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Energy Flow and Transverse Momentum of Hadron Jets Produced in Deep Inelastic Muon Scattering *

The E-665 Collaboration

presented by

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ENERGY FLOW AND TRANSVERSE MOMENTUM OF HADRON JETS PRODUCED IN DEEP INELASTIC MUON SCATTERING

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ABSTRACT

Forward di-jet production observed in μp and μd interactions (Fermilab E665) is reported. The W^2 range studied, $100 < W^2 < 900$ GeV^2, is the largest yet achieved. Results from separate analyses, one using only charged hadrons and the other using both charged and the neutral energy deposited in the EM calorimeter, are presented. Correlations with $\Sigma|P_T| \simeq E_T$, an event variable, are studied. An azimuthal asymmetry of the hadrons about the virtual photon is observed.

Introduction

In the quark-parton model, deep inelastic scattering is described by virtual photon-quark scattering (Fig. 1a). The subsequent hadronization of the quark gives rise to a jet of hadrons which propagate along the direction of the parent quark with limited transverse momentum. The lowest order QCD corrections to the one-photon exchange diagram, gluon bremsstrahlung (Fig. 1b,c) and photon-gluon fusion (Fig. 1d,e) can result in final states with two forward partons each of which will fragment into hadron jets with the result that the transverse momentum of the hadrons with respect to the virtual photon direction increases.

Explicit calculations of the lowest order QCD corrections show that the average transverse momentum with respect to the virtual photon should increase with W^2 [1] with little or no dependence on other muon vertex variables. Since the virtual photon and the $q\bar{q}$ or qg pair lie in a plane (the hadronic event plane), the component of a hadron's transverse momentum that lies in the event plane ($P_{T,IN}$) should grow with W^2 whereas the component of the hadron's transverse momentum that is perpendicular to the event plane ($P_{T,OUT}$) should not depend on W^2. Further, calculations of the diagrams of Figures 1b,c by Georgi and Politzer have shown that the azimuthal distribution of hadrons about the virtual photon should be asymmetric, with the hadrons preferring to be opposite the muon [2]. Cahn has pointed out that such a correlation also arises naturally from the intrinsic transverse momentum of the partons [3].

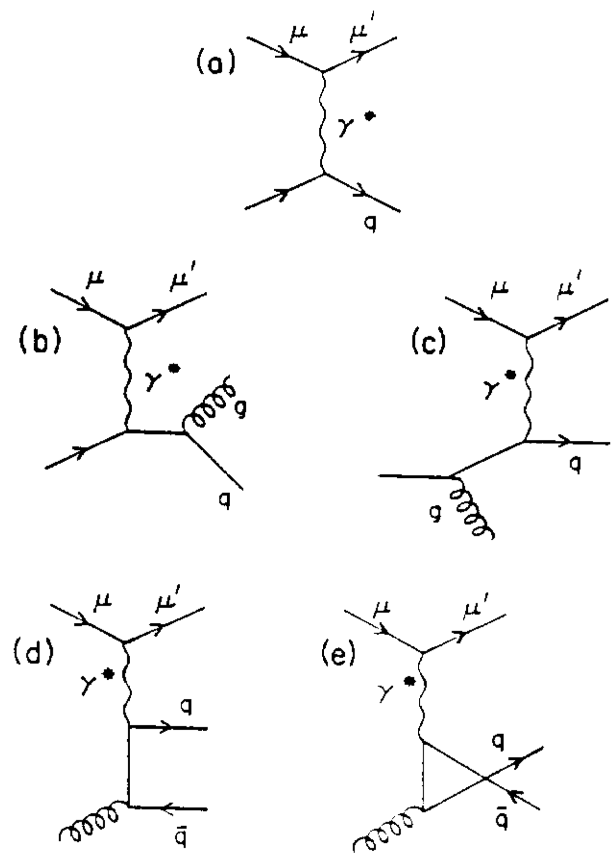

Figure 1: One photon exchange (a) and lowest order corrections; b,c): Gluon bremsstrahlung; d,e): Photon-gluon fusion.

