Hard Photoproduction at HERA

M Klasen
Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier/CNRS-IN2P3, 53 Avenue des Martyrs, F-38026 Grenoble, France
E-mail: klasen@lpsc.in2p3.fr

Abstract. In view of possible photoproduction studies in ultraperipheral heavy-ion collisions at the LHC, we briefly review the present theoretical understanding of photons and hard photoproduction processes at HERA, discussing the production of jets, light and heavy hadrons, quarkonia, and prompt photons. We address in particular the extraction of the strong coupling constant from photon structure function and inclusive jet measurements, the infrared safety and computing time of jet definitions, the sensitivity of dijet cross sections on the parton densities in the photon, factorization breaking in diffractive dijet production, the treatment of the heavy-quark mass in charm production, the relevance of the color-octet mechanism for quarkonium production, and isolation criteria for prompt photons.
1. Introduction

Electron-proton scattering at HERA is dominated by the exchange of low-virtuality (almost real) photons [1]. If the electron is anti-tagged or tagged at small angles, the photon flux from the electron can be calculated in the Weizsäcker-Williams approximation, where the energy spectrum of the exchanged photons is given by

\[ f_{\gamma/e}(x) = \frac{\alpha}{2\pi} \left[ 1 + \frac{(1 - x)^2}{x} \ln \frac{Q_{\text{max}}^2(1 - x)}{m_e^2 x^2} + 2m_e^2 x \left( \frac{1}{Q_{\text{max}}^2} - \frac{1 - x}{m_e^2 x^2} \right) \right] \]  

(1)

and the subleading non-logarithmic terms modify the cross section typically by 5% [2]. In the QCD-improved parton model, valid for hard scatterings, the photons can then interact either directly with the partons in the proton (Fig. 1 left) or resolve into a hadronic structure, so that their own partonic constituents interact with the partons in the proton (Fig. 1 right). While this separation is valid at leading order (LO) in QCD perturbation theory, the two processes are intimately linked at next-to-leading order (NLO) through the mandatory factorization of a collinear singularity, that arises from the splitting of the photon into a quark-antiquark pair and induces a mutual logarithmic factorization scale dependence in both processes. In close analogy to deep-inelastic electron-proton scattering, one can define a photon structure function

\[ F_2^\gamma(Q^2) = \sum_q 2x e_q^2 \left\{ f_{q/\gamma}(Q^2) + \frac{\alpha_s(Q^2)}{2\pi} \left[ C_q \otimes f_{q/\gamma}(Q^2) + C_g \otimes f_{g/\gamma}(Q^2) \right] + \frac{\alpha}{2\pi} e_q^2 C_\gamma \right\} \]  

(2)

that is related to the parton densities in the photon and has been measured in electron-positron collisions at LEP. Even the strong coupling constant \( \alpha_s \) that appears in the expression above can be determined rather precisely in fits to these data [3]. A convenient modification of the \( \overline{\text{MS}} \) factorization scheme consists in absorbing the point-like Wilson coefficient

\[ C_\gamma(x) = 2N_C C_g(x) = 3 \left[ (x^2 + (1 - x)^2) \ln \frac{1 - x}{x} + 8x(1 - x) - 1 \right] \]  

(3)

in the Altarelli-Parisi splitting function \( P_{q\rightarrow \gamma}^{\text{DIS}} = P_{q\rightarrow \gamma}^{\overline{\text{MS}}} - e_q^2 P_{q\rightarrow q} \otimes C_\gamma \) [4].
2. Inclusive and Diffractive Jet Production

While at LO hadronic jets are directly identified as final-state partons, their definition becomes subtle at higher orders, when several partons (or hadrons) can be combined to form a jet. According to the standardization of the 1990 Snowmass meeting, particles $i$ are added to a jet cone $J$ with radius $R$, if they have a distance $R_i = \sqrt{(\eta_i - \eta_J)^2 + (\phi_i - \phi_J)^2} < R$ from the cone center. However, these broad combined jets are difficult to find experimentally, so that several modifications (mid-points, additional seeds, iterations) have been successively applied by the various experiments. The deficiencies of the cone algorithm are remedied in the longitudinally invariant $k_T$ clustering algorithm, where one uses only the combination criterion $R_{ij} < 1$ for any pair of particles $i$ and $j$. Unfortunately, this algorithm scales numerically with the cubic power of the number $N$ of the particles involved. Only recently a faster version has been developed making use of geometrical arguments and diagrammatic methods known from computational science [6]. The publicly available FastJet code scales only with $N \ln N$ and is now rapidly adopted, in particular for the LHC, where the particle multiplicity is high.

