

# Differential elliptic flow at forward rapidity in 200 GeV AuAu collisions <sup>\*</sup>

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## Abstract

Identified particle elliptic flow results are presented for the Au+Au reaction at  $\sqrt{s_{NN}} = 200$  GeV as a function of transverse momentum and pseudorapidity. Data at pseudorapidities  $\eta \approx 0, 1, \text{ and } 3.4$  were obtained using the two BRAHMS spectrometers. Differential  $v_2(\eta, p_t)$  values for a given particle type are found to be essentially constant over the covered pseudorapidity range, in contrast to the integral  $v_2$  values which have previously been observed to decrease at forward rapidities. A softening of the particle spectra at forward angles is found to account for at least part of the integral  $v_2$  falloff. The data are found to be consistent with existing constituent quark scaling systematics.

**Key words** elliptic flow, rapidity dependence

## 1 Introduction

The azimuthal anisotropy of particle production in relativistic heavy-ion reactions is believed to reflect pressure gradients of the thermalized medium formed early in the collisions. In a Fourier expansion of the azimuthal behavior, the 2<sup>nd</sup>-harmonic term, with coefficient  $v_2$ , defines the “elliptic flow” of the reaction. Measurements near mid-rapidity at RHIC energies have shown that elliptic flow for particles below 2 GeV is close to that expected from hydrodynamic models that assume the formation of a strongly interacting quark-gluon plasma<sup>[1, 2, 3]</sup>. However, integral  $v_2$  values, which are based solely on the asymmetry of the overall charged-particle production, are found to fall off going away from mid-rapidity, dropping by about 35% by pseudorapidity  $\eta = 3$ <sup>[4]</sup>.

BRAHMS has now measured  $v_2$  and the associated particle spectra as a function of transverse momentum for pions, kaons, and protons at angles (pseu-

dorapidities)  $90^\circ (\eta = 0)$ ,  $40^\circ (\eta = 1)$ , and  $4^\circ (\eta = 3.4)$ . The analysis of the elliptic flow behavior together with the particle spectra makes it possible to determine the extent to which the fall off of the integral  $v_2$  values can be attributed to a softening of the particle spectra going to forward rapidity.

## 2 Experimental Details

Elliptic flow measurements characterize the azimuthal dependence of the particle production with respect to the reaction plane. For any given collision, an empirical reaction plane can be established by measuring the particle yield observed in detectors mounted symmetrically about the beam axis. BRAHMS used several different detector systems for this purpose: Two rings of modestly segmented Si strip detectors (7 segments per strip) were configured with 42 active segments surrounding the beam axis in each ring. Another ring using the same type of Si strip

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detector was configured with six segments around the axis, and seven segments along the axis. A scintillator tile ring with six panels was also arranged around the beam axis. Depending on the location of the beam vertex, for collisions within  $\pm 20\text{cm}$  of the nominal vertex location the Si and tile detectors covered pseudorapidity values from  $-3$  to  $+1.5$ . At a somewhat larger rapidity ( $\approx -3$ ), Cherenkov radiators mounted to phototubes in one of the experiment's Beam-Beam counter arrays<sup>[7]</sup> were also used for the reaction-plane

determination. The general procedure for determining the reaction plane and the corresponding reaction-plane correction factor is described by Poskanzer and Voloshin<sup>[8]</sup>. The reaction plane corresponding to the second moment of the angular distribution is found with

$$\Psi_2 = \frac{1}{2} \sum_i \frac{w_i \sin(2\phi_i)}{w_i \cos(2\phi_i)}, \quad (1)$$

where the sum is over all detector elements with geometric weighting factors  $w_i$  and azimuthal angle  $\phi_i$ .

