Particle physics with cosmic accelerators

F. Halzen, K. Hikasa,* and T. Stanev†
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
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We discuss the atmospheric showers initiated by $1-10^4$-TeV photons emitted by cosmic accelerators such as Cygnus X-3. The direction and characteristic time structure of the radiation from such sources can be used to tag a beam of known composition (γ rays) with well-understood interactions (QED) with the target atmosphere. An experiment using a cosmic beam, therefore, overcomes the classic hurdles in interpreting cosmic-ray data. Tagged photon experiments covering a $(10^2-10^3\text{-m})^2$ area can conceivably achieve the statistics and signal-to-noise ratio to probe the anticipated new structure in particle physics at a scale of $(\sqrt{2}G_F)^{-1/2}\simeq 0.25$ TeV. They would at the same time constitute a new generation of telescopes at the highest energies of the emission spectrum. We also extend our discussion of muons to underground experiments in the corresponding energy region.

I. INTRODUCTION AND SUMMARY

Roughly 15 different experiments have by now suggested[1] the emission of very-high-energy γ rays from the direction and with the characteristic time structure of the binary system Cygnus X-3. The flux can be approximated by[2]

$$F(>E)=\frac{4\times 10^{-11}}{E\ (\text{TeV})}\ \text{particles cm}^{-2}\text{sec}^{-1} \tag{1}$$

for $E \gtrsim 0.1$ TeV. The data suggest a cutoff at the high-energy end of the emission spectrum around $E \simeq 10^5$ TeV. As further estimates depend strongly on the assumed flux, it should be pointed out that Eq. (1) stems from time-averaged data from Čerenkov-light observation of air showers. Ground arrays, such as Kiel, yield for certain epochs fluxes higher by more than 1 order of magnitude.

In this paper we discuss the feasibility of using the Cygnus beam (or beams from similar cosmic sources) to perform "tagged" photon experiments by observing the electromagnetic and muon showers originated by the photons in Earth's atmosphere. (We here do not speculate on recent indications[3] that the particles carrying Cygnus's radiation might not be photons. If confirmed, the searches for new particle physics using cosmic beams have already become reality.[4,5])

Tagging of the photon "beam" can be performed by making use of the characteristic space-time structure of the signal—directionality and periodicity—in the uniform background. The most discriminating signature of the photon-induced shower against hadron-induced cosmic-ray showers is the scarcity of muons in the observed showers. In the first part of this paper we therefore qualitatively describe the structure of the electromagnetic γ showers and subsequently study in detail the muon production through the dominant channels: photoproduction of pions followed by the decay $\pi\rightarrow\mu\nu$, prompt leptonic decay of charmed particles in the shower, and electromagnetic pair production $\gamma\rightarrow\mu^+\mu^-$. We make a detailed Monte Carlo study of the muon content of air showers in the $1-10^5$-TeV region and also present results for high-energy muons observed in deep-underground experiments covering the same range of primary energies. Our main result is that experiments with 10^5-10^6 tagged photon events per year with a signal-to-background ratio of 10^4-10^5 are conceivable. A coverage of $(10^2-10^3\text{ m})^2$ will be required. The power of such an experiment as a telescope is obvious. We draw attention to its possible role as a conventional particle-physics experiment. It overcomes the classic hurdles in extracting particle-physics information from routine cosmic-ray experiments: here the composition of the beam is known (photons) and its interactions with the atmosphere is well understood (QED). New thresholds signaling the (anticipated) physics beyond the standard model with energy scale $(\sqrt{2}G_F)^{-1/2}\simeq 0.25$ TeV could be searched for. We illustrate this by studying a range of possibilities: anomalous interactions of photons, substructure of electrons (roughly half of the atmospheric cascade consists of high-energy electrons), and supersymmetry. We will argue that such new thresholds in high-energy photon or electron interactions are observable by a sudden increase in the otherwise low muon content of photon-induced cascades. We identify new-physics scenarios such as photons acquiring strong interactions, constituent exchanges between electrons and quarks in composite models, which can be revealed or ruled out even if realistic experiments fall far short of the goals anticipated in this paper. The possibility of admixture of stable gluinos or photinos in the photon beam is also discussed.

