LBL-38506
UC-414

**Lawrence Berkeley Laboratory**
UNIVERSITY OF CALIFORNIA

Presented at the 12th Winter Workshop on Nuclear Dynamics, Snowbird, UT, February 3–10, 1996, and to be published in the Proceedings

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February 1996

**Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098**

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This work was supported by the Director, Office of Energy Research Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098

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## INTRODUCTION

Azimuthal correlations have been studied in heavy ion reactions over a wide range of beam energies. At low incident energies up to 100 MeV/nucleon where collective effects like the directed sidewards flow are generally small, azimuthal correlations provide a useful tool to determine the reaction plane event by event [1]. In the energy regime of the BEVALAC (up to 1 GeV/nucleon for heavy ions) particular emission patterns, i.e. azimuthal correlations of nucleons and light nuclei with respect to the reaction plane, have been associated with the so called *squeeze out* [2] and *sidesplash* [3] effects. These effects are of particular interest because of their sensitivity to the equation of state at the high baryon density which is build up during the collision process [4]. Angular distributions similar to the *squeeze out* have been observed for pions at the SIS in Darmstadt [5, 6] as well as from the EOS - collaboration [7]. Recently also the sideward flow was measured for pions and kaons [7, 8]. However, the origin of the signal in the case of produced mesons is thought to be of a different nature than that for the nucleon flow [9, 10].

At the AGS, azimuthally anisotropic event shapes have been reported from the E877 collaboration [11] for the highest available heavy ion beam energy (11.4 GeV/nucleon). Using a Fourier analysis of the transverse energy distribution measured in calorimeters, it was concluded that sideward flow is still of significant magnitude.

Here we will report a first analysis of azimuthal correlations found in the transverse energy distribution from Pb on Pb collisions at the CERN SPS (158 GeV/nucleon).

## Experimental Setup

The experimental setup relevant for our analysis is shown in Fig. 1. (the full NA49 setup including the time projection chambers can be found in [12]). The beam is defined by a 0.2 mm quartz Cherenkov counter and a veto scintillator with a 10 mm central hole. The scintillator paddle S5 placed slightly below the beam further suppresses background from interactions in the air/counting gas. Two separate calorimeters are used to measure the energy flow: a Ring calorimeter covering the midrapidity region ($2.1 < \eta < 3.4$, $\eta$ being the pseudorapidity) and a Veto calorimeter detecting essentially the energy of beam fragments. The cylindrical Ring calorimeter is subdivided longitudinally into a photon part of 16 radiation lengths followed by a hadron part of 6 interaction lengths. Its azimuthally symmetric acceptance is segmented into 24 sectors and 10 radial rings. In total the energy is measured in 480 independent cells. The Veto

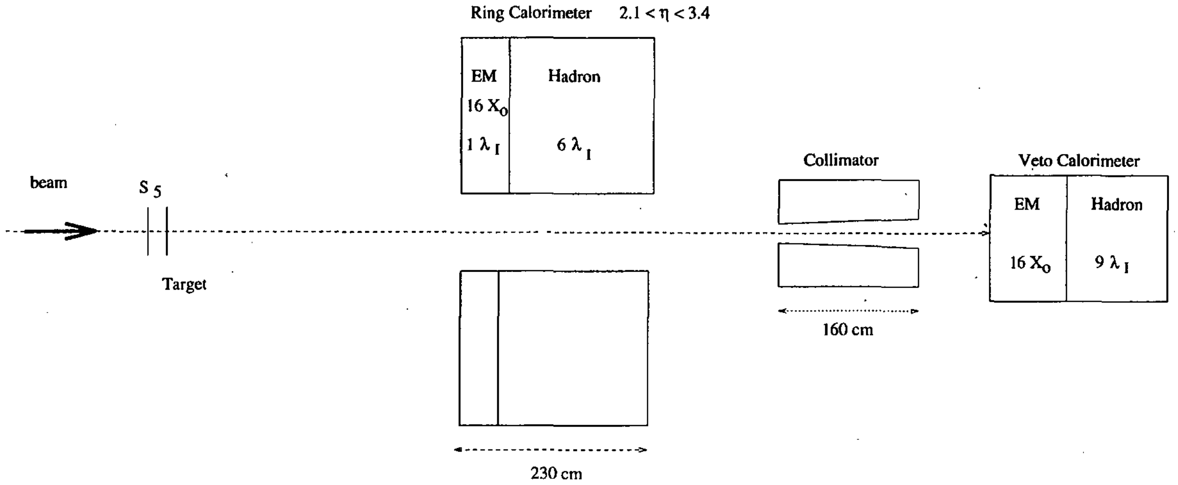

**Figure 1.** Top view of the NA49 calorimeter structure

calorimeter is also divided into a photon part and a hadron part. It covers completely the region defined by the aperture of the iron collimator, typically 0.3 degrees with respect to the beam axis. The collimator enhances the relative fraction of the energy signal in the Veto calorimeter produced by the beam fragments (for more details see [13]). The calorimeters have been used and studied in the previous CERN experiments NA5, NA24 and NA35 [14].

