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Abstract

At HERA energies photoproduction of jets is sensitive to very high parton densities and so the probability of more than one hard partonic scattering occurring in a single photon-proton collision may be significant. This effect has been simulated using an eikonal prescription for the generation of the hard processes and the HERWIG parton showering and hadronization models. The first results on simulated jet cross sections indicate that the effect could be important when interpreting measurements of jet cross sections at HERA, and that the presence of a significant amount of multiple hard interactions could be directly confirmed by experiment.

1 Introduction

At the HERA accelerator in DESY, Hamburg, 820 GeV protons collide with 30 GeV electrons. The ep cross section is dominated by the exchange of almost real photons (*i.e.* with virtuality $Q^2 \approx 0$). At these energies, such γp interactions can produce jets of high transverse energy [1, 2]. The presence of a 'hard' energy scale means that perturbative QCD calculations of event properties can be confronted with experimental data.

At leading order (LO, $O(\alpha\alpha_s)$), two processes are responsible for jet production. The photon may interact directly with a parton in the proton or it may first fluctuate into an hadronic state. In the first case, known as the 'direct' contribution, the fraction x_γ of the photon's momentum entering into the hard process is 1. In the second case, known as the 'resolved' contribution, the photon acts as a source of partons, which then scatter off partons in the proton. In this case x_γ is less than 1. The presence of both these contributions has been confirmed at HERA [3].

With a typical cut on the jet transverse energy of around $E_T^{jet} > 6$ GeV, these events involve the parton distributions in the proton down to $x_p \approx 2 \times 10^{-3}$, while the parton distributions in

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the photon can be probed down as low as $x_\gamma \approx 10^{-2}$. At these low values of x, QCD predicts a rapid increase in parton densities. This can lead to an unphysical rise in perturbative QCD calculations of the total γp cross section with increasing centre-of-mass energy. A large number of small x partons contributing to jet production can also lead to a significant probability that there is more than one hard scatter per γp interaction, and this may provide the mechanism for taming rise in the QCD cross section [5]. This approach, which will be described briefly in the next section, has implications for the hadronic final state as well as for total cross sections. In order to study these effects with an eye to the direct confirmation of the presence of events with multiple hard interactions, this model has been incorporated into the hard process generation of HERWIG [6, 7, 8] for resolved photon interactions.

A further motivation for studying the implications of multiple hard interactions is related to the problem of the so-called 'soft underlying event'. In hadron-hadron collisions this is typically assumed to be a soft collision between the hadronic remnants, independent of and lying underneath any jets produced in a the hard scattering. This contribution is sometimes subtracted from measured jet cross sections. The resolved photoproduction part of the jet cross section at HERA is well modelled as a hadron-hadron collision, and some similar procedure may be expected to apply. However, for many of the collisons which produce jets within the detector acceptance the x_γ sampled is relatively large (recall that at leading order for the direct photon part it is 1). Thus the presence or otherwise of a soft underlying event might be expected to depend heavily upon the hard process itself, and to perhaps be absent for the direct contribution. These features are all true of multiple hard interaction models. The model implemented in PYTHIA [9, 10] has already had some success in describing the jet pedestal energies in photoproduction events at HERA [11].

Thus multiple parton scattering is expected to affect jet rates in two ways. The average number of jets per event should be increased when partons from secondary hard scatters are of sufficiently high p_T to give jets in their own right, and lower p_T secondary scatters produce extra transverse energy in the event which can contribute to the pedestal energy underneath other jets in the event. Thus multiple scattering can influence jet cross sections even when no parton from the secondary scatters is of high enough p_T to produce an observable jet. In fact, by boosting the transverse energy of jets in this way, multiple scattering can lead to an increase in jet cross section above a certain E_T^{jet} cut, even though the total γp cross section is reduced.

