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# Azimuthal anisotropy in S + Au reactions at 200 A GeV

WA93 Collaboration

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**Abstract**

Azimuthal correlations of photons produced at mid-rapidity in 200 A GeV S + Au collisions have been studied using a preshower photon multiplicity detector in the WA93 experiment. The Fourier expansion method has been employed to estimate the event plane via the anisotropy of the event as a function of centrality. The event plane correlation technique has been used to determine the true event anisotropy, beyond the anisotropy which arises due to finite multiplicity. The VENUS event generator with rescattering and proper simulation of the detector response can explain only a portion of the observed anisotropy. The residual anisotropy is found to be of the order of 5% for semi-central collisions. This suggests that directed collective flow of the produced particles is present at SPS energies. © 1997 Published by Elsevier Science B.V.

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In the search for evidence of the phase transition from hadronic matter to quark gluon plasma in relativistic heavy-ion collisions, it is important to establish that thermalization occurs in the reacting system. If the system reaches local thermal equilibrium pressure gradients may be produced in the matter. The evolution of such a system will be accompanied by collective flow of the produced particles. Collective phenomena at energies up to 1 A GeV are by now well established [1]. At these energies one determines the flow direction as the direction of maximum kinetic energy flow. Recently collective flow has been observed at AGS energies by studying the correlation between the transverse energy in the forward and backward hemispheres [2] and also by using azimuthal correlation functions of projectile fragments in emulsion data [3]. A source of anisotropy at lower energies is the squeezeout effect which arises due to absorption of the emitted particles in the spectator matter and results in preferential particle emission at 90° to the reaction plane. At SPS energies the time taken for the nuclei to cross each other is much smaller than the time necessary for the transverse flow to develop and thus the role of the spectator matter should be negligible.

At SPS energies directed flow should arise from pressure gradients which develop in the participant matter and should lead to preferential emission of particles in the reaction plane [4–6]. In non-central collisions the overlap volume, when projected onto

the transverse plane, is not azimuthally symmetric. It has a smaller size along the direction of impact parameter than in the perpendicular direction. If thermal equilibrium is reached, collective flow develops with a velocity proportional to the pressure gradient, which is larger along the direction of impact parameter than along the perpendicular direction. Matter is thus expected to flow preferentially in the reaction plane which should result in an azimuthal anisotropy of the distribution of particles. In head-on collisions the anisotropy should disappear, even if thermalization occurs, due to the azimuthal symmetry of the overlap volume.

In this letter we describe a search for collective flow in 200 A GeV S + Au collisions in the WA93 experiment [7] from an analysis of the azimuthal distribution of photons. Preliminary results of this analysis have been reported earlier [8]. Preliminary evidence for collective flow effects at SPS energies have also been reported by NA49 [9]. Photons were detected in a fine granularity preshower Photon Multiplicity Detector (PMD) [10]. The PMD consisted of a rectangular matrix of 7500 plastic scintillator pads of size 20 × 20 × 3 mm<sup>3</sup> mounted behind a 3X<sub>0</sub> thick lead converter plate and divided into four quadrants which enclosed the beam axis. The light from the pads was transported via wavelength shifting fibers to Image Intensifier – CCD readout devices. The principle of photon identification in the PMD makes use of the fact that photons are much more likely to shower in the lead converter and produce a large signal, while non-showering hadrons will give a scintillator signal corresponding to a single minimum ionizing particle (MIP). A threshold of 3 MIP on the preshower signal gave an average photon counting efficiency in the range of 65%–75% depending on centrality, with a

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30% contamination of showering hadrons. Thus the measured particles consist mostly of photons from  $\pi^0$  decay together with a sizeable contribution of charged pions. Although there is some correlation between the incident photon energy and the observed signal, the PMD is used in the present analysis simply to count photons and measure their emission angles. Details of the detector along with methods for extracting photon hit positions, efficiencies, and backgrounds have been described in [10].

The PMD covered the pseudorapidity region  $2.8 \leq \eta \leq 5.2$ , of which the region  $3.3 \leq \eta \leq 4.9$  had full azimuthal coverage. For the results presented here [11], only those photons within the region  $3.4 \leq \eta \leq 4.7$  have been used. The centrality of the event was characterized by the transverse energy measured in the Mid-Rapidity Calorimeter (MIRAC) [12,13]. The magnetic field, used for tracking and momentum measurement of charged particles in WA93, was on for the major portion of the data taken and for the results presented here. However, sufficient data with field off were taken to check the consistency of the results.

