

Structure of photon and the muon puzzle. *

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Abstract

In this talk I first briefly explain the puzzle presented by the high muon content observed in air-showers which point to the ultra high-energy γ sources like the HER-X-1. Since it had been suggested that a possible explanation of the puzzle might come from the effects of the hadronic structure of the photon, I briefly explain the concept of photon structure function and comment on the uncertainties in the predictions of the $\sigma_{\gamma p}^{tot}$. Then I show that while the current experiments at the e^+e^- (TRISTAN and LEP) and ep (HERA) colliders have seen clear evidence for the hadronic structure of the photon, the observed muon excess in the air shower experiments, if confirmed by other experiments to be at the same high level, can not be explained in terms of the photon structure function.

1 What is μ puzzle?

One of the aims of the TeV/PeV γ ray astronomy is to gain information about the origin of cosmic rays [1]. The extensive air-shower array experiments look for point sources of ultrahigh energy γ rays [2, 3, 4, 5]. These experiments can serve as directional cosmic γ ray telescopes. But they have to be able to distinguish between photon and hadron initiated air-showers. One of the criteria that is normally used is the expected low μ content of the γ showers. The γ initiated showers are supposed to be μ poor and the reasoning goes as follows. The muons in the air-showers come from $\pi \rightarrow \mu\nu$ as well as from the Bethe-Heitler production of μ pairs and at still higher energies from the heavy quark decays. In case of γ induced air-showers, the total cross-section is dominated by the Bethe-Heitler production of e^+e^- pairs. Hence one expects the μ content of the γ initiated showers to be at few % level that of (roughly a factor 30 below) the hadron initiated showers.

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However, so far there never has been evidence for directional showers associated with point sources of γ rays which are μ poor. On the other hand, the experiments [4] reported air showers associated with known ‘point’ γ sources whose μ content is consistent with that of the hadron initiated showers or even more. Ref. [2] reported observation of air showers associated with the point source Cyg X-3, ref. [3] reported air–showers associated with Crab-Nebula. Air showers reported in ref. [4] were associated with the point source HER X-1 which were μ rich, *i.e.*, their μ content was consistent with that of a hadronic shower. This observation as well as any failure to see a μ poor shower associated with ‘point’ sources, signalled existence of what is termed as the μ puzzle, *i.e.*, the cosmic ray air shower experiments ‘see’ more muons than they ‘ought’ to.

Let us now turn more specifically to the theoretical predictions [6, 7, 8, 9] of the μ content of the γ induced showers. The actual predictions involve detailed Monte Carlo simulation of the shower development, but the essential features of how one arrives at these predictions can be summarised as follows (see, e.g., ref. [7]). One starts with measured photoproduction cross–sections in the laboratory. In the days before the results from the ep collider HERA at DESY, the maximum centre of mass energy $(\sqrt{s})_{\gamma p}$ for which data were available was ~ 20 GeV. At these energies the $\sigma_{\gamma p}^{tot}$ is $\sim 100 \mu b$. Now to estimate the μ content of the airshowers one has to extrapolate these cross–sections to TeV/PeV energies using the experimentally well known logarithmic rise of total cross–sections. Using this one then calculates the production of hadrons and hence production of muons, telling us how many μ ’s ought to be there in the γ induced showers. The observed μ excess [4] would require a $\sigma_{\gamma p}^{tot} \sim O(100) mb$ for PeV energy photons. This would imply a faster than the assumed logarithmic growth of $\sigma_{\gamma p}^{tot}$ in going from the laboratory measurements at GeV energies to the PeV energies involved in the cosmic ray experiments. This can happen only if there exist some new threshold in the photonuclear (γ air) cross–sections which gives it a steeper energy dependence. Hadronic structure of the high energy γ (in particular the gluon content) can indeed cause a sharp increase in the cross–sections with increasing γ energy [10]. It should be noted here that the increasing importance of the hadronic structure of the γ with rising energy was not *introduced* here to ‘explain’ the μ ‘puzzle’, but is a prediction of perturbative QCD. What is not clear, and hence has been a topic of debate, is how much does the hadronic structure of photon contribute to the rise in $\sigma_{\gamma p}^{tot}$ with energy.

