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MULTIJETS IN PHOTOPRODUCTION AT HERA*

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Cross-sections for the photoproduction of events containing four high-E_{T} jets have been measured with the ZEUS detector using an integrated luminosity of 38.7 pb^{-1}. At low invariant mass of the four-jet system, $m_{4\mathrm{J}}$, the observed event distributions are sensitive to the underlying event model. The inclusion of multi-parton interactions in Monte Carlo simulations lead to a significantly better description of the data. For $m_{4\mathrm{J}} > 50$ GeV the data is adequately described by models with no simulation of an underlying event, suggesting that this is a kinematic region suitable for comparison with perturbative QCD calculations.

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1. Introduction

The study of multijet production provides sensitive tests of perturbative QCD (pQCD) at intrinsically higher orders. In photoproduction at leading order, two types of process contribute to the cross-section. In **direct** events, the photon enters directly into the hard interaction whilst in **resolved** events the photon acts as a source of partons and contributes a fraction x_γ of the total photon momentum to the hard scatter. At next-to-leading order, only the *sum* of the direct and resolved processes is unambiguously defined. It is therefore useful to define a variable correlated to x_γ which is well defined to all orders of perturbation theory. This variable, $x_{\gamma;\mathrm{NJ}}^{\mathrm{OBS}}$, is chosen such that,

$$x_{\gamma;\mathrm{NJ}}^{\mathrm{OBS}} = \frac{\sum_{\mathrm{jet}=1}^{\mathrm{N}} E_{\mathrm{T}}^{\mathrm{jet}} \exp\left(-\eta^{\mathrm{jet}}\right)}{2yE_e}\,, \tag{1}$$

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where yE_e is the energy of the exchanged photon and the sum runs over the N highest E_{T} jets within the accepted η^{jet} range.

In resolved events it is possible for further hard scatters to take place between the proton and photon remnants. This is known as multiple parton scattering, or **multi-parton interactions**. The first clear observation of this phenomenon has been reported in hadron–hadron collisions by the CDF Collaboration [1]. At HERA, the effects of multi-parton interactions are expected to be most significant at low $x_{\gamma;\mathrm{NJ}}^{\mathrm{OBS}}$. One of the main consequences of multiple parton scattering is expected to be an increase in the energy flow of the event, particularly in the forward (proton) direction. In this way, multi-parton interactions can form part of the **underlying event**. In extreme cases, the transverse energy of the secondary scatters is sufficient to produce additional pairs of jets. Therefore, the presence of four jets allows searches for signatures of multi-parton interactions in a region of phase-space where their effects may be maximised.

Photoproduction events with three jets in the final state have been measured at HERA [2] using variables defined in the scheme of Geer and Asakawa [3]. In the present analysis, four-jet observables, defined under this same scheme, have been measured. These variables span the multi-jet parameter space and have a relatively simple interpretation within the context of pQCD. In addition, they allow the three- and four-jet variables to be easily compared, although this is not the focus of the present paper. The variables are defined in the four-jet centre-of-mass frame. The two jets of lowest two-jet invariant mass are combined to form a single **pseudo-jet** system and the remaining three bodies are labelled 3, 4 and 5 in order of decreasing energy. The resulting pseudo-three-jet system is described by the

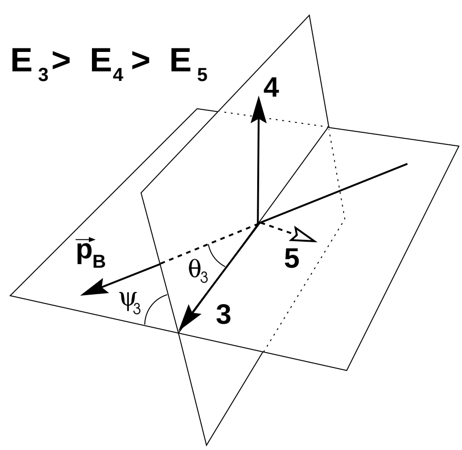

Fig. 1. The four-jet rest frame.

following dimensionless variables:

$$\cos\theta_3 = \frac{\boldsymbol{p}_3 \cdot \boldsymbol{p}_{\rm B}}{|\boldsymbol{p}_3||\boldsymbol{p}_{\rm B}|};\ \psi_3 = \frac{(\boldsymbol{p}_3 \times \boldsymbol{p}_{\rm B}) \cdot (\boldsymbol{p}_4 \times \boldsymbol{p}_5)}{|\boldsymbol{p}_3 \times \boldsymbol{p}_{\rm B}||\boldsymbol{p}_4 \times \boldsymbol{p}_5|};\ X_3 = \frac{2E_3}{m_{4\rm J}};\ X_4 = \frac{2E_4}{m_{4\rm J}}\,, \quad (2)$$

where $\boldsymbol{p}_{\rm B}$ is the average beam direction and $m_{4\rm J}$ is the invariant mass of the four-jet system. The four-jet rest frame is illustrated in figure 1.