Anisotropies arising due to trivial or non-dynamical effects, such as the magnetic field, the geometry of the experimental setup, finite particle multiplicities, or meson decays have been investigated by detailed simulations using the VENUS v3.11 event generator [14] with rescattering, and taking the full detector geometry into account using the GEANT simulation package [15]. The GEANT results were converted to the CCD-like digital signals using prescriptions described in [10] and subsequently analyzed in the same manner as the experimental data.

For the study of azimuthal correlations the imperfections in the experimental setup are often taken into account by comparison of the experimental distribution with a mixed event distribution. Mixed events are generated artificially using the experimental data set by selecting  $M$  particles from  $M$  different events to form an artificial event in which detector biases persist but correlations due to physics are removed. The results presented here are based on the analysis of 95000 experimental events, 28000 simulated (VENUS+GEANT) events, and 80000 mixed events.

The transverse flow is studied using the second order Fourier coefficient,  $Q$  ( $\equiv Q_n, n = 2$ ), of the azimuthal particle distribution within one event [6]:

$$Q_n = \sum_{\nu=1}^M \omega_{\nu} e^{in\phi_{\nu}}, \quad (1)$$

where  $\phi_{\nu}$  is the azimuthal angle of particle  $\nu$  and  $\omega_{\nu}$  is a weight factor. The sum runs over all particles ( $M$ ) in an event. This analysis is equivalent to a sphericity tensor analysis [16], but here limited to the transverse plane. Because the PMD has a limited energy resolution, only the spatial distribution of particles is studied by taking  $\omega_{\nu} = 1$ . In this letter the vector notation  $Q = (Q^x, Q^y) = (Q \cos(2\Phi), Q \sin(2\Phi))$  will be used. Since the orientation of the impact parameter is random, the distribution of events as a function of laboratory angle  $\Phi$  should be uniform between  $0^\circ$  and  $180^\circ$ . The values of the projections of  $Q$  on the  $x$ - and  $y$ -axes averaged over many events ( $\langle Q^x \rangle, \langle Q^y \rangle$ ) must be zero. However, due to effects such as the asymmetries of the actual detector response and the magnetic field, an artificial event anisotropy will be observed. These 'detector effects' can be corrected for by subtracting  $\langle Q^x \rangle$  and  $\langle Q^y \rangle$  from  $Q^x$  and  $Q^y$  on an event-by-event basis [17].

Fig. 1 shows the  $\Phi$ -distributions for various event samples before and after correction for detector effects. Results are shown for the full sample of experimental data, for the simulated data, and for the mixed events. The large dip around  $\Phi = 90^\circ$  and sharp rise near  $\Phi = 0^\circ$  and  $180^\circ$  in Figs. 1a,b show the strong effect of the detector bias in the experimental and simulated data, mainly due to the magnetic field. The effect is faithfully carried over into the mixed events as shown in Fig. 1c. The distributions obtained after event-by-event subtraction of  $\langle Q^x \rangle$  and  $\langle Q^y \rangle$  are shown in Figs. 1d,e,f. The subtracted distributions are now uniform with no structure, which verifies the effectiveness of the subtraction method to remove the detector biases.

After subtraction of the detector effects, the event anisotropy  $\alpha$ , is obtained as  $\alpha = |Q|/Q_0 = |Q|/M$ . The event anisotropy extracted in this way will contain an anisotropy due to correlated particle emission or collective effects,  $\bar{\alpha}$ , and a contribution due to the finite multiplicity. (Note that  $\alpha$  and  $\bar{\alpha}$  lie within  $[0, 1]$  with 0 corresponding to isotropic emission and 1 corresponding to full alignment of the emitted particles.) The average value  $\langle \alpha \rangle$  is plotted for four different centrality classes characterized by the PMD multiplicity,

