

# Multiple Interactions in H1 and ZEUS

Tim Namssoo<sup>1</sup> on behalf of the H1 and ZEUS collaborations

<sup>1</sup>DESY

## Abstract

Multi-parton interactions (MPIs) and the underlying event are believed to contribute to the hadronic energy flow in hadron-hadron collisions and possibly even lepton-hadron collisions. Two measurements are presented here, each of which may be sensitive to MPIs. Both were conducted at the HERA electron-proton collider: a three- and four-jet analysis in photoproduction and a mini-jet analysis in deep-inelastic scattering (DIS) made by the ZEUS and H1 collaborations, respectively.

## 1 Introduction

The underlying event is a generic term for all energy flow not associated with the primary process, however, defining what constitutes the primary process is non-trivial. As a working definition, the primary process may be thought of as the idealised parton-parton interactions that would occur if the beams were simply sources of quasi-free partons. The primary interactions would be completely insensitive to the incoming particles (beyond their PDFs) and beam remnants. The underlying event, then, is everything else that can affect the primary process and contributes to the event. Thus, effects like secondary remnant-remnant interactions and multiple-scattering, as a primary parton re-scatters off the remnants, may contribute to the underlying event. Both contributions will be referred to as multi-parton interactions (MPIs).

Remnant-remnant interactions are only possible following a hadron-hadron-like collision since it is the composite nature of hadrons that leads to there being remnants. Multiple-scattering, however, only requires one of the incoming particles to be a hadron so may also be present in lepton-hadron interactions. Remnant-remnant interactions, in particular, may occur at a scale hard enough to generate additional jets and so constitute a potential source of multi-jets in the final state.

The electron-proton ( $ep$ ) collisions at HERA [1], with a centre-of-mass energy,  $\sqrt{s} = 318$  GeV, may be mediated by either direct or resolved photons. In a direct collision, the photon interacts as a point-like particle whereas in a resolved event, the photon fluctuates into a partonic system prior to interacting. The four-vector of the exchanged photon is denoted by  $q$ . In events with a virtuality,  $Q^2 \leq 1$  GeV<sup>2</sup>, where  $Q^2 = -q^2$ , which is a positive quantity at HERA, the photon is long-lived with respect to the characteristic interaction time. Such events are referred to as photoproduction events and the exchanged photon may fluctuate into a partonic system. In higher  $Q^2$ , deep-inelastic scattering (DIS) collisions, the resolved behaviour of the photon is suppressed and direct interactions dominate. Thus, both remnant-remnant and multiple-scattering may be present in a photoproduction sample, whereas the former is expected to be suppressed with increasing  $Q^2$ . The underlying event has been studied before at HERA in photoproduction collisions [2] but not in DIS.

# ZEUS

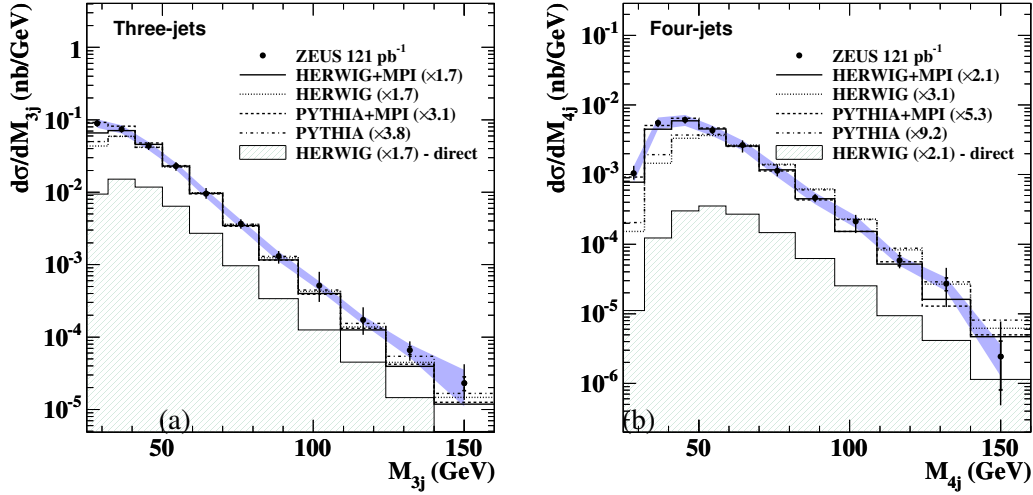


Fig. 1: Measured cross section as a function of (a)  $M_{3j}$  and (b)  $M_{4j}$  (solid circles). The inner and outer error bars and the shaded band represent the statistical, the statistical plus systematic and the calorimeter energy scale uncertainties, respectively.

