JET PRODUCTION AT HERA

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1. Introduction

Both H1 and ZEUS have recently presented new results on jet production using the high statistics and well understood data set from the 98/2000 running period of HERA at a centre-of-mass energy of $\sqrt{s} = 319$ GeV. Of particular interest are: inclusive jet production in high Q DIS [1,2], multi-jet production in high Q DIS [3,4] and high E_t dijet production in photoproduction [5]. The large scales involved in these processes (Q or jet E_t) provide a safe region of phase space for a comparison to DGLAP based NLO QCD predictions [6,7,8], the extraction of the strong coupling constant α_s and for inclusion into fits to extract the proton structure[a]. This paper will concentrate on a discussion of the uncertainties contributing to the experimental and theoretical errors on the jet cross sections.

The Breit frame is the preferred frame to measure jet production in DIS. In this frame contributions from the Born level and jets induced by the beam remnant are suppressed. In photoproduction the laboratory frame is used. Jets are reconstructed using the $k_\perp$ cluster algorithm in the longitudinally invariant inclusive mode.

2. Common Experimental Issues

The experimental data are corrected for limited detector acceptance and resolution and, in DIS, for QED radiative effects. Monte Carlo simulations are used to calculate these correction factors. In DIS the programs

[a]For a discussion on the last two issues see the contribution in these proceedings by Amanda Cooper-Sarkar: Measurements of α_s and Parton Distribution Functions using HERA Jet Data.

DJANGO[9] and RAPGAP[10] are used, implementing either the colour-dipole model or the parton shower model for the parton cascade. In photoproduction PYTHIA[11] and HERWIG[12] are used, implementing respectively the Lund string or cluster hadronisation models. The uncertainty in the correction factors arising from the model implementation is taken from the differences in the results obtained from the two models.

The uncertainty in the hadronic energy scale is quoted for ZEUS[13] as $\pm 1\%$ for jets with $E_t^{jet} > 10$ GeV, else $\pm 3\%$. For H1 the hadronic energy scale uncertainty is $\pm 2\%$ in high Q DIS and $\pm 1.5\%$ in high E_t^{jet} dijet photoproduction. The resultant systematic errors are highly correlated from bin to bin.

3. Common Theoretical Issues

The jet production cross section in perturbative QCD is given by the convolution of the proton PDF with the hard subprocess cross section. This provides a parton level prediction for the jet cross section,

$$\sigma_{jet} = \sum_{i=q,\overline{q},g} \int dx f_i(x, \mu_F, \alpha_s) \hat{\sigma}_{QCD}(x, \mu_F, \mu_R, \alpha_s(\mu_R).(1 + \delta_{had}),$$

where x is the fraction of the proton's momentum taken by the interacting parton, f_i is from the proton PDF, μ_F is the factorisation scale, $\hat{\sigma}_{QCD}$ is the subprocess cross section and μ_R is the renormalisation scale. In order to compare with the measured cross section an additional correction factor is required, δ_{had} , to take into account the nonperturbative effect of hadronisation. Each component of the theoretical calculation has an associated uncertainty.

The proton parton density function has to be extracted from data and the global analyses presently used rely on a variety of data to make fits of the proton structure. In recent years significant progress has been made in the estimation of the uncertainties of these PDFs. Most analyses presented here include a contribution to the theoretical uncertainty calculated from the 40 eigenvectors of the CTEQ6 PDF analysis [14].

The choice of factorisation and renormalisation scales is to some extent arbitrary although sensible choices are: Q the hard scale in DIS, E_t the transverse energy of the jet (the only choice in photoproduction), or a function of the two. The theoretical uncertainty due to terms beyond NLO is obtained by varying the choice of the scale for μ_R and μ_F by a factor of four.

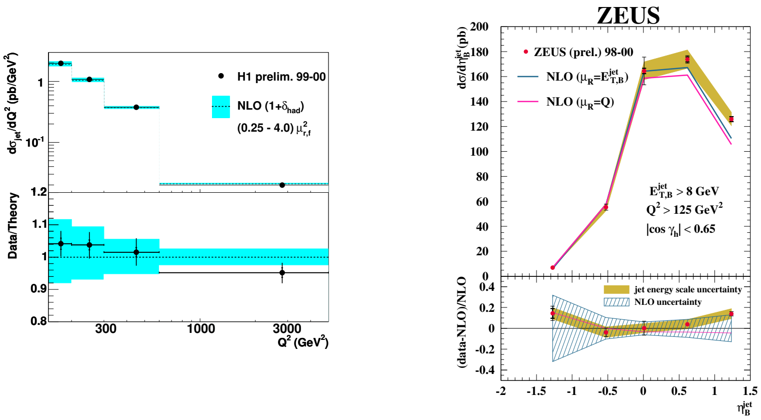

Figure 1. Left: $d\sigma/dQ^2$ measured by H1. Right: $d\sigma/d\eta^{jet}_{Breit}$ measured by ZEUS. Both are compared with NLO QCD predictions corrected for hadronisation effects.