Single (inclusive) jets benefit from high statistics and the presence of a single (transverse) energy scale $E_T$, which makes them easily accessible experimentally and predictions for them theoretically stable. The $E_T$-distribution of the single-jet cross section can then be used to determine e.g. the strong coupling constant from scaling violations, as shown in Fig. 2. However, the single-jet cross section

$$\frac{d^2\sigma}{dE_T d\eta} = \sum_{a,b} \int_{x_{a,\text{min}}}^1 dx_a x_a f_{a/A}(x_a, M^2_a) x_b f_{b/B}(x_b, M^2_b) \frac{4E_A E_T}{2x_a E_A - E_T e^\eta} \frac{d\sigma}{dt} \quad (4)$$

Figure 2. Strong coupling constant as measured from scaling violations in inclusive single-jet production at ZEUS [5].
Figure 3. Sensitivity of the dijet photoproduction cross section as measured by H1 on the GRV and AFG parameterizations of the parton densities in the photon [7].

includes a convolution over one of the longitudinal momentum fractions of the partons, so that parton densities can not be uniquely determined.

In addition to the transverse energy $E_T$ and pseudorapidity $\eta_1$ of the first jet, the inclusive dijet cross section

$$\frac{d^3\sigma}{dE_T^2d\eta_1d\eta_2} = \sum_{a,b} x_a f_{a/A}(x_a, M^2_a) x_b f_{b/B}(x_b, M^2_b) \frac{d\sigma}{dt}$$

(5)
depends on the pseudorapidity of the second jet $\eta_2$. In LO only two jets with equal transverse energies can be produced, and the observed momentum fractions of the partons in the initial electrons or hadrons $x_{a,b}^{\text{obs}} = \sum_{i=1}^2 E_{T,i} e^{\pm \eta_i}/(2E_{A,B})$ equal the true momentum fractions $x_{a,b}$. If the energy transfer $y = E_\gamma/E_e$ is known, momentum fractions for the partons in photons $x_\gamma^{\text{obs}} = x_{a,b}^{\text{obs}}/y$ can be deduced. In NLO, where a third jet can be present, the observed momentum fractions are defined by the sums over the two jets with highest $E_T$, and they match the true momentum fractions only approximately. Furthermore, the transverse energies of the two hardest jets need no longer be equal to each other. Even worse, for equal $E_T$ cuts and maximal azimuthal distance $\Delta\phi = \phi_1 - \phi_2 = \pi$ the NLO prediction becomes sensitive to the method chosen for the integration of soft and collinear singularities. The theoretical cross section is
then strongly scale dependent and thus unreliable. This sensitivity also propagates into the region of large observed momentum fractions. It is thus preferable to cut on the average $\bar{E}_T = (E_{T_1} + E_{T_2})/2$. The sensitivity of the dijet photoproduction cross section as measured by H1 on the GRV and AFG parameterizations of the parton densities in the photon is shown in Fig. 3.

In diffractive processes with a large rapidity gap between a leading proton [9], neutron [10] or some other low-mass hadronic state and a hard central system, QCD factorization is expected to hold for deep-inelastic scattering, so that diffractive parton densities can be extracted from experiment, but to break down for hadron-hadron scattering, where initial-state rescattering can occur. In photoproduction, these two scenarios correspond to direct and resolved processes, which are however closely related as noted in Section 1. It is thus interesting to investigate the breakdown of factorization in kinematic regimes where direct or resolved processes dominate. This can either be done by measuring the dependence on the photon virtuality $Q^2$ (transition from virtual to real photons) [11], $E_T$ (direct processes are harder than resolved photons), or $x_{\gamma}^{\text{obs}}$ (=1 for direct processes at LO). The latter distribution is confronted in Fig. 4 with the hypothesis of no (or global) factorization breaking (left) and with a suppression factor $S$ of 0.34 [12] applied to resolved processes only (right). Note that the inter-dependence of direct and resolved processes requires the definition of a new factorization scheme.

