TOTAL AND JET PHOTOPRODUCTION CROSS SECTIONS
AT HERA AND FERMILAB*

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ABSTRACT

We present results of calculations of the total and jet photoproduction cross sections at HERA and Fermilab energies. The calculations take into account the high-energy QCD structure of the photon and are performed for different photon structure functions. We discuss how recent measurements of the total photoproduction cross section at HERA energies can provide important information on the low $x$ behavior of the photon structure function and in a more general context, to the nature of strong interactions. In addition, we show that the photoproduction cross section measurements at Fermilab E683 energies could provide a firmer value for $p_T^\text{min}$, the lower bound on the transverse momentum of outgoing jets, which signals the onset of hard scattering. The extrapolation of our cross section to ultra-high energies, of relevance to the cosmic ray physics, gives significant contribution to the "conventional" value, but cannot account for the anomalous muon content observed in the cosmic ray air-showers associated with astrophysical point sources.

1. Introduction

Recent photoproduction measurements at HERA have provided important confirmation of the hadronlike character of the high-energy photon. The probability of the photon producing a $q\bar{q}$ pair, and then through subsequent QCD evolution filling up the confinement volume with quarks and gluons with a density akin to that of a pion, increases with energy. Thus, it is not surprising that even low-energy measurements of the total photoproduction cross section up to $\sqrt{s} = 18\text{GeV}$ show some rise with energy similar to the one observed in low-energy hadronic collisions. In hadronic collisions, the rapid growth of the total cross section was associated with a dominance of hard scattering partonic processes over the nonperturbative (soft) ones, supported by the detection of the semi-hard QCD jets (so-called "minijets") at CERN Collider energies. Similarly, recent observation of the hard scatterings in photoproduction at HERA energies corroborates this hypothesis.

2. Photoproduction Cross Sections at HERA and Fermilab Energies

The total photoproduction cross section measured in the low-energy range...
$10\text{GeV} \leq \sqrt{s} \leq 18\text{GeV}$ and, most recently, at HERA energies\textsuperscript{2} points towards the hadronic behavior of the photon. Few years ago, we have made predictions for the total and jet photoproduction cross sections in a simple QCD minijet-type model based on analogy with hadronic collisions\textsuperscript{1}. We have assumed that the total photoproduction cross section can be represented as a sum of the soft (nonperturbative) and hard (jet) part (i.e. $\sigma_T = \sigma_{\text{soft}} + \sigma_{\text{JET}}$), where the soft part is energy independent, determined from the low-energy data ($\sqrt{s} \leq 10\text{GeV}$). The jet (hard) part has contributions from two subprocesses: the “standard” (direct) QCD process ($\gamma q \rightarrow qg$ and $\gamma g \rightarrow q\bar{q}$) and the “anomalous” process (for example, $\gamma \rightarrow q\bar{q}$, followed by quark bremsstrahlung, $q \rightarrow qg$ and $gg \rightarrow gg$). The later process is the same as the jet production process in p-p collisions up to a photon structure function. We note that the photon structure function is proportional to $\alpha_{\text{em}}/\alpha_s$, where $\alpha_{\text{em}}$ is the electromagnetic coupling. The effective order of the above processes is therefore $\alpha_{\text{em}}\alpha_s$, since the jet cross sections are of order $\alpha_s^2$. Thus, they are of the same order as direct two-jet processes, in which the photon-parton vertex is electromagnetic and does not involve the photon’s hadronic content. The existing parametrizations of the photon structure function, Duke and Owens (DO), Drees and Grassie (DG) and Abramowicz et al. (LAC1)\textsuperscript{9}, all describe low-energy photoproduction data very well. However, they differ dramatically at very high energies (i.e. low $x$ region), the region of the HERA experiment, for example. Therefore recent photoproduction measurements at HERA energies can provide valuable information about the photon structure function at small $x$ ($x \sim 4p_T^2/s$), and in particular its gluon content.

The QCD jet cross section for photon-proton interactions is given by

$$\sigma_{\text{QCD}}^p = \sum_{ij} \frac{1}{1 + \delta_{ij}} \int dx \, dx_p \int dp_{\perp}^2 \left[ f_i^\gamma(x,\tilde{Q}^2)f_j^{(p)}(x_p,\tilde{Q}^2) + i \leftrightarrow j \right] \frac{d\hat{\sigma}_{ij}}{dp_{\perp}^2}, \quad (1)$$

where $\sigma_{ij}$ are parton cross sections and $f_i^\gamma(x,\tilde{Q}^2)$ ($f_j^{(p)}(x_p,\tilde{Q}^2)$) is the photon (proton) structure function. The expressions for all the subprocesses that contribute to $\sigma_{ij}$ can be found in Ref. 10. We take the choice of scale $\tilde{Q}^2 = p_T^2$, which is shown to give very good description of the hadronic jet data\textsuperscript{10}. For parton structure function we use EHLQ parametrization\textsuperscript{11}. The results do not show appreciately sensitivity to the choice of the proton structure function.