The hadronisation correction factor, δ_{had}, is calculated using the Monte Carlo models. An assumption is made that the description of the final state by the Monte Carlo simulation after the parton cascade is equivalent to that of the NLO calculation. Then the effect of the hadronisation on the Monte Carlo jet cross sections can directly be applied to the NLO prediction. The uncertainty on δ_{had} is calculated from the difference between two Monte Carlo models.

4. Inclusive Jet Production in DIS

The inclusive jet cross section has been measured by H1[1] as a function of jet E_t in four Q^2 bins, as a function of Q^2 integrated over E_t (figure 1 left) and of E_t integrated over Q^2. H1 have used a luminosity of about 61 pb^{-1} and find about 20,000 events in the phase space defined by:

$$150 < Q^2 < 5000\ \mathrm{GeV}^2,\ 0.2 < y < 0.6,\ E^{\mathrm{jet}}_{\mathrm{t,Breit}} > 7\ \mathrm{GeV},$$
$$-1.0 < \eta^{\mathrm{jet}}_{\mathrm{lab}} < 2.5.$$

ZEUS[2] have used a luminosity of about 82 pb^{-1} and also about 20,000 events in the phase space defined by:

$$Q^2 > 125\ \mathrm{GeV}^2,\ |\cos\gamma_h| < 0.65,\ E^{\mathrm{jet}}_{\mathrm{t,Breit}} > 8\ \mathrm{GeV},\ -2.0 < \eta^{\mathrm{jet}}_{\mathrm{Breit}} < 1.5.$$

where γ_h corresponds to the of the scattered quark in the quark parton model and is calculated from the hadronic final state. In addition ZEUS measure the inclusive jet cross section as a function of jet pseudorapidity in the Breit frame (figure 1 right).

From figure 1 it can be seen that the NLO QCD predictions provide a good description of the data within the quoted uncertainties. Typical errors on the measured cross section are ±5% from the hadronic energy scale and ±7% from the model uncertainty. Typical errors on the predicted cross sections are ±5% from the scale uncertainty, ±3% from the PDF uncertainty and ±3% from the hadronisation uncertainty. It can also be seen that the scale uncertainty is smaller at higher Q and that the choice of renormalisation scale (Q or E_t) has little effect on the predicted cross section.

5. Multi Jet Production in DIS

An analysis of multi jet production has recently been published by ZEUS[3] presenting dijet and trijet cross sections as a function of $E_{t,Breit}^{jet}$, η_{lab}^{jet} and Q^2 (figure 2). The ratio of dijet to trijet events as a function of Q^2 is used to extract α_s. ZEUS have used a luminosity of about 82 pb^{-1} and find about $37,000$ dijets and $13,500$ trijets in the phase space defined by:

$$10 < Q^2 < 5000\ \mathrm{GeV}^2,\ 0.04 < y < 0.6,\ E_{\mathrm{t,Breit}}^{\mathrm{jet}} > 5\ \mathrm{GeV},$$
$$-1.0 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5,\ M_{2jets(3jets)} > 25\ \mathrm{GeV}.$$

H1[4] have used a luminosity of about 65 pb^{-1} and find about $5,500$ dijets and $1,800$ trijets in the phase space defined by:

$$150 < Q^2 < 15000\ \mathrm{GeV}^2,\ 0.2 < y < 0.6,\ E_{\mathrm{t,Breit}}^{\mathrm{jet}} > 5\ \mathrm{GeV},$$
$$-1.0 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5,\ M_{2jets(3jets)} > 25\ \mathrm{GeV}.$$

In figure 2 the dijet and trijet cross sections are shown as a function of Q^2. The NLO QCD predictions give a good description of the cross section over about four orders of magnitude. At high Q^2 the measurement is statistically limited. At low Q^2 the scale uncertainty is large (± 20%). Typical errors on the measured dijet cross section are ±6% from the hadronic energy scale and ±2% from the model uncertainty. Typical errors on the predicted dijet cross sections are ±10% from the scale uncertainty, ±2% from the PDF uncertainty and ±6% from the hadronisation uncertainty. For the trijet cross section most of the uncertainties are larger and the statistics are smaller. In the ratio of dijet to trijet cross sections (figure 3) many of the uncertainties cancel and the extraction of α_s from this ratio provides a competitive result.