The increase of transverse momentum with W^2 and the azimuthal asymmetry have been observed for both μN and νN deep inelastic scattering [4]. E665 by virtue of its 490 GeV/c beam extends the W^2 range of the existing data by approximately a factor of two.

Results

The data reported here were obtained during Fermilab's 1987-88 Fixed Target run with a 490 GeV/c muon beam incident upon deuterium and hydrogen targets. The ratio of μd to μp events is approximately 3:1. E665 employs an open geometry spectrometer which is described in ref. [5]. The data used for this analysis consist of hadrons with $x_F = 2P_L^*/W > 0$. The momentum of the charged tracks is measured in the forward spectrometer. The neutral energy is obtained from the electromagnetic calorimeter. The incident muon momentum is determined by the beam spectrometer to 0.5% and the scattered muon momentum is determined to 2.5% at 490 GeV/c. Typical hadron momenta are determined to a few percent. For the data shown only charged hadrons with $\Delta P/P < 5\%$ are included. The trigger used for these data is the Large Angle Trigger (LAT) which requires the detection of the scattered muon behind the hadron absorber outside of the beam region.

We first present results which include only charged hadrons. We begin by comparing to transverse momentum distributions obtained by the EMC at lower incident muon energies [6]. All transverse momenta are measured with respect to the virtual photon direction. Figure 2 compares distributions of $\Sigma P^2_{T,IN}$ and $\Sigma P^2_{T,OUT}$. The event plane is defined to be the plane where $\Sigma P^2_{T,IN}$ is a maximum. The same kinematic cuts as used by the EMC are applied to our data: $Q^2 > 4$ GeV^2/c^2, $20 < \nu < 260$ GeV, $0.1 < Y_{Bj} < 0.9$, $X_{Bj} > 0.01$, and $100 < W^2 < 400$ GeV^2. Within the statistical significance of the data agreement is good. We also find (not shown) that the fragmentation function $(1/N_\mu)dN^\pm/dz$ agrees well with EMC results.

Note that the event plane defined above becomes an experimental definition of the plane formed by the virtual photon and the $q\bar{q}$ or gq pair. Further, the $P_{T,OUT}$ distribution may be used as a measure of the single jet transverse momentum distribution since the $P_{T,OUT}$ distribution will be the same for one-jet and two-jet events.

In the following analysis we restrict ourselves to events with charged hadrons with the following selection criteria: $60 < \nu < 500$ GeV, $Q^2 > 3.0$ GeV^2/c^2, $0.1 < Y_{Bj} < 0.85$, $100 < W^2 < 900$ GeV^2, $x_F > 0$, $n_{ch} \geq 4$, $P_{charge\ track} > 8.0$ GeV/c. After these cuts we are left with a sample of 4262 μd events and 932 μp events.

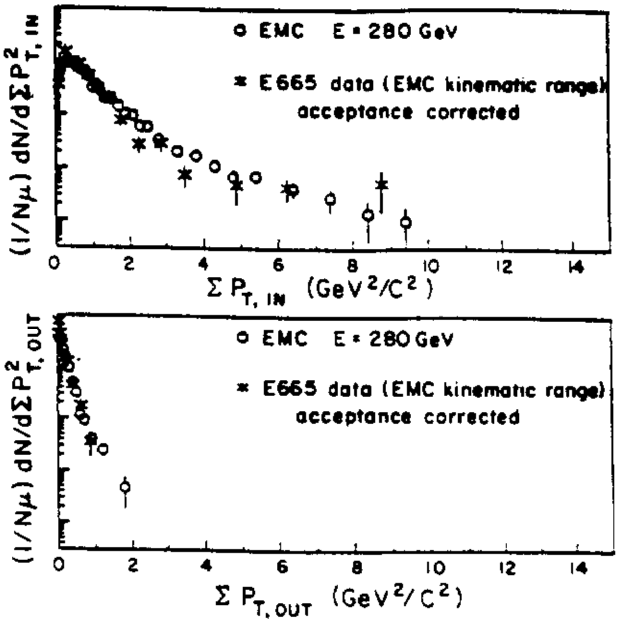

Figure 2: Normalized $\Sigma P^2_{T,IN}$ and $\Sigma P^2_{T,OUT}$ distributions compared with EMC results.