2. Models

At lowest order, four-jet photoproduction is an $\mathcal{O}(\alpha\alpha_{\rm s}^3)$ process. There are no pQCD calculations of this order currently available for photoproduction. However, the measurement of multijet events also provides sensitive tests of parton shower extensions to fixed order theories. The HERWIG [4] and PYTHIA [5] Monte Carlo programs have been used for this purpose.

These contain only the two-to-two matrix elements but are able to produce final states with more than two jets through the initial and final state parton showers. These programs can also be used to investigate the sensitivity to the underlying event model. The **soft underlying event** (SUE) model of HERWIG is a simulation of a soft collisions between the proton remnant and the outgoing struck quark system. It is also possible to simulate the effects of multi-parton interactions. Both PYTHIA[1] and HERWIG have been used for this purpose. For HERWIG, the Jimmy package [6] was used.

3. Event selection

The analysis is based on HERA e^+p data collected during 1996-1997 and corresponds to an integrated luminosity of 38.7 pb^{-1}. Photoproduction events were selected with photon virtualities of $Q^2 < 1$ GeV^2 and photon-proton centre-of-mass energies in the range $134 < W_{\gamma p} < 277$ GeV. Jets were defined using the $k_{\rm T}$ algorithm [7] in the inclusive mode [8]. Events containing two jets with $E_{\rm T}^{\rm jet} > 6$ GeV and a further two jets with $E_{\rm T}^{\rm jet} > 5$ GeV were selected. All jets were required to have pseudorapidities in the range $|\eta^{\rm jet}| < 2.4$. The cut $X_3 < 0.95$ was also imposed to increase the amount of energy available to the lowest energy pseudo-jet. The requirement of high transverse energies for the four jets ensures that the process is calculable in pQCD. However, it also introduces a bias in the angular distributions by excluding jets produced close to the beam-line. The additional requirement that $|\cos\theta_3| < 0.8$ has been imposed to reduce this effect. Whilst, in principle, the presence of a hard scale allows comparisons with

[1] The simplest PYTHIA multi-parton interaction model was used, corresponding to MSTP(82)=1.

pQCD, non-perturbative effects can still play a role. In particular, the presence of an underlying event can have an important effect on the measured distributions.

In this analysis, two kinematic regions are defined. In the first, referred to as the **inclusive** sample, no additional cuts further to those already described were imposed. In the second, called the **high-mass** sample, a further demand of $m_{4\mathrm{J}} > 50$ GeV was required. This is expected to remove the majority of non-perturbative effects. Figure 2 shows the uncorrected $x_{\gamma;4\mathrm{J}}^{\mathrm{OBS}}$ distribution for the selected events. The data is compared to the Pythia and the Pythia+MPI Monte Carlo programs. In the inclusive sample, the data show a clear enhancement at low $x_{\gamma;4\mathrm{J}}^{\mathrm{OBS}}$ compared to the high-mass sample. Whilst the Pythia model fails to describe the data in the low $x_{\gamma;4\mathrm{J}}^{\mathrm{OBS}}$ region, the Pythia+MPI model gives a reasonable description over the whole range of this variable. For the high-mass sample, both models give an adequate description of the data. This suggests that multiple parton scattering has little effect in this kinematic region.

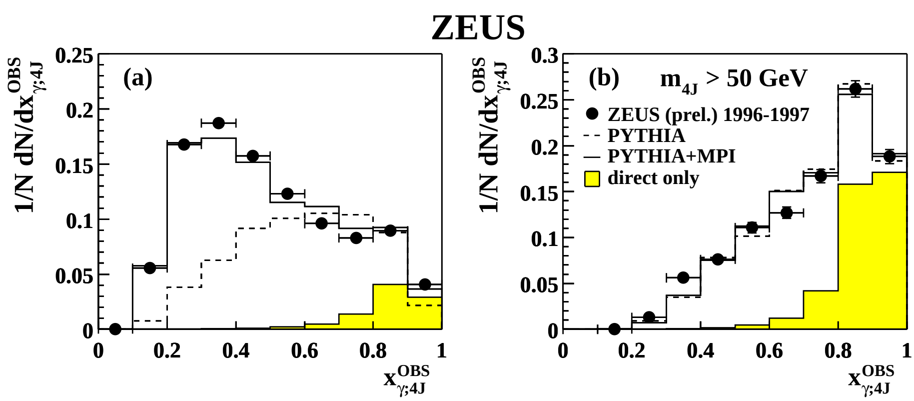

Fig. 2. The $x_{\gamma;4\mathrm{J}}^{\mathrm{OBS}}$ distribution for the: (a) inclusive and (b) high mass samples.

