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# TeV to EeV Diffuse Gamma Rays and Neutrinos*

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## Abstract

We discuss the origin and detection of diffuse $\gamma$ rays and neutrinos of TeV energy and above. Their detection can provide us with clues on the mystery of where and how cosmic rays are accelerated above PeV energy even in the absence of the direct detection of their sources. Diffuse photon and neutrino fluxes are produced by interaction of the high energy cosmic rays with the interstellar gas and with cosmic background photons. Speculations also exist on the existence of diffuse fluxes directly produced by cosmic ray accelerators such as active galactic nuclei. Detection of any diffuse flux is challenging but could be within reach of a new generation of Cherenkov-, air-shower and neutrino telescopes.

## 1. Introduction

The confirmation of the detection of point sources of PeV ($10^{15}$eV) and EeV ($10^{18}$eV) $\gamma$-rays has been a frustrating task. Improved detectors establish flux limits at the 5% level of the sporadic fluxes of sources like Cygnus X-3 and Hercules X-1 reported several years ago.[1] What is certain, however, is that cosmic rays of PeV energy and above do exist and that their origin remains a total mystery. Standard wisdom is that the bulk of the cosmic rays originate in galactic supernova remnants. A supernova accelerator is, however, unable to accelerate cosmic rays above PeV energy for reasons that are essentially dimensional.[2] It is generally believed that the break in the cosmic ray spectrum, referred to as "the knee," is associated with the cut-off in the energy of particles accelerated by supernova blast waves. The excitement about the search for point sources is very much related to the fact that they might be the accelerators of the highest energy cosmic rays. In this talk I emphasize that one can search for indirect clues on the origin of cosmic rays by searching for diffuse photon and neutrino background radiation. One attractive feature is that the fluxes, unlike those of point sources, can be reliably predicted. The experimental goal is well defined but challenging as we will see further on.

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The galactic component of the high energy cosmic rays is the source of a diffuse background of high energy photons resulting from interactions of the particles with interstellar gas in the galactic disc.[3] The flux is mostly confined to the plane of the galaxy and is predicted at a level of $10^{-5}$ of the cosmic ray flux. As the production and subsequent decay of pions is the origin of the photons, a roughly equal (or larger) diffuse flux of neutrinos must exist.

It is generally believed that the cosmic rays beyond the 10 EeV break in the spectrum, referred to as "the ankle," are extra-galactic. Their presence in the spectrum is signalled by a decrease in the spectral index near the energy where the gyroradius of galactic cosmic rays is too large for the particles to be effectively contained in the galaxy. The observation of an isotropic diffuse photon flux produced by the highest energy cosmic rays on the cosmic photon background, would confirm their extra-galactic origin. Although the benchmark calculation,[4] presented here, will predict a diffuse flux at the $10^{-5}$ level of the cosmic ray flux at PeV energy, i.e. a value close to that predicted for the radiation from the plane of the galaxy, and as large as $10^{-1}$ above EeV energy, one should regard the results as a lower limit. Extra-galactic photon production is a cosmological process. The calculation conservatively assumes that nearby active galaxies, at distances of order 100 Mpc or less, are the origin of the bulk of the extra-galactic cosmic rays. The flux of cosmogenic photons will be increased if the density of cosmic rays was larger at some early epoch, e.g. during galaxy formation. This is referred to as a "bright phase."[5] Also, it has recently been pointed out that the totality of all active galaxies might produce a "direct" diffuse background.[6] The possibility has been raised that "all" cosmic rays, not accounted for by supernovae, are of AGN origin[7] and that their diffuse neutrino flux actually dominates the atmospheric background above 100 TeV energy. The recent discovery[8] that Markarian 421, a nearby blazar, emits TeV gamma rays with a luminosity which may account for a significant fraction of the cosmic ray flux, has given sudden respectability to these speculations.[9]

We will review the status of the theoretical estimates. A conservative experimenter will however aim for diffuse fluxes at the $10^{-5}$ level of the cosmic ray flux. Increased sensitivity to photons is, of course, worth achieving even in the absence of reaching the $10^{-5}$ mark. We will review the experimental possibilities: i) improved imaging techniques for Cherenkov observations, ii) proton rejection by muon content in air shower experiments and, iii) neutrino searches.

## 2. Radiation from Cosmic Ray Interactions in the Galaxy

The photon emission from matter in the galaxy irradiated by cosmic rays, first observed by the SAS-2 and COS-B satellite experiments,[10] should extend to PeV energy. A realistic calculation of the high energy flux is important as a new generation of gamma ray telescopes in the TeV and PeV energy range may have the capability to search for a photon component in the primary cosmic ray spectrum smaller than $10^{-4}$. The extrapolation of the satellite data is straightforward. Imagine a concentration of matter of density $\rho$ and linear dimension $R$. The flux at Earth of photons and neutrinos generated by the decay of pions produced in interactions of cosmic rays with this matter is given by

$$\Phi_{\gamma,\nu} = \phi_{\mathrm{CR}} f_A \left[\frac{\sigma_{\mathrm{inel}}}{m_N}\right] \frac{4}{3}[\rho R] \frac{2 z_{N\pi}}{\gamma + 1} , \tag{1}$$

where $\Phi_{CR}$ is the cosmic ray flux per steradian, $\sigma_{inel}$ the total inelastic $pp$ cross section, $m_N$ the nucleon mass, $\rho R$ the column density of the source, $z_{N\pi}$ is

$$z_{N\pi} = \int dx\, x^{\gamma} \frac{d\sigma}{dx} \tag{2}$$

for neutral and charged pion production, respectively, and $\gamma$ is the spectral index of the cosmic ray spectrum. The factor $f_A$ is a correction for the fact that some of the primaries and targets are nuclei. For $\gamma = 1$ in Eq. (2), $z_{N\pi}$ is the average Feynman-x of pion production by nucleons. In our estimates we have explicitly taken into account the energy dependence of all these quantities,[11] including that of the spectral index $\gamma$. Neglecting this energy dependence, Eq. (1) states that the ratio of the diffuse photon to cosmic ray flux is proportional to $\rho R$ and about $6 \times 10^{-5}$ for a density of 0.1 grams/cm$^2$. Using Eq. (1), maps of the linear column density of the galaxy can be directly translated into photon and neutrino fluxes.