2 Model and Implementation

In the model implemented in HERWIG, the number of hard scatters arises from the simple probability theory formula,

$$\#\text{events} = \#\text{trials} \times \text{event probability per trial.}$$

In the case of a proton colliding with a resolved photon at an impact parameter b, the 'number of trials' is the product of the number densities of the partons in the overlapping regions of the proton and the photon;

$$\#\text{trials} = \int d^2b' \, n_{i/\gamma}(b', x_\gamma) n_{j/p}(b' - b, x_p) = A(b) \, n_{i/\gamma}(x_\gamma) n_{j/p}(x_p). \tag{1}$$

where it is assumed that the x and b dependence of the parton densities factorize, and $A(b)$ is defined as the area overlap function. The '#events' is the multiplicity of final state jet pairs produced per resolved γp interaction. The 'event probability per trial' may be written as $d\hat{\sigma}_{ij}/(P_{\rm res}\sigma_H(s))$ where $\sigma_H(s)$ is the γp cross section for the production of one or more jet pairs and $d\hat{\sigma}_{ij}$ is the parton-parton cross section in this x interval. $P_{\rm res}$ is the probability that the photon interacts hadronically rather than directly, and is proportional to $\alpha_{\rm em}$.

The b dependence of the parton density is assumed to be given by the electromagnetic form factor of the parent particle. By normalizing the integral of the 'area overlap' function, $A(b)$, to unity we can identify

$$A(b)d^2b\frac{\sigma_H^{\rm inc}(s)}{P_{\rm res}} = \chi(b,s)d^2b \tag{2}$$

with the mean number of hard scatters occuring in the element d^2b of impact parameter space (per resolved photon interaction). This defines the 'eikonal' function, $\chi(b,s)$. Poisson statistics then allows the probability for m (and only m) jet pairs to be produced to be written:

$$p_m = \frac{[\chi(b,s)]^m}{m!}\exp[-\chi(b,s)]. \tag{3}$$

To select the fraction of the electron energy carried by the (on-shell and colinear) photon we use the distribution of ref.[12], i.e.

$$f_{\gamma/e}(z) = \frac{\alpha_{\rm em}}{2\pi}\left\{\frac{1+(1-z)^2}{z}\ln\frac{E_e^2(1-z)^2\theta_c^2}{m_e^2 z} - \frac{2(1-z)}{z}\right\} \tag{4}$$

where θ_c is the maximum angle of the final state electron in the lab frame. In the results shown here $\theta_c = 4^o$.

Having selected the γp CM energy, the equation 3 is used to decide upon the number of scatters the event is to have. Once this is decided the specification of the hard scatter proceeds as in the standard hard scattering Monte Carlos, each hard scatter being decoupled from the others. The parton showering and hadronization is carried out using HERWIG. At present the colour connections for the highest p_T scatter are complete, whereas lower p_T hard scatters are assumed to be all of the subprocess $gg \to gg$ and the final state gluons are connected only to each other. This has the consequence that initial state radiation is generated only for the hard scatter with the largest p_T. Thus in the remnant regions the simulation may not be satisfactory. However, for the results shown here the effect of this approximation is not expected to be large.

The assumption of decoupled scattering is expected to break down for large x_γ and x_p. At high x we are not in the high parton density regime where the use of Poisson statistics is expected to be valid, and in addition there is the possibility of violating energy-momentum conservation by generating i scatters such that $\sum_1^i x_i > 1$. In the present model we deal with this by approximating the effects of these correlations by a simple step function such that the probability of generating a further scatter with $x = x_i$ which would lead to $\sum_1^i x_i > 1$ is zero. More detailed discussion of the model and its implementation can be found in reference [13].

$\sqrt{\hat{s}}$ (GeV)	$\langle n_H \rangle$	$\sigma_H(s)$ (μb)
26	1.0	0.57
39	1.01	1.73
58	1.02	4.12
87	1.03	8.64
131	1.07	16.1
197	1.12	28.5
296	1.21	46.8

Table 1: Mean multiplicities and cross sections for resolved photon events.