## 2 Three- and four-jet events in photoproduction

### 2.1 Introduction

Multi-jet events may be produced by primary processes beyond leading order (LO) in the strong coupling constant,  $\alpha_s$ , or, as described above, by the overlay of a hard remnant-remnant interaction onto a LO primary process. Moreover, even soft MPIs may affect the distribution of multi-jet events by adding to or redistributing the energy flow generated by a beyond-LO primary process. More specifically, the lowest order primary process capable of generating an  $n$ -jet direct photoproduction event, in the absence of a hard MPI, is  $\mathcal{O}(\alpha\alpha_s^{n-1})$ , where  $\alpha$  is the fine structure constant.

The multi-jet analysis by the ZEUS collaboration looked at photoproduction events ( $Q^2 < 1 \text{ GeV}^2$ ) that contained at least three (or four) jets with transverse energies,  $E_T^{\text{jet}} \geq 6 \text{ GeV}$ , in the pseudorapidity range,  $|\eta^{\text{jet}}| \leq 2.4$ , and in the kinematic region  $0.2 \leq y \leq 0.85$ , where  $y$  is the inelasticity. These events were studied in two regions defined in terms of invariant  $n$ -jet mass,  $M_{nj}$ , as  $25 \leq M_{nj} < 50 \text{ GeV}$  and  $M_{nj} \geq 50 \text{ GeV}$ , and the cross sections were measured differentially.

To assess the influence of MPIs in each of the four samples, that will be referred to as the three- or four-jet, high- or low-mass samples, the data were compared to predictions from two Monte Carlo (MC) programs, HERWIG 6.505 [3] and PYTHIA 6.206 [4] both with and without simulated MPIs. The MPIs in HERWIG were simulated using a separate program called JIMMY 4.0 [5], which is an impact parameter model. The MPIs in PYTHIA were generated according to the so-called ‘‘simple model’’ [4], available via an internal PYTHIA routine.

In addition, the three-jet cross sections were compared to the  $\mathcal{O}(\alpha_s^2)$  perturbative quantum chromodynamics (pQCD) prediction by Klasen, Kleinwort and Kramer [6]. This was, at the time, the highest order prediction available in photoproduction. It is only LO for the three-jet process and so could not be compared with the four-jet data.

## ZEUS

### 2.2 Results

The three- and four-jet cross sections are given as a function of  $M_{nj}$  in Fig. 1. In general, both cross sections decrease exponentially with increasing  $M_{nj}$ . Also shown in Fig. 1 are the HERWIG and PYTHIA predictions with and without MPIs, normalised to the high-mass region ( $M_{nj} \geq 50$  GeV). Both models without MPIs fail to describe the  $M_{nj}$  dependence of the cross section and significantly underestimate the low mass data. The discrepancy is larger in the four-jet case. With the inclusion of MPIs, both scaled MC predictions give a reasonably good description of the data over the full  $M_{nj}$  ranges.

It is noted that the predicted influence of MPIs in the samples is highly sensitive to the tunable parameters within the models. The PYTHIA model was run using its default setting whereas the JIMMY model was tuned to the data shown [7].

Figure 2 shows an  $\mathcal{O}(\alpha_s^2)$  prediction, corrected for hadronisation effects and MPIs, compared to the measured  $d\sigma/dM_{3j}$  cross section. The hadronisation and MPI corrections, including their estimated uncertainties, are given in Fig. 2b. The hadronisation corrections are constant in  $M_{3j}$ , while the MPI corrections increase significantly towards low  $M_{3j}$ . The theoretical uncertainties on both the MPI corrections and the pQCD predictions are large. The magnitude and shape of the calculation is consistent with the data within the large theoretical uncertainties. This is best seen in the data over theory ratio shown in Fig. 2c. The level of consistency between data and theory would be far worse at low  $M_{3j}$  if it were not for the large MPI corrections.