## Data Analysis

In fall of 1994 more than $2 * 10^5$ events have been recorded with the NA49 - calorimeters. The typical target thickness corresponded to 2% total nuclear interaction probability. Previous analysis of these data [15] focussed on the production cross section and pseudorapidity dependence of the transverse energy as well as the fractions of electromagnetic to hadronic transverse energy. Assuming a Bjorken scenario [16] energy densities in excess of 3 GeV/fm$^3$ (for a formation time of $\tau = 1$ fm/c) were estimated for head on $Pb + Pb$ collisions. Large non statistical fluctuations in the ratio of the electromagnetic to hadronic transverse energy were not observed. In the following we use the Ring calorimeter to study the azimuthal energy distribution on an *event by event* basis.

## Eventshape Study via Tensor Analysis

In the search for collective effects at ultrarelativistic energies it is useful to construct a two dimensional sphericity tensor as suggested in [17]. The Ring calorimeter measures the transverse energy in a given cell k centered at $\phi_k$ and covering a pseudorapidity range $\triangle\eta$. We define a vector:

$$\vec{E}_{T,k} = (E_{T,k} * cos\phi_k, E_{T,k} * sin\phi_k) \qquad (2)$$

and the tensor

$$F_{xy} = \sum_k E_{T,k}(x) * E_{T,k}(y) \qquad (3)$$

with $E_{T,k}(x), E_{T,k}(y)$ being the vector components of $\vec{E}_{T,k}$ (here we use only the hadronic part of the transverse energy). Before calculating the tensor we have applied a careful

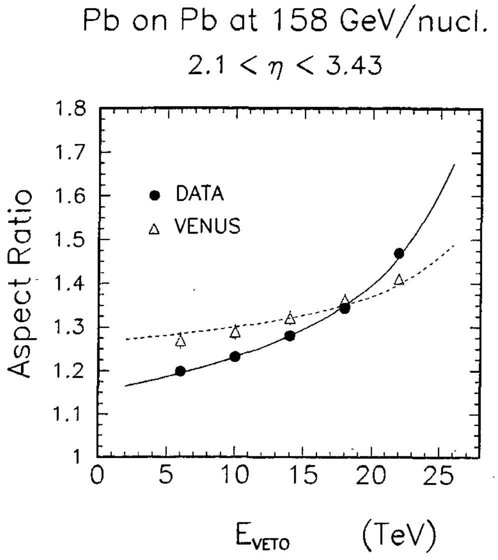

**Figure 2.** Degree of azimuthal isotropy via the mean aspect ratio as function of the energy deposit in the Veto calorimeter. The lines represent a fit according to $f = c + a/sqrt(N_{HAD})$ (see text).

cell gain equalization in each ring belonging to a given pseudo rapidity interval. The tensor is then evaluated and diagonalized for each event. A first overview about the degree of isotropy is given in Fig. 2, which shows the average value of the aspect ratio (ratio of eigenvalues from major and minor axis) as function of the centrality. As measure of the centrality we have used the total energy deposit $E_{VETO}$ in the Veto calorimeter which is roughly proportional to the number of projectile spectators. We find that the aspect ratio is increasing with decreasing centrality. In very central collisions it drops below 1.2 which is close to azimuthal isotropy. An average aspect ratio of 1.0 is indeed only reachable in the limit of very high particle multiplicty.

In our case we estimate from simulations with the VENUS model 4.12 [18] particle multiplicities of roughly 600 (dominantly pions) within the Ring calorimeter acceptance for very central collisions. Using the predicted particle multiplicity $N_{HAD}$ from VENUS in a given bin of $E_{VETO}$ we can fit the centrality dependence of the aspect ratio with

$$f = c + a/\sqrt{N_{HAD}} \tag{4}$$

where $c$ and $a$ are the fit parameters. This suggests that the nature of the increasing aspect ratio is at least partially due to an increase of fluctuations. The question whether there are underlying *collective effects* present which contribute to the general anisotropy in addition to the trivial fluctuations due to finite particle number can be studied via performing the tensor analysis in two separated regions of pseudo rapidity.