The results are compared to LUND Monte Carlo calculations [7]. We use Lepto version 5.2 [8] to simulate lepton-nucleon scattering and Jet Set 6.3 [9] to simulate the hadron fragmentation. We also compare our results to the predictions of Ariadne 3.0 [10], which simulates color dipole radiation. For all acceptance calculations we use Jet Set 4.3. We have used the Morfin-Tung [11] parton distributions except where noted. The average transverse momentum squared vs. x_F (the seagull plot) is compared with LUND model predictions in Figure [3].

It is expected that $q\bar{q}$ and qg events will have increased total transverse energy or $\Sigma|P_T|$, where P_T is the momentum of the hadron in the plane perpendicular to the virtual photon. $\Sigma|P_T|$ has a well behaved perturbative expansion (see for example ref. [12]). The single forward jet events (Fig. 1a) have hadrons with P_T distributed symmetrically in the transverse momentum plane while the two-jet events (Fig. 1b-e) would have a non-symmetric distribution. This suggests a variable which can be used to select events with large transverse energy and therefore with increased probability of containing $q\bar{q}$ or qg jets.

The event variable we use is an extension of $\Sigma|P_T|$. It was first introduced by Ballagh, *et al.* [13]. Because a single jet has a uniform P_T distribution with a most probable value P_{T^0}, the distribution in $\Pi_F = A\Sigma(|P_T| - P_{T^0})/\sqrt{n_F}$ is approximately a random walk of n_F steps from the origin with width of 1, independent of multiplicity (n_F is the number of forward hadrons in the event). A is chosen to give $< \Pi_F^2 > \simeq 1$. We use $P_{T^o} = 0.32$ GeV/c and $A = 4.0$ consistent with Ballagh, *et al.*

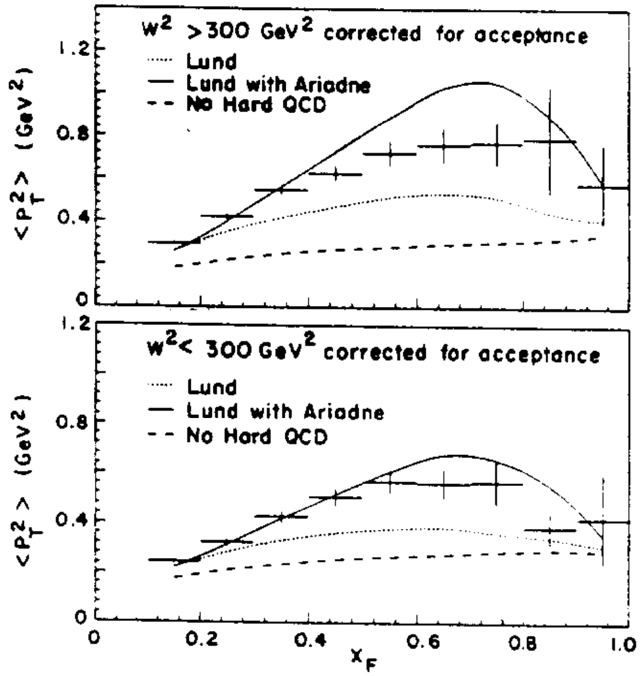

Figure 3: Average P_T^2 vs. x_F for different W^2 ranges.

