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Rapid Communications

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Ultrahigh-energy photonuclear cross sections

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We present results of calculations of the total inelastic photon-air cross sections at ultrahigh energies (up to 10^8 GeV in the laboratory) of relevance to on-going cosmic-ray experiments. The calculations take into account the high-energy QCD structure of the photon and are performed for a variety of photon and proton structure functions. The total inelastic photon-air cross section is obtained from the photon-proton jet cross section via an eikonalization procedure using a QCD-based diffractive model. The results are discussed in the context of the apparent excess muon content of air showers associated with point sources.

In the past few years, a number of cosmic-ray groups have reported increasingly firm evidence for the observation of γ rays of very high energy (VHE, primary laboratory energies $E_p^{\rm lab}\sim 10\text{–}10^5$ GeV) and ultrahigh energy (UHE, $E_p^{\rm lab}\sim 10^5$ GeV and above) from point sources.[1] In addition to their obvious significance for astronomy and astrophysics, these observations may be of importance to the particle-physics community since the energy thresholds realized are currently beyond the reach of all operating accelerators. In this latter context, there also seems to be a growing (but not conclusively firm) number of indications that the muon content of air showers initiated by neutral primaries from some well-known sources (Cygnus X-3,[2] Hercules X-1,[3] and most recently the Crab nebula[4]) is anomalous. It seems to exceed, by an order of magnitude or more, the expected muon content of photon-initiated showers, and apparently approximates that of hadron-initiated showers. (We do not address here the reports of TeV muon observations in deep underground detectors[5–8] because, due to significant inconsistencies among the various experiments, they collectively lack credibility.)

Among the known particles with standard interactions, the neutron is excluded because of the distance of the sources and its decay rate, while neutrino interactions with the atmosphere are too weak to explain the muons. The photon would be an obvious candidate were it not for the hadronlike muon content observed. Cosmic-ray physics has provided major clues in the advancement of particle physics, and it is certainly possible that the excess muon content is a signal of "new" physics.[9] However, before this can be conclusively asserted, firmer experimental evidence is required. If indeed there is an anomaly, it is important to thoroughly examine the possibility that conventional, but incompletely understood, physics can explain it.

In this vein, Halzen and co-workers[10,11] pointed out that at high energies the photon can interact hadronically by producing virtual quark-antiquark pairs and bremsstrahlung gluons which can interact with atmospheric nuclei. This can lead to a final muon content in the subsequent shower which is qualitatively different from that which would conventionally be expected in a photon shower. (We recall that in the standard scenario for electromagnetic-shower development the photon produces e^+e^- pairs which subsequently bremsstrahlung as the shower develops. The magnitude of the cross section for these two processes, ~ 450 mb for electron pair production and ~ 600 mb for bremsstrahlung, dwarfs all contributions to the shower from other processes. In particular, the muon content of a photon shower is conventionally expected to be at least an order-of-magnitude smaller than that for a hadron-initiated shower.[11])

The primary purpose of this Rapid Communication is to translate the consequences of the above parton-level process into cross sections which are of direct relevance to VHE and UHE γ-ray air-shower experiments. We use the photon-proton jet cross sections to obtain the total inelastic cross section, σ_T(photon-air), for the "hadronic" breakup of an incoming photon in the atmosphere, for a large range of primary laboratory energies of relevance to cosmic-ray experiments, extending up to 10^8 TeV. We calculate $\sigma_T(\gamma\text{-air})$ using an eikonalized QCD-based diffractive model which treats the incoming high-energy photon and the target nucleus as distributions of uncorrelated partons. We find that semihard interactions at the parton level drive a sharp increase in $\sigma_T(\gamma\text{-air})$, with results which differ radically from conventional calculations of this quantity.

We begin by giving the QCD jet cross section for photon-proton interactions:

$$\sigma_{\rm QCD}(\gamma+p\to 2\ \text{jets})=\sum_{ij}\frac{1}{1+\delta_{ij}}\int dx_\gamma dx_p\int_{p_{t,\min}^2} dp_t^2[f_i^{(\gamma)}(x_\gamma,\hat{Q}^2)f_j^{(p)}(x_p,\hat{Q}^2)+i\leftrightarrow j]\frac{d\hat{\sigma}_{ij}}{dp_t^2}(i+j\to 2\ \text{jets}). \quad (1)$$