From the constant low-energy data\textsuperscript{4}, we determine the soft part of the cross section to be $\sigma_{\text{soft}} = 0.114\text{mb}$. The observed 3% increase of the cross section in the energy range between $10\text{GeV}$ and $18\text{GeV}$ can be described by adding the hard (jet) contribution with jet transverse momentum cutoff $1.4\text{GeV} \leq p_{\perp,\text{min}} \leq 2\text{GeV}$ to the soft part\textsuperscript{1}. The actual value of $p_{\perp,\text{min}}$, however, below which nonperturbative processes make important contributions, is impossible to pin down theoretically using perturbative techniques. As the energy increases direct and soft part become negligible in comparison with the anomalous part, because the later has a steep increase with energy. We find that in the Fermilab E683 energy range ($\sqrt{s} \leq 28\text{GeV}$), the results for the cross sections are not sensitive to the choice of the photon structure function. Therefore, in addition to providing important confirmation of the hadronlike nature
of photon-proton interactions, one could use forthcoming E683 experiment to pin
down the theoretical parameter $p_{\perp,\text{min}}$ to a few percent (see Fig. 2 in Ref. 1).

In Fig. 1 we show our results for $\sigma_{\gamma p}$ at HERA energies. We note that the
results are very sensitive to the choice of the photon structure function due to their
different $x$ behavior at very high energies. For example, DO gluon structure function
behaves as $f_g^\gamma = x^{-1.97}$, while DG has less singular behavior, $f_g^\gamma \sim x^{-1.4}$ at the scale
$Q^2 = p_T^2 = 4\text{GeV}$. The cross sections obtained using DG photon structure function are
more realistic, since the extrapolation of DO parametrization to small $x$ region give
unphysically singular behavior. For this reason, the cross sections obtained using
DO function should be treated only as an illustration of the strong dependence of
the cross section to a different choice of the photon structure function.

Figure 1: Total inelastic cross section ($\sigma_{\text{soft}} + \sigma_{\text{JET}}$) predictions for HERA energies, compared to
the recent ZEUS and H1 measurements. The jet part includes contributions from direct processes.
Shown separately are contributions of direct processes, added to the constant soft part (curve 5).

In Fig. 1 we also present the results for the cross section when only soft and
direct part are included, indicating its very weak energy dependence. The rise of
the total cross section is thus mostly driven by the “anomalous” (hadronic) part
of the cross section. We note that HERA measurement has some resolving power
to distinguish between different sets of photon structure function and therefore
determine presently unknown low $x$ behavior of its gluon part. For example, the
cross sections obtained using DO structure functions are already excluded by HERA
data, while theoretical result obtained using DG structure function and $p_{\perp,\text{min}} = 2\text{GeV}$
is consistent with the data (see Fig. 1). However, one should keep in mind that
all the theoretical predictions presented in Fig. 1 do not take into account multiple
scatterings for which one needs to use proper eikonal treatment of high-energy
scattering process. The eikonalization procedure results (effectively) in reducing the cross section at HERA energies by 10% for $p_{\perp,\text{min}} = 2\text{GeV}$ and by about 30% for $p_{\perp,\text{min}} = 1.41\text{GeV}$.

We have also calculated the total jet cross sections at Fermilab and HERA energies for jet $p_T$ triggers of 3, 4, 5GeV and 5, 10, 15GeV respectively. The energy dependence of the total jet cross section is much steeper than of the direct part of the jet cross section only. This can be seen in Figs. 4 and 5 in Ref. 1. Again, jet measurements at HERA energies can distinguish between different photon structure functions, but in this case one is probing the photon structure function at slightly higher values of $x$ than in the case of the total cross section.

3. The Hadronic Photon and the “Muon Puzzle”

The ultra-high energy photoproduction cross sections play an important role in understanding recently observed anomalous muon content in cosmic ray air-showers associated with astrophysical “point” sources (such as Cygnus X-3, Hercules X-1 and Crab Nebula). The number of muons observed is comparable with what one would expect in a hadronic shower, but the fact that primary particle has to be long-lived and neutral, makes photon the only candidate in the Standard Model. Conventionally, one would expect that photon produces electromagnetic cascade and therefore muon poor. However, if the photonuclear cross section at very high energies becomes comparable with pair production and bremsstrahlung cross section ($\sigma_{\gamma\rightarrow e^+e^-} \sim 500\text{mb}$) the muon content in a photon initiated shower will be affected. The hadronic character of the photon enhances the photonuclear cross section at very high energies. We have calculated the total inelastic photon-air cross sections in a QCD-based diffractive model, which takes into account unitarity constraints necessary at ultra-high energies.

Our results for the photon-proton and photon-air cross sections at energies $10\text{GeV} \leq \sqrt{s} \leq 10^4\text{GeV}$ are presented in Fig. 6 in Ref. 12. We find that $\sigma_{\gamma-p}$ at $\sqrt{s} \geq 10^3\text{GeV}$ is about two times larger than the conventional value, large enough to be interesting, but much too small to account for the reported muon anomalies in photon-initiated showers.

4. Conclusion

We have shown how measurement of the total photoproduction cross section at HERA energies provides valuable information about the hadronic character of the photon. In particular we emphasized how measurements of $\sigma_{\gamma p}$ at HERA energies can impose strong constraint on the value of the theoretical jet momentum cutoff and, more importantly, determine the small $x$ behavior of the photon structure function and its gluon content. With the theoretical uncertainties being reduced, we have extrapolated our predictions for the photonuclear cross section to ultra-high energies relevant for cosmic ray experiments. The new results on $\gamma$-air interactions make it quite clear that the hadronic interactions of the photon cannot explain the reported muon anomalies in cosmic ray air-showers, if the anomalies in fact exist.
Furthermore, future cosmic ray experiments might be able to put the “muon puzzle” observations on firmer grounds and to provide valuable input to particle physics at ultra-high energies, currently far beyond the range of accelerator experiments.

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