2 Hadronic content of photon

The terminology of the ‘structure ’ of a photon is essentially a short hand way of describing how a high energy photon interacts with other particles: hadrons and photons. The idea that photons behave like hadrons when interacting with other hadrons dates back to the early days of strong interaction physics and is known to us under the name of the Vector Meson Dominance (VMD) picture. This essentially

means that at low 4-momentum transfer, the interaction of a photon with hadrons is dominated by the exchange of vector mesons which have the same quantum numbers as the photon. While this picture works reasonably well for ‘soft’ processes (i.e., reactions characterized by small 4-momentum transfer), it is not at all clear that it should describe the whole story of interactions of photons with hadrons at high energies as well. In the VMD picture one then expects

$$\sigma_{\gamma p}^{tot} \propto \alpha \sigma_{Vp}^{tot},$$

where α is the fine structure constant. However, since the photon ‘behaves’ like a hadron while interacting with other hadrons it must be possible to get information about the photon structure just like the other hadrons, e.g., the proton. This information is obtained by studying the deep inelastic scattering (DIS) of high energy leptons of energy E off proton targets,

$$e^- + p \rightarrow e^- + X \tag{1}$$

The double differential cross-section for the process is a function of two independent variables $y = \nu/E$ where ν is the energy carried by the probing photon in the laboratory frame, and $x = Q^2/(2M\nu)$ where M is the proton mass and $-Q^2$ is the invariant mass of the virtual photon in fig. 1a. In the quark-parton-model (QPM) it is given

Figure 1: Deep Inelastic Scattering for the proton and photon.

by,

$$\frac{d^2\sigma^{ep \rightarrow X}}{dx dy} = \frac{2\pi \alpha^2 s}{Q^4} \times \left[(1 + (1 - y)^2) F_2^p(x) - y^2 F_L^p(x) \right], \tag{2}$$

where

$$F_2^p(x) = \sum_q e_q^2 x f_{q/p}(x);$$

$$F_L^p(x) = F_2^p(x) - 2xF_1^p(x)$$

are the two electromagnetic structure functions of the proton (in the QPM $F_L^p(x)$ is identically zero but not so in QCD) and $f_{q/p}(x)$ the probability for quark q to carry

a momentum fraction x of the proton and e_q denotes the electromagnetic charge of quark q in units of the proton charge.

To measure the structure function of a photon such an experimental situation is provided at e^+e^- colliders in $\gamma^*\gamma$ reactions as shown in fig. 1 (b). Here the virtual photon with invariant mass square $-Q^2$ probes the structure of the real photon. If the VMD picture were the whole story then one would expect that such an experiment will find

$$F_2^\gamma \simeq F_2^{\gamma,VMD} \propto F_2^{p^0} \simeq F_2^{\pi^0}. \quad (3)$$

Then with increasing Q^2 , the structure function F_2^γ will behave just like a hadronic proton structure function and shrink to lower values of x as predicted by QCD [11]. However, there is a very important difference in case of photons, *i.e.*, photons possess pointlike couplings to quarks. This has interesting implications for $\gamma^*\gamma$ interactions as first noted in the framework of the QPM by Walsh [12]. It essentially means that $\gamma^*\gamma$ scattering in fig. 1 contains two contributions as shown in fig. 2. The contribution

Figure 2: Two contributions to F_2^γ .

of fig. 2 (a) can be estimated by eq.(3), whereas that of fig. 2 (b) was calculated in the QPM [12]. This is done by considering the cross-section for the reaction

$$\gamma + \gamma^* \rightarrow q + \bar{q}.$$

Due to t and u channel poles this can be calculated only when one considers quarks with finite masses. The result can be recast in a form equivalent to eq. (2):

$$\begin{aligned} \frac{d^2\sigma^{e\gamma\rightarrow X}}{dx dy} &= \frac{2\pi\alpha^2 s_{e\gamma}}{Q^4} \times \frac{3\alpha}{\pi} \\ &\sum_q e_q^4 \left\{ (1 + (1 - y)^2) \times [x(x^2 + (1 - x)^2) \times \ln \frac{W^2}{m_q^2} \right. \\ &\left. + 8x^2(1 - x) - x] - y^2[4x^2(1 - x)] \right\}, \end{aligned} \quad (4)$$

where $W^2 = Q^2(1 - x)/x$. On comparing eqs.(2) and (4) we see that the factors in square brackets in the above equation have the natural interpretation as photon

structure functions F_2^γ and F_L^γ and one has

$$\begin{aligned}
F_2^{\gamma,\text{pointlike}}(x, Q^2) &= 3\frac{\alpha}{\pi} \sum_q e_q^4 \left[x(x^2 + (1-x)^2) \times \ln \frac{W^2}{m_q^2} + 8x^2(1-x) - x \right] \\
&= \sum_q e_q^2 x f_{q/\gamma}^{\text{pointlike}}(x, Q^2).
\end{aligned} \tag{5}$$