Section III contains detailed information on the abundance and properties of muons in photon showers. Although very relevant to the design of future and the interpretation of present experiments, the information is technical and can be omitted in reading the paper.

II. THE COSMIC BEAM IN THE ATMOSPHERE

The primary flux of photons given by Eq. (1) is not directly observed. Photons originate a shower of electromagnetic particles. The experiment views the shower as a pancake of electromagnetic radiation 10^2-10^3 m^2 in area, a few nanoseconds thick and moving down the atmosphere at the speed of light. The enhancement of emission in source direction over the isotropic background of hadron-induced cosmic rays is established by timing or on/off-source subtraction.

A primary photon is converted to a e^+e^- pair after 1 radiation length λ_R on average near the top of the atmosphere. In subsequent layers of the atmosphere, which is approximately 25 radiation lengths thick in total, particles further lose energy by bremsstrahlung or pair production. The integrated flux of photons as a function of depth (linear density) z in the atmosphere for the primary E^{-1} spectrum (1) is approximately given by[6]

$$N_\gamma(>E,z) \simeq \tfrac{1}{2} A E^{-1} \tag{2}$$

with $A = 4\times10^{-11}$ in the units of Eq. (1). The number of photons with energy E is independent of depth. This somewhat surprising result can be understood as follows: while photons lose energy with depth, others are generated by the higher-energy component of the spectrum. For a flat E^{-1} spectrum, energy loss and feed down are in equilibrium, hence the z-independent result of Eq. (2). As the particles lose approximately half of their energy per radiation length, photons of energy E continue to be present in the atmosphere down to a number

$$n_{\max} = \frac{\ln(E_{\max}/E)}{\ln(\frac{1}{2})} \tag{3}$$

of radiation lengths. Here $E_{\max}$ represents the $\sim 10^5$-TeV cutoff of the source spectrum.[1] This simplified picture of the cosmic beam above will be used further on to estimate the effects of new particle-physics thresholds on the showers. Given the central importance of the muon production to the discussion, we however attempt to make quantitative estimates of the muon content of γ rays by Monte Carlo simulation. We discuss this next.

III. MUONS IN PHOTON SHOWERS

The most prominent feature to set the on-source γ-ray showers apart from background cosmic-ray showers is their low hadron and muon content. The number of muons is typically a few percent of that in a hadron shower where muons are abundantly generated by $\pi^\pm$ decay. In γ-initiated showers, processes generating muons are characterized by small cross sections: π photoproduction followed by $\pi\to\mu\nu$ decay, $\gamma\to\mu^+\mu^-$ pair production which is suppressed by a large factor $(m_e/m_\mu)^2$ relative to $\gamma\to e^+e^-$, and the production and subsequent leptonic decay of heavy quarks, predominantly charm.

The muon production through these three channels is the subject of a Monte Carlo study. In principle, one could extend the list of "ordinary μ-producing process" and include electroproduction (through virtual photons) as well as QED production of pairs of particles heavier than muons and subsequent decays. The yield of muons from these processes is, however, very low. The reasons for this are easy to understand. The energy spectrum of the virtual photons in the electroproduction is soft and while the total cross section approaches that of photoproduction at high energies, only a small fraction of the electron energy is transferred to hadrons. As far as the QED production of pions and heavier pairs is concerned, in addition to the $(m_\mu/m_\pi)^2$ factor in the total cross section, the time dilation in $\pi\to\mu$ decay and the competition between pion interactions and decay decrease significantly the muon yield.

The time dilation of the decay of muon parents plays a significant role in determining the muon yields from different processes. While the direct muon production (QED $\mu^+\mu^-$ pairs and charm decay in our calculations) follows the energy spectrum of the primary photons in the scaling limit, the yield of photoproduced muons (through π and K decays) is steeper by one power of E. As a result, although photoproduction is the only process which significantly contributes to GeV muons in photon showers, direct production is increasingly important at muon energies above 1 TeV and prevails above several TeV, as will be shown further on.

