  $\tilde{v}_n$  for all centrality bins, selected by PCal  $E_T$  as shown in the top plot, in middle and forward pseudorapidity intervals. The lines are the results from RQMD (version 1.08, cascade mode) calculations folded with the detector response using the GEANT package. The most dramatic discrepancy between data and the model is for  $\tilde{v}_1$  in the forward pseudorapidity window. There the amplitude of sideward flow is about a factor of two larger in the data compared to the model. This striking difference might be linked to the fact that the model exhibits a large flow of pions in the opposite direction to that of the nucleons thereby reducing the size of  $\tilde{v}_1$  for the azimuthal  $E_T$  distribution. As will be shown later, in the analysis of particle spectra with respect to the reaction plane, pions exhibit less sideward flow.

Other differences beyond bin to bin fluctuation are seen for  $\tilde{v}_1$  and  $\tilde{v}_4$  in the middle pseudorapidity window. RQMD gives  $\tilde{v}_4$  consistent with zero in contrast to the data. Conversely, the predicted non-zero  $\tilde{v}_1$  is not observed. Concerning the quadrupole component  $\tilde{v}_2$ , an azimuthal distribution with non-zero  $\tilde{v}_1$  will after integration over a fairly large pseudorapidity interval result in a non-zero  $\tilde{v}_2$ . Opposite motion of nucleons and pions as seen in the model will also give rise

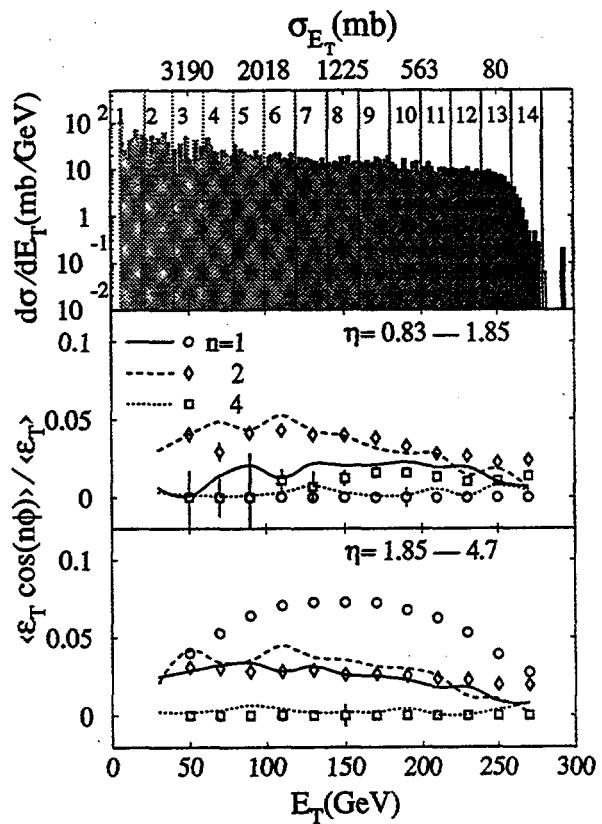


Figure 1. Anisotropy parameters as a function of centrality. Symbols are data, and lines are filtered RQMD calculations.

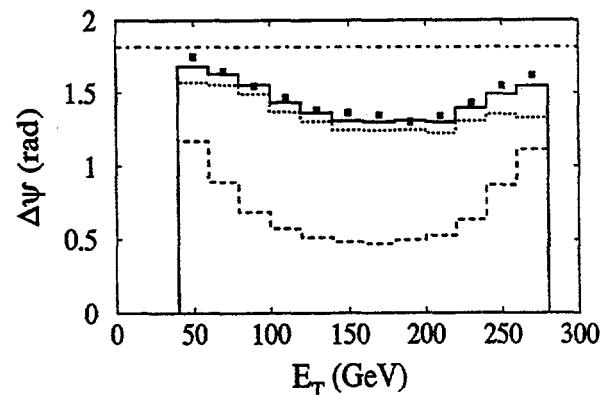


Figure 2. Reaction plane resolutions for TCal and PCal (forward) windows. Squares: data points for the correlation between TCal and PCal (forward). Dash-dotted line: random distribution. Resolution calculated from  $\tilde{v}_n$  using PCal (forward) - dashed line; TCal - dotted line; the correlation between the two - solid line.

to larger  $\tilde{v}_2$ . Because of these competing effects, at this stage we do not assign any significance to the agreement between the data and the calculation for  $\tilde{v}_2$ .