Two points are worth noting: the function $F_2^{\gamma,\text{pointlike}}(x, Q^2)$ can be completely calculated in QED and secondly this contribution to F_2^γ increases logarithmically with Q^2 . So in this simple ‘VMD + QPM’ picture, F_2^γ consists of two parts, $F_2^{\gamma,\text{pointlike}}$ and $F_2^{\gamma,\text{VMD}}$, with distinctly different Q^2 behaviour and with the distinction that for one part both the x and the Q^2 dependence can be calculated completely from first principles.

This QPM prediction received further support when it was shown by Witten [13] that at large Q^2 and at large x , both the x and Q^2 dependence of the quark and gluon densities in the photon can be predicted completely even after QCD radiation is included. An alternative way of understanding this result is to consider the evolution equations [14] for the quark and gluon densities inside the photon. These contain an inhomogeneous term on the r.h.s proportional to α , which describes $\gamma \rightarrow q\bar{q}$ splitting, i.e. the pointlike coupling of photons to quarks. In the ‘asymptotic’ limit of large Q^2 and large x , the $f_{q_i/\gamma}(x, Q^2)$ have the form

$$\begin{aligned}
f_{q_i/\gamma}^{\text{asympt}}(x, Q^2) &\propto \alpha \times \ln \left(\frac{Q^2}{\Lambda_{\text{QCD}}^2} \right) F_i(x) \\
&\simeq \frac{\alpha}{\alpha_s} F_i(x),
\end{aligned} \tag{6}$$

where Λ_{QCD} is the usual QCD scale parameter, $\alpha_s(Q^2)$ is given in terms of the running strong coupling constant by $\frac{g_s^2(Q^2)}{4\pi}$ and the x dependence of the $F_i(x)$ is completely calculable. Note here the factor $\ln \left(\frac{Q^2}{\Lambda_{\text{QCD}}^2} \right)$ on the r.h.s. Measurements [15] of the photon structure function F_2^γ in $\gamma^*\gamma$ processes did indeed confirm the basic QCD predictions of the linear rise of F_2^γ with $\ln(Q^2)$ at large x . This discussion thus means that just like one can ‘pull’ quarks and gluons out of a proton one can look upon the photon as a source of partons and that the parton content of the photon rises with its energy. Physically this means that the photon splits in a $q\bar{q}$ pair and these radiate further gluons and thus fill up a volume around photon with partons.

The asymptotic solutions discussed above, though very useful to understand the rise of the photon structure function with Q^2 , are valid only at large x and large Q^2 . At small values of x these solutions diverge, indicating thereby that ‘hadronic’ part of F_2^γ can not be neglected at small x . Hence in practice, this separation of F_2^γ in two parts as in fig. 2 is not very meaningful, especially when one wants to use this parton language to predict the high energy photon interactions. Although the debate

on the subject is not yet closed [16] , it is now generally accepted that it is better to forego the absolute predictions of F_2^γ of the asymptotic part, that are possible in perturbative QCD (pQCD) and use only the prediction of the Q^2 evolution of the photon structure function in analogy to the case of the proton structure function. At present there exist eight different parametrisations of the photon structure function [16, 17]. The DIS measurements described above measure only the quark-parton densities $f_{q_i/\gamma}(x, Q^2)$ (for $x > 0.05$ and $Q^2 < 100 - 200 \text{ GeV}^2$) directly and $f_{g/\gamma}(x, Q^2)$ is only inferred indirectly. As a result there is considerable uncertainty in the knowledge of $f_{g/\gamma}(x, Q^2)$. The different parametrisations differ quite a lot from each other in the gluon content. It should also be mentioned here, that these differences reflect the differences in different physical assumptions in getting $f_{g/\gamma}(x, Q^2)$ from the data on F_2^γ . So independent information on $f_{g/\gamma}(x, Q^2)$ is welcome.