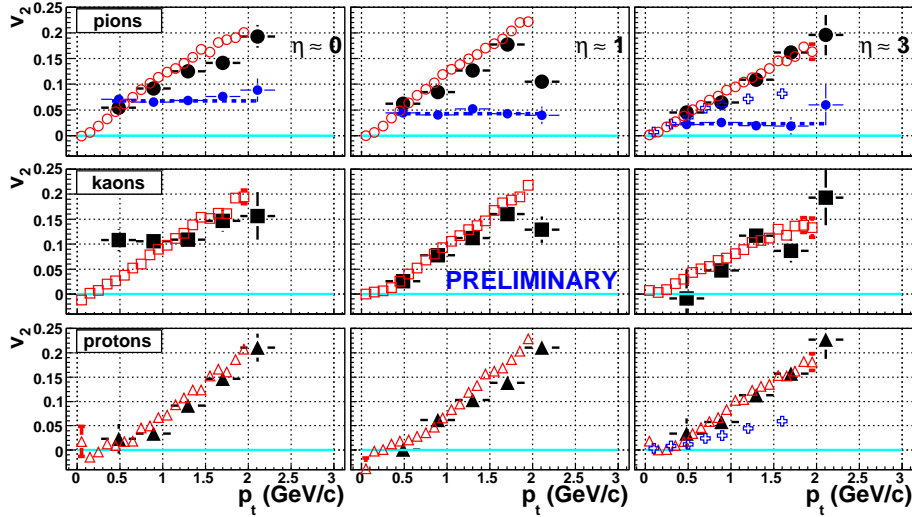


Figure 1:  $v_2(p_t, \eta)$  for pions (both charges), kaons (both charges), and protons (filled symbols). Theoretical values based on the hydrodynamic calculations of Hirano *et al.* [9] are shown by the open circles, squares, and triangles. The open crosses correspond to  $\eta \approx 4$  calculations using the AMPT model [10]. The smaller (blue in color) points in the pion panels are from a mixed-event analysis, as discussed in the text.

The angular correlation with respect to the reaction plane of particles detected in the BRAHMS mid-rapidity and forward spectrometers determine the observed  $v_2$  values, with

$$v_2^{obs} = \langle \cos(2[\phi - \Psi_2]) \rangle. \quad (2)$$

Here the angular bracket denotes an average over all events of a given class, such as all pions within a given range of transverse momenta. Since the BRAHMS spectrometers are small acceptance devices, all particles detected in the mid-rapidity spectrometer have  $\phi \approx 0^\circ$ , while those detected by the forward spectrometer have  $\phi \approx 180^\circ$ .

The true  $v_2$  value, which is based on the actual reaction plane, is found from the  $v_2^{obs}$  value using the

reaction-plane correction factor  $R$ , with

$$v_2 = v_2^{obs} / R. \quad (3)$$

The reaction-plane correction for any given ring (or ring combination) is determined using two additional rings that are far enough apart so as to avoid autocorrelations. Considering rings A, B, and C, the reaction-plane correction factor for ring A is found as:

$$R_A = \sqrt{\frac{\langle \cos(2[\Psi_2^A - \Psi_2^B]) \rangle \langle \cos(2[\Psi_2^A - \Psi_2^C]) \rangle}{\langle \cos(2[\Psi_2^B - \Psi_2^C]) \rangle}}. \quad (4)$$

The reaction-plane correction factor was typically in the range  $0.18 < R < 0.25$ .

Figure 1 shows the resulting values (closed sym-

bols) of  $v_2(p_t)$  for pions, kaons, and protons at the indicated pseudorapidities, selecting events in the 10% - 50% centrality class. The behavior for the three different particle species shows very little change with pseudorapidity. The smaller (blue in color) filled circles shown in the pion panels are the results of a mixed event analysis, where the reaction-plane angle used for the analysis of a given identified pion is taken as that obtained from the previous event where a particle of any type is detected in the same spectrometer. Because of the limited angular acceptance of the spectrometers, the deduced  $v_2(p_t)$  values from the mixed-event analysis reflect the integral  $v_2$  behavior. The scatter of the points with  $p_t$  mirrors the statistical uncertainty in the measurements. The fall off of the average behavior, as indicated by the dashed lines, is consistent with the known fall-off of the integral  $v_2$  values going to forward rapidity.

We have also measured the  $p_t$ -dependent particle spectra for the channels where the differential el-

iptic flow has been determined. The average value of transverse momentum for pions in the 10% - 50% centrality class at  $90^\circ$  is  $(475 \pm 60)$  MeV/c, falling to  $(380 \pm 45)$  MeV/c at  $4^\circ$ . These values are obtained by fitting a power-law dependence to the respective particle spectra. The softening of the particle spectrum going to more forward rapidities can have a significant effect on the integral  $v_2$  values, as illustrated in Figure 2. The insert shows an assumed form of  $v_2(p_t)$  that is taken as being constant as a function of pseudorapidity. Folding this behavior with the experimentally observed normalized particle spectra for pions at  $90^\circ$  and  $4^\circ$  results in the solid and dashed lines of the main figure panel, respectively. The softer spectrum at the more forward pseudorapidity leads to the weighted  $v_2$  distribution peaking at a lower mean  $p_t$  value, resulting in a 22% smaller integral  $v_2$  value than a mid-rapidity. Two-thirds of the observed integral  $v_2$  change is then attributable to the softening of the particle spectrum.

