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AZIMUTHAL ENERGY FLOW IN DEEP INELASTIC NEUTRINO SCATTERING*

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Abstract

We study gluon emission and the transverse momentum (p_t) of partons confined in nucleons using deep-inelastic charged-current neutrino-nucleon interactions. For this analysis we use the flow of hadronic energy in the azimuthal direction around the momentum transfer referenced from the neutrino-muon scattering plane. We find a five standard deviation asymmetry. Analysis of this asymmetry indicates a $\langle p_t \rangle$ of 0.35 ± 0.12 GeV/c if QCD corrections are included, and 0.56 ± 0.05 GeV/c if they are excluded. We also observe some evidence for x dependence in p_t. Data were taken at Fermilab in 1982 using a 200 ton (fiducial mass) fine grained calorimeter and a dichromatic neutrino beam.

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Deep-inelastic neutrino-nucleon (νN) scattering provides a tool to study the small-scale structure of nucleons. Previous experiments have concentrated on structure functions; these measure the longitudinal (along the momentum transfer) momentum distribution of struck partons. The evolution of the structure functions with increasing Q^2 tests QCD radiative corrections. In our work we consider the flow of hadronic energy around the momentum transfer direction. This measures the transverse momentum of struck partons (p_t), and provides a more sensitive test of perturbative QCD.

Analyses of this kind have been done by bubble chambers[1], but lower energies and lack of statistics have made the results ambiguous. An equivalent analysis using muon-nucleon deep-inelastic scattering has been performed by EMC[2]. Similar information can be extracted from dilepton production in hadron-hadron scattering via the Drell-Yan process[3], but the purely hadronic interaction complicates the analysis. In our study of the azimuthal asymmetry in νN deep-inelastic scattering, we measure $\langle p_t \rangle$ versus the Bjorken scaling variable $x=Q^2/(2m\nu)$ and give more consideration to a threshold effect in production of 3-jet final states.

Our detector was a 200-metric-ton (fiducial mass) calorimeter with 5mm lateral binning and 3cm (.25 radiation length, 0.03 absorption length) longitudinal segmentation[4]. The detector measured two orthogonal views of energy flow from which an azimuthal asymmetry is determined by looking at a correlation between hadronic energy flow and the muon scattering angle[5]. The data sample consists of 9200 neutrino events obtained with three momentum settings of the dichromatic beam, and 1800 antineutrino events from one beam setting.

To measure the flow of hadronic energy around the momentum transfer direction, we define the azimuthal angle ϕ_i for a single hadron i referenced from the neutrino-muon scattering plane as shown in Fig. 1. The quantity we will study is the energy weighted average of $\cos\phi_i$

$$\cos\phi = \frac{\Sigma\cos\phi_i E_i}{E_i} \qquad (1)$$

where E_i is the energy of hadron i and the summations are over all particles in the hadronic final state. Equation (1) is for a single event; we use $\langle\cos\phi\rangle$ to refer to an average over events. With no gluon emission, the final hadron state has two jets: the current jet and target jet. If the struck parton has no component of momentum transverse to the exchanged W^* boson which mediates the interaction, both jets are aligned with the momentum transfer direction. Therefore the mean value of $\cos\phi$ is zero.

If the struck parton has nonzero transverse momentum, the current and target jet directions are shifted away from the momentum transfer direction and an asymmetry in the energy flow is possible. The νN cross section is proportional to s, the square of the center-of-mass energy of the incident neutrino and parton. A kinematic analysis shows that s depends on the orientation of p_t, giving events with the target jet between the outgoing lepton and current jet a larger cross section than other configurations. At the parton level for $Q^2 >> p_t^2$ it has been shown that:

$$\langle \cos\phi \rangle = -(p_t/Q)(1-y)^{\pm 1/2}, \qquad (2)$$

where the "+" sign is used for neutrino-quark or antineutrino-antiquark, the "-" sign for antineutrino-quark or neutrino-antiquark scattering[6]. This effect causes $\langle \cos\phi \rangle$ to be of order -.1 for $\langle p_t \rangle = 0.3$ GeV/c in the energy range of this experiment.