Here, a caret denotes a parton-level quantity. The $\hat{\sigma}_{ij}$ are thus the appropriate parton-parton interaction cross sections for partons i and j, the expressions for which may be found, for instance, in Ref. 12. $f_i^{(\gamma)}(x_\gamma,\hat{Q}^2)$ $[f_j^{(p)}(x_p,\hat{Q}^2)]$ is the probability that the photon [proton] contains a parton i [j] which carries a fraction x_γ [x_p] of its momentum. $\hat{Q}^2$ characterizes the scale of the parton-level process. A theoretical analysis[12] of the CERN minijets[13,14] indicates that in the low-p_t regime the choice $\hat{Q}^2=p_t^2$ provides the best agreement with experimental data, and we use that choice of scale in our calculations. We also note that the photon structure functions are proportional to $\alpha_{\rm em}/\alpha_s$, where $\alpha_{\rm em}$ is the electromagnetic coupling.[15] The effective order of the above processes is therefore $\alpha_{\rm em}\alpha_s$, since the jet cross sections are of order α_s^2. Thus, they are of the same order as conventional two-jet processes, in which the photon-parton vertex is electromagnetic and does not involve the photon's hadronic content. These have been included in the results shown in Figs. 2 and 3, but their contribution at the energies under consideration is completely negligible.

In this study, we have looked at seven different structure functions[16–19] for the quark-gluon distributions within the proton. The results are not very sensitive to different choices and we have used the Eichten-Hinchliffe-Lane-Quigg[17] (EHLQ) distribution for most of the curves displayed in the figures. For comparison, however, a curve using the Martin-Roberts-Stirling (MRS, set 1) distribution[19] is also included in Fig. 3.

For the photon, we have performed calculations with the Duke and Owens[20] (DO) distribution and the Drees and Grassie[21] (DG) distribution. The results in the UHE regime depend sensitively on which of these is chosen, as we discuss below. Finally, the standard expression for α_s is used, with four flavors and $\Lambda=200$ MeV.

The procedure we use to compute the total inelastic cross sections from QCD jet cross sections has been employed previously to obtain the proton-air cross sections at very high energies, and the results are in very good agreement with cosmic-ray and accelerator experiments.[22] Here, we simply give the basic equations underlying the results:

$$\sigma_T(\gamma\text{-air})=2\pi\int db\, b\left\langle i\left|1-\exp\left[-2\sum_{j=1}^{A}\chi_j^R\right]\right|i\right\rangle .$$

Here χ^R is the real part of the photon-nucleon eikonal function, and b is the impact parameter of the photon, viewed at ultrahigh energies as a collection of uncorrelated quarks and gluons. The complete nuclear eikonal function is a sum over the eikonal functions of the individual nucleons and the expectation value averages over the initial nuclear state i. Quasielastic processes in which the nucleus is broken up, but no new particles are produced, have been summed over using a closure approximation.

The photon-nucleon eikonal function χ^R is given in the parton picture by[22]

$$\chi^R(b,s)=\tfrac{1}{2}A(b)[\sigma_{\rm soft}+\sigma_{\rm QCD}(s)] ,$$

where $\sigma_{\rm QCD}$ is given in Eq. (1); $\sigma_{\rm soft}$ is an approximately constant cross section consistent with low-energy photon-nucleon data and s is the square of the center-of-mass energy. The geometrical factor $A(b)$ is given in terms of the proton and photon form factors by

$$A(b)=\frac{1}{2\pi}\int G^{(p)}(k_t^2)G^{(\gamma)}(k_t^2)J_0(k_t b)k_t dk_t .$$

In the calculations reported here we used the standard dipole form factor for the proton,

$$G^{(p)}(k_t^2)=\left[\frac{\nu^2}{\nu^2+k_t^2}\right]^2,\ \nu^2=0.71\ (\text{GeV}/c)^2 ,$$

and a pionlike form factor for the photon:

$$G^{(\gamma)}(k_t^2)=\frac{\mu^2}{\mu^2+k_t^2},\ \mu^2=0.47\ (\text{GeV}/c)^2 .$$

We begin our discussion of the results by addressing two issues to which they are sensitive. These are, first, the choice of $p_t^{\min}$, the lower bound on the transverse momentum of the outgoing jets and, second, the photon structure function used. To a great extent, this sensitivity mirrors our ignorance of hadronic physics at high energies, low p_t, and low parton fractional momentum x. Even though the precise value of p_t at which higher-order effects become important is difficult to pin down theoretically, certain considerations can guide us to reliable choices. We note that the form of the cross section must remain qualitatively and semiquantitatively valid even when nonperturbative effects begin to come in. In other words, the QCD and soft parts must merge smoothly. The soft part typically has a momentum scale of ≈ 500 MeV. For the specific values chosen here, we have relied upon an analysis of low-energy data[23] (up to 20 GeV center-of-mass energy) on γ-p interactions. This indicates that towards the upper end of the energy range, a rise of about 3% is seen in the total cross section. This is presumably the tail of the expected increase due to QCD effects. For this region, the DG and DO structure functions give similar results and