In our calculation we will use the maps of the column density $n_H$ of $H_I$ and $H_{II}$ of Bloemen. The particle physics parameters were calculated as a function of energy using the mini-jet model with energy-dependent inelastic cross sections. Following Dermer[10] we took $f_A = 1.45$ in order to take into account the presence of heavier elements in both beam and target. Shown in Fig. 1 is the column density of atomic and molecular hydrogen averaged in longitude bins of 10 degrees in the galactic plane. The galactic disk has been defined as extending between $b = -10$ and $b = +10$ degrees, a choice which is appropriate for PeV air shower observations. The width can be reduced for TeV observations. This will result in an increased signal-to-noise ratio. The right-hand scale shows the predicted flux of $\gamma$ rays above 100 TeV which is, according to our assumptions, proportional to the density $n_H$. The integral flux above 100 TeV is $2.7 \times 10^{-14}$ photons per cm$^2$ per second per steradian at $n_H = 10^{22}\,\mathrm{cm}^{-2}$. The calculation is in good agreement with flux calculations from the galactic center.[12] In comparing with data it is also important to take into account the time averaged threshold and the effective area of the detector as a function of the galactic longitude. After applying such corrections to our calculation for the Chicago-Michigan experiment in Utah, we compare in Fig. 2 the expectations with their data which represent the best limits achieved today.[13] We conclude that the sensitivity of the experiment falls short by about an order of magnitude. For TeV telescopes this gap is, if anything, slightly larger.[14] There are several molecular clouds that have sufficient column density to yield non-negligible fluxes, e.g. Orion with a column density of $n_H = 2.4 \times 10^{22}\,\mathrm{cm}^{-2}$ emits a flux close to $10^{-13}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$.

It should be pointed out, however, that our analysis made the usual hidden assumption that the cosmic ray density is uniform throughout the galaxy. The measurement is indeed of interest to cosmic ray physics because the predictions are sensitive to such assumptions. There is a hint in the COS-B data[15] that the cosmic ray spectrum is harder in the outer Galaxy ($90° < l < 270°$). The spectral index $\gamma$ is reduced by 0.4 which might be an indication of an increase in the cosmic ray lifetime as predicted by some models. Extrapolating this flattened spectrum, obtained for 5 GeV photons, all the way to 100 TeV yields the revised flux predictions for the 30°–220° longitude range shown in Fig. 2. We also show the predictions for a change in spectral index of 0.3, 0.2 and 0.1. The experiment rules out a change as large as 0.4 all the way

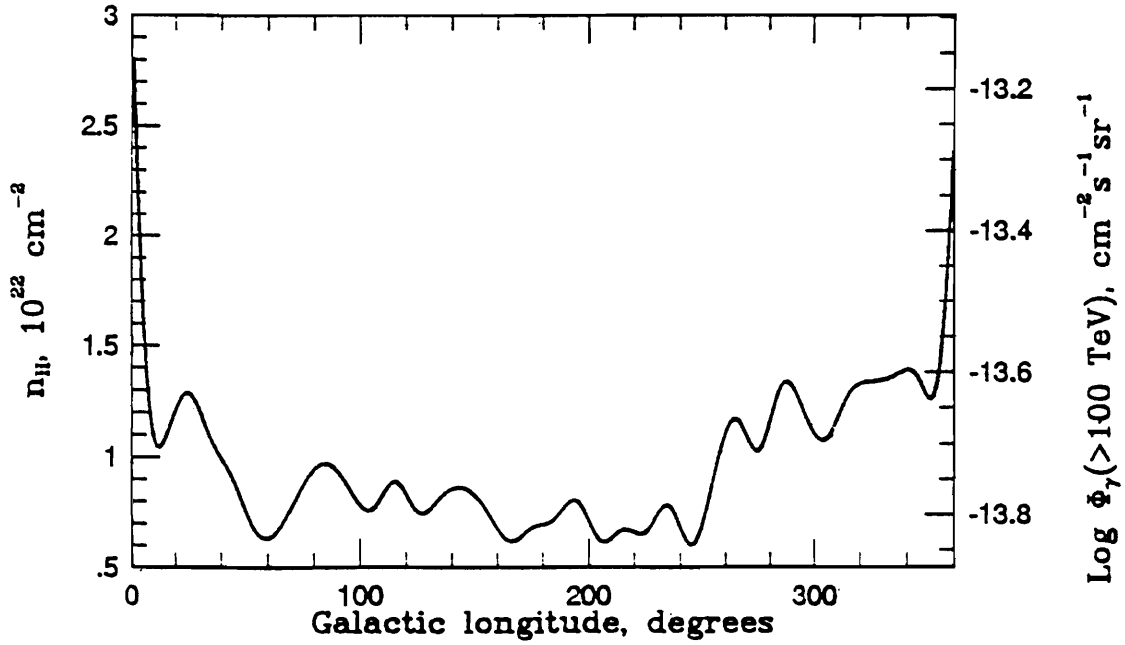


Fig. 1. Column density of hydrogen in the galactic plane ($-10$ degrees $< b <$ 10 degrees) averaged in longitude bins of 10 degrees. The right hand side shows the flux of $\gamma$-rays above 100 TeV.

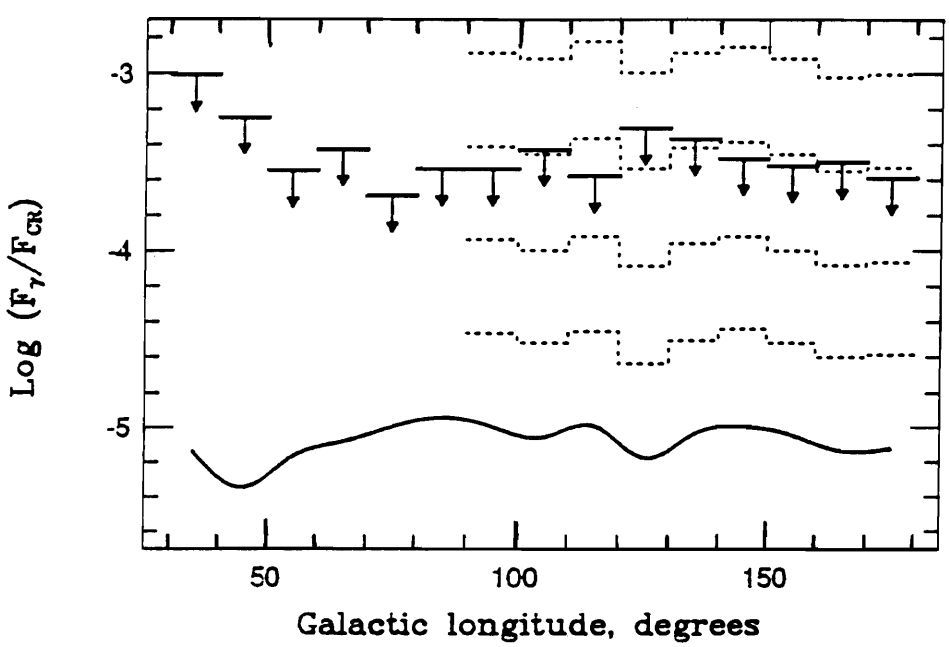


Fig. 2. Upper limits on the diffuse photon flux from the galactic plane are compared to the prediction of reference 3. Also shown is the effect of reducing the spectral index of the cosmic ray flux in the outer galaxy by, from top to bottom, 0.1, 0.2, 0.3 and 0.4.

up to Pev energy. The discussion illustrates the relevance of diffuse photon limits/observations to our search for the origin of the highest energy cosmic rays.