The photoproduction cross section used in this calculation is obtained by interpolating accelerator γ-proton data and is subsequently converted to a γ-air cross section using an $A^{0.91}$ dependence on the atomic number. The cross section shows a very slow logarithmic rise with the incident photon energy and has a value of 2.3 mb at 10^6 GeV. A constant diffractive cross section of 0.194 mb is also included. It is assumed to proceed via ρ production. A more detailed description of the photoproduction cross section is given in Ref. 7.

The QED production cross section of $\mu^+\mu^-$ pairs is well known. We have used the formula from Ref. 8, which gives a slow approach to the full screening value of 12 μb, which is achieved at 10^6 GeV.

The charm photoproduction cross section in air is taken to be

$$\sigma_{\gamma\to c}\ (\mu\text{b}) = 4.13\ln[E\ (\text{GeV})] \tag{4}$$

which yields a value of 57 μb at 10^6 GeV. The charm-muon decay spectrum is

$$D_{c\to\mu}(x) = 2B(1-x)^2(1+2x) \tag{5}$$

with a branching ratio of $B=0.1$. Motivation for (4) is discussed in Sec. IV.

The Monte Carlo calculation was performed in three steps. In step one the energy distribution of photons in photon-initiated electromagnetic cascades $(dN/dE)(E,z)$ was calculated at a number of atmospheric depths using the algorithms and programs described in Ref. 9. A second set of Monte Carlo runs calculated the muon yields from photoproduction interaction $\sigma_{\text{ph}}(E)$ of energy E at atmospheric depth z. Finally, the number of photoproduced muons was calculated as

$$N_\mu(>E_\mu) = \int_{E_\mu}^{\infty}\int_{E_\mu}^{E_0}\int_0^z Y(E_\mu,E')\sigma_{\text{ph}}(E') \times \frac{dN(E',E_0,z)}{dE'} dE_0\, dE'\, dz\ . \tag{6}$$

Here $Y(E_\mu,E')$ is the number of muons of energy $>E_\mu$ photoproduced by a photon of energy E'. This procedure does not fully account for the fluctuations in the shower development and tends to produce muon numbers slightly smaller than the ones obtained in the direct Monte Carlo calculation of Ref. 7 performed under the same assumptions. A comparison with these previous results, when possible, shows that the three-step procedure gives results compatible with the median value of the direct Monte Carlo calculation. It has, however, the advantage to minimize the necessary CPU time, which allowed us to perform a consistent set of calculations.

A similar procedure was used to calculate the muon production from QED $\mu^+\mu^-$ pairs and charm photoproduction. The results were cross-checked through numerical integration with the use of $(dN/dE)(E,t)$ from the cascade theory[6] in the approximation A.

Table I lists the number of muons at sea level per shower of primary photon energy E_0. Direct production, though included, is not important for GeV muons. The results are given for a shower zenith angle of 30°, which is representative of the average angle under which Cygnus X-3 is seen by observers at a latitude of 40°.

The results summarized in Table I are relevant to GeV muons observed in sea-level photon showers. The physics changes qualitatively when calculating TeV muons observed by deep-underground experiments in showers of similar primary energy. Figure 1 shows the rate of TeV muons for the primary photon spectrum of Eq. (1). Larger values of E_μ/E_0 now play an important role when folding over the primary photon spectrum. Therefore, prompt muon production characterized by a flatter E_μ dependence becomes important and clearly dominates muon production in the multi-TeV muon energy range, see Fig. 1. TeV muons of direct and decay origin also have different angular dependence. Prompt muons are isotropic, while the number of those which come from π and K decays increases as secθ up to a zenith angle of 60°.