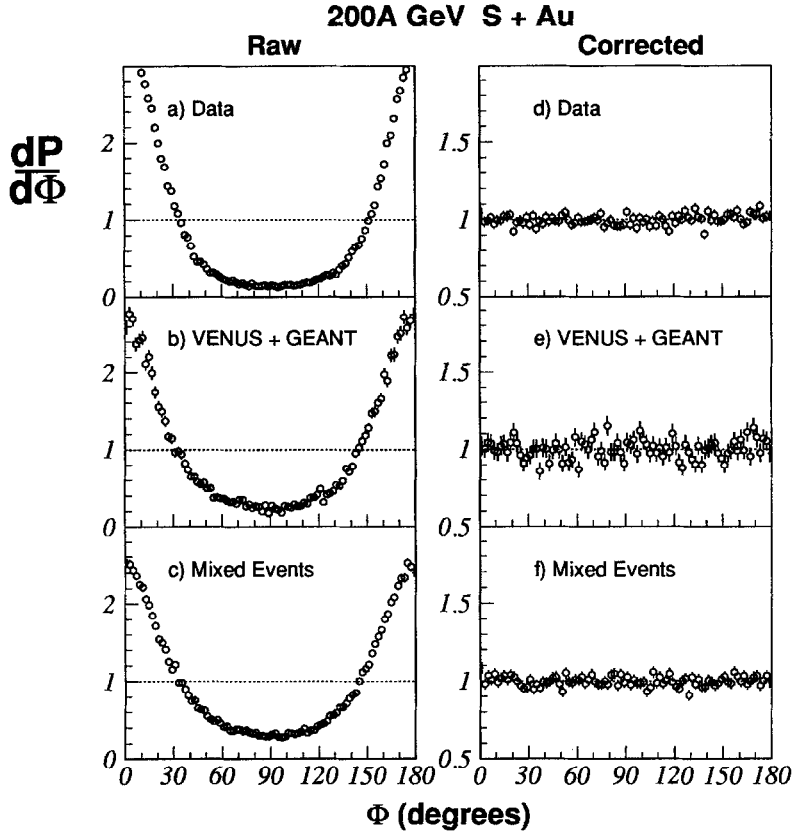


Fig. 1. Distribution of azimuthal angle  $\Phi$  of the estimated event plane: (a) raw experimental data, (b) simulated VENUS + GEANT data, (c) mixed events, (d) experimental data after subtraction of detector effects, (e) simulated data after subtraction of detector effects, (f) mixed events after subtraction of detector effects.

$M$ , in Fig. 2. The results show a  $\langle \alpha \rangle \sim 1/\sqrt{M}$  dependence on multiplicity as expected for the finite multiplicity effect. The magnet on and magnet off data are seen to give consistent results, which are only slightly larger than the null result obtained from the mixed event results. This indicates that collective effects, if present, are small relative to the finite multiplicity effect and must be studied by a more sensitive method.

Because the events are created independently, the probability distribution of  $Q$  may be described by a Gaussian. The width of this Gaussian is determined by the fluctuation of the observed event shapes due to the finite multiplicity which is, for sufficiently large multiplicities ( $M \gg 1$ ), proportional to the square root of the multiplicity ( $\sigma \sim \sqrt{M}$ ). The probability distribution for observing a certain transverse event shape (defined by  $Q$ ) can then be written as [6]:

$$\frac{d^2P}{dQ^2} = \frac{1}{\pi\sigma^2} \exp\left(-\frac{|Q - \langle Q \rangle|^2}{\sigma^2}\right), \quad (2)$$

where  $\langle Q \rangle$  is the event averaged value of  $Q$ .

If the anisotropy is small, a more sensitive method to detect the presence of an event plane is to perform an azimuthal correlation analysis [5,6]. The particles of each event are distributed into two arbitrary, equal-sized groups (subevents). For both subevents, the Fourier coefficients  $Q^1$  and  $Q^2$  are constructed and the orientations of the event planes ( $\Phi_1, \Phi_2$ ) are determined. The angle between the two event planes,  $\Psi = \Phi_1 - \Phi_2$ , is calculated. In the case of finite multiplicity effects alone, there will be no correlation between the two event planes and  $\Psi$  will have no preferred value. If, however, collective effects are present, the event planes of the two subevents will be the same, which

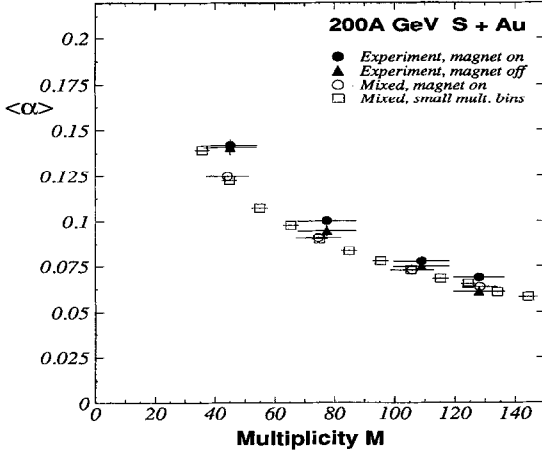


Fig. 2. The average anisotropy parameter  $\langle \alpha \rangle$  as a function of the photon multiplicity for the four centrality bins for the experimental data (solid points) with and without magnetic field on, and for the magnet on mixed event data (open points). Mixed event results are also shown for smaller centrality bins. The horizontal bars indicate the rms multiplicity of the bin. Statistical errors, which generally lie within the plotted points, are shown only.

will result in an enhancement of the  $\Psi$  distribution at small values of  $\Psi$ .