3 Calculation of jet production in $\gamma\gamma$, γp collisions

In this section let us discuss how one can compute the high energy γ cross-sections using the parton language and what are the crucial factors affecting these predictions. In the parton language, interaction of a hadron with others can be described, at high energies and for processes involving final state particles at large angles to the original beam direction (large transverse momentum p_T), in terms of the scattering of the pointlike constituents inside the two hadrons against each other. In this picture, the differential cross-section for the production of a pair of two large p_T jets in the collision of a γ with a proton(say) will be given by

$$\begin{aligned} \frac{d\sigma}{dp_T}(\gamma p \rightarrow \text{jets} + \text{X}) = & \sum_{P_1, P_2, P_3, P_4} \int dx_\gamma f_{P_1/\gamma}(x_\gamma) \int dx_p f_{P_2/p}(x_p) \\ & \times \frac{d\hat{\sigma}}{dp_T}(P_1 + P_2 \rightarrow P_3 + P_4), \end{aligned} \quad (7)$$

where the sum is over all the different initial (final) state partons P_1, P_2 (P_3, P_4) and $\frac{d\hat{\sigma}}{dp_T}$ is the subprocess cross-section that can be computed in pQCD. As we have already seen in the discussions on F_2^γ one can get effectively ‘real’ high energy γ beams in the laboratory by using e -beams and then making sure that the final state e is scattered in the forward direction at a very small angle. In this situation the large p_T jet production in high energy $e - p$ collisions can be computed as

$$\begin{aligned} \frac{d\sigma}{dp_T}(ep \rightarrow \text{jets} + \text{X}) = & \sum_{P_1, P_2, P_3, P_4} \int dz f_{\gamma/e}(z) \int dx_\gamma f_{P_1/\gamma}(x_\gamma) \\ & \times \int dx_p f_{P_2/p}(x_p) \frac{d\hat{\sigma}}{dp_T}(P_1 + P_2 \rightarrow P_3 + P_4). \end{aligned} \quad (8)$$

The γ induced processes are of two types :

Figure 3: ‘Direct’ and ‘resolved’ contributions to jet production in ep collision.

- 1) The ‘direct’ processes, an example of which is depicted in fig. 3 (a), where the γ couples directly to the partons in the photon. In this case all the energy of the photons goes into the subprocess and the hadronic content of the γ plays no role and in eq.(8),

$$f_{P_1/\gamma}(x_\gamma) = \delta(1 - x_\gamma).$$

- 2) The ‘resolved’ processes where the partons in the proton interact with the partons in the photon and hence only a partial fraction of the γ energy is available for the subprocess. One of the possible contribution is shown in fig. 3 (b).

It should be noted here that although the ‘resolved’ processes have an extra factor of α_s , due to the factor of $\frac{\alpha}{\alpha_s}$ in the parton densities of the photon (recall eq. (6)), both the ‘direct’ and the ‘resolved’ processes are formally of the same order in the coupling constants. With rising γ energies, increasingly more energy becomes available for the subprocess, at a fixed p_T or mass of the final state. Hence the importance of the ‘resolved’ processes increases with the γ energies. The gluon content of photon $f_{g/\gamma}(x, Q^2)$ is peaked at small values of x and hence the importance of the contributions involving the gluon in the photon in the initial state in eq. (8), increases with the increasing γ energy at a fixed p_T or with decreasing p_T at a fixed γ energy. The ‘resolved’ events will also have additional ‘spectator’ jets in the direction of the incident γ (*i.e.* the direction of the incident e).

Such high photon energies are available at the HERA collider at DESY (Hamburg) in the collision of a 30 GeV e beam with a p beam of 800 GeV. This corresponds to c.m. energies for the γp system ≤ 300 GeV (which in turn means $E_\gamma \leq 40$ TeV in the frame where the proton is at rest). Indeed a calculation [18] showed that at the HERA collider the photo-production of jets in the process

$$\gamma + p \rightarrow \text{jets} + X,$$

is dominated by the ‘resolved’ processes upto $p_T \simeq 40$ GeV. This dominance is sensitive to the gluon content of the photon and fortunately not very sensitive to the choice of gluon parametrisation of the proton, partially because of the much better

Figure 4: Ratio of resolved and direct contributions for $d\sigma(ep \rightarrow \text{jets})/dp_T$ as a function of p_T [18]. For details see ref. [18].