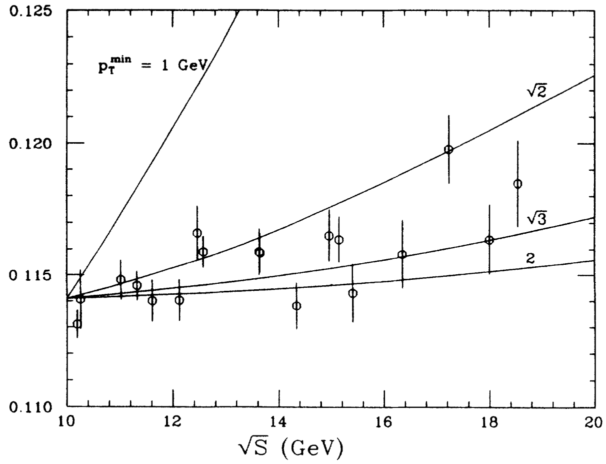

FIG. 1. Low-energy fits to the data of Ref. 23 to determine the $p_t^{\min}$ values used in our calculations. The curves are $\sigma_T = \sigma_{\rm soft} + \sigma_{\rm QCD}$, with the soft part adjusted to always give the same cross section at $\sqrt{s} = 10$ GeV. The curves are for $(p_t^{\min})^2 = 1$, 2, 3, and 4 GeV^2. The best value of $p_t^{\min}$ lies in the range ~ 1.5 to 2 GeV, while 1 GeV is ruled out by the data. The DG and DO structure functions agree in this range of energy.

our calculations indicate that the observed rise corresponds to a $p_t^{\min}$ value between 1.5 and 2 GeV (see Fig. 1). We give results for both these values. Note that the choice $p_t^{\min} = 1$ GeV seems to be clearly ruled out. The forthcoming Fermilab fixed-target γ-p experiment and results from the DESY ep collider HERA should help to fix the value of the transverse-momentum cutoff better, and provide much-needed information about the photon's hadronic content.

Figures 2 and 3 show our results for the photon-proton

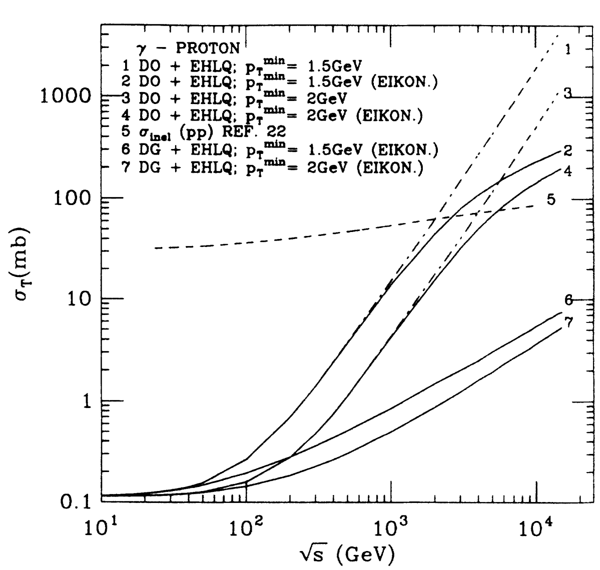

FIG. 2. Jet (dashed curves) and eikonalized (solid curves) inelastic cross sections vs total center-of-mass energies for photon-proton interactions for the various choices of transverse jet momentum cuts and structure functions discussed in the text.

