Dynamics of Multijet Processes in Photoproduction

L. E. Sinclair

for the ZEUS Collaboration

Abstract

The cross section for producing three high transverse energy jets with a three-jet invariant mass of $M_{3J} > 50$ GeV has been measured in photoproduction at HERA. The angular distribution of the three jets is presented and found to be inconsistent with a uniform population of the available phase space. In contrast, parton shower models and $\mathcal{O}(\alpha_s^2)$ pQCD calculations are able to describe the three jet dynamics.

talk given at the 6th International Workshop on Deep Inelastic Scattering and QCD (DIS '98),
Brussels, Belgium.
April 4-8, 1998
1 Introduction

The study of multijet production provides a direct test of perturbative QCD (pQCD) predictions beyond leading order. It provides in addition sensitive tests of extensions to fixed order theories such as parton shower models. We have measured distributions of observables which span the multijet parameter space and have a relatively straightforward interpretation within pQCD [1]. Such distributions have previously been measured for two jet production at HERA [2] and for three or more jets at the Tevatron [3, 4]. Here these distributions are presented for inclusive three-jet photoproduction for the first time.

The measured quantities are the three-jet invariant mass, \( M_{3J} \), and the dimensionless quantities \( X_3, X_4, \cos \theta_3 \) and \( \psi_3 \) which determine the configuration of the three jets. These quantities are defined,

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X_3 \equiv \frac{2E_3}{M_{3J}}, \quad X_4 \equiv \frac{2E_4}{M_{3J}}, \quad \cos \theta_3 \equiv \frac{\vec{p}_{AV} \cdot \vec{p}_3}{|\vec{p}_{AV}| |\vec{p}_3|}, \quad \text{and} \quad \cos \psi_3 \equiv \frac{(\vec{p}_3 \times \vec{p}_{AV}) \cdot (\vec{p}_4 \times \vec{p}_5)}{|\vec{p}_3 \times \vec{p}_{AV}| |\vec{p}_4 \times \vec{p}_5|},
\]

where \( E_j \) and \( \vec{p}_j \) are the energies and three-vectors respectively of the jets in this frame, the jets are numbered 3, 4 and 5 in order of energy decreasing and \( \vec{p}_{AV} \) represents the average beam direction.

The definition of the angles \( \theta_3 \) and \( \psi_3 \) is illustrated in figure 1a). \( \theta_3 \) is the angle between the highest energy jet and the beam direction. It is similar to the cm scattering angle \( \theta^* \) familiar from dijet studies. We therefore expect the distribution of \( \cos \theta_3 \) to have approximately a Rutherford scattering form \( \sim (1 - \cos \theta^*)^{-2} \) and to reflect the spin of the primary exchanged parton. \( \psi_3 \) is the angle between the plane containing the three jets and the plane containing the highest energy jet and the beam direction. The coherence property of QCD causes these two planes to tend to coincide leading to a \( \psi_3 \) distribution which peaks toward 0 and \( \pi \).

2 Event Selection

Photoproduction events are selected by restricting the momentum transfer at the positron vertex to \( < 1 \text{GeV} \) and photon-proton cm energies \( W_{\gamma p} \) are selected in the range \( 134 \text{ GeV} < W_{\gamma p} < 269 \text{ GeV} \). Jets are found using the KTCLUS [5] finder in inclusive mode [6]. This is a longitudinally invariant cluster algorithm which combines particles with small relative transverse momenta into jets. Because it suffers from no ambiguities due to overlapping jets it is ideal for the study of multijet processes. The jets are required to have transverse energies \( E_T^{jet} > 6 \text{ GeV} \) and pseudorapidities \( |\eta^{jet}| < 2.5 \). The requirement of high transverse energy for the jets ensures that the process should be calculable within pQCD. However it introduces a bias on angular distributions by throwing away jets which are produced close to the beam-line. We make the additional requirements \( M_{3J} > 50 \text{ GeV}, |\cos \theta_3| < 0.8 \) and \( X_3 < 0.95 \) in order relieve the angular distributions of this effect.
3 Results

The three-jet invariant mass distribution is shown in figure 1 b) and compared with $O(\alpha_s^2)$ calculations from two groups of authors, Harris & Owens [9] and Klasen & Kramer [10]. The pQCD calculations are in relatively good agreement with the data, given that the calculation is leading order for this process. The Monte Carlo models PYTHIA 5.7 [7] and HERWIG 5.9 [8] contain only the two-to-two matrix elements but are able to produce three jet events through the initial and final state parton showers. The $M_{3J}$ distribution predicted by these models is in agreement in shape with the data although the predicted cross section is too low by 30-40%.

The fractions of the available energy taken by the highest and second highest energy jets are shown in figures 2 a) and 2 b) respectively. Here the prediction for three jets uniformly distributed in the available phase space is also shown. The pQCD calculations (completely overlapping) and the parton shower models are all able to describe these energy sharing quantities. However, notice the similarity of the measured distributions with the three-body phase space distributions. These distributions have little sensitivity to the pQCD matrix element.

In figures 3 a) and 3 b) the $\cos \theta_3$ and $\psi_3$ distributions are shown. The measured angular distributions are dramatically different from the distributions obtained from phase space. This shows that these quantities have a high degree of sensitivity to the QCD matrix element. The $\cos \theta_3$ values are indeed distributed approximately according to the Rutherford form. The $O(\alpha_s^2)$ pQCD and parton shower calculations, which take into account the dependence of this distribution on quark and gluon spin, are in excellent agreement with the data. The
jet algorithm and the $E_T^{\text{jet}} > 6$ GeV requirements have thrown away portions of the phase space near $\psi_3 \sim 0$ and $\pi$ as indicated by the shape of the phase space curves. Taking this into account the data indicate a strong tendency for the three-jet plane to lie near the plane containing the beam and the highest energy jet. This effect is reproduced in the $O(\alpha_s^2)$ calculations via the QCD initial state radiation pole. It is remarkable that the colour coherence phenomenon, implemented as angular ordering in parton shower models, allows the leading order Monte Carlo programs PYTHIA and HERWIG also to provide a reasonably accurate representation of the $\psi_3$ distribution.

4 Conclusions

The cross section for photoproduction of three jets with high invariant mass has been measured. It is described by $O(\alpha_s^2)$ calculations but underestimated in leading order parton shower models. The orientation of the three jets is not uniform in the available phase space. Both fixed order pQCD calculations which contain the full two-to-three matrix elements and Monte Carlo models which produce three jet events through the parton shower mechanism are able to reproduce the angular distribution of the jets. This constitutes a significant advance in the understanding of multijet photoproduction.

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