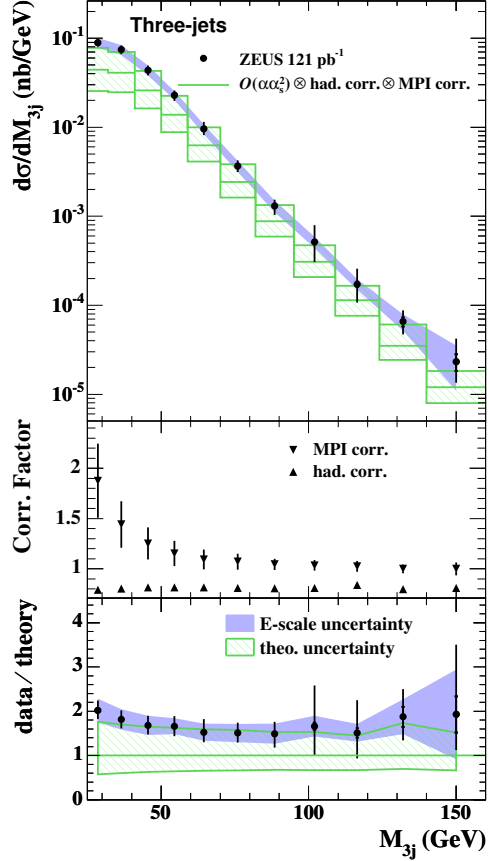


Fig. 2: (a) Measured three-jet cross section as a function of  $M_{3j}$  in compared with an  $\mathcal{O}(\alpha_s^2)$  prediction, corrected for hadronisation and MPI effects. (b) The hadronisation and MPI corrections as a function of  $M_{3j}$ . (c) The ratio of the  $M_{3j}$  cross section divided by theory. The theoretical uncertainty is represented by the dashed bands.

### 3 Mini-jets in DIS

#### 3.1 Introduction

Although the presence of MPIs in photoproduction is far from universally accepted, their presence in DIS is even less so.

Investigation at HERA into low- $x$  hard scattering, where  $x$  is the Björken scaling variable, identifies the large contribution from diffractive events. Such events are described, in part, by the exchange of pomerons. In a pQCD framework, the pomerons may be described by sums of gluon ladders. With this description, applying the AKG cutting rules [8] (slicing through multiple ladders, i.e. pomerons) highlights the potential importance of MPIs in DIS [9]. It is, therefore, interesting to see if evidence of such a phenomenon can be identified within the data.

The H1 collaboration looked at DIS events with  $5 \leq Q^2 \leq 100 \text{ GeV}^2$  and  $0.1 \leq y \leq 0.7$ , that contained at least one jet, defined using the  $k_T$  clustering algorithm [10] in the hadronic centre-of-mass (HCM) frame, with  $E_T^{\text{jet}} \geq 5 \text{ GeV}$  in both the HCM and laboratory frames. Four regions in azimuthal angle,  $\phi$ , were then defined with respect to the highest  $E_T^{\text{jet}}$  jet in the HCM frame, as depicted in Fig. 3. This “leading-jet” was required to have  $-1.7 \leq \eta^{\text{jet}} \leq 2.79$  in the laboratory frame and the hadronic system was required to have an invariant mass,  $W \geq 200 \text{ GeV}$ . Finally, the average multiplicity,  $\langle N_{\text{minijet}} \rangle$ , of so-called mini-jets, with  $E_T^{\text{mini}} \geq 3 \text{ GeV}$ , was measured in each of the four  $\phi$  regions. A possible signature of MPIs would be an inflated value of  $\langle N_{\text{minijet}} \rangle$ , most noticeably, in the less populated, high- and low-activity transverse regions.