knowledge of $f_{g/p}$ in the relevant x_p region. An example is shown in fig. 4 for two different parametrisations of $f_{g/\gamma}(x, Q^2)$ that were then available. Since then the HERA experiments H1 and ZEUS [19, 20] have studied the photo-production of the jets, and confirmed the existence of the ‘resolved’ contribution at the expected level, verified various expected qualitative features of the resolved contributions such as existence of the spectator jets in the backward direction, different angular distribution expected for the jets produced from the hard scattering of the partons in the photon etc. An example of the same is shown in fig. 5. As a matter of fact the ‘resolved’ contributions

Figure 5: The total ep cross-section measured [20] for transverse energies larger than E_T^0 . The curve is the HERWIG prediction, using the DG parametrization with $p_{T,min} = 1.5$ GeV.

to the jet–production have been isolated and used to extract $f_{g/\gamma}(x, Q^2)$ [21].

Similar studies of the jet–production in $\gamma\gamma$ collisions [22] at the e^+e^- collider TRISTAN and LEP, have confirmed the existence of the ‘resolved’ contributions [23]. These studies have already ruled out some of the very hard parametrisations of $f_{g/\gamma}(x, Q^2)$ [22, 24]. Thus these observations have provided a confirmation (in addition to the DIS measurements) of the ideas about F_2^γ and these experiments will continue to add to our knowledge of the $f_{g/\gamma}(x, Q^2)$, $f_{q_i/\gamma}(x, Q^2)$.

4 F_2^γ and QCD prediction of $\sigma_{\gamma p}^{tot}$

What is more relevant for the issue of μ puzzle is the total photoproduction cross–section $\sigma_{\gamma p}^{tot}$. The calculation of the ‘hard’ processes such as the jet–production cross–sections is well defined in pQCD but valid upto $\simeq 1\text{--}2$ GeV. The total inclusive γp cross–section for production of jets with $p_t > p_T^{\min}$ given by,

$$\sigma_{\text{incl}}^{\gamma p} = \int_{p_{T,\min}} \frac{d\sigma}{dp_T}(\gamma p \rightarrow j_1 + j_2 + X) dp_T, \quad (9)$$

rises very strongly with decreasing $p_{T,\min}$ at a fixed γ energy or with γ energy at a fixed $p_{T,\min}$. The differential cross–section $\frac{d\sigma}{dp_T}(\gamma p \rightarrow j_1 + j_2 + X)$ receives contribution from the ‘direct’ as well as the ‘resolved’ processes as discussed before and it also rises strongly with decreasing p_T . At high γp c.m. energies the resolved photon processes then cause copious production of the ‘minjets’ and a very rapid rise of the inclusive γp cross–section, as was first pointed out in ref. [10]. An example is shown in fig. 6,

Figure 6: Predictions [10] of the increase of the inclusive (mini)jet cross–section in γp collisions with \sqrt{s} , for $p_{T,\min} = 2$ GeV and various parametrizations for $f_{\bar{q}/\gamma}$.

for $p_{T,\min} = 2$ GeV and various parametrizations of $f_{\bar{q}/\gamma}$. Of course, the total cross–section cannot grow indefinitely at the rate shown in fig. 6; some mechanism will

have to unitarize it. This problem is well known for hadronic (pp or $p\bar{p}$) collisions. In this case unitarization is usually achieved by eikonalization. The crucial observation here is that LO QCD predictions for cross-sections, like those shown in fig. 6, refer to *inclusive* jet cross-sections; in other words, they differ from the jet production contribution to the total cross-section by a factor of the average jet pair multiplicity $\langle n_{\text{jet}} \rangle$. Formally one writes (following ref. [25] and modifying for the γp case as pointed out in [26])

$$\sigma_{\gamma p}^{\text{inel}} = \int d^2b P_{\text{had}} \left\{ 1 - \exp \left[- \left(\sigma_{\gamma p}^{\text{hard}}(s) + \chi_{\gamma p}^{\text{soft}} \right) A(b)/P_{\text{had}} \right] \right\}, \quad (10)$$