First order QCD introduces an additional forward jet from gluon emission which is usually soft compared to the current jet. An interference between gluon emission from initial and final parton lines emphasizes events where this soft jet lies between the outgoing lepton and the current jet. A similar effect occurs for 3-jet events from gluon fusion, but as this makes a much smaller contribution we restrict our discussion to the gluon emission events. At the parton level for small x we find:

$$\langle \cos\phi \rangle = -\alpha_s(Q^2) f(x) (1-y)^{\pm 1/2}, \qquad (3)$$

where the double sign has the same convention as in equation (2), $\alpha_s(Q^2)$ is the strong coupling constant, and $f(x)$ is a convolution over structure functions[7]. The QCD contribution to $\langle \cos\phi \rangle$ is expected to be also of order -.1 for the energy range of this experiment.

In converting the parton level first order QCD calculation to the corresponding result for observable particles we encounter some difficulties. The derivation of equation (3) included zero energy and colinear jets. The cross section for scattering with gluon emission (3-jet events) has nonintegrable singularities in these regions, some of which are cancelled by summing diagrams and the rest are factored into the structure functions. These analytic methods cannot be implemented in a phenomenological Monte Carlo calculation (MC) to convert the parton jets to observed particles. The nonintegrable regions of the cross section must somehow be excluded.

Most popular MCs apply a cut on energy and colinearity (with the struck parton) of the radiated gluon[8] which results in very few 3-jet events and a negligible $\langle\cos\phi\rangle$ contribution. The treatment of 3-jet production in our MC is to duplicate the analytic parton level result as nearly as possible. All events contain three jets, with the gluon spectrum cut to keep the inclusive cross section fixed[5]. Since this strategy is not an obvious one, we also consider the other extreme, a 2-jet MC (no event has 3-jets), which is equivalent to the MCs used in other experiments.

The p_t contribution to $\langle\cos\phi\rangle$ (equation 2) can be viewed as absorbing all QCD terms not included in equation (3). In principle, a complete QCD calculation should predict $\langle\cos\phi\rangle$ without any p_t term, or equivalently should predict the p_t to use in equation (2). Note there is no theoretical reason why this p_t should be independent of the scaling variable x. Lacking a complete all-order QCD calculation, we can use the measured structure functions to predict the effective p_t distribution by invoking spherical symmetry in the nucleon rest frame. The principal result is that $\langle p_t \rangle$ is proportional to x at small x. The detailed validity of this calculation is however not clear since structure functions do not provide a good description of a nucleon in its rest frame. We note the x dependence predicted by this calculation is similar to those from other methods[9], and we will use it as a guide for an experimental study of $\langle p_t \rangle$ versus x.

The parton level asymmetry is reduced by hadronization and secondary interactions. Our hadronization model and simulation of secondary interactions predict a reduction factor of about five, giving an expected $\langle \cos\phi \rangle$ of about -0.02. The measured $\cos\phi$ distribution and its mean (-0.016 ± 0.003) are shown in Fig. 2. The plot is folded to emphasize that the mean of the distribution is small compared to the width, but it is not dominated by a few events in the tails of the distribution.

We investigated the following possible sources of systematic error: identification of the muon track (± 0.0004 in $\langle \cos\phi \rangle$); removal of leptonic energy deposition (± 0.0001); shower containment (± 0.0005); and bias in the determination of the momentum transfer direction (±0.0005). The total systematic error, $\sigma_{\langle\cos\phi\rangle}=0.0008$, is found to be an order of magnitude smaller than the statistical error. Details of the analysis and the study of systematic errors may be found in reference 5.

If we assume $\langle p_t\rangle$ is independent of x and fit $\langle\cos\phi\rangle$ averaged over all events, we find $\langle p_t\rangle=0.35\pm0.12$ GeV/c using our 3-jet MC and $\langle p_t\rangle=0.56\pm0.05$ GeV/c using the 2-jet MC. Statistical and systematic errors have been combined in the quoted error.