## Forward / Backward Correlations

The above defined tensor is calculated separately in a forward region of the pseudo rapidity $3.3 < \eta < 3.8$ and backward region $2.1 < \eta < 2.6$. Both regions were chosen almost symmetrically around mid rapidity, leaving a gap of $\Delta\eta = 0.6$. The gap reduces the influence of shower leakage to our correlation analysis. In the upper part of Fig. 3 we show the distribution of the azimuthal angle of the major axis. We obtain a flat distribution in both hemispheres which is a precondition for the correlation study. The lower part of Fig. 3 demonstrates that the orientation of the transverse energy

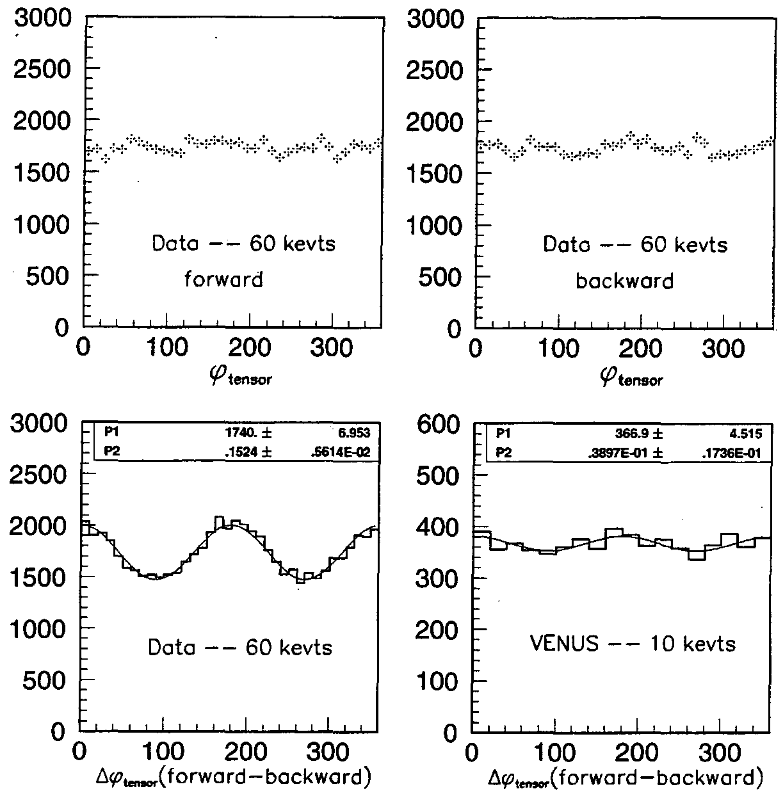

**Figure 3.** Upper part: angular distribution of the major axis found from the tensor analysis. Lower part: Correlation signal $\Delta\phi$ between the orientation of the major axis in the forward and backward hemisphere.

flow from forward and backward hemispheres is correlated. This represents a *strong evidence for collective effects* which in turn lead to anisotropic event shapes. Without any correlation one would expect a flat distribution of the relative angle $\Delta\phi$ between the two major axis. In fact we obtain a much smaller correlation signal in the case of the VENUS simulations. Experimental effects such as the finite energy resolution of the calorimeter and shower spreading of the deposited energy have been taken into account. To quantify the correlation signal we fit the $\Delta\phi$ distributions with a function

$$f(\Delta\phi_{fb}) = c * (1 + a2 * cos2\Delta\phi_{fb}) \tag{5}$$

where c is a normalization constant. The centrality dependence is displayed in Fig. 4. We observe the strongest correlation at an $E_{VETO}$ energy which corresponds roughly to half overlap collisions (according to a VENUS simulation of the relation between the average impact parameter and the energy expected in the Veto calorimeter). The decrease towards higher centrality is to be expected since for the limit of head on collisions no azimuthal anisotropies exist in the geometrical configuration of the colliding nuclei. We note that VENUS fails to reproduce the data whereas RQMD [19] (mean field mode) agrees within the statistical errors. This is a quite remarkable difference between the model predictions since both describe the overall transverse energy production cross section. To find out what degree of anisotropy is necessary on top of the present VENUS events to 'fit' our correlations we have introduced an elliptical event shape via the following transformations to the particle momenta:

$$p'_x = \lambda_x * p_x \tag{6}$$

$$p'_y = \lambda_y * p_y \tag{7}$$

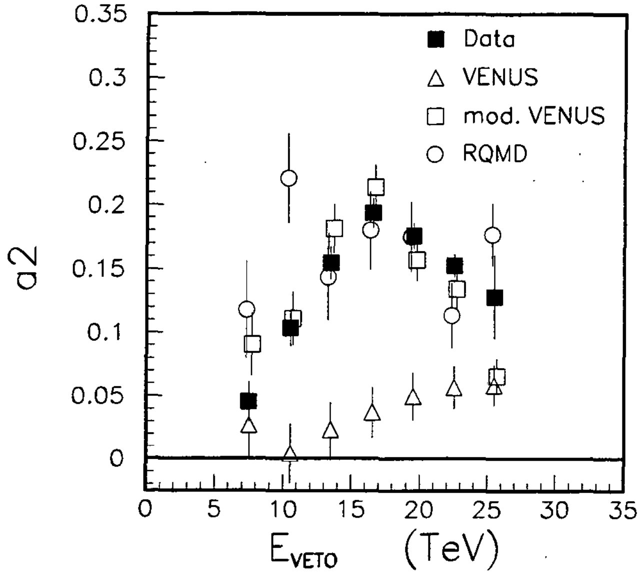

**Figure 4.** Fit parameter a2 of the $\Delta\phi$ distribution as function of the centrality.

$$Rp = \lambda_y^2/\lambda_x^2 \tag{8}$$

The constraint of (average) energy conservation leads to:

$$\lambda_x^2 + \lambda_y^2 = 2 \tag{9}$$

The quantity $Rp$ was used at BEVALAC/SIS energies [20] to study the *squeeze-out* effect:

$$Rp = \frac{< p_y^2 > - < p_y >^2}{< p_x^2 > - < p_x >^2} \tag{10}$$

The comparison with the modified VENUS events showed that a reasonable fit is achieved with a deformation parameter of $Rp \approx 1.2$ for the centrality region of maximum anisotropy. In the case of the RQMD (not modified) we extracted $Rp \approx 1.1$. Even with a *squeeze out* parameter $Rp > 1$ we don't know whether our observed anisotropy indicates a similar phenomenon since the relative orientation of the major axis to the direction of the impact parameter is not derived from data (the Ring calorimeter acceptance is restricted to a narrow region around mid rapidity). The analysis of RQMD events predicts that our major axis is in fact *parallel* to the direction of the impact parameter and not orthogonal as it would be the case for a *squeeze out.*

## Fourier Expansion

We have discussed so far the tensor analysis which is equivalent to second order Fourier expansion analysis as was used in [21]:

$$\nu_n e^{in\psi_n} = \frac{\sum_j \varepsilon_T^j e^{in\phi_j}}{\sum_j \varepsilon_T^j} \tag{11}$$

where $\nu_n$ are the Fourier coefficients (n = 1, 2, 3,...), $e^{in\psi_n}$ is the resulting direction, $\phi_j$ the azimuthal angle and $\varepsilon_T^j$ the transverse energy detected in the $j$th cell.

According to the definition, the first Fourier coefficient $\nu_1$ reflects the displacement of the distribution and $e^{i\psi_1}$ gives the direction of the displacement. The correlation of

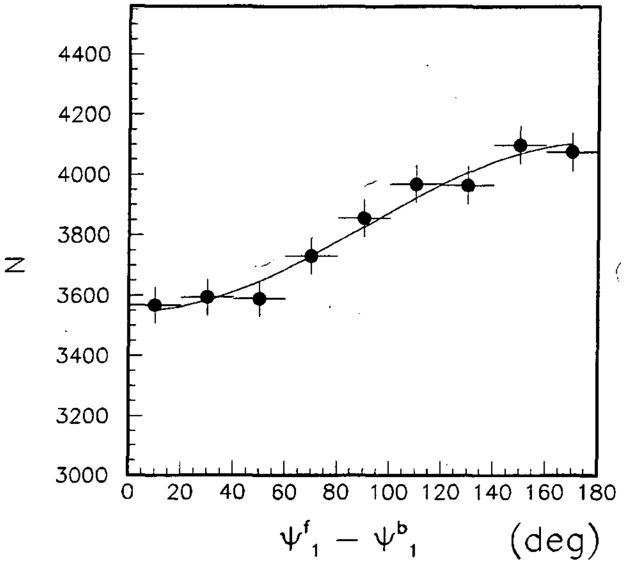

**Figure 5.** Correlation of the resulting angles $\psi_1^f$ (forward region) and $\psi_1^b$ (backward region) for the first order in the Fourier expansion analysis.

