Jets and Prompt Photons in Photoproduction at HERA

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Recent measurements of jet and prompt photon production by the H1 and ZEUS experiments are reviewed. The results are compared to next-to-leading order QCD calculations. No large deviations from the data are observed using proton and photon parton densities derived from other processes.

1. Introduction

The dominant hard processes in *ep* collisions at HERA are the direct and resolved production of jets in photoproduction. To leading order (LO) in the strong coupling α_s a quasi-real photon interacts either directly with a parton from the proton or a parton from the resolved photon interacts with a parton from the proton. These processes lead to final states containing two hard partons, which then hadronize into jets of particles. A rarer but nonetheless interesting process occurs when a so-called prompt photon is produced instead of a gluon. Experimentally (theoretically) jets are defined by finding clusters of charged particles and calorimetric energy depositions (partons) using the inclusive $k_\perp$ algorithm [1].

In QCD the jet-jet or jet-photon cross section may be written symbolically as $\sigma_{\mathrm{JJ}(\gamma)} \sim f_{\gamma/e}(y) \otimes f_{i/\gamma}(x_\gamma, \mu) \otimes f_{j/p}(x_p, \mu) \otimes \sigma_{ij}(\theta^\star, \mu)$ with the parton density functions (pdfs) of the photon being replaced by unity for direct processes. The scale μ represents the QCD renormalization and factorization scales. The variable x_p (x_γ) is the fractional momentum of the parton from the proton (photon), while $\cos\theta^\star$ is the scattering angle of the jets in the dijet center of mass system.

We review here the latest measurements of inclusive jets, dijets, multijets, and prompt photons performed by the H1 and ZEUS collaborations at HERA. The main aim of these measurements is to provide stringent tests of our calculational abilities in QCD, specifically the adequacy of next to LO (NLO) matrix elements and the current parameterizations of proton and photon pdfs, obtained from deep-inelastic scattering measurements made at HERA, and other processes at other colliders.

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2. NLO calculations

The data are compared to the NLO calculations of various groups [2–4]. Typically, the following settings are used: 5 flavors, $\alpha_s(M_Z) = 0.118$, $\mu = \mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \mu_\gamma = \mu_p = E_{\mathrm{T,jet}}$ or $1/2 \sum_{\mathrm{partons}} E_T$, proton pdfs CTEQ5M [5] and MRST99 [6], photon pdfs GRV-HO [7] and AFG-HO [8].

The band of uncertainty shown in the following figures is due to scale dependence and is obtained by varying the scale up and down by a factor of two, which typically leads to a 10 to 20% change in the cross section.

In order to compare data and NLO calculations, the latter are usually corrected for the effects of hadronization, which at high transverse jet energy $E_{\mathrm{T,jet}}$, are typically less than 10%.

3. Inclusive jet production

Preliminary results on inclusive jet production, demanding high $E_{\mathrm{T,jet}}$, i.e. $E_{\mathrm{T,jet}} > 17$ GeV (ZEUS [10]) or 21 GeV (H1 [9]), have become available. These measurements are experimentally the least restrictive in terms of phase space and theoretically most "safe". The NLO calculations are in good agreement with the data within the two dominant errors, the jet energy scale (1 to 2%) and the QCD scale uncertainty. Here we only show in Fig. 1 the ratio of the scaled invariant jet cross section $(E_{\mathrm{T,jet}})^4(E_{\mathrm{jet}}d^3\sigma/d(p_{\mathrm{jet}})^3)$ as a function of $x_T = 2E_{\mathrm{T,jet}}/W_{\gamma p}$ for two mean values of $W_{\gamma p}$ of 180 and 255 GeV. In the naive parton model the scaled cross section as a function of x_T is independent of $W_{\gamma p}$ and the ratio therefore should be unity. The photoproduction results show clear scaling violations in agreement with expectations from NLO QCD. In $p\bar{p}$ collisions scaling violations in jet production have been observed at the TEVATRON [11]. There, runs with different beam energies are needed while at HERA different $W_{\gamma p}$ are available in the same run, leading to smaller systematic errors.