We finally comment on the flux of neutrinos obtained from Eq. (1). We calculate a flux of 0.3 detected neutrinos per year from Orion for a $10^5 \mathrm{m}^2$ telescope with a threshold of 1 TeV. The number is obtained after multiplying with a factor of 2 in order to take into account that neutrinos are produced by the decay of muons as well as pions. A South Pole neutrino telescope[2] views 1.1 steradian of the outer Galaxy with an average density of 0.013 grams/cm$^2$. The predicted number of events is 5 per year within 10 degrees of the disk. This would be increased to 15 events if the spectral index were indeed as small as 1.4 in the outer Galaxy. One should bear in mind that these rates are significantly below the background of neutrinos from cosmic ray interactions in the atmosphere.

## 3. Cosmogenic photons

We next investigate the possibility that a fraction of the cosmic rays are extra-galactic. Although, as previously discussed, it is a common assumption that cosmic rays above the "ankle" are extra-galactic, models exist where all cosmic rays with energy in excess of the PeV supernova cut-off come from active galaxies.[7] Such cosmic rays travel over distances of 100 Mpc or more through a Universe filled with cosmic photons of known energy ($kT = 2.7\,\mathrm{K}$) and density ($N_\gamma = 400\,\mathrm{cm}^{-3}$). A diffuse photon and neutrino flux is generated in their interactions with the cosmic photons

$$\begin{array}{lcl} p+\gamma & \rightarrow & \pi^0 \quad + \quad \pi^\pm \quad + \quad X \\ & & \hookrightarrow \gamma+\gamma \quad \hookrightarrow e^\pm\nu \\ p+\gamma & \rightarrow & p+e^+e^- \end{array} \tag{3a, 3b}$$

Calculation of the diffuse flux requires a model for the sources.[16] Because the source flux is distorted by propagation through the cosmic photon background, it is different from the flux observed at Earth. It has been pointed out,[4] however, that the effect of reactions (3a,b) is weak below an energy of $5 \times 10^{18}\,\mathrm{eV}$. Therefore, below that energy, the data reveal the source flux essentially without distortion. It can be fitted as

$$\rho_p(E_p) = \frac{4\pi}{c} I_p(E_p) = 1.5 \times 10^{-43} \left[\frac{E_p}{10^{18}\mathrm{eV}}\right]^{-2.94} \left(\mathrm{cm}^{-3}\mathrm{eV}^{-1}\right) , \tag{4}$$

We further assume that this flux is isotropic and extends up to a distance of only $R = 300\,\mathrm{Mpc}$. This benchmark calculation will therefore establish a minimal value for the diffuse flux created by local sources such as nearby active galaxies. A corollary to this assumption is that although the cosmic rays are extra-galactic, they have been uniform for the last $10^9$ years and have no cosmological history. Predicted fluxes of diffuse $\gamma$-rays and neutrinos produced by these cosmic rays on the 3K background are very large. One must, however, take into account that our galaxy is not transparent to high energy photons. The photons are themselves absorbed by the 3K background via the reaction

$$\gamma\gamma \rightarrow e^+e^- , \tag{5}$$

which has a threshold near 1 PeV. Taking this into account we obtain the larger flux shown in Fig. 3. Photons of very high energy are further absorbed by the higher order QED process $\gamma\gamma \to (e^+e^-)(e^+e^-)$ as well as by interaction on the radio background. Inclusion of these processes yields the lower estimate shown in Fig. 3. While the cosmic rays lose energy in interactions with cosmic photons resulting in the Greisen-Zatsepin cut-off, a photon flux emerges which is at the level of 10% of the cosmic ray flux at the highest energies; see Fig. 3. Observation of this flux might be within range of future experiments such as the upgraded Fly's Eye detector HIRES[17] or air shower arrays of 100 km$^2$ area. Observing the predicted neutrino flux, also shown in the figure, is, however, not likely unless it is boosted by the type of cosmological enhancements mentioned in the introduction.

There is an interesting sequel to this story. The interaction of "first generation" photons with the cosmic background leads to a suppression of their flux near the Greisen-Zatsepin cut-off, as just described. The energy-loss of the photons is dumped in an electromagnetic cascade which will evolve until the photons fall below the threshold for producing electron pairs on the 3K background. A photon flux will thus pile up just above the PeV threshold of the reaction of Eq. (5). As a result, a diffuse flux of PeV photons, also of cosmological origin, is predicted at a level $10^{-5}$ of the cosmic ray flux. The result is shown in Fig. 4. The diffuse flux from the galactic plane, discussed in Section 2, is shown for comparison. Both peak at the $10^{-5}$ level of the cosmic ray flux near 100 TeV which, conveniently, corresponds to an energy where air shower arrays have optimal sensitivity.

This PeV flux of cosmogenic photons is isotropic. Its prediction should be very reliable as it is basically obtained by energy conservation. The energy-loss of the photons near the Greisen-Zatsepin cut-off is dumped in photons just above the threshold of the reaction $\gamma\gamma \to e^+e^-$. The detailed spectrum and the composition of the cosmic rays do not matter. The result does depend on our assumptions that the prominent sources are within a radius of 300 Mpc. Roughly

$$\frac{I_\gamma}{I_{\rm CR}} = 10^5 \left[\frac{R}{300\,{\rm Mpc}}\right]^n , \tag{6}$$

with $n \simeq 1$. One cannot, however, abuse this linear dependence to generate fluxes much larger than the one anticipated in Fig. 4 as PeV photons are absorbed on optical and IR light over distances much larger than 300 Mpc.[16]

## 4. Diffuse fluxes from AGN

The flux of PeV cosmic rays in our galaxy is roughly $4 \times 10^{38}$ergs/sec. A few "super-Eddington" cosmic accelerators in our galaxy could explain their origin. Some believe Cygnus X-3 is such a source. Even when subscribing to the theory that point sources are the origin of PeV cosmic rays, one should realize that it is not at all obvious that they must be galactic. A quasar might be more distant by a factor $10^4$ (100 Mpc versus a typical galactic distance of 10 kpc), it will yield the same cosmic ray flux at Earth if its luminosity is higher by a factor $(10^4)^2$. Quasars with luminosity $10^{46}$ergs/sec do exist and are, in the absence of any other information, as likely a source of PeV cosmic rays as galactic cosmic accelerators such as Cygnus X-3.