For GeV muons the dependence on zenith angle is more complicated. Beyond a certain energy-dependent atmospheric depth, the number of muons in the shower decreases because of ionization loss and decay. As shown in Ref. 7, only a small fraction of the low-energy muons survives to observation depth. Thus the muon number is inversely proportional to the distance between the observation level and the effective muon generation depth, which increases as cosθ. This is still true for 1-GeV muons. When at higher energy the muon decay length exceeds the thickness of the atmosphere, the ionization loss becomes negligible and the trend reverses to the secθ law for TeV muons previously mentioned. The angular behavior of GeV muons is therefore directly related to their energy

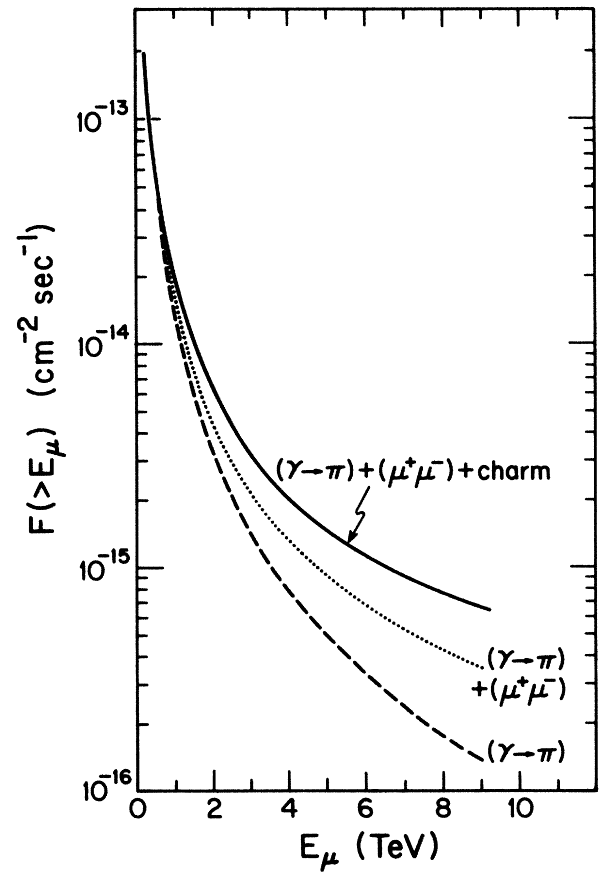

FIG. 1. Integral vertical flux of TeV muons generated by the primary γ-ray spectrum of Eq. (1). Dashed curve shows muons from photoproduction; dotted curve adds muons from QED pairs and the solid curve includes, also, muons from charm.

spectrum, which is steeper for photon- than for proton-initiated showers at all ground observation levels. Figure 2 compares the energy spectrum of GeV muons in photon and proton showers at sea level, 30° zenith angle. At high altitude both spectra are steeper with the slope for photon showers increasing faster than for proton ones.

A useful experimental parameter for atmospheric showers is the average number of muons N_μ per shower of a given size N_e. Figure 3 compares the $N_\mu(N_e)$ dependence for γ showers with the one for proton showers in the energy range 10—1000 TeV. The number of muons in

TABLE I. Number of muons in photon showers at sea level, zenith angle 30°. First line is for photoproduction, second (only for TeV muons) for direct production.

E_0 (GeV) \ E_μ	1 GeV	4 GeV	16 GeV	0.25 TeV	1 TeV	4 TeV
10^3	0.121	0.062	0.016	8.0×10^{-5}		
				4.0×10^{-6}		
10^4	2.00	1.02	0.27	3.9×10^{-3}	2.1×10^{-4}	1.3×10^{-6}
				3.2×10^{-4}	9.2×10^{-5}	8.4×10^{-6}
10^5	26.3	12.7	3.33	5.7×10^{-2}	3.9×10^{-3}	1.8×10^{-4}
				3.8×10^{-3}	1.4×10^{-3}	3.5×10^{-4}
10^6	340	157	39.8	6.5×10^{-1}	4.9×10^{-2}	3.1×10^{-3}
				3.8×10^{-2}	1.4×10^{-2}	4.2×10^{-3}

