TOTAL AND JET PHOTOPRODUCTION CROSS SECTIONS AT HERA

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ABSTRACT

We show that the recent measurements of the total photoproduction cross section at HERA energies [1] are in agreement with our earlier prediction based on high-energy hadronic structure of the photon in the QCD minijet-type model [2]. We discuss an improved calculation of the photoproduction cross section, in which the soft part, motivated by the Regge theory, is taken to be energy-dependent and the semi-hard hadronic part is carefully eikonalized to take into account for the multiple scatterings and to include the appropriate hadronic probability of the photon [3]. We show that 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 [4].

1. INTRODUCTION

One of the most striking aspects of high energy photoproduction is the unusual hadronic character of the photon, the fact that photon can produce $q\bar{q}$ pair, and then through subsequent QCD evolution fill up the confinement volume with quarks and gluons with a density akin to that of a pion or nucleon [2,3]. The probability of photon acting hadronicaly increases with energy and therefore it is not surprising that measurements of the total photoproduction cross section up to $\sqrt{s} = 18GeV$ [5] show rise with energy similar to the one observed in hadronic collisions [6]. Recent HERA measurements [1] make this even more pronounced. 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 [7], supported by the detection of the semi-hard QCD jets (so-called "minijets") at CERN Collider energies [8]. Similarly, recent observation of the hard scatterings in photoproduction at HERA energies corroborates this hypothesis [9].

2. PHOTOPRODUCTION CROSS SECTIONS AT HERA ENERGIES

The total photoproduction cross section measured in the energy range $10GeV \leq \sqrt{s} \leq 18GeV$ and, most recently, at HERA energies 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 [2]. 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. $\sigma_T = \sigma_{soft} + \sigma_{JET}$), where the soft part is energy independent, determined from the low energy data ($\sqrt{s} \leq 10GeV$). 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 α_{em}/α_s, where α_{em} is the electromagnetic coupling. The effective order of the above processes is therefore $\alpha_{em}\alpha_s$, since the jet cross sections are of order α_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) [10], 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

$$\sigma^{\gamma p}_{\rm QCD} = \sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_\gamma dx_p \int_{p^2_{\perp,\rm min}} dp^2_\perp [f_i^{(\gamma)}(x_\gamma, \hat{Q}^2) f_j^{(p)}(x_p, \hat{Q}^2) + i \leftrightarrow j] \frac{d\hat{\sigma}_{ij}}{dp^2_\perp}, \qquad (1)$$

where $\hat{\sigma_{ij}}$ are parton cross sections and $f_i^{(\gamma)}(x_\gamma, \hat{Q}^2)$ ($f_j^{(p)}(x_p, \hat{Q}^2)$) is the photon (proton) structure function. The expressions for all the subprocesses that contribute to $\hat{\sigma_{ij}}$ can be found in Ref. [11]. We take the choice of scale $\hat{Q}^2 = p_T^2$, which is shown to give very good description of the hadronic jet data [11]. For parton structure function we use EHLQ parametrization [12]. The results do not show appreciately sensitivity to the choice of the proton structure function.

From the constant low energy data [5], we determine the soft part of the cross section to be $\sigma_{soft} = 0.114mb$. The observed 3% increase of the cross section in the energy range between $10GeV$ and $18GeV$ can be described by adding the hard (jet) contribution with jet transverse momentum cutoff $1.4GeV \leq p_{\perp,\min} \leq 2GeV$ to the soft part [2]. The actual value of $p_{\perp,\min}$, 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 ($\sqrt{s} \leq 28GeV$), 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 $p_{\perp,\min}$ to a few percent.

In Fig. 1 we show our results for $\sigma_{\gamma p}$ at HERA energies [2]. 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 $Q^2 = p_T^2 = 4GeV$. 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, all the cross sections obtained using DO function should be treated as *extreme* theoretical upper bounds. 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 $p_{\perp,\min} = 2GeV$ 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 the possibility of multiple scatterings which, as we will show later, will result in reducing the cross sections by 10% for $p_{\perp,\min} = 2GeV$ and by about 30% for $p_{\perp,\min} = 1.41GeV$.

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 [2]. 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. [2]. 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.

Recently, we have improved our calculation of the total photoproduction cross section by incorporating the possibility of multiple parton collisions in a single photon-nucleon collision by using an eikonal treatment of the high-energy scattering process [3]. In our general formulation of the theory the γp cross section is expressed as a sum over properly eikonalized cross sections for the interaction