4. Results

The $\cos\theta_3$ distribution for the inclusive sample is shown in figure 3. The data show a relatively flat distribution with an enhancement in the forward direction compared to the backward. This is suggestive of a large contribution from low x_γ partons which tend to be boosted further forward compared to those at high x_γ (for the same fraction of the proton momentum entering the hard scatter). The Herwig Monte Carlo with *no* simulation of the underlying event shows a relatively symmetric distribution and is unable to describe the distribution of the data. The Herwig+SUE model is also disfavoured. In contrast, inclusion of multi-parton interactions leads to a significantly improved description of the data as illustrated by the Herwig+Jimmy and the Pythia+MPI models.

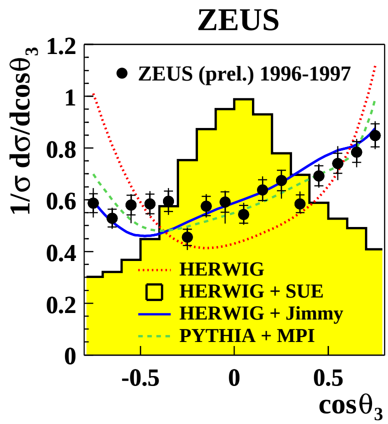

Fig. 3. The inclusive $\cos\theta_3$ distribution.

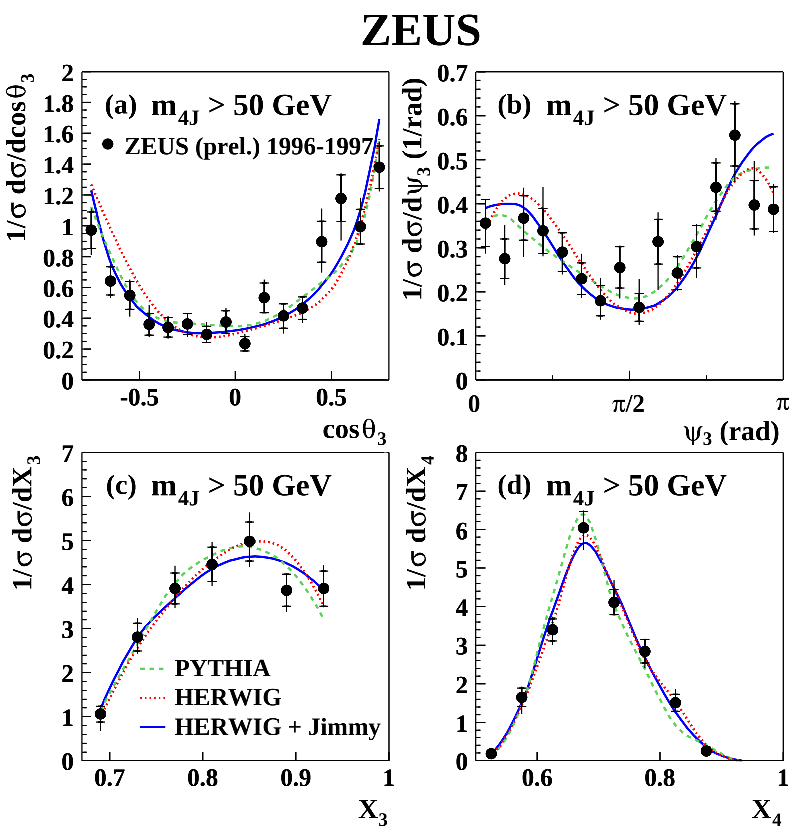

Fig. 4. The high-mass four-jet distributions.

The distribution of $\cos\theta_3$ for the high-mass sample is shown in figure 4(a). In this kinematic region, the data show a strong tendency for the highest energy pseudo-jet to lie close to the beam. There is little sensitivity in the Monte Carlo to the inclusion of multi-parton interactions and all models give a reasonable description of the data. The high-mass ψ_3 distribution is shown in figure 4(b). The depletion of the data at $\psi_3 \sim 0$ and π is due to constraints imposed by phase space. Taking this into account, the data show a tendency for the pseudo-three-jet plane to lie close to the plane containing the highest energy pseudo-jet and the beam. This is a consequence of colour coherence and was also observed in the three-jet distributions of [2]. The parton shower models, in which the phenomenon of colour coherence is implemented as angular ordering, are able to reproduce the trend of the data. The effects of angular ordering appear to be stronger in HERWIG than in PYTHIA. However, the data are not precise enough to discriminate between the models. The energy sharing variables, X_3 and X_4 are shown in figures 4(c) and 4(d). All models give a reasonable description of the data.

5. Conclusions

The angular distributions and energy fractions in four-jet photoproduction have been measured at HERA. To-date, this is the highest order photoproduction process that has been studied. Two kinematic regions have been defined based on a cut on $m_{4\mathrm{J}}$. In the inclusive sample, the distributions are sensitive to the underlying event model. Inclusion of multi-parton interactions, which would give a hard scattering contribution to the underlying event, is favoured. For the high-mass sample, the standard parton shower models with no simulation of multi-parton interactions are found to adequately describe the data. This indicates that this kinematic region is not significantly affected by long distance contributions from the underlying event and can be considered as a perturbative region suitable for comparison with pQCD calculations when they become available.

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