In addition we define a quantity called planarity $\underline{P} = \Sigma(P_{T,IN}^2 - P_{T,OUT}^2)/\Sigma(P_{T,IN}^2 + P_{T,OUT}^2)$ where $P_{T,IN}$ and $P_{T,OUT}$ are the components of the hadron's transverse momentum lying in and out of the event plane, respectively. The scatter plot of Π_F vs. $\underline{P}$ for $W^2 > 300$ GeV^2 is shown in Figure 4 where data (Fig. 4a) are compared to the LUND Monte Carlo [11] with (Fig. 4b) and without (Fig. 4c) forward di-jet events (with diagrams 1b-1e turned on and off). The expected enhancement of planar events (large $\underline{P}$) with large Π_F is apparent in both the data and LUND with hard QCD, whereas the LUND with only single quark jets (Fig. 1a) has no events in this region. We also observe that the number of events with both large Π_F and large planarity increases with W^2, in qualitative agreement with perturbative QCD expectations.

The average multiplicity per unit P_T^2 for events with $n_{ch} \geq 4$ is shown in Figure 5 for $W^2 > 300$ GeV^2. As expected, there are considerably more hadrons with large P_T^2 for $\Pi > 3.0$ and $\underline{P} > 0.5$ whereas for $\Pi_F < 3.0$ or $\underline{P} < 0.5$ the P_T^2 distribution decreases much faster. The curves are the predictions of the LUND Monte Carlo [7] with similar cuts. The dotted curve is the LUND prediction with only single jet production.

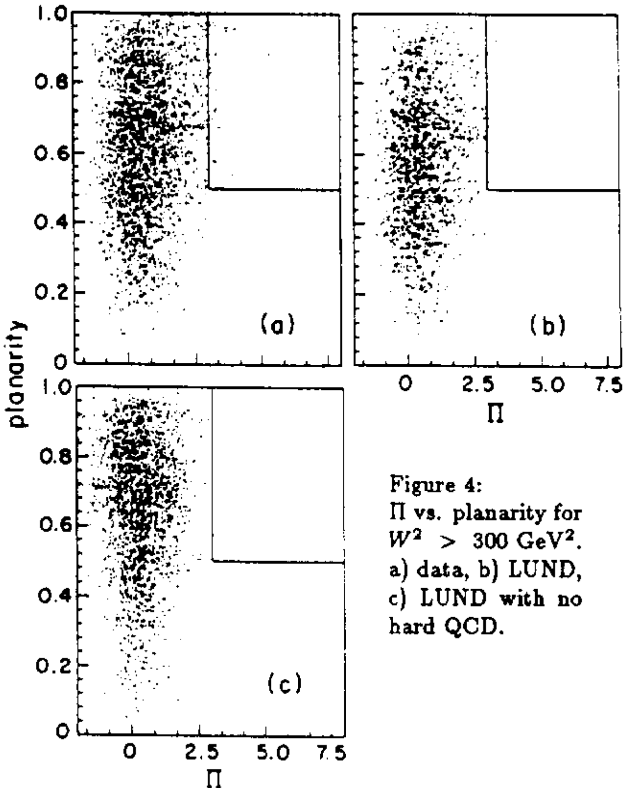

Figure 4: Π vs. planarity for $W^2 > 300$ GeV^2. a) data, b) LUND, c) LUND with no hard QCD.

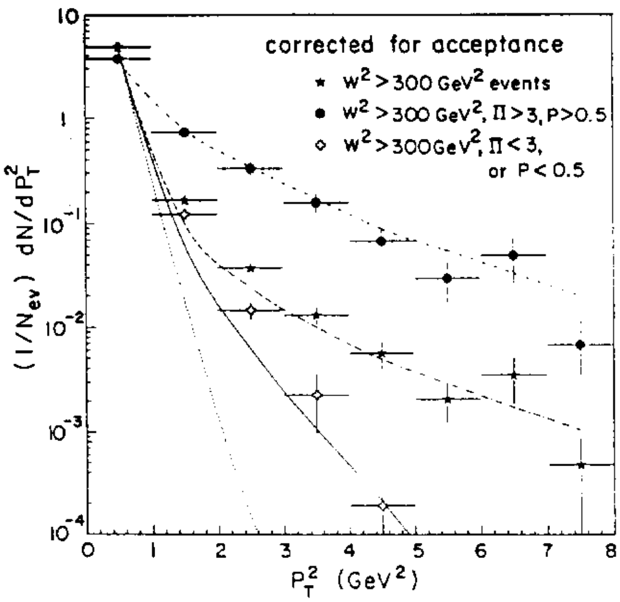

Figure 5: The average charged particle multiplicity per unit P_T^2 for $n_{ch} \geq 4$.