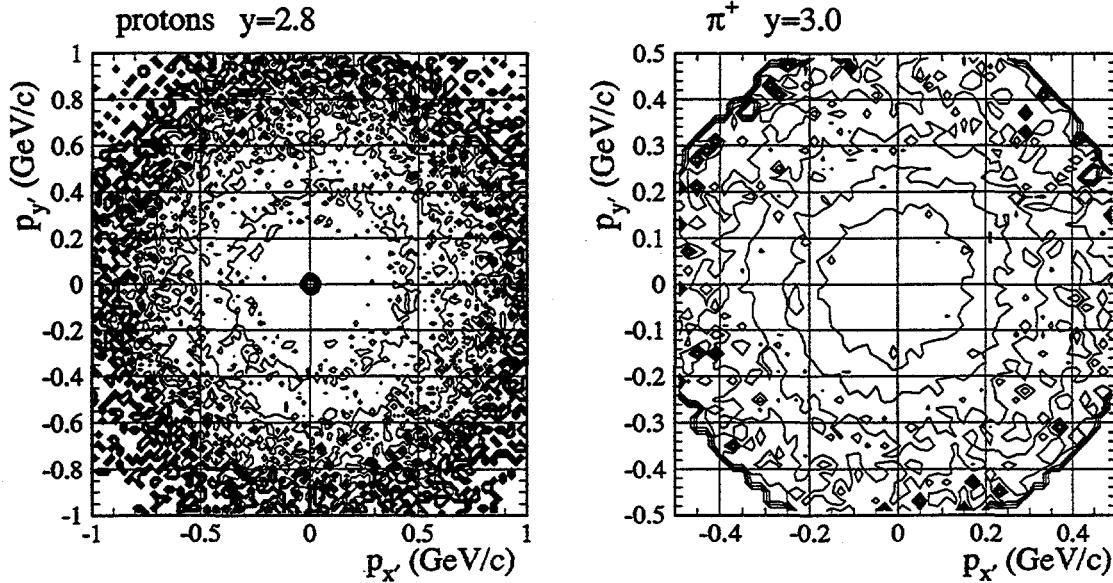


Figure 3. Triple differential cross section  $d^3N/dydp_{x'}dp_{y'}$  at rapidity  $y = 2.8 \pm 0.05$  for protons (left) and  $y = 3.0 \pm 0.05$  for  $\pi^+$  (right).

As a measure for the resolution of the reaction plane angle in Figure 2 we show the RMS difference  $\Delta\psi = \psi_1 - \psi$ , between the measured and the true reaction plane angle for TCal and PCal (forward interval) extracted from calculations using the anisotropy parameters. Also plotted is the difference between the TCal (backward) and the PCal (forward) interval, from data as well as from the calculation. The good agreement between the two shows the internal consistency of the analysis, and also indicates that particles emitted into different pseudorapidity intervals are independent, as is assumed in the calculation. In the following we take the reaction plane angle from TCal alone, where at present the systematics is better understood. Ultimately we will combine TCal and PCal to obtain the best determination of the reaction plane.

### 3. PROTON AND PION SPECTRA

Particles are identified, and momenta are measured with the E877 forward spectrometer [5,7]. For each identified proton and  $\pi^+$ , rapidity  $y$ ,  $p_t$  and azimuthal angle  $\phi$  are evaluated. For different rapidity bins, two dimensional distributions  $d^2N/dp_{y'}dp_{x'}$  are obtained by decomposing  $p_t$  into components with respect to the measured reaction plane:

$$p_{x'} = p_t \cos(\phi') \quad p_{y'} = p_t \sin(\phi') \quad (2)$$

Here  $\phi' = \phi - \psi_1$  is the azimuthal emission angle of the particle relative to the measured reaction plane with  $\psi_1$  pointing in  $x'$ -direction.

The left panel of Figure 3 shows contours of  $d^2N/dp_{y'}dp_{x'}$  for protons at rapidity  $y = 2.8 \pm 0.05$ . The azimuthal asymmetry is clearly visible. The yield is higher for momenta in the reaction plane to the same-side ( $+x'$ ) as the sideward flow observed at forward

rapidity. Emission to the opposite-side ( $-x'$ ) is diminished. The right panel shows the same representation for  $\pi^+$  at rapidity  $y = 3.0 \pm 0.05$ . If there is any anisotropy for  $\pi^+$  it is not perceivable at this level. See [7] for more details.

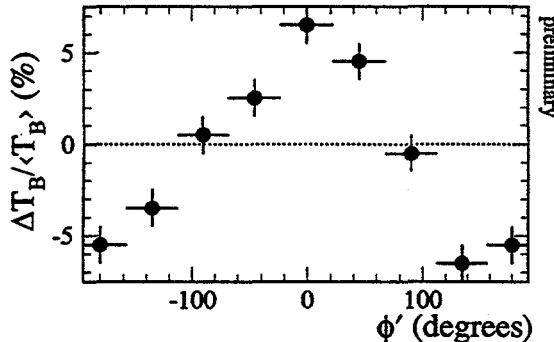


Figure 4. Relative variation of the Boltzmann temperature parameter as a function of azimuthal angles  $\phi'$  for protons with  $y = 2.8 \pm 0.05$ .

To quantify the strong azimuthal anisotropy for protons,  $\phi'$  is divided evenly into bins of  $45^\circ$  width. Then the  $p_t$  distributions obtained in each azimuthal bin are fitted with a Boltzmann spectrum yielding a temperature ( $T_B$ ). The relative change of this temperature parameter as a function of the emission angle with respect to the reaction plane is plotted in Figure 4 for protons.

#### 4. CONCLUSION

In conclusion, the sideward flow as determined by the anisotropy of  $E_T$  is larger than predicted by RQMD calculations in cascade mode. This measured anisotropy is a signature for significant collective effects in Au on Au collisions at AGS energies. In a first measurement of triple differential cross sections protons are identified as the main carriers of the sideward flow. In the future, with improved reaction plane resolution and higher statistics, it will be possible to study the flow effects of different particle species in a more quantitative way as a function of centrality. This will allow for model comparisons in a detailed and exclusive fashion.

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