THREE- AND FOUR-JET FINAL STATES IN PHOTOPRODUCTION AT HERA

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Three- and four-jet final states have been measured in photoproduction at HERA, using the ZEUS detector and an integrated luminosity of 121 pb^{-1}. The events have been studied in a semi-inclusive, $M_{nj} \geq 25$ GeV, and high-mass region, $M_{nj} \geq 50$ GeV, where M_{nj} is the invariant mass of the n-jet system. The three-jet cross sections have been compared to an $\mathcal{O}(\alpha\alpha_s^2)$ perturbative QCD calculation. The calculation describes the high-mass region reasonably well but underestimates it for $M_{3j} < 50$ GeV. In addition, the three- and four-jet cross sections have been compared with two leading-logarithmic Monte Carlo models that rely on parton showers to generate events with jet-multiplicities greater than two. In certain phase space regions the Monte Carlo simulations poorly describe the data. It is shown that including multi-parton interactions in the simulations can generally aid the description although this is highly tune dependent.

1. Introduction

Multi-jet events are manifestly produced by processes beyond leading order (LO) in the strong coupling constant, α_s. The perturbative quantum chromodynamics (pQCD), tree-level description of an n-jet direct photoproduction event is $\mathcal{O}(\alpha\alpha_s^{n-1})$, where α is the fine structure constant. Multi-jet states, therefore, provide a potentially sensitive test of higher-order pQCD calculations as well as higher-order approximations such as parton-showers.

In photoproduction (γp), the underlying-event may be produced in part from multi-parton interactions (MPIs). These can occur at HERA in the hadron-hadron-like resolved category of collisions, in which the quasi-real photon fluctuates into a system of coloured partons. In an MPI, more than one pair of partons from the incoming hadrons interact. A schematic of an MPI is shown in Fig. 1. The secondary scatters generate additional hadronic energy flow in the event.

2. Definition of the cross section

Photoproduction events were studied in a kinematic region given by $Q^2 < 1$ GeV^2, where Q^2 is the virtuality of the exchanged boson, and with a photon-proton centre-of-mass energy, $W_{\gamma\text{p}}$, in the range 142 to 293 GeV. Each event is required to have at least three or four jets with $|\eta^{\text{jet}}| \leq 2.4$, such that the two highest E_T^{jet} jets have $E_T^{\text{jet}} \geq 7$ GeV and any additional jets have $E_T^{\text{jet}} \geq 5$ GeV. The jets were reconstructed by applying the k_T cluster algorithm[1] in the longitudinally invariant inclusive mode[2] to the final-state hadrons. The jets were defined to be massless. In addition, it was required that $\cos(\theta_{3(\prime)}) \leq 0.95$ and $X_{3(\prime)} \leq 0.95$ to remove regions of phase-space heavily depleted by the E_T^{jet} and η^{jet} selection criteria[a]. In both the three- and four-jet analyses, two mass regions were studied. The first will be referred to as the semi-inclusive-mass region and has $M_{\text{nj}} \geq 25$ GeV and the second, the high-mass region, with $M_{\text{nj}} \geq 50$ GeV.

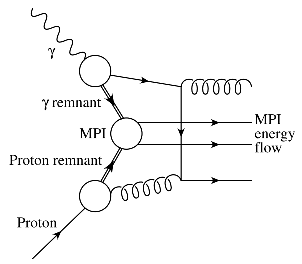

Figure 1. A multi-parton interaction occurring in a resolved photoproduction event.

3. Comparing the cross sections with Monte Carlo models

The cross sections were compared with HERWIG version 6.505[4] and PYTHIA version 6.206[5]. In HERWIG, the MPIs were simulated using JIMMY 4.0[6]. The PYTHIA MPIs were generated using the simple model[5]. The parameters used for the simple model were taken from a tune to generic collider data. In contrast, the JIMMY model was tuned to the data presented here. Thus, the two generators were, in this respect, treated differently and at no point will it be claimed that one MPI model is better than the other. The point of interest is to see whether the MC with the MPI model tuned to generic collider data describes the γp multi-jet data and if not, whether a model could be tuned to give a resonable description.

Both MC models underestimated the magnitude of the cross sections, as is expected of a LO model. To better compare the shape of the cross sections the MC predictions were scaled. The magnitude of the scaling factor was calculated as the ratio of the measured cross section above $M_{nj} \geq 70$ GeV, where MPIs are expected to be negligable, divided by that predicted by

[a]See[3] for definitions of $\cos(\theta_{3(\prime)})$ and $X_{3(\prime)}$.

each MC model without MPIs. The scaling factors applied to the HERWIG and PYTHIA three-jet predictions were 1.8 and 4.0, respectively. The four-jet predictions were scaled by 2.4 and 7.4 for HERWIG and PYTHIA, respectively.

Figure 2 shows the three- and four-jet cross sections measured differentially in $M_{\rm nj}$. In general, both the three- and four-jet cross sections decrease exponentially with increasing $M_{\rm nj}$, although both deviate from this behaviour in the lowest mass region due to a reduction in the available phase-space as a result of the $E_T^{\rm jet}$ criteria. It is more marked in the four-jet case due to the additional $E_T^{\rm jet}$ constraint imposed on the fourth jet.