3 Results and Discussion

Using this version of the simulation, the effects of multiple scattering are studied using the following choices for the various parameters of the model, structure functions used and kinematic cuts. $P_{\rm res} = 1/300$, which is motivated by assuming that the resolved photon interacts dominantly like a ρ-meson. The minimum transverse momentum of a hard scatter, $p_{\rm Tmin} = 2.5$ GeV. For the structure functions, MRS D- for the proton [14] and GRV for the photon [15] are used. A cut on the γp CM energy was made, i.e. 114 GeV $\leq \sqrt{s} \leq$ 265 GeV, similar to those usually made by the experiments. Events were generated both with and without multiple interactions. Events generated without multiple interactions are in good agreement with those generated by the unmodified HERWIG.

Table 1 shows the variation of the mean multiplicity of hard scatters ($\langle n_H \rangle$) with γp CM energy, for events with at least one hard scatter. Also shown is the total hard scattering cross section, $\sigma_H(s)$. As expected, we see a significant rate for multiple interactions over the HERA range. The hard cross section for $\sqrt{\hat{s}} \approx 200$ GeV represents around 20% of the total γp cross section.

In order to make our study as realistic as possible, we have performed jet finding on the hadronic final state using a cone algorithm [16]. The cone radius used is $R = 1$ (as has been used by both HERA experiments so far), and jets have $E_T \geq 6$ GeV and pseudorapidity $-2 \leq \eta = -\ln(\tan\theta/2) \leq 2$. These cuts place our jets well within the region observable by the HERA detectors. In figure 1a we show the η distribution for inclusive jets. Inclusive jet cross sections are only affected by the increase in pedestal energy, and a small enhancement in the jet rate is seen around $\eta^{jet} = 1$. Higher jet multiplicity rates are expected to provide more sensitivity to the effects of multiple scattering. In figure 1b and c we show the η^{jet} and E_T^{jet} distributions for jets in dijet events. An enhancement at high η^{jet} and at low E_T^{jet} is seen.

For two-to-two parton scattering (*i.e.* leading order QCD without any additional effects included), energy and momentum conservation gives

$$x_\gamma^{LO} = \frac{\sum_{\rm partons} E_T^{\rm parton} e^{-\eta^{\rm parton}}}{2yE_e} \tag{5}$$

$$x_p^{LO} = \frac{\sum_{\rm partons} E_T^{\rm parton} e^{-\eta^{\rm parton}}}{2E_\gamma}. \tag{6}$$

The proton direction defines the positive z axis. E_γ and E_p are the initial photon and proton energies and the sum is over the two final state partons. For direct photon events, $x_\gamma^{LO} = 1$. Jets,