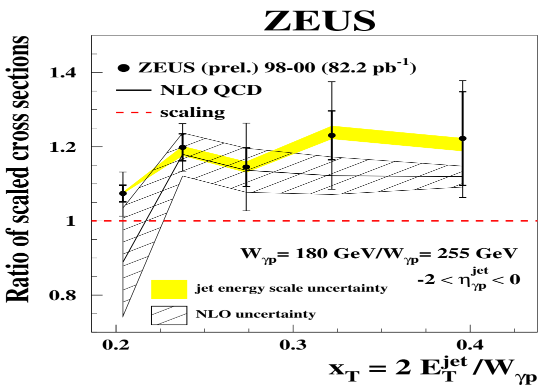

Figure 1. The ratio of the scaled invariant inclusive jet cross sections as a function of x_T.

4. Dijet production

The advantage of requiring at least two hard jets per event lies in being able to determine the x_p, x_γ and $\cos\theta^\star$ distributions by measuring $E_{\mathrm{T,jet}}$ and η_{jet} for both jets, using the following LO expressions: $x_p = \sum_{1,2} E_{\mathrm{T,jet}} \exp(\eta_{\mathrm{jet}})/2E_p$, $x_\gamma = \sum_{1,2} E_{\mathrm{T,jet}} \exp(-\eta_{\mathrm{jet}})/2yE_e$, and $\cos\theta^\star = \tanh(\eta_{\mathrm{jet1}} - \eta_{\mathrm{jet2}})/2$. By selecting events with $x_\gamma < 0.75$ or > 0.75, for example, one can divide the dijet events into samples in which resolved or direct processes dominate. Many dijet distributions have been measured by H1 [12] and ZEUS [13] and compared to NLO calculations. The shapes of the $\cos\theta^\star$ distributions for example agree with the expectations from the dominant propagators, i.e. gluon propagator for resolved and quark propagator for direct processes. The x_p distribution in the range $0.05 < x_p < 0.6$ for $x_\gamma > 0.8$ was measured by H1. They note that the data at the highest x_p are sensitive to the gluon density of the proton, which contributes almost 40% of the cross section there. Currently, at high x_p, the NLO predictions agree well with the data, which are however statistics limited. This will change with the high luminosity of HERA II.

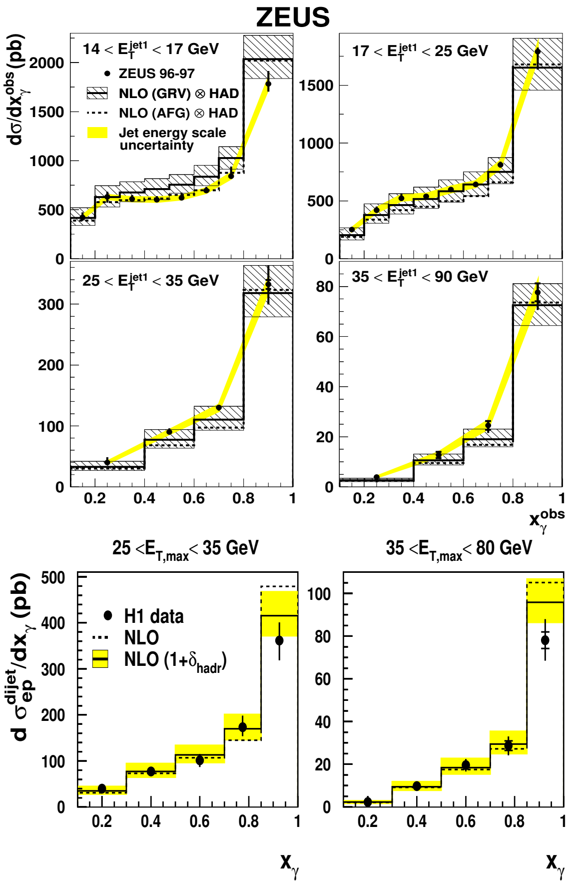

Figure 2. The dijet cross section as a function of x_γ in different regions of $E_{\mathrm{T,jet1}}$.

While both experiments conclude that overall the data are described by NLO QCD, ZEUS find that neither the GRV-HO nor the AFG-HO photon pdfs fully describe all features of the data. This is in contrast to H1 which find GRV-HO to be quite adequate. The ZEUS and H1 data in question and the NLO calculations are shown in Fig. 2.