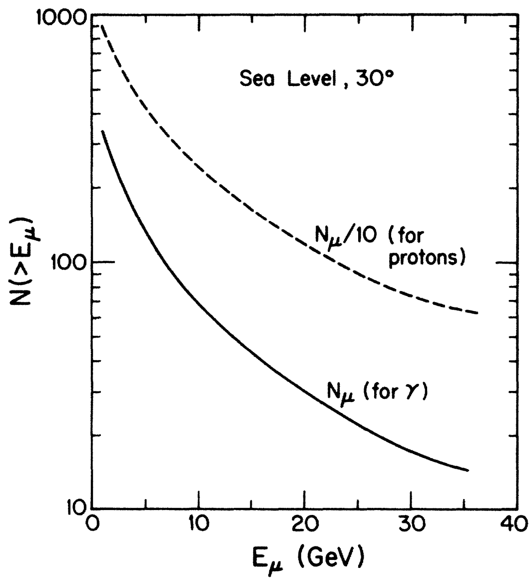

FIG. 2. Energy spectrum of GeV muons in showers produced by 10^6 GeV primary γ rays (solid curve) and protons (dashed curve).

photon showers is less than in proton showers of the same size N_e by more than 1 order of magnitude. The ratio decreases slowly with the shower size.

Another major difference between the showers of γ and nucleonic origin are the fluctuations of the muon numbers for fixed primary energy E_0. In proton showers the muon number is relatively stable—its fluctuations are a factor of 3 smaller than those of the shower size. In photon showers, the small photoproduction cross section makes the generation of muons a rare event. Muon number fluctuations are as large as, or exceeding, those of the size N_e.

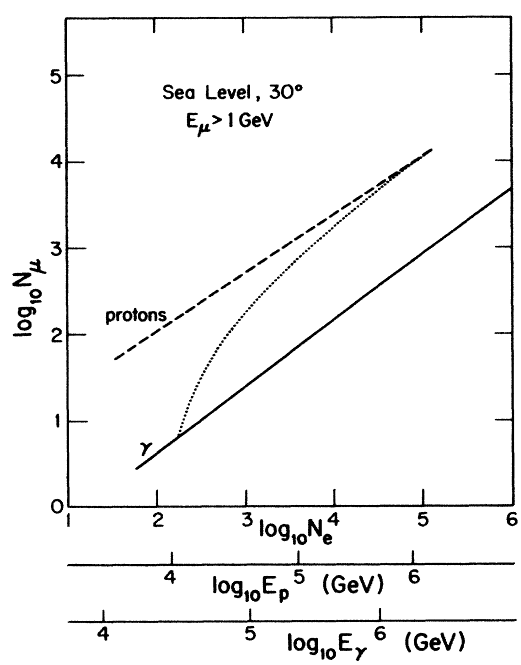

FIG. 3. Muon number (N_μ) vs shower size (N_e) for γ (solid line) and proton (dashed line) showers. The dotted curve shows the transition of γ showers due to a strong-coupling process. The energy scales show the conversion of shower size to proton and γ-ray energy.

IV. NEW THRESHOLDS IN PARTICLE PHYSICS AND THEIR EFFECT ON γ-RAY CASCADE DEVELOPMENT

The crucial result in Sec. III is that γ- and hadron-induced air showers differ dramatically in their muon content: the number of muons in a γ shower is only a few percent of that in a hadron shower of similar energy or size, see Figs. 2 and 3. Photon showers develop on the average higher in the atmosphere, i.e., they have a smaller age parameter than hadron showers, but this as well as other parameters (lateral spread, electron size, . . .) of photon showers are not distinctive enough to do γ tagging on an event-by-event basis. The directionality and pulsation of the source should be fully utilized for best background suppression.

Given that photon showers are muon poor, new physics thresholds should be most easily observed via the increased production of muons. The muon flux is related to the parent γ flux by the relation

$$\frac{dI_\mu}{dz\,dE}(E,z)=\int_E^{E_{\max}}\frac{dI_\gamma}{dE'}(E')\frac{1}{\lambda}\frac{dN_{\gamma\to\mu}}{dE}(E',E)dE' \,, \quad (7)$$

where I_γ is independent of z as given by Eq. (2). λ is the interaction length in the atmosphere for the process producing the muons

$$\lambda\ (\text{g/cm}^2)=\frac{2.4\times 10^4}{\sigma\ (\text{mb})} \,. \quad (8)$$