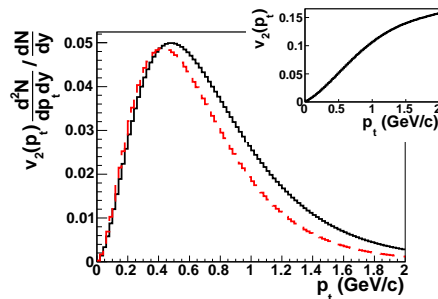


Figure 2: Illustration of how the softening of the particle spectra going to forward angles affects the integral  $v_2$  values. The insert shows the general behavior of the differential  $v_2(p_t)$  values for pions, which for this illustration is assumed to be independent of pseudorapidity. Folding this distribution with the corresponding experimentally observed pion spectra at  $4^\circ$  and  $90^\circ$  results in the dashed and solid curves, with integral  $v_2$  values of 0.046 and 0.036, respectively.

The small change in the differential  $v_2$  signal going from mid- to forward rapidity suggests a longitudinally extended region for the medium produced in the collision. Rapidity dependent changes in the radial flow or other rescattering behavior of the hadronic stage might then account for most of the fall off of the integral  $v_2$  signal going to forward rapidities.

Hydrodynamic calculations are able to reproduce the observed behavior. This is seen by the open cir-

cles in Figure 1 which show the results of the hybrid hydrodynamic calculations of Hirano *et al.* <sup>(9)</sup>, and private communication) that include dissipative effects of the late hadronic expansion stage. Good agreement is found with the experimental values. The open crosses in Figure 1 show the results of the AMPT model for pseudorapidity  $\eta = 4$ . At this angle the string melting mechanism that allows for a good reproduction of mid-rapidity results has been turned

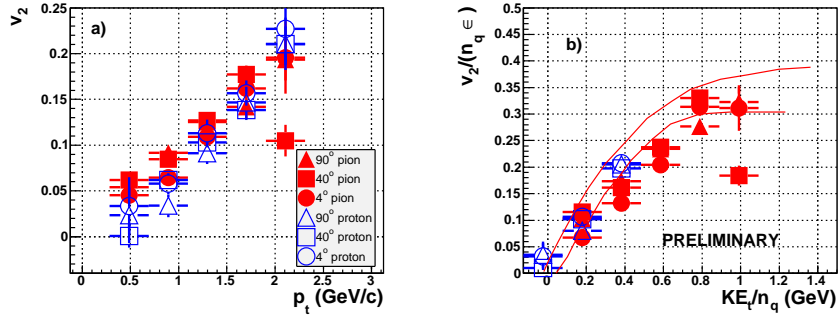


Figure 3: a)  $v_2(p_t)$  vs.  $p_t$  for pions and protons at  $\eta=0,1$ , and 3. b) Constituent quark scaled values, as discussed in the text. The lines indicate the band containing most of the previous experimental results near mid-rapidity.

off ([10], and private communication). Although the comparison is subject to poor matching of pseudorapidity, there is a suggestion that the longitudinal extent of the produced medium may be greater than that assumed in current AMPT calculations.

The mid-rapidity elliptic flow behavior for many different systems have been found to follow similar constituent scaling behavior when the  $v_2$  value per valence quark, scaled by the inverse of the Glauber-model eccentricity, is plotted as a function of the mean transverse kinetic energy per valence quark [11]. In Figure 3a we show the  $v_2$  vs.  $p_t$  behavior of pions and protons for the three measured angles on the same plot. In Figure 3b these same data are now shown in terms of their constituent-quark scaling behavior. The two solid curves mark the approximate limits established by the previous measurements. The current data show a very similar trend, although with a tendency to fall somewhat below the previous re-

sults. This may reflect a systematic error in the measurement of the reaction-plane correction factor or in the assumed Glauber eccentricity which is calculated for the trigger-weighted center of the centrality range. An error in either of these quantities will tend to have a similar scaling effect on all of our results.

### 3 Conclusions

BRAHMS has measured  $v_2(p_t, \eta)$  for pions, kaons, and protons at  $\sqrt{s_{NN}} = 200$  GeV for the Au+Au reaction. The results indicate a longitudinally extended region is produced where the eccentricity of the created medium and the corresponding pressure gradients remain remarkably constant. Hydrodynamic calculations with final stage dissipation are found to be in excellent agreement with the measured differential  $v_2$  values. The data are consistent with constituent quark scaling over the covered pseudorapidity range.

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