There are small differences in the phase space selected by the two experiments, ZEUS requires for the hardest jet $E_{\rm T,jet1} > 14$ GeV and for the second hardest jet $E_{\rm T,jet2} > 11$ GeV, while H1 demands 25 GeV and 15 GeV, respectively. These asymmetric cuts on $E_{\rm T,jet}$ are needed to avoid an infra-red sensitivity of the NLO calculation in the case of symmetric cuts.

The seemingly contradictory conclusions by the two experiments can be at least partly understood by studying the significantly different sensitivity of the cross section to the cut on $E_{\rm T,jet2}$ between data and NLO calculations, which is shown in Fig. 3. With the $E_{\rm T,jet2}$ cut

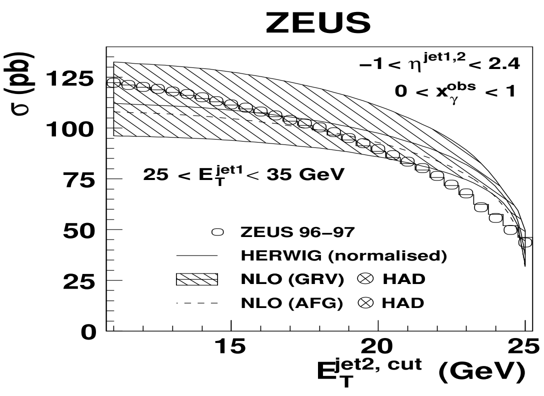

Figure 3. The dijet cross section as a function of $E_{\rm T,jet2}$ for one range of $E_{\rm T,jet1}$ compared to NLO predictions and to the Herwig MC model.

chosen by H1 the NLO calculation lies closer to the data than with the choice of ZEUS. It is also interesting to observe that the HERWIG Monte Carlo model (MC), incorporating LO matrix elements matched to parton showers, describes the $E_{\rm T,jet2}$ dependence of the data quite well (it is normalized to the data in the lowest $E_{\rm T,jet2}$ point). This success of HERWIG seems to indicate that the NLO calculations could be improved significantly by including soft perturbative effects.

5. Multijet production

Events with 4 jets resulting from a hard interaction are of $O(\alpha_s^3)$ in LO. In resolved events they may arise from additional interactions between partons of the proton and photon remnants and these are referred to as multi-parton interactions (mpi). The ZEUS collaboration has looked for mpi in events with 4 final state jets [14] $(1 + 2 \rightarrow 3 + 4 + 5 + 6)$ requiring low x_γ. For simplicity, the 4 jets are mapped onto three by combining the two jets of lowest invariant mass into one jet. The remaining three pseudo-jets are relabeled 3', 4', and 5' in order of decreasing energy. The resulting "3-jet" system can then be described by the usual two angles, $\cos\theta_3$ and ψ_3, and energy fractions $X_{3'} = 2E_{3'}/M_{4J}$ and $X_{4'} = 2E_{4'}/M_{4J}$. The jets 3 and 4 are required to have $E_{\rm T,jet} > 6$ GeV and the jets 5 and 6 $E_{\rm T,jet} > 5$ GeV. The resulting x_γ distribution shows a significant enhancement at low x_γ, which can be better described by the PYTHIA MC including mpi. As soon as one requires, in addition, a high invariant mass of the jet system, the enhancement disappears, and the inclusion of mpi has no noticeable effect. The $\cos\theta_3$ distribution, with θ_3 the angle between the beam direction and jet 3', turns out to be sensitive to whether mpi are modeled by adding a soft underlying event, as done in HERWIG, or as true mpi as done in Jimmy (interfaced to HERWIG) or in PYTHIA. The data clearly favor the latter.

6. Prompt photon production

Prompt photons are produced in direct and resolved interactions, with a hard photon emerging instead of a gluon jet. Since the properties of a hard photon can be better measured than those of a gluon jet, this process is expected to probe most sensitively our understanding of QCD at the parton level. Of course photons are also produced radiatively and in fragmentation and most copiously in the decays of π^0's, and η's. In order to suppress this background one looks for energetic and isolated photons. For the latest preliminary results by H1 [15], the requirements for prompt photon candidates are: $5 < E_T^\gamma < 10$ GeV, $-1 < \eta^\gamma < 0.9$, and an isolation cone with $E_T^{\rm cone}/E_T^\gamma < 0.1$. This isolation criterion was chosen to be able to compare to measurements from ZEUS [16]. Other criteria, more appropriate for theoretical calculations, have been suggested but not yet tried. The prompt photon fractions are determined in a likelihood analysis using shower shape observables for prompt photons, and for photons from π^0 and η decays.