σ is the interaction cross section on air nuclei. The factor N in Eq. (7) counts muons of energy E resulting from a γ ray with $E'>E$. Assuming that λ is energy independent and that N scales in

$$x=\frac{E}{E'} \,, \quad (9)$$

we obtain for the power spectrum of Eq. (2) that

$$\frac{dI_\mu}{dz\,dE}=\frac{dI_\gamma}{dE}\frac{1}{\lambda}X_{\gamma\to\mu} \quad (10)$$

with

$$X_{\gamma\to\mu}=\int_0^1 x\frac{dN_{\gamma\to\mu}}{dx}dx \,. \quad (11)$$

X is therefore the average momentum of the produced muons. Finally, integrating Eq. (10) over z is done by multiplying by $n_{\max}\lambda_R$, see Eq. (3). Analyses (7)—(11) can be trivially generalized to any power spectrum $E^{-\alpha}$ with $\alpha\neq 1$, which results in replacing x in Eq. (11) by x^α.

A. New photon couplings to matter

In Sec. III we considered conventional sources of muons in γ-initiated showers. Many of the results can be qualitatively verified using the formalism of Eqs. (7)—(11). We now turn our attention however to the possibility that new particles or interactions, not revealed at accelerator energies, constitute additional sources of muons above some threshold which would be observable against the generally low level of conventional muons in the shower.

As a first example, we consider the possibility that the photon has new interactions with matter as shown in Fig. 4. It couples to nucleons via new fermions f. The momentum distribution of the new fermions inside the photon is of the Weiszacker-Williams form:

$$\frac{dN}{dx}=3[x^2+(1-x)^2]\ . \tag{12}$$

The total γ-nucleon interaction rate via f is obtained[10] by integrating (12)

$$\sigma=\frac{\alpha_f}{\pi}\frac{1}{3}(1-\tau)(2-\tau+2\tau^2)\sigma_{fN}\ln\frac{s}{s_0}\ . \tag{13}$$

Here s_0 is the threshold for producing f (in the c.m. energy squared s) and $\tau=s_0/s$. $\alpha_f=e_f{}^2/4\pi$ is the coupling and σ_{fN} the f-nucleon total cross section as defined by the diagram in Fig. 4. An example of (not so) new physics in this category is heavy quarks $f=c,b,t$, etc. For charm

$$\alpha_f=3e_c{}^2\alpha \tag{14}$$

and σ_{cN} is the charmed-quark–nucleon cross section:[10]

$$\sigma_{cN}=\left[\frac{m_u}{m_c}\right]^2\sigma_{uN}\ . \tag{15}$$

Taking $m_u=0.25$ GeV, $m_c=1.5$ GeV, and $\sigma_{uN}=7$ mb as expected from the additive quark model, parametrizations (12)–(15) describe low-energy accelerator data.[10] Prompt leptonic decay of heavy quarks will deposit muons in the γ cascade according to Eqs. (10) and (11). It is easy to show that for a E^{-1} integral photon spectrum

$$X_{\gamma\to\mu}=\langle x\rangle_{\gamma\to c}\langle x\rangle_{c\to\mu}B_{c\to\mu}\ . \tag{16}$$

The factors in Eq. (16) are, respectively, the average momentum fraction of the produced c quark, the average momentum fraction of the muon in the decay and the leptonic branching ratio. Integrating (10) over z and using (3) and (16) we obtain

$$\frac{dI_\mu/dE}{dI_\gamma/dE}=n_{\max}\left[\frac{\lambda}{\lambda_R}\right]^{-1}\langle x\rangle_{\gamma\to c}\langle x\rangle_{c\to\mu}B_{c\to\mu}\ , \tag{17}$$

where λ is defined by (8) with $\sigma=\sigma(\gamma+\text{air}\to\text{charm})$. For 10-TeV γ rays, the charm cross section on air is predicted from (13)–(15) to be 40 μb. The various factors in Eq. (17) are $n_{\max}\simeq 15$ [Eq. (3)], $\lambda/\lambda_R=1.7\times10^4$ [from Eq. (8)], $\langle x\rangle_{\gamma\to c}=\frac{1}{2}$ [Eq. (12)], $\langle x\rangle_{c\to\mu}\simeq\frac{1}{3}$ (three-body decay), and finally $B_{c\to\mu}=0.1$. Therefore,