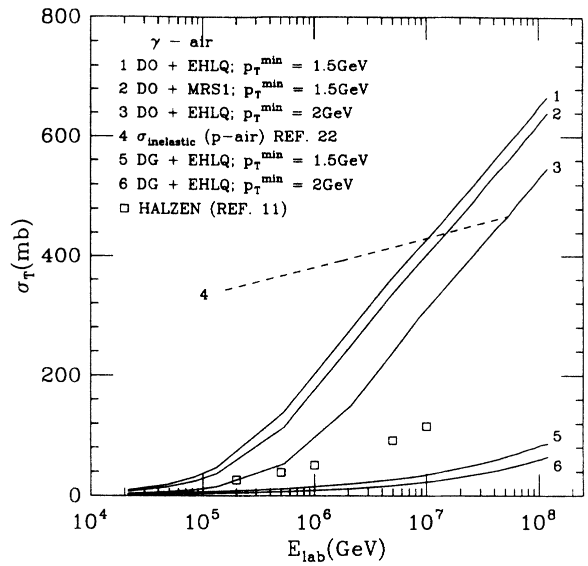

FIG. 3. Total inelastic cross sections for photon-air interactions vs the laboratory energy of the incoming primary photon. Solid lines are for various choices of $p_t^{\min}$ and different structure functions, as discussed in the text. The squares represent the calculation of Ref. 11, where the DG structure function is used for the photon and that of Ref. 18 for the proton, with a $p_t^{\min}$ of 1 GeV. Note that the DO curves are not a realistic estimate of the cross section. They serve to provide an upper limit on the possible range and to show the strong dependence of the results on the choice of the photon structure function.

and photon-air interactions, respectively. It is evident that the results are highly sensitive to the photon structure function chosen. The DO structure function, although satisfactory for photon energies up to ~ 100 GeV, gives unreasonably large cross sections at PeV energies. For the small values of x ($\leq 10^{-4}$) which dominate this calculation, the DO gluon distribution function in the photon is $G_\gamma^{\rm DO} \approx G_0(1 - x_\gamma)/x_\gamma^2$, where G_0 is a constant. This leads to a photon-proton cross section which, through its gluon component, grows roughly as s at high energies. Such behavior is evidently unrealistic, since at center-of-mass energies in the TeV range it leads to γ-p cross sections which exceed p-p cross sections. Curve 5 in Fig. 2 and curve 4 in Fig. 3, which give the total inelastic p-p and p-air cross sections,[22] respectively, illustrate this point. The physical picture underlying our calculations is that the photon produces a q-$\bar{q}$ pair with a probability proportional to $\alpha_{\rm em}$, and the subsequent QCD evolution fills up the confinement volume with quarks and gluons with a density much as in a pion or nucleon. The DO structure function is thus in conflict with this picture, since it is much more singular than either the proton or pion structure functions at low x. For this reason, the cross sections obtained with the DO function should be treated as extreme upper bounds. Those obtained from the DG structure function are a reasonable fraction of the corresponding proton cross sections, and are more realistic. However, as discussed in Ref. 10, they are probably too conservative, since the procedure employed in Ref. 21, if used to obtain the gluon structure function of the proton, considerably underestimates it. Until more information on the hadronic content of the photon is available, there is little one can do to avoid this uncertainty, and the DO and DG curves in Figs. 2 and 3 serve to provide upper and lower bounds, respectively, on the cross sections. In addition, they emphasize the dependence of the results on the photon structure function chosen.

As one would expect, the inclusive γ-proton jet cross sections (dashed curves in Fig. 2) rise rapidly with energy because of increasing contributions from the parton-level processes, $gg \rightarrow gg$ and $gq \rightarrow gq$, at small x. This rise is the most striking feature of QCD (as opposed to conventional QED) cross sections for γ-p interactions. In the QED case, one expects a cross section of ~ 0.1 mb, roughly independent of energy. All our results are strongly energy dependent; curve 6, for instance, yields a value of ~ 1 mb at 10^3 GeV, while the less conservative estimates provided in curves 2 and 4 are much higher. The high values of the cross sections (especially for curves 1 and 3) result from the presence of multiple parton-parton collisions (multiple jets) in a single γ-p collision, and lead to violations of partial-wave unitarity if the inclusive jet and the inelastic cross sections are (improperly) equated. The solid curves, which begin to deviate from the dashed ones at ~ 1 TeV, give the properly eikonalized inelastic cross sections for all choices of transverse momenta and structure functions. As is evident, these are significantly different from the jet cross sections in the UHE regime for EHLQ+DO structure functions.

Results for the eikonalized total inelastic cross section for γ-air are shown in Fig. 3. The sensitivity to the choice of photon structure function is even more apparent here. Results obtained using the DO function serve as an extreme upper bound on the expected cross sections, exceeding the p-air results (curve 4) at $\approx 10^7$ GeV laboratory energies ($p_t^{\min} = 1.5$ GeV) and at $\approx 5 \times 10^7$ GeV ($p_t^{\min} = 2$ GeV). The results are much less sensitive to the choice of proton structure function, as shown in curves 1 and 2, calculated using the EHLQ (Ref. 17) and MRS (Ref. 19) sets. The sensitivity is further reduced for the DG photon structure function. Also shown are results from Ref. 11 (curve 7), where a $p_t^{\min}$ of 1 GeV was chosen, along with DG structure functions for the photon and those of Ref. 18 for the proton.