In general, the probability distribution to observe  $\mathcal{Q}^1$  and  $\mathcal{Q}^2$  is the product of the two Gaussian probability distributions but with a correlation term [5,6]:

$$\frac{d^4P}{d(Q^1)^2 d(Q^2)^2} \sim \exp \left[ - \left( \frac{|\mathcal{Q}^1 - \langle \mathcal{Q}^1 \rangle|^2}{(1-c^2)\sigma_1^2} + \frac{|\mathcal{Q}^2 - \langle \mathcal{Q}^2 \rangle|^2}{(1-c^2)\sigma_2^2} - 2c \frac{\mathcal{Q}^1 \cdot \mathcal{Q}^2 - \langle \mathcal{Q}^1 \rangle \cdot \langle \mathcal{Q}^2 \rangle}{(1-c^2)\sigma_1\sigma_2} \right) \right], \quad (3)$$

where the correlation coefficient  $c = \sigma^{-2}(\langle \mathcal{Q}^1 \cdot \mathcal{Q}^2 \rangle - \langle \mathcal{Q}^1 \rangle \cdot \langle \mathcal{Q}^2 \rangle)$  accounts for the possibility of other direct correlations between the two subevents. The two subevents are assumed to be constructed to provide equivalent samples of the same event shape such that they are described by the same distribution of  $\mathcal{Q}$  with  $\sigma_1 = \sigma_2 = \sigma$ .

Integrating Eq. (3) over  $\Phi_1$  and assuming  $c \ll 1$ ,  $\frac{\bar{\alpha}M}{\sigma} \ll 1$  the normalised probability distribution of  $\Psi$  yields [5,6]:

$$\left( \frac{dP}{d\Psi} \right)_{\text{normalised}} = 1 + \frac{\bar{\chi}^2 \pi}{2} \cos(2\Psi), \quad (4)$$

where

$$\bar{\chi}^2 = \left[ c + \left( \frac{\bar{\alpha}M}{\sigma} \right)^2 \right] \quad (5)$$

gives the overall strength of the observed correlation. The probability distribution has been normalized by the probability distribution without correlations or collective effects  $dP/d\Psi = 2/\pi$  as obtained from the mixed event  $\Psi$  distribution.

If the two subevents are selected in such a manner that they provide two independent measurements of the underlying event shape, the direct correlation term,  $c$ , will be zero. The strength of the observed correlation can then be related directly to the event shape  $\bar{\alpha}$  relative to the multiplicity effect via Eq. (5). (We note that  $\sigma = \sqrt{M}$  to a good approximation for the present case [18]). On the other hand, processes such as two-particle correlations, or  $\pi^0$  decay in the case of photon measurements, may give stronger correlations between the event planes of the two subevents, via the direct correlation term  $c$ , than expected from the influence of the event shape alone. In this case, neglect of the  $c$  term in the use of Eq. (5) would result in an overestimate of the anisotropy  $\bar{\alpha}$  of the event. Such direct correlations might be expected to be very sensitive to how the subevents are selected, such as how far apart the subevents are separated in phase space.

The distributions of relative angles  $\Psi$  between the event planes for the two subevents are shown in Fig. 3 for the four centrality bins for the experimental, simulated, and mixed event data sets. Each event has been divided into two separated pseudo-rapidity regions of variable size to give equal multiplicity in each and with a minimum pseudo-rapidity gap of 0.1 between them. Mixed events and simulated data were treated in the same manner as the experimental data. The negative slope of the experimental data distributions indicates that correlations are present between the two subevent event planes for all centralities. In contrast, the results for the mixed events (histograms) are flat indicating negligible correlation, as they must. The distributions from the simulated VENUS+GEANT events suggest weak correlations, if any.