The best variable with which to separate the p_t and first order QCD effects is Q^2. The p_t term (equation 2) varies as 1/Q, while the 3-jet term (equation 3) varies logarithmically with Q^2 due to the running coupling constant $\alpha_s(Q^2)$. No matter what the x-dependence of $\langle p_t\rangle$ is, at sufficiently low Q^2 the p_t term should dominate, while at sufficiently high Q^2 the QCD term should dominate. We are however limited at the low Q^2 end by the range over which events may be considered deep-inelastic, and at the high Q^2 end by the finite energy of the beam. Fig. 3 shows the measured $\langle\cos\phi\rangle$ sliced in Q for data, and $\langle\cos\phi\rangle$ as predicted by 2- and 3-jet MCs with p_t independent of x. The agreement with either MC is poor, but is seen to be better in the 3-jet case compared to the 2-jet case.

To improve the fits, we have allowed $\langle p_t\rangle$ to be a function of x of the form $\langle p_t\rangle=ax+b$. We find the best agreement in the 2- or 3-jet MC is obtained with b=0, i.e. $\langle p_t \rangle$ proportional to x. The result of this fit is presented in Fig. 4. The agreement is seen to be better than in Fig. 3, but there is little distinction between the 2- and 3-jet cases.

We conclude that if $\langle p_t \rangle$ is required to be x-independent, the data favor our 3-jet MC over the 2-jet (standard) MC. Better fits are obtained with $\langle p_t \rangle$ proportional to x. In this case, both 2- and 3-jet MCs give reasonable agreement, and the only point favoring the 3-jet MC is the unexpected large value of $\langle p_t \rangle$ in the 2-jet case. Note that our 2-jet results are in agreement with EMC[2], who used the Lund[8] MC.

In summary, we have found a statistically significant asymmetry in the azimuthal distribution of hadronic energy in deep-inelastic charged-current neutrino-nucleon scattering. We interpret this as due to an intrinsic transverse momentum of partons confined in nucleons, with a mean of 0.35±0.12 GeV/c if gluon emission is included in the calculation, or 0.56±0.05 GeV/c with no gluon emission. We have some evidence for p_t being dependent on x. With the limited Q^2 range of our data, we cannot separate the QCD gluon radiation effect from intrinsic p_t effects. We are in the process of analyzing a larger, higher energy data sample which may significantly improve our measurement[10].

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Figure Captions

Figure 1. Lab frame event geometry. P_ν and P_μ define the lepton scattering plane. P_h is the total final state hadronic momentum; neglecting Fermi motion, this is also the momentum transfer. The azimuthal angle for a single hadron of momentum P_i is shown.

Figure 2. Event-by-event $\cos\phi$ estimator with the negative half of the distribution folded onto the positive half. The arrow marks the mean, $\langle\cos\phi\rangle=-0.016$, folded onto the positive axis.

Figure 3. $-\langle\cos\phi\rangle$ versus Q for all data, 2-jet MC with $\langle p_t\rangle=0.56$ GeV/c, and 3-jet MC with $\langle p_t\rangle=0.35$ GeV/c. Note the vertical scale has been multiplied by 1000.

Figure 4. $-\langle\cos\phi\rangle$ versus Q for all data, 2-jet MC with $\langle p_t\rangle=8.2x$ GeV/c, and 3-jet MC with $\langle p_t\rangle=1.3x$ GeV/c.