$$\frac{dI_\mu/dE}{dI_\gamma/dE}\simeq10^{-5}\ . \tag{18}$$

This is not a totally academic result. Combining Eqs. (1) and (18) we find a flux close to 10^{-15} cm^{-2}sec^{-1} for muons initiated by 1-TeV γ rays from Cygnus. Muons initiated by neutrinos emitted by the binary are expected to be produced at the same level.[11] The above atmospheric flux should not be confused with the direct beam whose detection is at present one of the more promising possibilities for doing neutrino astronomy. Zenith-angle distributions should distinguish these sources of prompt muons. (Zenith angles do not discriminate against neutrinos from charm decay initiating muon above the underground detectors, but we estimate this muon flux to be very small: 10^{-20}–10^{-21} cm^{-2}sec^{-1}.)

Measurements of heavy-quark photoproduction are interesting; more important is, however, the possibility to discover new physics thresholds even before the flux level (18) is achieved by the experiments. Speculations that photon interactions become strong at high energies,[12] though unpopular in the context of gauge theories, could be investigated. If at some energy $\alpha_f\simeq1$ in Eq. (13), then $\lambda\simeq\lambda_R$ and the muon rate given by Eq. (17) could be as large as or even larger than the parent γ rate. This possibility has been proposed[12] in association with the observation of a large muon flux.[3] We investigated the case $\alpha_f=1$ with the Monte Carlo study, keeping all other parameters the same as for charm production. The dotted line in Fig. 3 shows the transition of the muon-number dependence on shower size initiated by a new strong-coupling process with threshold at $\sqrt{s}=0.25$ TeV. While totally changing the muon content of photon showers, such a process will not affect proton showers in a detectable way. Such a process will also increase the number of TeV muons from photon showers by a factor of 20. From the flux of Eq. (1) one thus expects correspondingly 90 and 13 events per 1000-m^2 detector per year at depths of 2 and 4 km water equivalent (w.e.) This estimate takes into account the fact that TeV muons are produced only when the source is at a zenith angle not bigger than 60°.

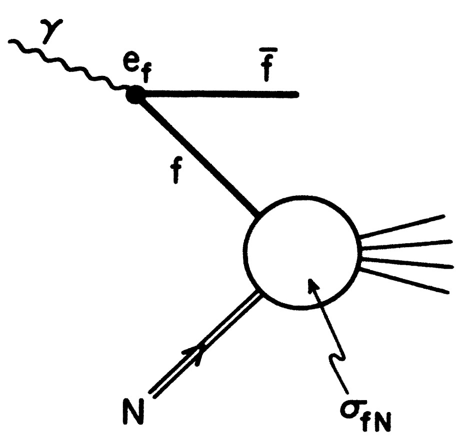

FIG. 4. Diagram for photon interaction with a nucleon via a new fermion f.

B. Composite quarks and leptons

It is important to realize that the electromagnetic cascade contains roughly equal numbers of high-energy photons and electrons. Therefore, new physics in electron-nucleon interaction will also affect the composition of the γ-initiated cascades at observation level. An example is provided by models where the electron and quarks are composite.

If the c.m. energy of the eN system is less than the compositeness scale Λ, the deviation from the standard pointlike coupling appears as a residual interaction of the strong-binding force. The interaction is described by an effective four-fermion coupling:[13]

$$\mathscr{L}=\frac{g_H{}^2}{\Lambda^2}\bar{e}e\bar{q}q\ , \tag{19}$$

where we expect $g_H{}^2/4\pi\sim 1$. This coupling gives a rising contribution to the eN cross section

$$\sigma\simeq\frac{\pi s}{\Lambda^4}\mathscr{F}\ , \tag{20}$$

where $\mathscr{F}$ is the structure-function factor. Depending on the Lorentz structure of the interaction, an additional contribution can result from the interference with the conventional electroweak contribution.