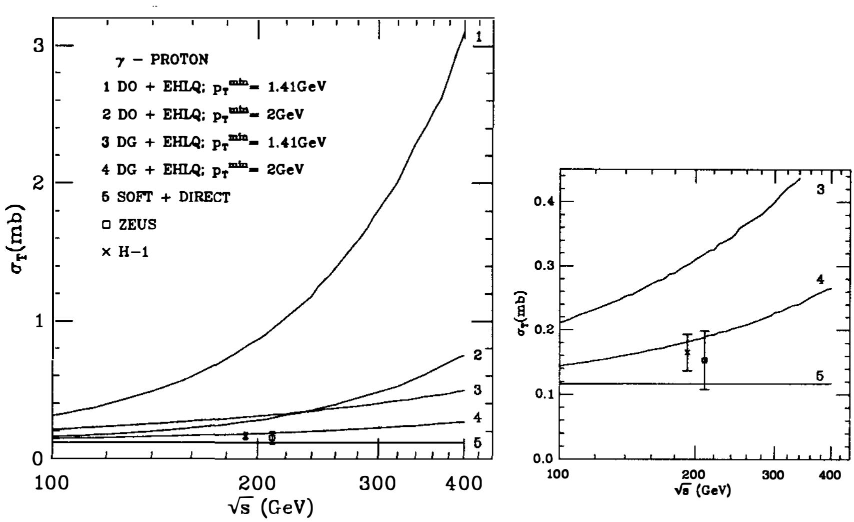

Figure 1: Total inelastic cross section ($\sigma_{soft} + \sigma_{JET}$) predictions for HERA energies [2], compared to the recent ZEUS and H1 measurements [1]. The jet part includes contributions from direct processes. Also shown separately are contributions of direct processes, added to the constant soft part (curve 5).

of the virtual hadronic components of the photon with the proton, with each cross section weighted by the probability with which that component appears in the photon. We have developed a detailed model which includes contributions from light vector mesons and from excited virtual states described in a quark-gluon basis. The parton distribution functions which appear can be related approximately to those in the pion, while a weighted sum gives the distribution functions for the photon. The "soft" contributions to the eikonal functions are parametrized in the form expected from Regge theory to assure that the calculated high-energy cross sections connect smoothly with the cross sections measured at lower energies. The parton distribution functions which appear in the "hard scattering" contributions to the eikonal functions can be related approximately to those in the pion. This approach allows us to use the (not-well-determined) pion distributions to predict the high-energy behavior of the γp cross section, and also gives an approximate prediction for the parton distributions in the photon in terms of these in the pion. We have also developed an alternative approach based directly on the photon distribution functions, in accord with the analysis done in Ref. [2].

In our QCD-based eikonal model the total inelastic γp cross section is given by [3]

$$\sigma_{\rm inel}^{\gamma p} = \sigma_{\rm dir} + \lambda \mathcal{P}_\rho \int d^2b \left(1 - e^{-2{\rm Re}\,\chi_{\rho p}}\right) + \sum_q e_q^2 \frac{\alpha_{\rm em}}{\pi} \int_{Q_0^2} \frac{dp_{\perp 0}^2}{p_{\perp 0}^2} \int d^2b \left(1 - e^{-2{\rm Re}\,\chi_{q\bar{q}p}}\right), \quad (2)$$

where

$$2{\rm Re}\,\chi_{\rho p}(b,s) = A_{\rho p}(b)\left[\sigma_{\rm soft}(s) + \sigma_{\rm QCD}^{\rho p}(s)\right], \quad (3)$$

and

$$2{\rm Re}\,\chi_{q\bar{q}p}(b,s,p_{\perp 0}) = A_{q\bar{q}p}(b,p_{\perp 0})\left[\sigma_{\rm soft}^{q\bar{q}p}(s,p_{\perp 0}) + \sigma_{\rm QCD}^{q\bar{q}p}(s,p_{\perp 0})\right]. \quad (4)$$

$A_{\rho p}$ and $A_{q\bar{q}p}$ are the overlapping spatial densities of the corresponding systems and $\sigma_{\rm QCD}^{q\bar{q}p}$ is given by the analog of Eq. (1) with f_i^ρ replaced by $f_i^{q\bar{q}} \approx (Q_0/p_{\perp 0})^2 f_i^\rho$. In Eq. (2), the parameter λ is the "weight" for the low-mass vector meson contributions. For example, $\lambda = 4/3$ for equal ρp, ωp and ϕp cross sections and $\lambda = 10/9$ for complete suppression of the ϕ contribution [3].

The incident hadronic systems in a ρp collision can interact inelastically through soft as well as hard processes. The soft scattering is dominant at low energies. Motivated by Regge theory, we parametrize $\sigma_{\rm soft}$ as energy-dependent, i.e.

$$\sigma_{\rm soft}^{\rho p}(s) \approx \sigma_0 + \sigma_1(s - m_p^2)^{-1/2} + \sigma_2(s - m_p^2)^{-1}. \tag{5}$$