Here \vec{b} is the two-component impact parameter, $A(b)$ describes the transverse overlap of partons in the nucleon and the photon, $\sigma_{\gamma p}^{\text{hard}}$ is the perturbative QCD prediction for the minijet cross-section (obtained by integrating $d\sigma/dp_T$ in the region $p_T \geq p_{T,\text{min}}$), and χ_{pp}^{soft} is the non-perturbative (soft) contribution to the eikonal, which is fitted from low-energy data and P_{had} is a parameter describing the probability that the photon goes into a hadronic state; clearly $P_{\text{had}} \sim \mathcal{O}(\alpha)$. Thus we see that unlike the predictions of the jet cross-sections the predictions of $\sigma_{\gamma p}^{\text{tot}}$ depend not only on the $f_{g/\gamma}(x, Q^2)$ and $f_{q_i/\gamma}(x, Q^2)$ but also on $p_{T,\text{min}}$, P_{had} , $A(b)$ and the nonperturbative contribution to the eikonal. There is considerable theoretical uncertainty in the ansätze used for σ^{soft} and the choice of P_{had} , as well as $p_{T,\text{min}}$ and $A(b)$ [27, 28, 29]. Thus the predictions of the total γp cross-sections will depend on all these parameters apart from the information about $f_{g/\gamma}(x, Q^2)$ and $f_{q_i/\gamma}(x, Q^2)$.

Thus to recapitulate the predictions for $\sigma_{\gamma p}^{\text{tot}}$ in the framework of QCD depend on the following factors:

1. The parton densities in the photon, particularly $f_{g/\gamma}(x, Q^2)$. The range of x values that are relevant shifts to smaller values from $x < 0.01$ to $x < 0.001$ or smaller, as one goes from HERA energies to the case of the PeV energy photons relevant for the μ puzzle.
2. Value of $p_{T,\text{min}}$.
3. Modelling of the soft cross-section.
4. The probability P_{had} for the proton to go to a hadron state.
5. The transverse overlap $A(b)$ of the partons in the nucleon and the photon.

Fortunately the experiments at HERA [30, 31] also measured $\sigma_{\gamma p}^{\text{tot}}$ in addition to electro-(photo-)production of ‘hard’ jets. This information from HERA when coupled with information about the multi-jet production in $\gamma\gamma$ collisions [22, 24], can be used to reduce the uncertainty in the knowledge of $f_{g/\gamma}(x, Q^2)$ and $p_{T,\text{min}}$. The $\gamma\gamma$ data are consistent with $p_{T,\text{min}} \simeq 2.0 - 2.5$ GeV depending upon the choice of parametrisation for $f_{g/\gamma}(x, Q^2)$ and $f_{q_i/\gamma}(x, Q^2)$. But the very broad gluon distribution of LAC3

parametrisation is ruled out already by these data. The observation of the resolved contribution to large p_T jets at HERA [19, 20, 21] allows an extraction of $f_{g/\gamma}(x, Q^2)$ which is essentially consistent with almost all the modern parametrisations (that rise somewhat steeply at small x) other than LAC3 and a similar value of $p_{T,min}$. It should also be mentioned here that the present ‘extractions’ of $f_{g/\gamma}(x, Q^2)$ has large experimental as well as (Monte Carlo related) theoretical errors. Both these errors are likely to go down in further analysis/data from HERA, allowing perhaps a better discrimination.

As seen above, calculation of $\sigma_{\gamma p}^{tot}$ involves, in addition to $p_{T,min}$ and $f_{g/\gamma}(x, Q^2)$, $f_{q_i/\gamma}(x, Q^2)$, P_{had} , $A(b)$ as well as model for σ^{soft} . Here some model-builders take recourse to the low-energy measurements of $\sigma_{\gamma p}^{tot}$ to determine the model parameters. Here almost the whole cross-section is dominated by the soft process and the only relevant ‘hard’ contribution is the ‘direct’ process. As a result of these the low energy predictions are independent of $f_{\bar{q}/\gamma}$ and can determine some of the nonperturbative parameters, especially χ^{soft} quite well. The ZEUS measurement [30] along with the (pre-HERA) predictions using the eikonalised calculation mentioned above for different choices of the parameters mentioned are shown in fig. 7. The two solid curves show

Figure 7: Comparison of various predictions of total γp cross-sections with low-energy data and the recent ZEUS measurement [30].