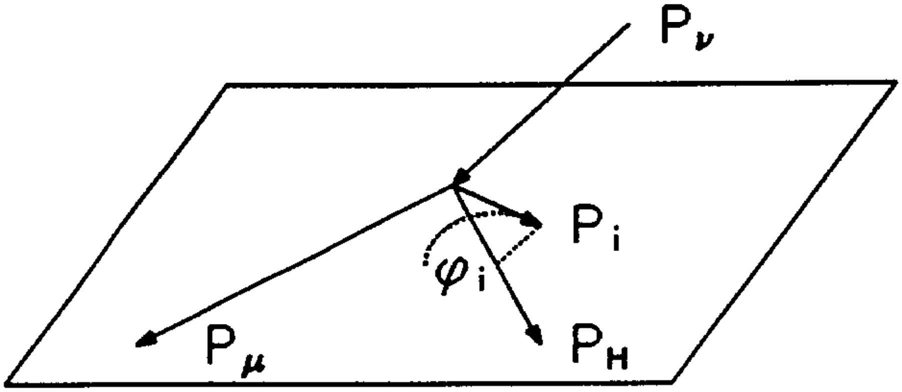


Fig. 1

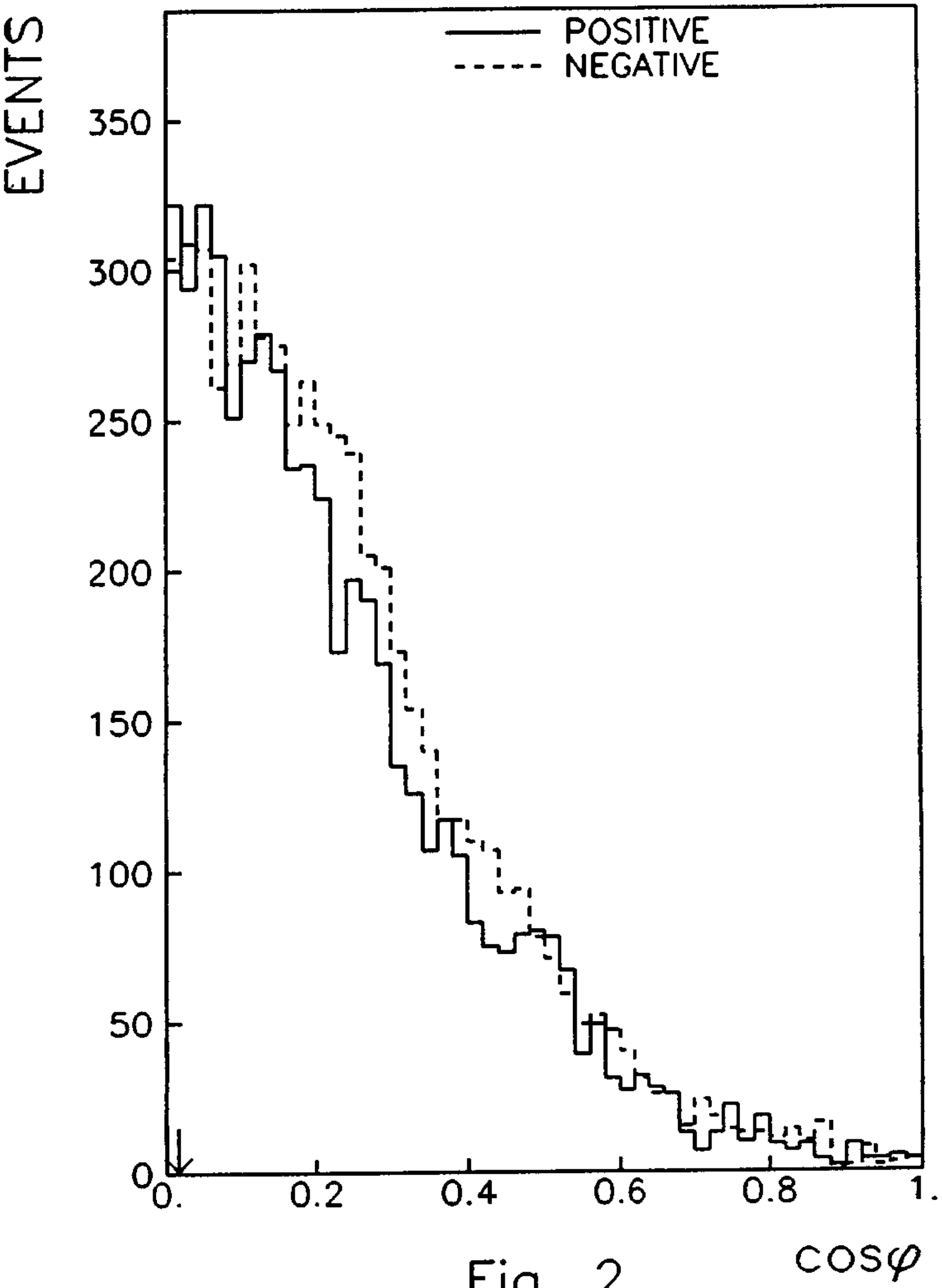
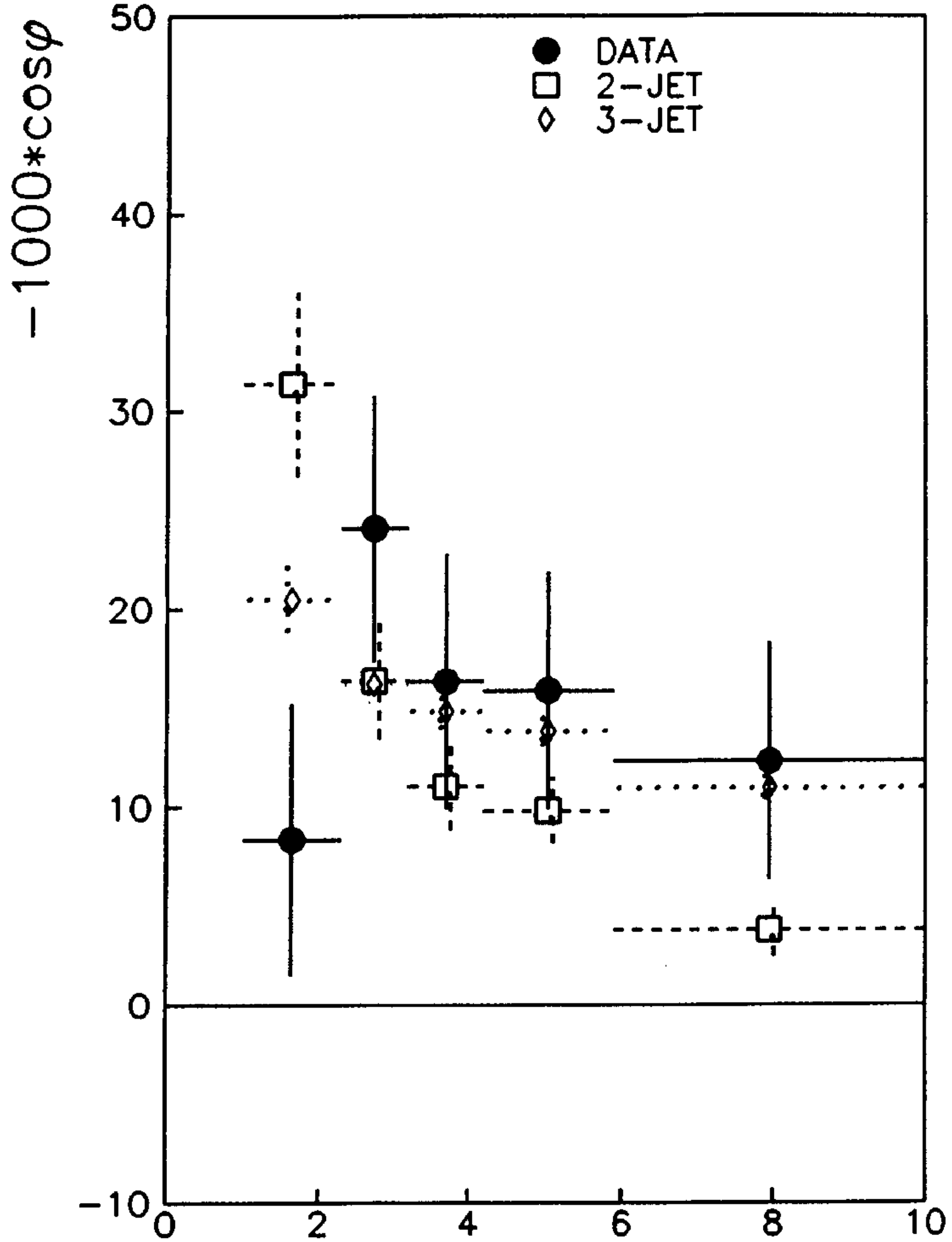