Finally, we emphasize the point that the hadronic structure of the photon dramatically changes the conventional picture of photon-air interactions in the UHE regime. The standard γ-air cross section is ~ 1.5 mb, and is expected to be roughly constant (or logarithmically rising) with energy. The cross sections presented here, which increase much more with energy, are much larger than this old standard, notwithstanding the uncertainties in the calculation. For instance, our most conservative estimates lead to a value ≈ 20 mb at laboratory energies of 10^6 GeV. To obtain a better idea of the difference this makes to cosmic-ray experiments, we apply them to the case of a UHE photon impinging on the atmosphere.

The probability that the photon's first interaction in air is a QCD interaction and, hence, that the photon acts hadronically from the start is given by the ratio $\sigma_T/(\sigma_T + \sigma_p)$. The γ-air cross sections depicted in Fig. 3 imply that at the highest energies of this study ($E_{\text{lab}} \sim 10^8$ GeV), the photon can be quite hadronic ($\sim 50\%$) only if the unreasonably large DO structure function is employed. However, the trends seen in Fig. 3 imply that, for *all* the curves, there is a laboratory energy above which the photon is hadronic in character from the start of its cascade in the atmosphere. Even if the first few photon interactions are electromagnetic and a classic pair-photon cascade begins, there is an increased chance that early in the cascade a photon will interact hadronically and yield a rich muon harvest. We will defer a full Monte Carlo analysis to a later work. However, a simple-minded Monte Carlo simulation of a photon-initiated cascade through the high-energy regimes in Fig. 3 can illuminate the potential of these new cross sections to explain muon richness.

We have calculated two quantities for curves 1, 3, and 5 of Fig. 3: (i) the probability (P_1) that the first interaction is hadronic and (ii) the probability (P_2) that a QCD jet is produced in the photon-initiated shower before $E_\gamma = 100$ TeV is reached in the cascade. Table I depicts these results for various primary energies. We see immediately that even when P_1 is modest, P_2 can be large and is a stiffly increasing function of energy. However, it is only when the DO structure function obtains that there is a good chance that a photon-initiated shower will have hadronic character somewhere early in the cascade. Though it is only for the unrealistically high cross sections of curves 1 and 2 in Fig. 3 that a PeV photon primary can mimic a hadron's muon yield a majority of the time, the general trend towards hadronic character in P_1 and P_2 is suggestive.

To summarize, we have investigated the hadronic nature of UHE photons. Respecting unitarity constraints, we have calculated total inelastic photon-proton and photon-air cross sections in a form directly useful to ongoing cosmic-ray experiments. An effort has been made to minimize the uncertainty in the p_t cutoff (by analyzing

TABLE I. P_1 is the probability that the first γ-air interaction will be hadronic in character, while P_2 is the probability that the γ-initiated shower will have at least one hadronic-type interaction between E_{lab} and 100 TeV. We emphasize that the DO results below are not to be treated as realistic estimates, but as extreme upper bounds, as discussed in the text.

	E_{lab} (PeV)	P_1 (%)	P_2 (%)
Curve 1:	0.3	15	24
DO+EHLQ	1.0	30	66
$P_t^{\min} = 1.5$ GeV	10.0	47	100
	100.00	57	100
Curve 3:	0.3	7	10
DO+EHLQ	1.0	16	36
$p_t^{\min} = 2$ GeV	10.0	40	99
	100.0	50	100
Curve 5:	0.3	2	3
DG+EHLG	1.0	3	12
$p_t^{\min} = 1.5$ GeV	10.0	7	72
	100.0	14	100

available low-energy data and considerably narrowing its possible range) and in the photon structure function (by making a comparison with high-energy p-p and p-air cross sections and using them as upper bounds on γ-p and γ-air cross sections). Although this still leaves us with a range of "possible" cross sections, the analysis makes clear that it is the lower, and not upper, end of this range that is probable. Nevertheless, the simple Monte Carlo analysis of the last section demonstrates that even at their lowest values, the QCD-enhanced cross sections of the photon demand a revision of Monte Carlo techniques currently used to analyze air-shower data before a final verdict on the muon anomalies can be given.

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