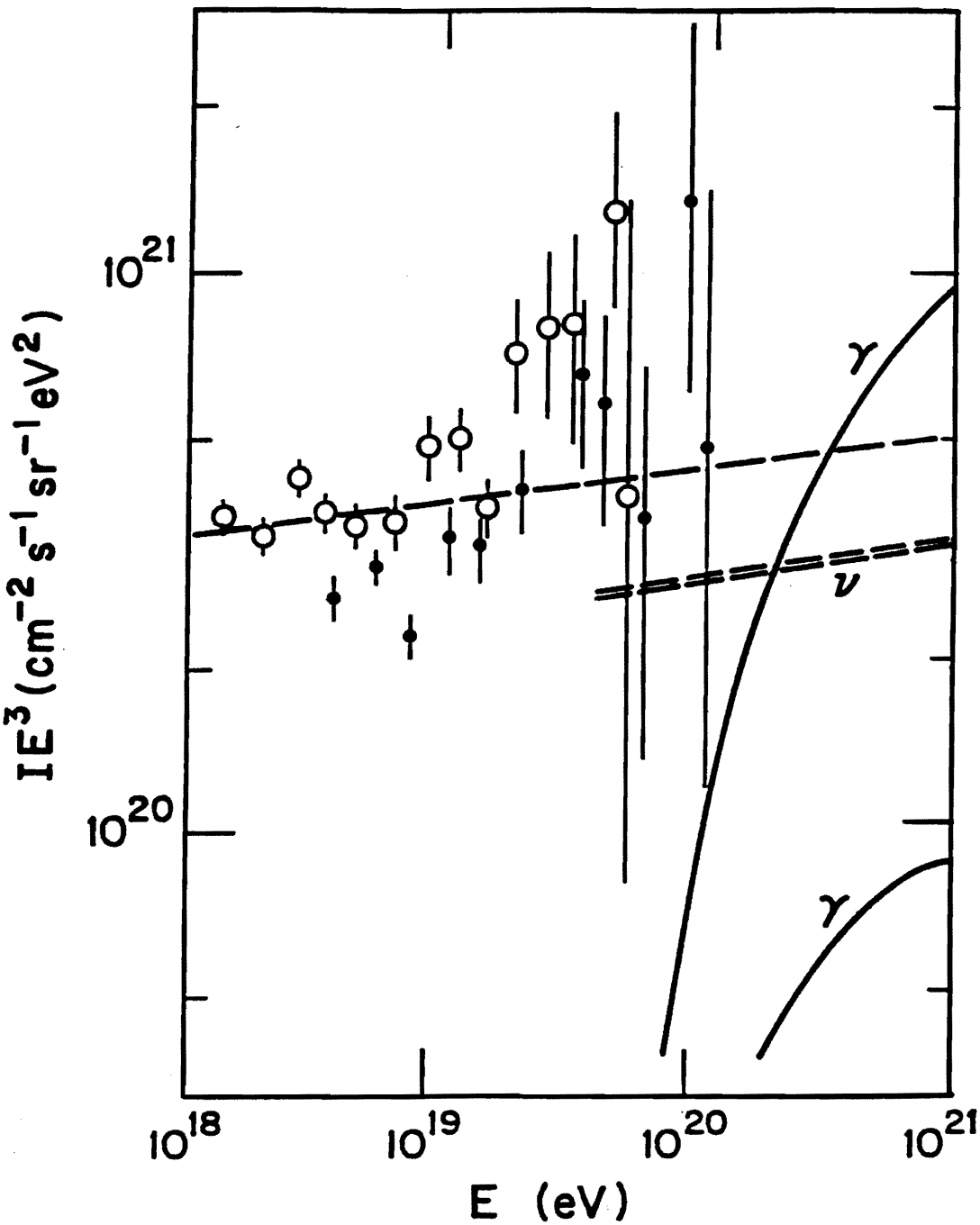


Fig. 3. Experimental data on the high energy cosmic rays are compared to a fit (dashed line) to the undistorted proton spectrum in the 1–10 EeV energy range. A cosmogenic $\gamma$-ray flux, from photoproduction of neutral pions on cosmic photons, is obtained after taking into account their absorption by the reaction $\gamma\gamma \rightarrow e^+e^-$ (upper curve). Taking into account absorption by higher order processes and radio-photons yields the lower curve. The double dashed line is the neutrino flux from the photoproduction and decay of charged $\pi$'s.