$\psi_1^f$ (forward) and $\psi_1^b$ (backward) is slightly peaked at $180^0$ (Fig. 5). The solid line represents a fit with

$$f(\triangle\psi_{fb}) = c * (1 + a1 * cos\triangle\psi_{fb}) \tag{12}$$

The strength of the $\psi_1^f - \psi_1^b$ correlation is significantly smaller than the correlation seen with the tensor analysis (compare to Fig. 3). However, this is not in contradiction to the results reported at AGS energies since particles at rapidities closer to target and projectile rapidity were included in their analysis [11]. At those rapidities the directed sidewards flow component was found to be large in contrast to the mid rapidity zone [21].

## Conclusion

The presented analysis of the transverse energy distribution in Pb on Pb collisions at 158 GeV/nucleon gives strong evidence for anisotropic event shapes. This was obtained from forward backward correlations using tensor analysis. Although pion absorption in target spectator matter has been reported previously for SPS energies [22, 23] our observation demonstrates the presence of *collective effects* at mid rapidity where the high energy density region is formed. Indications for anisotropies have also been observed from photon distributions in the system S on Au at 200 GeV/nucleon [24]. The origin of the *collective effects* might be explained by a strong rescattering of pions in anisotropic surrounding matter (rescattering within the source itself) [25]. In this case, anisotropic event shapes should exist in heavy ion collisions even at the higher RHIC and LHC energies.

## Acknowledgments

This work was supported by the U.S. Department of Energy, the Bundesministerium für Bildung und Forschung, Germany, the Alexander von Humboldt Foundation, Germany, University of Athens, the Polish State Committee for Scientific Research, the Polish–German Foundation, the Hungarian Scientific Research Fundation and EPSRC, U.K.

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## REFERENCES

1. W.K. Wilson, R. Lacey, C.A. Ogilvie and G.D. Westfall, Phys. Rev. **C45** (1992) 738.
2. H.H. Gutbrod, K.H. Kampert, B.W. Kolb, A.M. Poskanzer, H.G. Ritter and H.R. Schmidt, Phys. Lett. **B216** (1989) 267
3. K.G.R. Doss, H.Å. Gustafsson, H.H. Gutbrod, K.H. Kampert, B. Kolb, H. Löhner, B. Ludewigt, A.M. Poskanzer, H.G. Ritter, H.R. Schmidt and H. Wieman, Phys. Rev. Lett. **57** (1986) 302
4. H. Stöcker and W. Greiner, Phys. Rep. **137** (1986) 277
5. D. Brill *et al.* (KaoS Collab.), Phys. Rev. Lett. **71** (1993) 336
6. Venema *et al.* (Taps Collab.), Phys. Rev. Lett. **71** (1993) 835
7. D. Cebra *et al.* (EOS Collab.), these proceedings
8. D. Best *et al.* (FOPI Collab.), these proceedings
9. B.A. Li *et al.*, Phys. Rev. **C44** (1991) 2095
10. S.A. Bass *et al.*, Phys. Lett. **B302** (1993) 381
11. J. Barrette *et al.* (E877 Collab.), Phys. Rev. Lett. **73** (1994) 2532
12. S. Margetis *et al.* (NA49 Collab.), Nucl. Phys. **A590** (1995) 355c
13. I. Huang, S. Margetis, P. Seyboth, and D. Vranic, LBL report 36877 (1995)
14. J. Bächler *et al.* (NA35 Collab.), Z. Phys. **C52** (1991) 239
15. T. Alber *et al.* (NA49 Collab.), Phys. Rev. Lett. **75** (1995) 3814
16. J.D. Bjorken, Phys. Rev. **D27** (1983) 140
17. J.-Y. Ollitault, Phys. Rev. **D48** (1993) 1132
18. K. Werner, Phys. Lett. **B208** (1988) 520
19. H. Sorge *et al.*, Ann. Phys. **192** (1989) 266
20. H.H. Gutbrod *et al.*, Phys. Rev. **C42** (1990) 640
21. Y. Zhang and J. Wessels (E877 Collab.), Nucl. Phys. **A590** (1995) 557c
22. H.R. Schmidt *et al.* (WA80 Collab.), Nucl. Phys. **A544** (1992) 449c
23. T.C. Awes *et al.* (WA80 Collab.), LANL preprint number hep-ex/9601007
24. V.P. Viyogi *et al.* (WA93 Collab.), Nucl. Phys. **A590** (1995) 503c
25. P. Filip, preprint (CU/PH1/96) and private communication

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