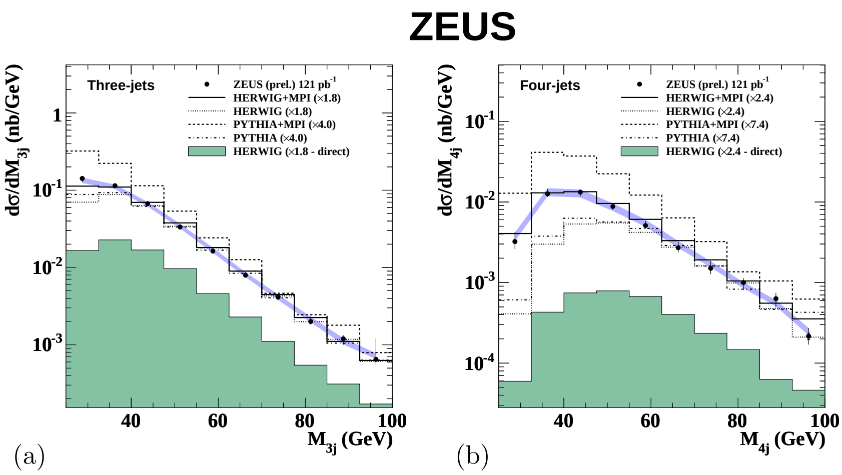

Figure 2. The M_{3j} cross section in the semi-inclusive mass, three-jet sample (a) and the M_{4j} cross section in the semi-inclusive mass, four-jet sample (b). The calorimeter energy scale uncertainty is represented by the shaded band. Shown also are predictions from HERWIG and PYTHIA, with and without MPIs, as well as the HERWIG direct component. Each MC cross section has been scaled by the amount indicated in the legend.

Included in Fig. 2 are the predictions of both HERWIG and PYTHIA without MPIs. Both MC models describe the $d\sigma/dM_{\rm nj}$ cross sections well at high $M_{\rm nj}$ but significantly underestimate it at lower values. In the three-jet case, the MC prediction deviates from the data below $M_{\rm 3j} = 45 \pm 5$ GeV, whereas the four-jet cross section is underestimated for $M_{\rm 4j} < 55 \pm 5$ GeV. Clearly, either the processes modelled by the MC are done so incorrectly at low $M_{\rm nj}$ or there is something missing from the simulation.

In the low $M_{\rm nj}$ region it is possible that MPIs contribute. Shown also in Fig. 2 are the predictions of the two MC models with MPIs included. The PYTHIA prediction, tuned to generic collider data, is seen to grossly overestimate the cross section. The HERWIG prediction, however, that had been tuned to the data presented here, gives a good description.

By tuning the HERWIG MPI model to the data, it is implicitly assummed that the other elements of the model, for instance, the jet forming parton showers, are correctly simulated. The good description at high $M_{\rm nj}$ gives weight to this assumption but it is possible that the accuracy of the model deteriorates with $M_{\rm nj}$. If this is the case, tuning to the data will hide these inadequecies. What is shown, however, is that MPIs are expected to contribute in a manner that aids the MC descriptions and moreover, can be tuned so that the description is good. A caveat to the introduction of MPIs, which is not shown here and conflicts with the MPI assumption, is that the description of the $d\sigma/dy$ cross section deteriorates. In particular, MPIs cause the MC models to overestimate the cross scetion at high y.

4. Comparing the cross sections with $\mathcal{O}(\alpha\alpha_s^2)$ pQCD

The three-jet differential cross sections were compared with a $\mathcal{O}(\alpha\alpha_s^2)$ pQCD calculation[7]. The calculation is LO for this process. The calculation was convoluted with hadronisation and MPI corrections. These were obtained using HERWIG and PYTHIA. The hadronisation corrections, $\mathcal{C}_{\rm had}$, were calculated by taking the bin-by-bin ratio of the MC cross sections at the hadron- and parton-shower-levels, $\mathcal{C}_{\rm had} = \sigma_{\rm HL}/\sigma_{\rm PSL}$. To obtain $\sigma_{\rm PSL}$, the jet finder was run over all of the partons leaving the parton-shower, prior to hadronisation. The MPI corrections, $\mathcal{C}_{\rm MPI}$, were calculated by taking the bin-by-bin ratio of the HERWIG hadron-level cross sections, with and without MPIs, $\mathcal{C}_{\rm MPI} = \sigma_{\rm HL}^{\rm MPI}/\sigma_{\rm HL}^{\rm noMPI}$. The theoretical uncertainties were large, as is expected from a LO calculation, indicating the need for additional orders. However, the calculation largely agreed with the measured $d\sigma/dM_{\rm 3j}$ cross section at $M_{\rm 3j} > 50$ GeV but underestimated it in the lower $M_{\rm 3j}$ region. It is likely that this descrepincy is due to the absence of higher-orders in the LO calculation, which are expected to become more influential in the low mass region.

References

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