The scaled angular energy flow $d < E/W > /d\theta$ in the photon-nucleon center of mass system projected onto the event plane is given in Figure 6 for several Π_F regions and $\underline{P} > 0.5$. The curves are LUND model predictions. In these distributions the orientation is such that the scattered muon projected onto the event plane lies at $\theta < 0$. In each case the distributions are normalized to the number of events which pass the $\underline{P}$ and Π_F cuts. The di-jet behavior expected from the lowest order QCD corrections at large Π_F is evident and is in qualitative agreement with the LUND model.

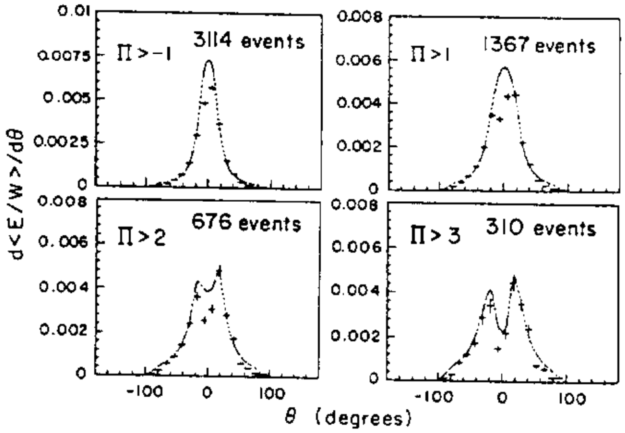

Figure 6: The angular energy flow for $W^2 > 300$ GeV^2. Curves are LUND model predictions.

We conclude from the above results that we are observing di-jet events in the forward region and that these events are, as expected from perturbative QCD calculations, associated with large transverse momentum.

In Figure 7 the azimuthal distribution, ϕ, of hadrons about the virtual γ direction is given for $\Pi_F < 1$ and $\Pi_F > 1$ for the selection $x_F > 0.2$. The $\Pi_F < 1$ distribution is consistent with little or no asymmetry, while the large values of Π_F show a significant asymmetry. The data were fit to $A + B\ cos\ \phi + C\ cos(2\phi) + D\ sin\ \phi$. For $\Pi_F < 1$ we also obtain a good fit, $\chi^2/\mathrm{DF}=1.15$, for an isotropic distribution ($(1/N_{ev})dN/d\phi = A$). We also observe an increase of the asymmetry as a function of x_F and P_T^2 consistent with previous results [4].

Thus far we have not made use of the electromagnetic shower energy observed in the calorimeter. We now add the electromagnetic shower energy, which allows us to include events with $n_{ch} < 4$, for our energy flow studies. Data with the EM calorimeter are only available for approximately 1/3 of the μd events. Thus in this sample we have approximately an equal number of μd and μp events. The data presented below lie in the kinematic range $0.01 < Y_{Bj} < 0.85$, $0.003 < X_{Bj} < 1.0$, $Q^2 > 3.0$ GeV^2/c^2, and $W^2 > 400$ GeV^2.