POSITIVE
NEGATIVE
EVENTS
350
300
250
200
150
100
50
0
0.
0.2
0.4
0.6
0.8
1.
cosφ

Fig. 2



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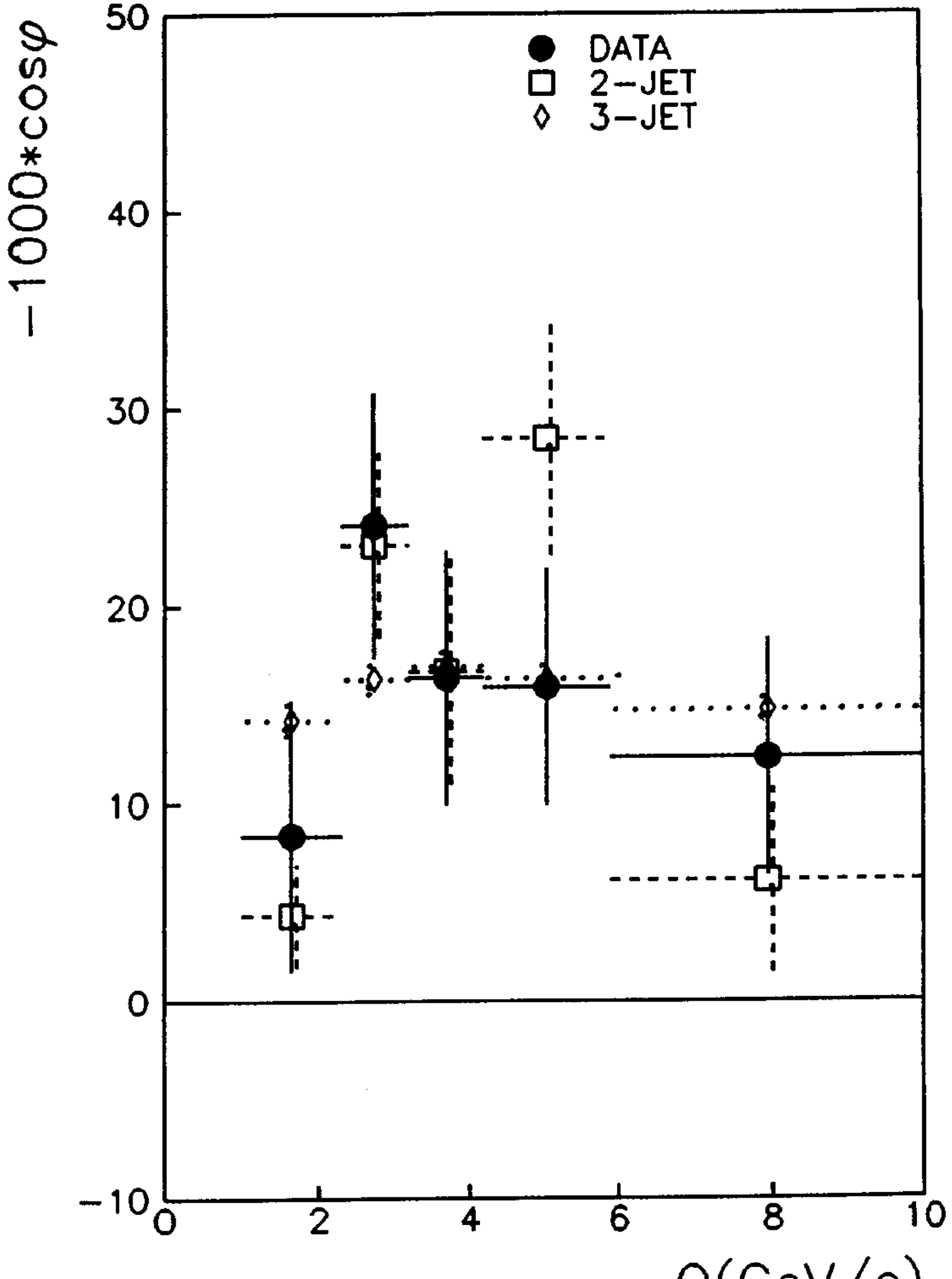

Fig. 4