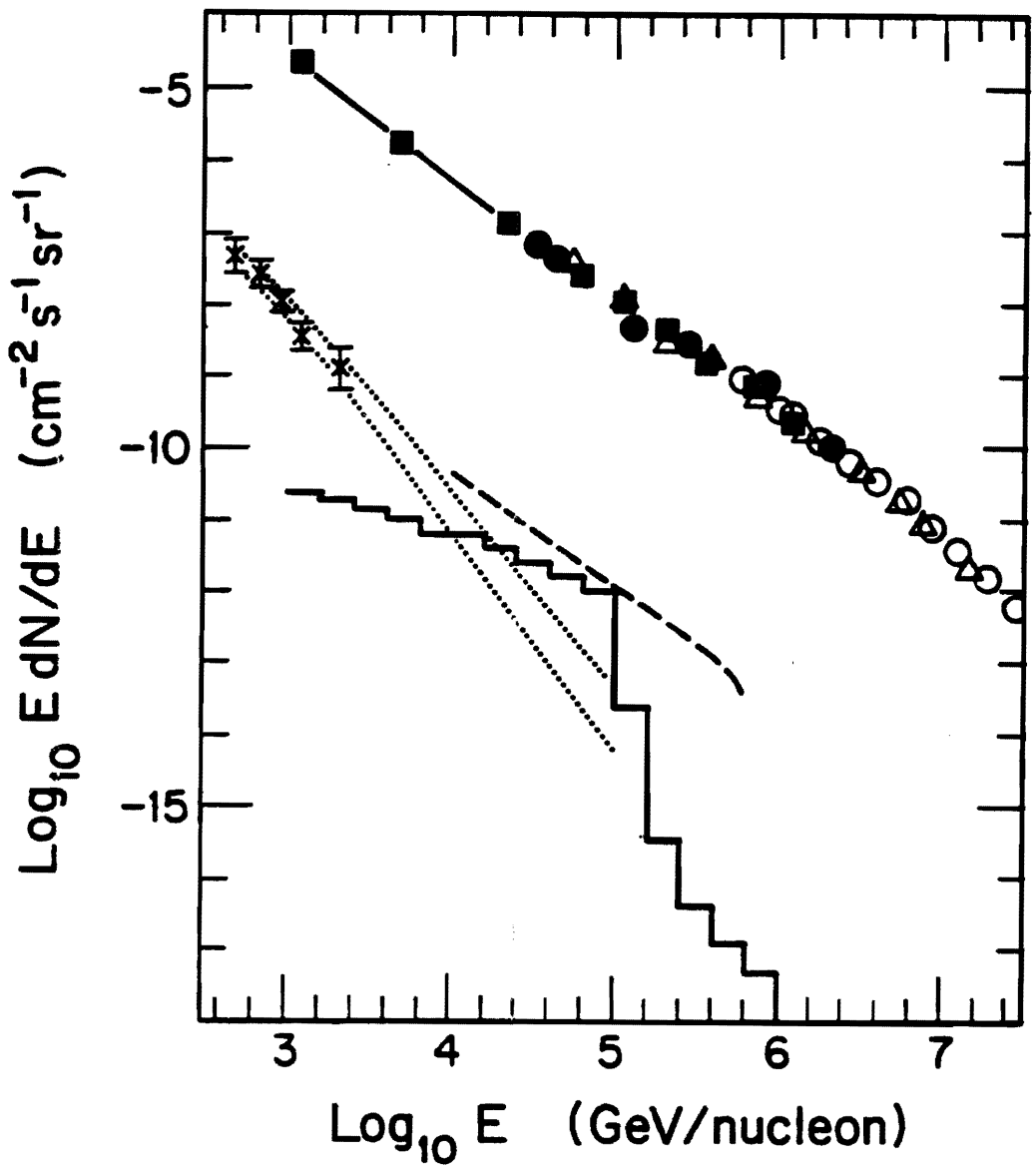


Fig. 4. Predictions for the fluxes of diffuse photons from the interactions of cosmic rays with interstellar matter in the galaxy (dashed line) and with cosmic background photons (histogram). Data on the cosmic ray and electron flux (dotted lines) are shown for comparison.

Szabo and Protheroe[7] have recently produced a scenario where the cosmic rays beyond the knee are indeed of AGN origin, with the cosmic rays near the knee being predominantly accelerated in the nearby source NGC4151. Obviously Markarian 421, which has been observed[8] to emit TeV gamma rays with fluxes at Earth similar to those from a galactic accelerator such as the Crab supernova remnant, might be a first identification of an important extra-galactic cosmic ray source.[9]

AGNs received much attention[2,18] in the high energy neutrino astronomy community because they are likely sources of neutrinos. The neutrinos, unaffected by the ambient matter inside the active galaxy or by interstellar infra-red star light, are likely to produce much larger signals at Earth than the attenuated high energy photons. AGNs such as Markarian 421 and NGC4151 are a cast of hundreds and it has been recently pointed out that their combined fluxes may be the source of a large diffuse neutrino flux.[6,18] It is predicted to dominate the neutrino sky at energies in excess of $10^2$–$10^3$ TeV. The flux not only exceeds the "background" of atmospheric neutrinos, but dwarfs the most optimistic predictions for cosmologically-enhanced cosmogenic neutrinos discussed in the previous section.

The diffuse flux from AGNs is not likely to have a counterpart in TeV or PeV photons. Even if most sources are, like Markarian 421, transparent to TeV gamma rays so that high energy photons do indeed get out of the source, this does not mean we can detect them at Earth. Photons of this energy are indeed efficiently absorbed on infra-red starlight on their way to Earth covering 100 Mpc distances.[19] This is nicely illustrated by the GRO source 3C279. A TeV gamma ray flux, obtained by extrapolation of the power spectrum observed by the Compton observatory in the GeV energy range, would predict a flux that is within the sensitivity of existing Cherenkov telescopes. This flux is, however, attenuated by 2 orders of magnitude or more on infrared starlight, putting it most likely out of the reach of the Whipple telescope. What is special about Markarian 421 is not its power, although its total luminosity could be as large as $10^{43}$ergs/sec in TeV photons, but its distance. With a redshift of 0.03, about 120 Mpc distance, the attenuation of the TeV flux is essentially negligible.

## 5. Detection of diffuse photons (and neutrinos!)

In the preceding discussion we have raised several experimental challenges:
i) search for a diffuse flux at the $10^{-4}$–$10^{-5}$ level of the cosmic ray spectrum with Cherenkov telescopes or conventional air shower arrays,
ii) search for a diffuse flux at the 10% level near the Greisen-Zatsepin cut-off, or
iii) do the same physics with neutrino telescopes.
We will discuss the three possibilities in reverse order. It should be pointed out at the start that even if an experiment cannot reach such sensitivities it is worth trying anyway as one can be lucky in the form of cosmological enhancements or a collection of strong nearby sources.

The case for neutrino telescopes has been discussed at length elsewhere.[2,18] A world-wide effort is underway to commission neutrino telescopes of 0.01–0.1 km$^2$ area to take a first look at the TeV neutrino sky. Theorized large diffuse fluxes from AGN, such as those shown in Fig. 5, should be within easy reach of these instruments. Assuming equal neutrino and gamma ray