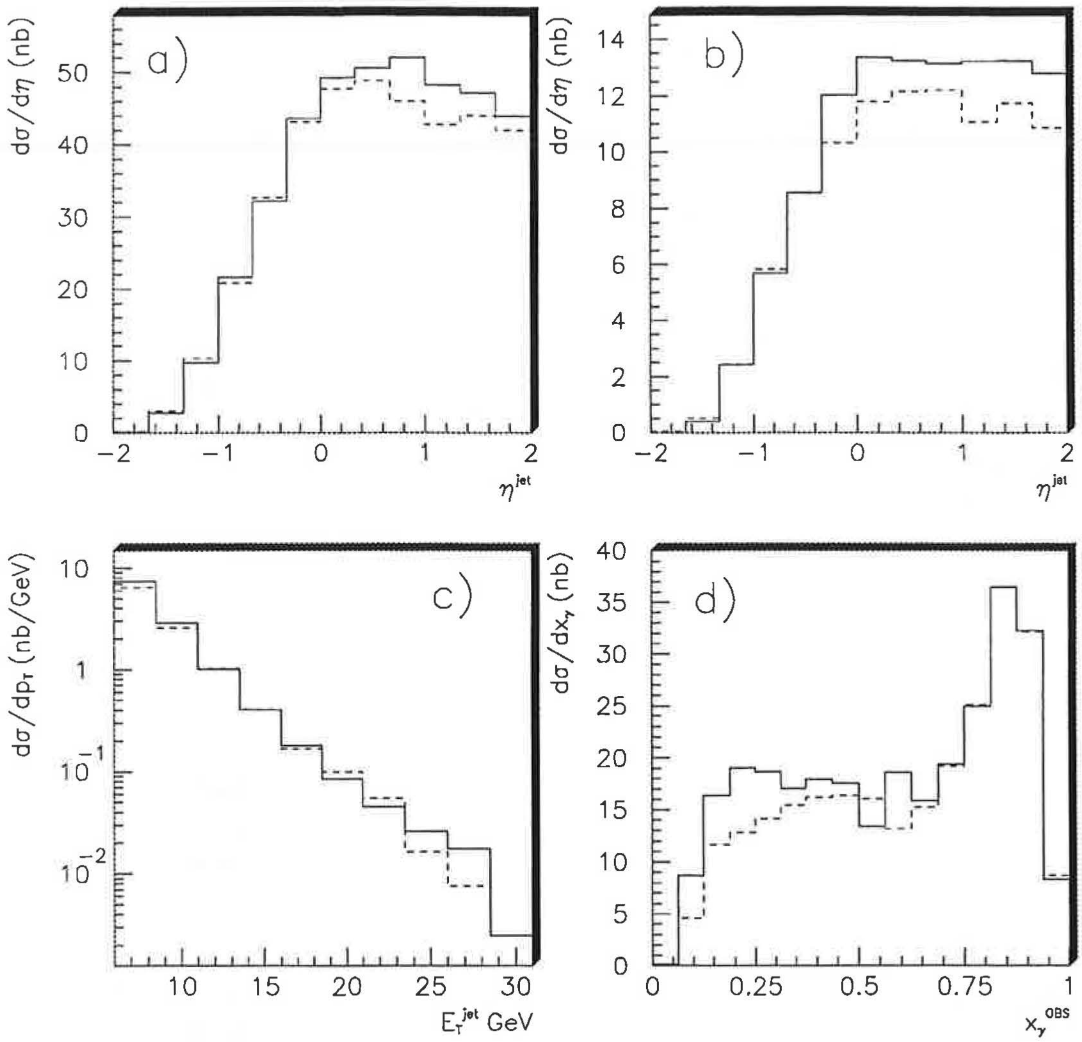

Figure 1: a) η^{jet} distribution for inclusive jets b) η^{jet} distribution for dijets c) E_T^{jet} distribution for dijets, d) x_γ^{OBS} distribution for dijets.
The solid lines show the distributions when multiple scattering is included, the dashed lines show the distributions when no multiple scattering is allowed. The direct contribution was generated using HERWIG.

as opposed to partons, are observed in photoproduction events, x_γ^{LO} and x_p^{LO} are approximated by x_γ^{OBS} and x_p^{OBS}, where

$$x_\gamma^{OBS} = \frac{\sum_{\text{jets}} E_T^{\text{jet}} e^{-\eta^{\text{jet}}}}{2yE_e} \tag{7}$$

$$x_p^{OBS} = \frac{\sum_{\text{jets}} E_T^{\text{jet}} e^{-\eta^{\text{jet}}}}{2E_\gamma}. \tag{8}$$

The sum runs over the two highest p_T jets in the event. The relationship between x_γ^{LO} and x_γ^{OBS} depends upon how well the hadronic final state is described by simple LO QCD. In fig 1d we show the x_γ^{OBS} distribution. The direct contribution generated using HERWIG is included. The inclusion of multiple scattering has a significant effect on the lower x_γ region.

4 Conclusions

A simulation of multiple parton scattering in photon-proton interactions has been interfaced to the general HERWIG Monte Carlo program. For reasonable experimental cuts, the results indicate that the effects of multiple parton interactions on hadronic final states could be important, leading to significant changes in inclusive and dijet cross sections. This would complicate the extraction of parton distributions from jet cross sections. In addition, multiple parton processes provide a means of extending perturbative QCD to describe part of the canonical 'soft underlying event'. The enhancement in multijet rates could provide a means of unambiguously discovering or ruling out multiple interaction models in the near future.

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