#### 3.2 Results

To ascertain whether the measured values of  $\langle N_{\text{minijet}} \rangle$  were indeed large, the results were compared to the predictions of three MC models, RAPGAP [11], ARIADNE, based on the colour dipole model (CDM) [12], and PYTHIA. The latter model was ran with and without simulated MPIs, whereas the previous two did not include MPIs. These data can be seen in Fig. 4 as a function of the transverse momentum of the leading-jet in the HCM frame, labelled  $P_{T,1j}^*$  on the figure, and in three  $Q^2$  bins.

The toward-region data are reasonably well described by all four MC models. The RAPGAP and PYTHIA models marginally underestimate  $\langle N_{\text{minijet}} \rangle$  at low- $P_{T,1j}^*$  in the lowest  $Q^2$  bin. The PYTHIA description is improved by the introduction of MPIs.

The away-region is well described by CDM and RAPGAP models but PYTHIA significantly over-estimates  $\langle N_{\text{minijet}} \rangle$  at low- $P_{T,1j}^*$  in all three  $Q^2$  bins, although more so at high- $Q^2$ . The PYTHIA model predicts the away-region to be the least sensitive to MPIs.

The  $\langle N_{\text{minijet}} \rangle$  values, in the low- and high-activity regions, tend to be underestimated by all of the models that do not include MPIs, in all  $P_{T,1j}^*$  and  $Q^2$  bins. The underestimation

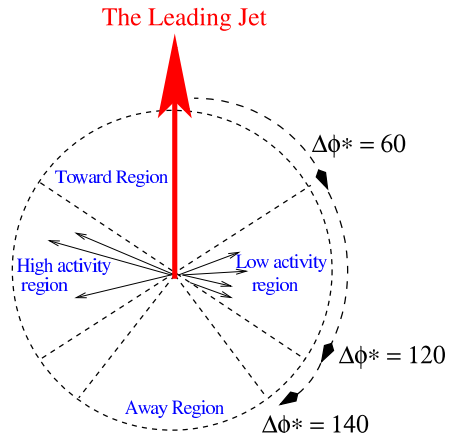


Fig. 3: Definition of the four azimuthal regions used in the mini-jet analysis in DIS.