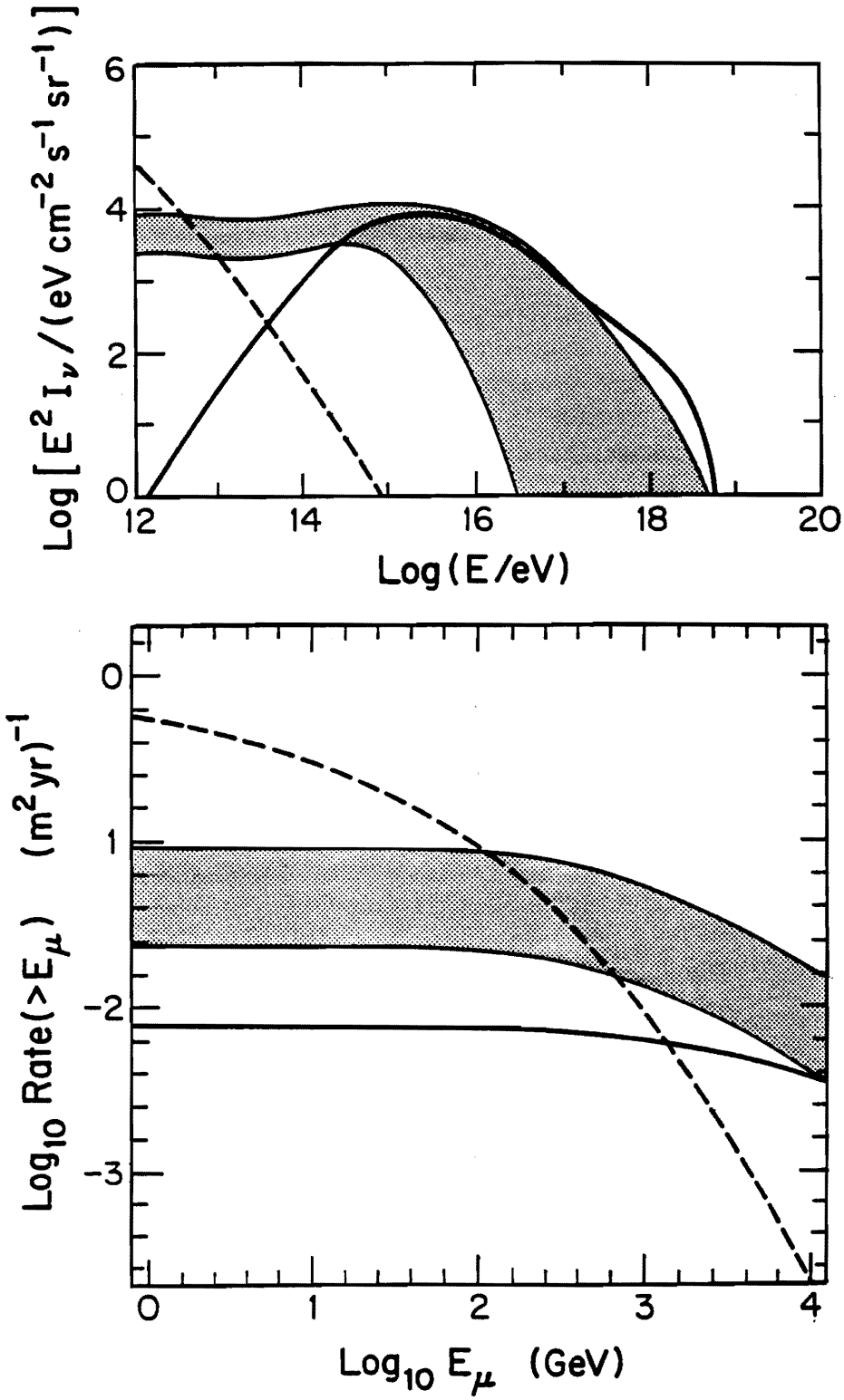


Fig. 5. a) The shaded area represents a range of predictions for the unresolved diffuse neutrino flux from AGNs (Szabo and Protheroe in reference 18). Also shown is a calculation[18] of the same quantity Stecker et al. (solid line). The dashed line represents the atmospheric neutrino background. b) Upcoming muon rates in an underground detector corresponding to the neutrino fluxes in a); from T. Stanev.[18]

fluxes, Markarian 421 should produce "several" events per year in the largest of these detectors. This assumption might not be correct as it assumes that the gamma rays are from pions produced by accelerated protons. Although many argument have been given for the acceleration of protons as well as electrons in AGN, there is no smoking gun. On the other hand, if the photons are of $\pi^0$ origin, the neutrino harvest is likely to be much larger. This can be illustrated in a model of blazars where particles are accelerated by shocks in the jets which are a characteristic feature of these active galaxies.[20] Such models accommodate observed fluxes at all wavelengths. Inevitably, beams of gamma rays and neutrinos from the decay of pions are created along the jets as a result of pion photoproduction by accelerated protons on the dense target of synchrotron photons produced by the electrons in the jet. In these models the maximum photon energy can be parametrized as[9]

$$E_{\gamma\mathrm{max}} = 5 \times 10^{19}\mathrm{eV} \left[\frac{\mathrm{B}}{1\,\mathrm{Gauss}}\right]^{-1/2} , \tag{7}$$

where $B$ is the magnetic field in the jet. Clearly blazars can be the source of the highest energy cosmic rays. It is interesting to parametrize the optical depth of the source in a similar fashion

$$\tau_{\mathrm{optical}} = 2 \left[\frac{B}{1\,\mathrm{Gauss}}\right]^{1/2} \left[\frac{E_\gamma}{1\,\mathrm{TeV}}\right] . \tag{8}$$

It is clear that the $B$-field is the critical parameter. Estimates cover the $10^{-4}$–$10^4$ Gauss range; the corresponding values for $E_{\gamma\,\mathrm{max}}$ and the photon energy for which $\tau_{\mathrm{optical}}$ is unity are given in the table below:

Table 1.

| $B$ (Gauss) | $E_\gamma$ where $\tau_{\mathrm{optical}} = 1$ | $E_{\gamma\,\mathrm{max}}$ (eV) |
|---|---|---|
| $10^{-4}$ | 50 TeV | $6 \times 10^{21}$ |
| 1 | 500 GeV | $6 \times 10^{19}$ |
| $10^4$ | 5 GeV | $6 \times 10^{17}$ |

E.g. for a 1 Gauss field the optical depth is unity for the 0.5 TeV photons observed by Whipple from the blazar Markarian 421. For a blazar with a $B$-value of 1 kGauss, a value typically assumed by workers in the field, TeV or PeV gamma rays cannot escape the source, and the ratio of high energy neutrino to gamma ray flux is enormous.

We already mentioned that neutrino telescopes of order 1 km$^2$ area are required to detect the neutrinos from the galactic plane. The detection of cosmogenic neutrinos is unlikely unless the results of our "benchmark" calculation, shown in Fig. 3, are boosted by large cosmological effects.

Although detecting diffuse photons at a level $I_\gamma/I_{\mathrm{CR}} \simeq 0.1$ near $10^{20}$eV might seem easy compared to the $10^{-5}$ to be achieved near $10^{14}$eV, detection is far from straightforward as the fluxes are very low at these extremely high energies. Also, the structure of the showers is poorly understood. A detailed study of the problem requires a Monte Carlo generator of cascades including the LPM effect and the interaction of the showers with the magnetic field of the Earth. Above $5 \times 10^{19}$ eV photon showers are destroyed on the geomagnetic field by synchrotron interaction. I am not aware of a complete study of the problem.