More generally, the correlation strength  $\bar{\chi}^2$  can be extracted from the ratio of the number of events with  $\Psi > 45^\circ$  to the number of events with  $\Psi < 45^\circ$  [5]

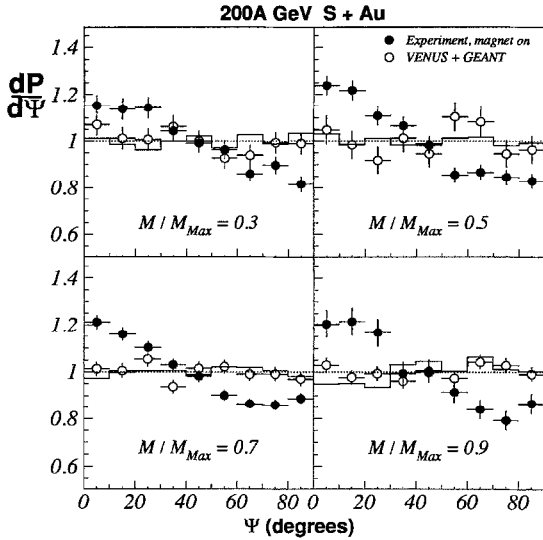


Fig. 3. The distribution of  $\Psi$  for the four centrality bins. The experimental (filled circles) and simulated event (open circles) results are superimposed for comparison. The solid lines are the  $\Psi$  distributions from the unnormalized mixed event data. The experimental results have been normalized by the mixed event distributions.

$$\frac{N(\Psi > 45^\circ)}{N(\Psi < 45^\circ)} \approx \frac{1}{2e\bar{\alpha}^2 - 1}, \quad (6)$$

the expression being exact for  $c = 0$ .

The anisotropy parameter  $\bar{\alpha}$  calculated using Eq. (5) (assuming  $c \equiv 0$ ) is plotted in Fig. 4 for the four centrality bins for the data from the present analysis [11] (solid circles) and for the simulated data (open circles). The simulated events show a small anisotropy similar in magnitude to the estimated systematic error. The systematic error estimate was deduced from the variations of the final result with variations of the hadron rejection threshold, the photon identification efficiency, the subevent selection method, and the magnetic field setting. In an independent analysis using a more restrictive pseudo-rapidity interval  $3.3 \leq \eta \leq 3.8$ , and a more restrictive photon identification criterion, the correlation between subevents was observed to be greater in both the real and simulated events. This additional correlation was clearly shown to be attributed to a direct correlation ( $c$  term) between photon pairs from  $\pi^0$  decay in the two subevents [18].

The extracted true anisotropies are small but significantly greater than the simulation which does not in-

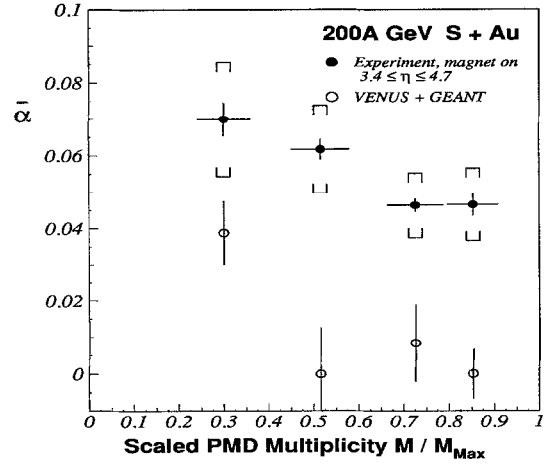


Fig. 4. The true anisotropy  $\bar{\alpha}$  as a function of the scaled multiplicity for the different centrality bins for the experimental data (filled circles) and VENUS + GEANT simulations (open circles). The vertical bars indicate statistical errors only. The horizontal bars indicate the rms multiplicity of the bin. The estimated systematic errors are indicated by the bracket on each data point.

clude flow effects. The observed anisotropy decreases with decreasing impact parameter from  $\bar{\alpha} \approx 0.07$  for peripheral collisions to  $\bar{\alpha} \approx 0.045$  for central collisions. This dependence is similar, but the values are roughly half as large, as has been predicted by hydrodynamical model calculations [4]. However, it is to be expected that the photon decay of the  $\pi^0$  should weaken the observable collective flow. The results suggest that directed flow of the pions is present.

In summary, the azimuthal anisotropy has been determined from the transverse distribution of photonlike hits measured with a preshower photon multiplicity detector. It should be emphasized once again that the identified photonlike hits consist mainly of photons from  $\pi^0$  decay with a contamination mostly from  $\pi^\pm$  misidentified as photons. The subevent correlation technique has been used to provide a reliable estimate of the true anisotropy since it is insensitive to anisotropy due to finite multiplicity. Simulations with the VENUS event generator including the details of the detector response cannot account for the observed anisotropy. The observed anisotropy suggests that directed transverse flow of the produced pions is present at SPS energies.

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