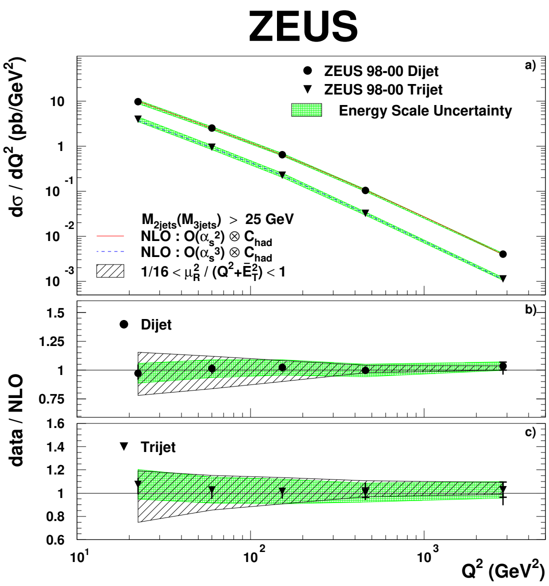

Figure 2. (a) The inclusive dijet and trijet cross sections as functions of Q^2. The predictions of perturbative QCD in next-to-leading order are compared to the data. (b) and (c) show the ratio of the data to the predictions.

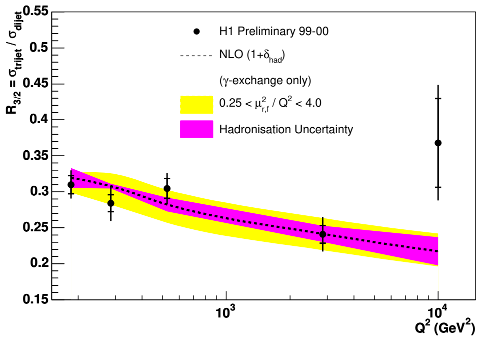

Figure 3. The ratio of dijet to trijet cross sections as a function of Q^2 compared with a NLO pQCD prediction, with hadronisation corrections. The light shaded band shows the scale uncertainty. The dark shaded band shows the hadronisation correction uncertainty.

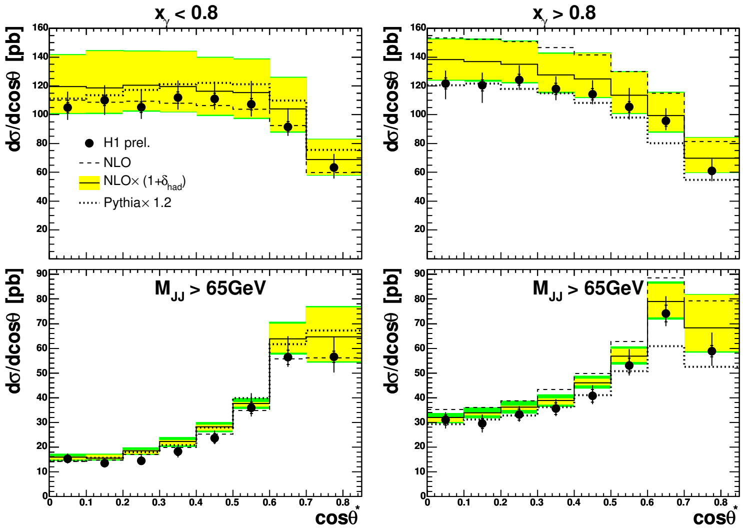

Figure 4. Cross section $|\cos\theta^*|$ for data (points), NLO with (solid line) and without (dashed) hadronisation corrections δ_{had} and for PYTHIA (dotted) scaled by a factor of 1.2. The inner band of the NLO $(1+\delta_{had})$ result reflects the scale uncertainty, the outer band is the total uncertainty which includes also the one from PDFs and hadronisation.

6. High E_t Dijet Production in Photoproduction

A new measurement of high E_t dijet photoproduction has recently been made by H1[5]. Results for the dijet cross section as a function of $|\cos\theta^*|$ (figure 4), x_γ, x_p, and E_t^{jet}. The measurements are studied in resolved photon enhanced ($x_\gamma < 0.8$) and direct photon enhanced ($x_\gamma > 0.8$) samples and with different jet topologies. H1 have used a luminosity of about 67 pb^{-1} and find about 14,000 dijet events in the phase space defined by:

$$Q^2 < 1\ \mathrm{GeV}^2,\ 0.1 < y < 0.9,\ E_{\mathrm{t,lab}}^{\mathrm{jet,1}} > 25\ \mathrm{GeV},\ E_{\mathrm{t,lab}}^{\mathrm{jet,2}} > 15\ \mathrm{GeV},$$
$$-0.5 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.75.$$

Both the NLO QCD prediction and the PYTHIA Monte Carlo simulation generally provide a good description of the data. There is a significant reduction in the theoretical scale uncertainty for $M_{JJ} > 65$ GeV. In this region the cross section is sensitive to the dynamics of the hard interaction.