fits to low-energy data based on Pomeron phenomenology which does not involve any ‘hard’ contribution. The two dot-dashed curves show minijet predictions [32] using the DG parametrization with $p_{T,min} = 1.4$ (upper) and 2.0 (lower curve) GeV, while the dotted and dashed curves have been obtained from the LAC1 parametrization using the same values of $p_{T,min}$. The LAC parametrization seems disfavoured but in view of the theoretical and experimental uncertainties it might be premature to exclude it altogether. The DG minijet prediction with $p_{T,min} = 2$ GeV is certainly

in agreement with the data. At the HERA energy the effect of eikonalisation on the predictions for $\sigma_{\gamma p}^{tot}$ is not very large, but it is certainly substantial when the PeV energy γ are involved. A further clarification between different models (eikonalised minijet or Pomeron based) will be possible if one can measure energy-dependence of $\sigma_{\gamma p}^{tot}$. At present, one can say definitely:

1. The resolved contribution to photoproduction of jets does rise with increasing γ energies and has been seen.
2. These processes also cause the $\sigma_{\gamma p}^{tot}$ to rise with energy. However, with $p_{T,min} \simeq 2$ GeV and almost all the current parametrisations of $f_{g/\gamma}(x, Q^2)$ and $f_{q_i/\gamma}(x, Q^2)$ this rise is much less steep than the most ‘optimistic’ pre-HERA predictions of $\sigma_{\gamma p}^{tot}$.
3. Further measurements of jet cross-sections, details of event shapes, e.g, multiplicity and various correlations [33] should provide further help in clarifying this situation.

Armed with this information now one can turn towards the predictions of $\sigma_{\gamma p}^{tot}$ for the TeV/PeV energy photons from the point γ sources. Fig. 8 shows predictions

Figure 8: $\sigma_{inel}^{\gamma air}$ and $\sigma_{inel}^{\gamma p}$ cross-section as a function of γ energy in an eikonalised model. [28].

of a particular model [28] for $\sigma_{inel}^{\gamma air}$. This model of γp interactions fits the $p_{T,min}$ from πN scattering data and the quark-gluon densities of the ‘hadronic states’ into

which the photon converts itself are related to parton-distributions for a pion. The model predictions, with the inclusion of soft scattering background, agree with data at low-energy ($8 \text{ GeV} \leq \sqrt{s_{\gamma p}} \leq 20 \text{ GeV}$) quite well and are reasonable (though somewhat high) for HERA energies. As can be seen from this figure σ_{inel} does rise with increasing E_γ (or equivalently $\sqrt{s_{\gamma p}}$) and is about $\simeq 2 - 3 \text{ mb}$ for the PeV energy photons. This falls way short of the $\sigma \simeq 100 \text{ mb}$ required to explain the muon excess observed in the CYGNUS experiment. One should keep in mind that since $\langle n_{\text{jet}} \rangle$ does rise sharply with energy (recall fig. 6) it is possible that fluctuations could sometimes produce μ rich showers. But if the future air shower experiments continue to see showers associated with point sources, with μ content as high as that seen by the earlier experiments [4], the explanation must lie somewhere else and not with the rising γp cross-sections

So in conclusion we can say that

1. There exists a hint of a μ excess seen by the extensive air shower experiments in the air showers associated with ‘point’ sources. This would mean that the γ induced showers look more like hadronic showers.
2. Since the photon does behave like a hadron at high energies and the ‘resolved’ contribution of the ‘partons in the photon’ increases with γ energy, feature (1) could have been, in principle, due to the hadronic content of γ .
3. The current collider experiments at e^+e^- (effective $\gamma\gamma$) colliders TRISTAN and LEP and ep (effective γp) collider HERA have seen these contributions coming from the hadronic structure of the photon and have provided some information about $f_{g/\gamma}(x, Q^2)$.
4. The prediction of $\sigma_{\gamma p}^{\text{tot}}$ has considerable theoretical uncertainties, but using the current experimental information from the e^+e^- , ep colliders on jet production and on $\sigma_{\gamma p}^{\text{tot}}$ from HERA, one can conclude that the hadronic structure of γ can cause an increase in $\sigma_{\gamma p}^{\text{tot}}$ by a factor of $\simeq 2-3$ for the PeV energy photons but not much more.
5. Hence the photon structure function effects can give rise to μ rich showers only as a fluctuation but if future experiments continue to report existence of extremely μ rich showers, the explanation can not be provided in terms of the photon structure.

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