We take $\sigma_{\rm QCD}^{\rho p}$ to be equivalent to $\sigma_{\rm QCD}^{\gamma p}$ given by Eq. (1). We find that the inelastic γp cross section is strongly suppressed at high energies relative to results reported earlier [13]. However, the QCD contributions to the hadronic interactions of the photon still lead to a rapid rise in $\sigma^{\gamma p}$ at HERA energies as predicted in earlier calculations [2] and observed in recent experiments [1]. The magnitude of the rise provides a quantitative test of the whole picture. In particular, our results presented in Fig. 2, show clearly that measurements of the total inelastic γp cross section at HERA can impose strong constraints on the parton distributions in the photon and, when combined with low-energy measurements, it can pin down the value of the theoretical cutoff $p_{\perp,\rm min}$, used to determine the onset of hard-scattering processes. From Fig. 2 we note that the cross sections obtained using the value of the cutoff $p_{\perp,\rm min} = 2GeV$ seem to be a bit too low for the observed increase of the cross section in the energy range between $10GeV$ and $18GeV$, but is in excellent agreement with ZEUS and H1 data, while our results with $p_{\perp,\rm min} = 1.41GeV$ are in better agreement with the data at all energies when pion structure function is used and slightly too large at HERA energies when DG structure function is used for the photon. Comparison of Fig. 1 and Fig. 2 shows that the eikonalization effect is to reduce the cross sections at HERA energies by about 10% for the case of $p_{\perp,\rm min} = 2GeV$ and by almost 30% when $p_{\perp,\rm min} = 1.41GeV$ is used.

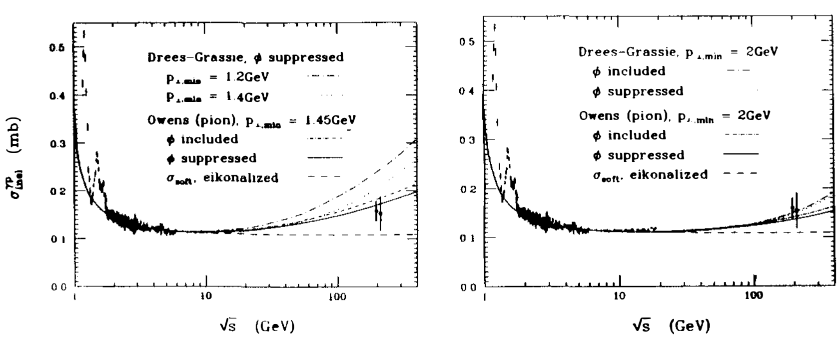

Figure 2: The predictions for $\sigma_{\rm inel}^{\gamma p}$ for $\sqrt{s} \leq 400$ GeV for the QCD model based on pion structure functions (solid and dashed curves) and on the Drees-Grassie structure functions for the photon (dash-dotted and dotted curves) with the ϕ meson contribution present or totally suppressed and with a) $p_{\perp,\rm min} = 1.2$ GeV and $1.4GeV$, b) $p_{\perp,\rm min} = 2.0$ GeV. The lower-energy data are from [5] and the HERA data at $\sqrt{s} \approx 200$ GeV are from [1].

3. THE HADRONIC PHOTON AND THE "MUON PUZZLE"

The unusually large cross sections at very high energies 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) [4]. 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 ($\sigma_{\gamma\to e^+e^-}\sim 500mb$) the muon content in a photon initiated shower will be affected [13]. The hadronic character of the photon enchances 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 [3].

Our model for the hadronic interactions of the photon can be extended to photon-nucleus interactions using Glauber's multiple scattering theory with the result [3]

$$\sigma_{\rm inel}^{\gamma-{\rm air}} = A\sigma_{\rm dir} + \lambda\mathcal{P}_\rho \int d^2b\,\langle\Psi|1-\exp\left(-\sum\nolimits_{j=1}^{A} 2{\rm Re}\,\chi_j^{\rho p}\right)|\Psi\rangle +$$

$$+\sum_q e_q^2\frac{\alpha_{em}}{\pi}\int_{Q_0^2}\frac{dp_{\perp 0}^2}{p_{\perp 0}^2}\int d^2b\,\langle\Psi|\,1-\exp\left(-\sum\nolimits_{j=1}^{A} 2{\rm Re}\chi_j^{q\bar{q}p}\right)|\Psi\rangle. \qquad (6)$$

The expectation values are to be taken in the nuclear ground state. ${\rm Re}\chi_j^m = {\rm Re}\chi^m(|\mathbf{b}-\mathbf{r}_{j\perp}|)$ is the eikonal function for the scattering of the hadronic component $|m\rangle$ of the photon on the $j^{\rm th}$ nucleon, where $\mathbf{r}_{j\perp}$ is the instantaneous transverse distance of that nucleon from the nuclear center of mass, and $\mathbf{b}$ is the impact parameter of the photon relative to the nucleus. We have evaluated the integrals using shell-model wave functions for the oxygen and nitrogen nuclei. The eikonal functions for γn and γp scattering were taken as equal.

Our results for the photon-proton and photon-air cross sections at energies $10\le\sqrt{s}\le 10^4$ are presented in Fig. 6 in Ref. [3]. We find that $\sigma_{\gamma-p}$ at $\sqrt{s}\ge 10^3 GeV$ is about four 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 low 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 γ-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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