In the TeV energy range imaging telescopes distinguish gamma rays from protons by identifying differences in the Cherenkov images of photon- and proton-initiated air cascades. Lamb discussed how the technique falls short by a factor 10–100 in cosmic ray rejection in order to detect diffuse gamma rays from the galactic plane.[14] Can the imaging technique be improved to bridge the gap? The Whipple collaboration uses over 100 fast photomultipliers to map the elliptic image painted by air showers on a 10 m optical concentrator. Mapping is done in terms of parameters characterizing this image, the most powerful of their parameters is the azimuthal width (azwidth) of the ellipse which is, on average, smaller for photon-initiated showers. Other parameters such as width, miss... can be used.[21] The image can also be mapped in time as well as in space. The conventional method of applying cuts to these parameters can be improved by training neural nets to efficiently separate nuclear from photon images. The main advantage is that neural nets exploit correlations between the different parameters used to parametrize the Cherenkov images, e.g. Vazquez et al.[22] found that the efficiency of a cut

$$\text{Azwidth} < 0.14^\circ - \text{miss} \tag{9}$$

is significantly higher than the combined effect of optimized cuts on each parameter separately. A summary of their results can be seen in the table below.

Table 2. Percentage of photons (protons) retained (misidentified).

| | % Photons accepted | % Protons accepted |
|---|---|---|
| Azwidth $< 0.07^\circ$ | 40.3(±0.6)% | 5.4(±0.5)% |
| Miss $< 0.05^\circ$ | 40.2(±0.6)% | 10 (±1.0)% |
| Neural Net 8 image parameters | 40.0(±0.6)% | 0.7(±0.2)% |
| Neural Net azwidth | 40.0(±0.6)% | 6.5(±0.5)% |
| Neural Net azwidth & miss | 40.0(±0.6)% | 2.2(±0.3)% |
| Azwidth $< 0.14^\circ -$ miss | 40.0(±0.6)% | 2.8(±0.3)% |
| Neural Net 10 time bins | 40.2(±0.6)% | 14.6(±0.7)% |
| Neural Net 10 time bins & 8 image parameters | 40.4(±0.6)% | 0.4(±0.1)% |
| Azwidth cut 2 telescopes (100 m) | 39.8(±0.6)% | 1.7(±0.6)% |
| Azwidth cut 2 telescopes (adjacent) | 40.1(±0.6)% | 2.2(±0.3)% |

A neural net with 10 time and 8 image parameters improves the rejection of protons by a factor 10 compared to a cut in azwidth without depleting the detected photon flux. The efficiency of a neural net and Whipple's azwidth cut are compared in Fig. 6. Although we should point out that these results were achieved in a computer simulation rather than on real data, neural nets are likely to yield even more powerful results in the future.[23]

Near $10^{14}$ eV the problem is well defined. The physics of air cascades is relatively well understood. Apart from small differences in lateral distribution and curvature of shower front, the only practical feature distinguishing $\gamma$-rays from cosmic rays in this energy range is the reduced production of hadrons and therefore muons in a photon-induced air shower. This is a consequence of the small value of the hadron photoproduction cross section relative to the Bethe-Heitler cross

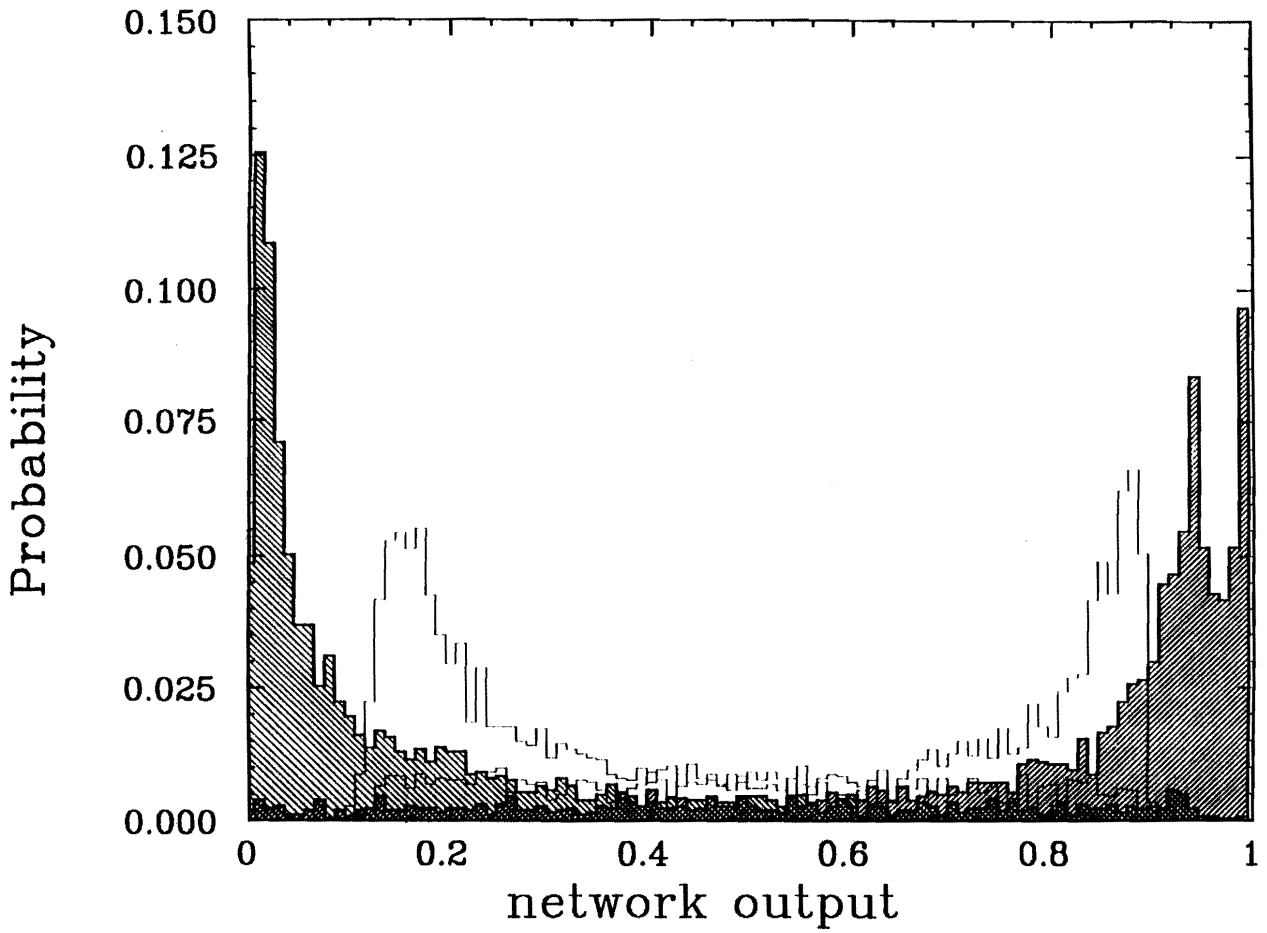


Fig. 6. Efficiency (cross-hatched) with which a neural net can differentiate photon and proton showers. Photons(protons) correspond to output parameter 1(0). The neural net rejects 98% of the protons while retaining 40% of the $\gamma$-rays. The efficiency of an azwidth cut is shown for comparison.