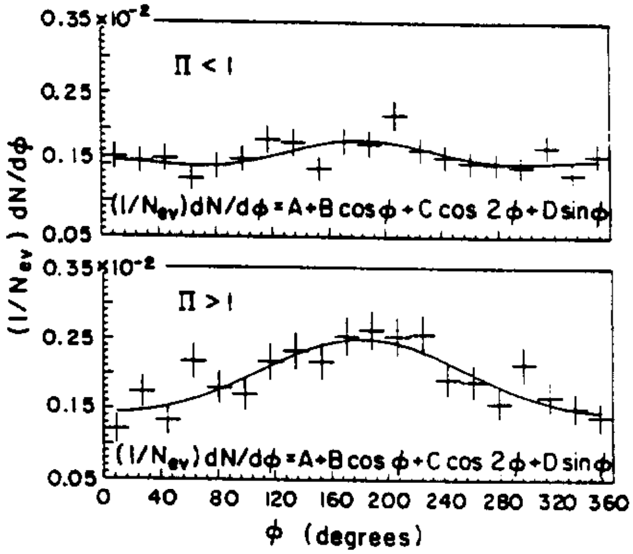

Figure 7: Azimuthal distribution of charged hadrons about the virtual γ directions (the scattered muon is at $\phi = 0°$).

We now apply a clustering algorithm to define two jets. Particles are divided into two sets on each side of the virtual photon in the event plane, and the momenta combined vectorially to yield two jet vectors. The component of momentum of each particle relative to each of these "jet axes" is calculated and particles are reassigned to the "jet axis" which yields the minimum P_T. This step is repeated three times beyond which Monte Carlo studies show that there is no significant reassignment of particles. Having thus defined the two forward jet axes we can enhance the fraction of di-jet events by selecting on the opening between the two jets (Θ_{jj}), the angle between the jet axis and virtual photon ($\Theta_{\gamma j}$), and the relative magnitude of the momenta of the jets, P_S and P_L for the smaller and larger jet momenta, respectively. The jet selection criteria we use are: $cos\ \Theta_{jj} < 0.7$, $cos\ \Theta_{\gamma j} < 0.98$, and $P_S/P_L > 0.25$.

The scaled angular energy flow in the event plane relative to the higher momentum jet axis with the lower momentum jet at positive angles is shown in Figure 8. With this jet cut, the events tend to be asymmetric in momentum. The data have been corrected for acceptance in each case. The calculations with the LUND Monte Carlo (Jet Set 4.3) using the Morfin-Tung [11] structure functions give results which are consistent with the data when hard QCD is included. The LUND curves include simulations with the GHR structure functions [14] where the main difference between reference [11] and [14] is in the gluon distribution. The Morfin-Tung distributions have much more glue at small X_{Bj} and correspondingly less at high X_{Bj} than do the GHR distributions.

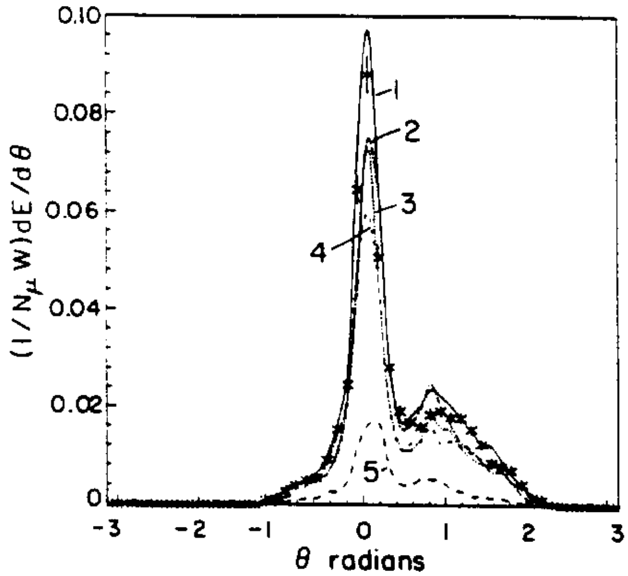

Figure 8: Scaled energy flow normalised to the number of scattered muons about the high and low momentum jet axis using charged hadrons and neutral energy. LUND model predictions: 1) Morfin-Tung structure functions, 2) No hard QCD but increased fragmentation P_T, 3) GHR structure functions with soft gluons, 4) GHR structure functions, 5) No hard QCD.

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