The cross section as a function of $E_{\rm T}^\gamma$ [15] is found to be in good agreement with the NLO prediction and with the shape, but not the normalization, predicted by PYTHIA. In Fig. 4 the cross

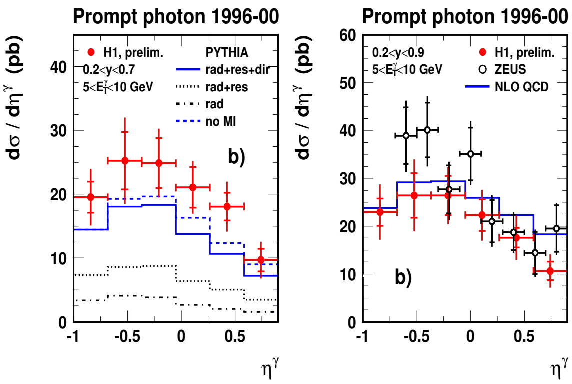

Figure 4. The prompt photon cross section of H1 as a function of η^γ compared to NLO predictions, the PYTHIA MC and ZEUS data.

section as a function of η^γ is shown. On the right, the NLO prediction can be seen to describe the data within the rather large errors. The ZEUS data agree with the H1 data and NLO calculations, but tend to be systematically above both at low η^γ. The figure on the left also includes comparisons to PYTHIA predictions which include radiative, resolved and direct contributions, with and without mpi effects. In PYTHIA the effects of mpi tend to reduce the cross section at positive η^γ. Taken at face value one expects that "adding" this effect to the NLO calculation would lower this prediction also.

7. Summary

The results reported here, and many more which can be found in the references, demonstrate that we have achieved a good understanding of jets in γp at HERA. NLO calculations with photon pdfs from $\gamma\gamma^\star$ scattering are able to describe the jet and prompt photon data. The data can also provide information on the gluon density in the photon and proton at large x and scales.

Since the experimental uncertainties are now often smaller than the theoretical uncertainties, we need help from our theoretical friends to ensure that the calculations match and challenge the experimental precision achieved. HERA II, with its expected significantly higher luminosity, will allow advances to be made at the high $E_{\rm T,jet}$ and high x frontiers.

REFERENCES

1. S.D. Ellis and D.E. Soper, Phys. Rev. D **48** (1993) 3160.
2. S. Frixione and G. Ridolfi, Nucl. Phys. B **507** (1997) 315.
3. M. Klasen et al., Eur. Phys. J. direct C1 (1998) 1.
4. M. Fontannaz, et al., Eur. Phys. J. C **21** (2001) 303.
5. H.L. Lai et al., Eur. Phys. J. C **12** (2000) 375.
6. A.D. Martin et al., Eur. Phys. J. C **14** (2000) 133.
7. M. Glück et al., Phys. Rev. D **45** (1992) 3986.
8. P. Aurenche et al., Z. Phys. C **64** (1994) 621.
9. H1 Coll., ABS 1010 submitted to this Conf.
10. ZEUS Coll., ABS 843 submitted to this Conf.
11. F. Abe et al. [CDF Coll.], Phys. Rev. Lett. **70** (1993) 1376;
    B. Abbott et al. [D0 Coll.], Phys. Rev. Lett. **86** (2001) 2523.
12. C. Adloff et al. [H1 Coll.], Eur. Phys. J. C **25** (2002) 13.
13. S. Chekanov et al. [ZEUS Coll.], Eur. Phys. J. C **23** (2002) 615.
14. ZEUS Coll., ABS 849 submitted to this Conf.
15. H1 Coll., ABS 1007 submitted to this Conf.
16. J. Breitweg et al. [ZEUS Coll.], Phys. Lett. B **472** (2000) 175.