section which dominates the development of the cascade, with

$$R = \frac{\sigma(\gamma N \to \pi X)}{\sigma(\gamma N \to e^+e^- X)} = 3 \times 10^{-3} \,. \tag{10}$$

Although the average number of muons in a $\gamma$-shower is a few percent of the number in a proton shower as a consequence of Eq. (10), the question facing us is one of fluctuations. In order to do muon-poor $\gamma$-ray astronomy with $10^{-5}$ precision, we must establish that protons do not impersonate photons at a level of one in $10^5$. In order to study the problem one must generate $\mathcal{O}(10^5)$ showers. We did.[24] In an attempt to study the fluctuations of the muon content of proton air showers we performed a massive Monte Carlo calculation based on 53640 showers initiated by protons generated on an $E_p^{-2.7}$ spectrum with primary energy above 100 TeV. Low, i.e. $\gamma$-like, muon content in $p$-initiated showers can occur in events with i) large depth of first interaction, ii) successive diffractive events, and finally iii) low $n(\pi^\pm)/n(\pi^0)$ ratio. The reduced production of charged pions was the origin for 4 photon-like showers in our sample of 53640. They are small showers easily removed by a cut $N_e > 10^5$. Figure 7 shows the integral muon distribution for $\gamma$- and $p$-initiated cascades with size $N_e > 10^5$, zenith angle $\theta < 40°$ at an atmospheric depth of $860\,\mathrm{g\,cm^{-2}}$. Only 2964 proton showers survived this cut so that this massive calculation is inadequate to establish the features of fluctuations at the $10^{-5}$ level. We therefore used extrapolations of our Monte carlo data to follow the fluctuations to small $N_\mu$-values. Even the most pessimistic extrapolation, shown in Fig. 7, sets the rejection power below the required $10^{-5}$ level. At this point I should emphasize that we did not take into account the experimental resolution. On the other hand we did not attempt to improve rejection power by introducing heavy primaries in the spectrum which are readily rejected or by exploiting differences in muon energy spectra or angular distributions.

We conclude with another word of caution. The crucial ratio $R$ in Eq. (10) has only been measured up to 0.1 TeV. It therefore provides no information on the gluon content of the photon which determines the true high energy behavior of the photoproduction cross section. The issue has been reviewed at length.[25] Relevant data on photoproduction at higher energies will soon be provided by FNAL and HERA experiments.

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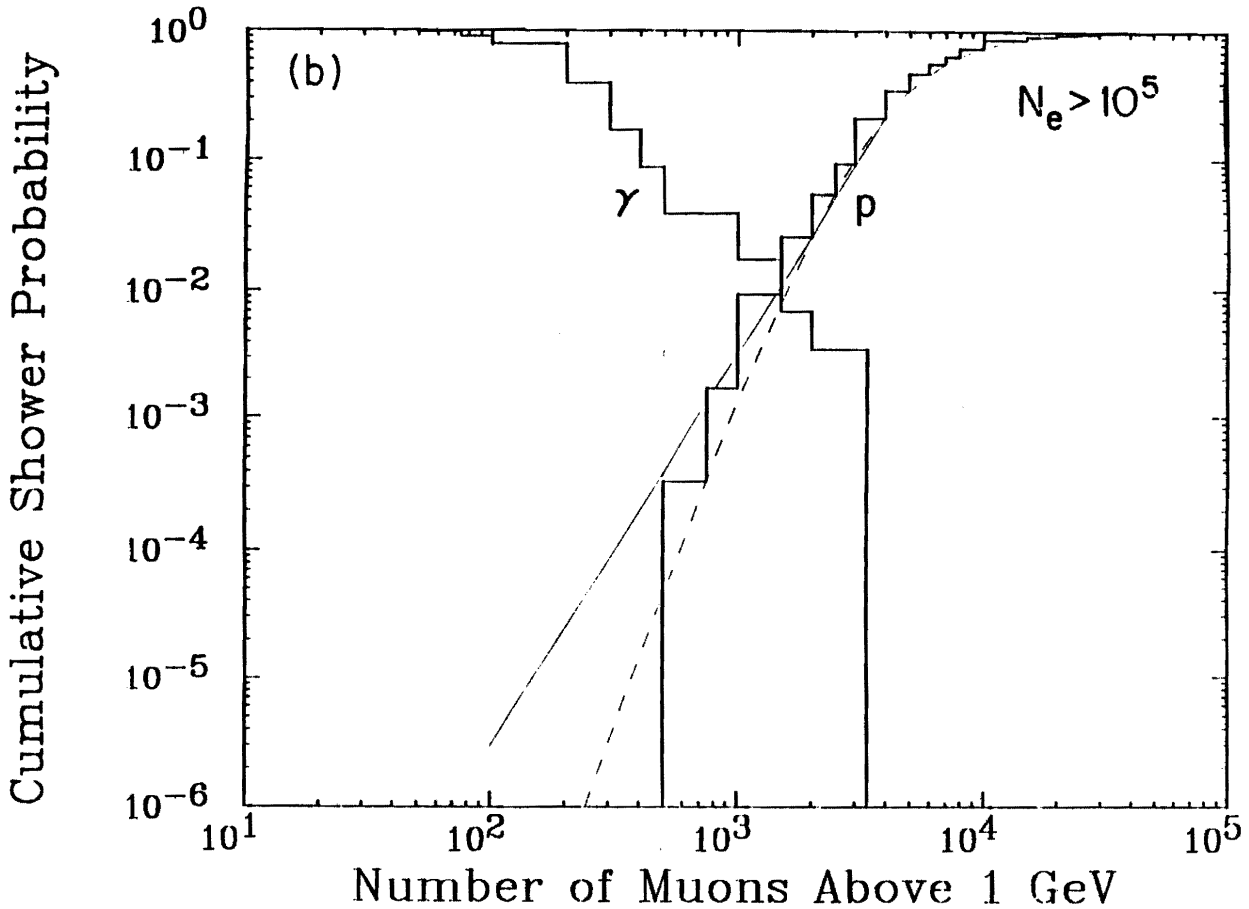


Fig. 7. Integral distribution of the number of muons $N_\mu$ for showers with electron size in excess of $10^5$ at an atmospheric depth of $860\,\mathrm{g/cm^2}$. The histogrammed quantity is the fraction of showers with muon number less than $N_\mu$ for protons and more than $N_\mu$ for photons. The lines show the actual and the pessimistic extrapolation of the Monte Carlo statistics.

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