**Figure 4.** Dependence of the diffractive dijet cross section on the observed longitudinal momentum fraction of the scattered photon at ZEUS [8].
with suppression of the scale-dependent logarithm also in the direct contribution \[13\]

\[
M(Q^2, S)_{MS} = \left[ -\frac{1}{2N_c} P_{q_i \to \gamma}(z) \ln \left( \frac{M_{\gamma}^2 z}{p_T^2 (1 - z)} \right) + \frac{Q_i^2}{2} \right] S \\
- \frac{1}{2N_c} P_{q_i \to \gamma}(z) \ln \left( \frac{p_T^2}{z Q^2 + y S} \right). \tag{6}
\]

3. Light and Heavy Hadron Production

If individual hadrons are experimentally identified, the cross sections above have to be modified to include convolutions over fragmentation functions \(D(z)\). For light quarks and gluons, these non-perturbative, but universal distributions must be fitted to \(e^+e^-\) data, but then produce successful predictions for HERA data at NLO. For heavy quarks, the fragmentation functions can in principle be calculated perturbatively, if the heavy-quark mass is kept finite (“fixed-order scheme”), although they must for large \(E_T\) be evolved using renormalization group equations (for example at “next-to-leading
The production of heavy quark-antiquark bound states is still far from being understood theoretically. While color-singlet (CS) states are to some extent formed already during hard collisions, their contribution has been shown to be both theoretically incomplete due to uncanceled infrared singularities as well as phenomenologically insufficient due to an order-of-magnitude discrepancy with the measured $p_T$-spectrum of $J/\psi$-mesons at the Tevatron. On the other hand, non-relativistic QCD (NRQCD) allows for a systematic expansion of the QCD Lagrangian in the relative quark-antiquark velocity and for additional color-octet (CO) contributions with subsequent color neutralization through soft gluons. $J/\psi$-production in photon-photon collisions at LEP can then be consistently described [18], as can be the photoproduction data from HERA in Fig. 6. At HERA, the color-octet contribution becomes important only at small momentum-transfer $z$ of the photon to the $J/\psi$-meson. Unfortunately, recent
CDF data do not support the prediction of transverse polarization of the produced $J/\psi$-mesons at large $p_T$ as predicted from the on-shell fragmentation of final-state gluons within NRQCD, so that further experimental and theoretical studies are urgently needed.

4. Prompt Photon Production

The production of prompt photons in association with jets receives contributions from direct and resolved initial photons as well as direct and fragmentation contributions in the final state as shown in Fig. 7. Photons produced via fragmentation usually lie inside hadronic jets, while directly produced photons tend to be isolated from the final state hadrons. The theoretical uncertainty coming from the non-perturbative fragmentation function can therefore be reduced if the photon is isolated in phase space. At the same time the experimental uncertainty coming from photonic decays of $\pi^0$, $\eta$, and $\omega$ mesons is considerably reduced. Photon isolation can be achieved by limiting the (transverse) hadronic energy $E_{(T)}^{\text{had}}$ inside a cone of size $R$ around the photon to

$$E_{(T)}^{\text{had}} < \epsilon_{(T)} E_{(T),\gamma}.$$  \hspace{1cm} (7)

This is illustrated in Fig. 8. Recently an improved photon isolation criterion

$$\sum_i E_{(T),\gamma} \theta(\delta - R_i) < \epsilon E_{(T),\gamma} \left( \frac{1 - \cos \delta}{1 - \cos \delta_0} \right),$$  \hspace{1cm} (8)

has been proposed, where $\delta \leq \delta_0$ and $\delta_0$ is now the isolation cone \[19\]. This procedure allows the fragmentation contribution to vanish in an infrared safe way.

Photoproduction of prompt photons and jets has been measured by the H1 collaboration and compared with two QCD predictions, which differ in their inclusion of NLO corrections to the resolved and fragmentation contributions. Only after modeling hadronization corrections and multiple interactions with Monte Carlo generators, the
Figure 8. Illustration of an isolation cone containing a parton $c$ that fragments into a photon $\gamma$ plus hadronic energy $E_{\text{frag}}$. In addition, a gluon enters the cone and fragments giving hadronic energy $E_{\text{parton}}$.

Figure 9. Various distributions of photoproduction of prompt photons in association with jets as measured by H1 and compared to two different QCD calculations [20].
measured distributions shown in Fig. 9 agree with the QCD predictions, showing the particular sensitivity of photon final states to hadronic uncertainties.

5. Summary

Photoproduction processes have been abundantly measured at HERA and stimulated many different theoretical studies, ranging from the investigation of the foundations of QCD as inscribed in its factorization theorems, over the determination of its fundamental parameter, the strong coupling constant, to improvements in our understanding of proton and photon structure as well as light and heavy hadron formation.

With the shutdown of HERA on July 1, 2007, many questions will remain unanswered, in particular in the diffractive and non-relativistic kinematic regimes, and this for quite some time until the eventual construction of a new electron-hadron collider such as eRHIC or an International Linear Collider. Photon-induced processes in ultraperipheral heavy-ion collisions may offer a chance to continue investigations in this interesting field, opening in addition a window to nuclear structure, if these processes can be experimentally isolated.

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