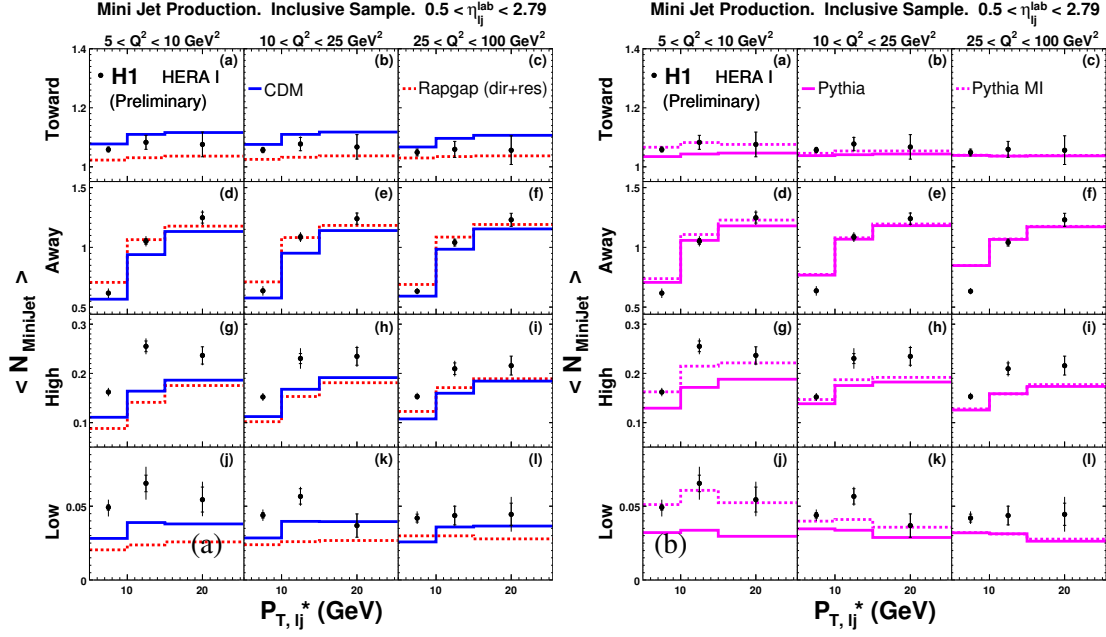


Fig. 4: The  $\langle N_{\text{miniJet}} \rangle$  data, in all four azimuthal regions, as a function of  $P_{T,1j}^*$  in three  $Q^2$  bins. Also shown are the predictions from four MC models.

of the data is more pronounced at low- $Q^2$  and low- $P_{T,1j}^*$ . The introduction of MPIs into the PYTHIA model certainly aids the description of the low- $Q^2$  data, however, the affect of the MPIs diminishes rapidly with  $Q^2$  and the high- $Q^2$  data is still underestimated.

Conclusions, similar to those made using the PYTHIA model, were drawn from comparisons with the HERWIG model (not shown). The analysis was also performed on a subsample of the data in which a second jet, with  $P_{T,1j}^* \geq 5 \text{ GeV}$ , was observed in the away-region. Again, the results were similar and not shown.

#### 4 Conclusions

Effects have been observed in both photoproduction and DIS  $ep$  data that are suggestive of an MPI contribution. More specifically, the ZEUS collaboration observed that the three- and four-jet photoproduction cross sections are larger at low  $M_{3j(4j)}$  than is predicted by two parton shower MC models, and in the three-jet case, a LO pQCD calculation. This behavior is expected if MPIs contribute to the data and two independent MPI models correctly account for the differences between the MC without MPIs and the data. However, the prediction of MPI models are highly tunable and the accuracy of the description of multi-jet final states by LO matrix element plus parton shower MC models is not assured.

The H1 collaboration have observed a larger average mini-jet multiplicity in DIS events than was predicted by both parton shower and colour dipole model MC models. In this case, MPIs, as predicted by the PYTHIA model, improved the description of the data at low- $Q^2$ , although were not predicted to influence the data at higher virtualities.

## References

- [1] G. Voss and B. Wiik, *Ann. Rev. Nucl. Part. Sci.* **44**, 413 (1994).
- [2] ZEUS Collaboration, M. Derrick *et al.*, *Phys. Lett.* **B348**, 665 (1995);  
H1 Collaboration, S. Aid *et al.*, *Z. Phys.* **C70**, 17 (1996).
- [3] G. Corcella *et al.*, HERWIG 6.5 Manual, hep-ph/0011363 (2000);  
G. Corcella *et al.*, HERWIG 6.5 Release Note, hep-ph/0210213 (2001);  
G. Marchesini *et al.*, *Comput. Phys. Commun.* **67**, 465 (1992).
- [4] T. Sjöstrand *et al.*, PYTHIA 6.206 Manual, hep-ph/0108264 (2002);  
T. Sjöstrand *et al.*, *Comput. Phys. Commun.* **135**, 238 (2001).
- [5] J. Butterworth, J. Forshaw, and M. Seymour, *Z. Phys.* **C72**, 673 (1996).
- [6] M. Klasen, T. Kleinwort, and G. Kramer, *Z. Phys. Rev.-e* **C1** (1998);  
M. Klasen, *Eur. Phys. J.* **C7**, 225 (1999).
- [7] T. Namsoo, PhD. Thesis, University of Bristol, UK. (unpublished) (2006).
- [8] V. Abramovski, V. Gribov, and O. Kancheli, *Yad. Fiz.* **18**, 595 (1973).
- [9] J. Bartels, M. Salvadore, and G. Vacca, *Eur. Phys. J.* **C42**, 53 (2005).
- [10] S. Catani *et al.*, *Nucl. Phys.* **C406**, 187 (1993).
- [11] H. Jung, *Comput. Phys. Commun.* **86**, 147 (1995).
- [12] L. Lönnblad, *Comput. Phys. Commun.* **71**, 15 (1992).