Typical errors on the measured dijet cross section are ±10% to 20% from the hadronic energy scale and ±6% from the model uncertainty. Typical errors on the predicted dijet cross sections are ±3% to 30% from the scale uncertainty, $\pm 4\%$ to 20% from the PDF uncertainty and $\pm 5\%$ from the hadronisation uncertainty. High E_t dijet photoproduction has been shown to be sensitive to the gluon density in the proton at medium and high x[15].

7. Future Improvments to Experimental Measurements

The HERAII running period should provide about seven times more data useful for analysis compared to the HERAI measurements presented here. Most obviously this is important for jet production at the highest Q and E_t as well as trijet (and four-jet) production which are all presently statistically limited. In addition the increased statistics allow for the use of a higher E_t jet selection where the smaller uncertainty on the hadronic energy scale might provide for a reduced total error on the cross section.

With increasing data and time also comes an improved understanding of our detectors. It is expected that the hadronic energy scale uncertainty should improve as $1/\sqrt{N_{\text{event}}}$. If this is true then as an example for HERAII H1 should be able to quote an uncertainty of $< 1\%$ for $E_t^{jet} > 7$ GeV resulting in a 2.5% error on the measured inclusive jet cross section.

The model uncertainty calculated using Monte Carlo programs, tuned to e^+e^- data, is becoming a large source of error. In order to understand and reduce this error a greater variety of models need to be used and possibly they need to be tuned to HERA data directly.

8. Future Improvements to Theoretical Predictions

The uncertainty due to the scale dependence is often one of the largest contributing errors to a jet analysis. The uncertainty is smaller at high jet E_t and large M_{JJ} but this is in part due to the fact that the NLO contribution to the cross section is small (i.e. the phase space for additional jet production is reduced) and NLO QCD is no longer being tested. The uncertainty is also smaller at high Q but here the steeply falling cross section will require the full exploitation of the HERAII data set to allow for an improved analysis of jet production.

The scale uncertainty is there to take into account the beyond next to leading order contributions to the predicted cross section. One way to reduce this uncertainty is to calculate these higher orders. Unfortunately due to the complexity of the calculation we can expect only inclusive and dijet predictions to be available in any reasonable time scale[b].

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[b]See the contribution in these proceedings by Zoltan Trocsanyi: Multi-jet production in

It has been suggested by Brodsky[16] that the renormalisation scale ambiguities can be eliminated. In his procedure it is n_f, the number of light fermion flavours, that sets the renormalisation scale in NLO QCD (although the ambiguity due to the choice of factorisation scale remains). This procedure has been demonstrated to work in QED but not yet for QCD.

A large error from the PDF uncertainty indicates that the predicted cross section is sensitive to the parton distributions in the proton and could be used to constrain these distributions[15]. Careful choice of cross section measurements and different event and jet selections can be used to enhance (or reduce) the sensitivity to the proton PDF. Studies of these effects can be done to maximise impact of future jet analyses in PDF fits.

The calculation of the hadronisation corrections applied to the NLO QCD parton level predictions rely on the fact that the Monte Carlo parton level simulation matches the NLO QCD predictions. Different Monte Carlo models provide different predictions of the parton level and the difference is used as the uncertainty. It could be said that this double counts the model uncertainty since a similar error exists for the measured cross sections. It is possible to correct the data to the parton level and compare directly to the parton level NLO QCD predictions. Then there is only one model uncertainty and in certain cases this is smaller than when both data and theory are corrected to the hadron level. This procedure implicitly assumes local parton hadron duality.

In the future the Monte Carlo programs such as MC@NLO[17] which implement NLO matrix elements matched with parton showers will be available for DIS. This could provide NLO QCD predictions at the hadron level with less uncertainty than with the present (leading order) Monte Carlo programs.

9. Conclusions

Several new results on jet production at high Q and high E_t in DIS and photoproduction have recently been made by H1 and ZEUS. They improve on previous measurements by using higher statistics and an improved understanding of the detector systematics. In general there is good agreement with NLO QCD predictions.

For future HERAII data analyses a significant increase in the statistics and an expected improved understanding of the detectors should result

lepton-proton scattering at next-to-leading order accuracy in further improvements to jet production measurements. These improvements will need to be matched by improvements in the uncertainties of the theoretical predictions for the full benefit of the HERAII data to be realised.

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