The rising behavior of Eq. (20) cannot continue forever. When the c.m. energy reaches the compositeness scale, the cross section would more or less saturate. At higher energies

$$\sigma\simeq\frac{\pi}{\Lambda^2}\ln\frac{s}{\Lambda^2}\mathscr{F}\ . \tag{21}$$

For Λ comparable to the weak scale, the cross section can be as large as 10^{-4}–10^{-5} mb. [Experimental limits[14] from e^+e^- and $p\bar{p}$ interactions do not directly constrain the coupling (19) as they involve pure leptonic or pure quarkonic couplings.]

The muon content of the final state is important for the observation. For the coupling (19), muons can originate from the struck quark. At higher energies, however, the scattering proceeds in a more complicated way. Electrons and quarks have a finite extent in which pointlike preons move around. After the electron and quark exchange a preon or preonic bound state, the forward-scattered preons fragment into a jet of quarks and leptons. In particular, if an electronic-flavored preon is exchanged, the remaining forward-going system does not have a quantum number of the electron, and hence there is no leading-particle effect. It is possible to have multimuon final states as a preon could fragment into a number of quarks and leptons. We therefore obtain in analogy with (14)

$$\frac{dI_\mu/dE}{dI_\gamma/dE}=n_{\max}\left[\frac{\lambda}{\lambda_R}\right]^{-1}\langle x\rangle_{e\to\mu}$$
$$\simeq 10^{-5}\ . \tag{22}$$

Also, muons from the decay of π, K's associated with these interactions could be produced.

There is a possibility to have much larger effects if leptons are composed of colored preons. As discussed in Sec. IV A, the photon has a hadronic component in itself with the probability of $O(\alpha)$ by the electromagnetic coupling. The electron, which interacts with photon, can be said to have an $O(\alpha^2)$ hadronic component via electromagnetism. The colored preons within the electron cannot be seen at low energies because they are tightly bound into a colorless state. However, if we go to high energies, the colored preons reveal themselves and the electron begins to interact like a hadron. A drastic effect in the muon yield may be expected if this is the case. Photon showers will be mixed electromagnetic hadronic, with enhanced muon production signaling the onset of the hadronic component. The Kiel data,[1] showing an increase of the muons in the shower by at least a factor of 10 over what is calculated in QED, could be interpreted along these lines.

C. Supersymmetric particles

We finally speculate on the detection of supersymmetric matter. Conservation of supersymmetric R parity requires the existence of a stable (lightest) supersymmetric particle. This can be the photino or gluino, respectively, the fermionic partners of the photon and gluon. Such particles should be abundantly produced by the binary accelerator and can possibly be detected as admixtures in the photon beam.[15,16] We discuss the supersymmetric cosmic beam first.

Assume the standard model of Cygnus X-3 where the atmosphere of the companion (a Sun-type main sequence star) acts as a beam dump for a beam emitted by its compact pulsar or neutron star partner. The generation of particles in the beam dump is described by one-dimensional evolution of the particle flux:

$$\frac{dN_j}{dE_j dz}=-\frac{1}{\lambda_j}\frac{dN_j}{dE_j}+\sum_i\int_{E_j}^{\infty}\frac{1}{\lambda_i}\frac{dN_i}{dE_i}\frac{dN_{i\to j}}{dE_j}dE_i\ . \tag{23}$$

The first term describes the depletion of the flux of particle j in the dump by interaction (or decay) while the second term accounts for production of j by particle(s) i. Assuming a power spectrum of the incident pulsar beam i

$$\frac{dN_i}{dE_i}\propto E_i{}^{-\beta} \tag{24}$$

and assuming Feynman scaling we obtain a simplified expression for (23):

$$\frac{dN_j}{dE_j dz}=-\frac{1}{\lambda_j}\frac{dN_j}{dE_j}+\sum_i\frac{1}{\lambda_i}\frac{dN_i}{dE_j}X_{i\to j}\ , \tag{25}$$

where

$$X_{i\to j}=\frac{1}{\sigma_i}\int_0^1 dx\, x^{\beta-1}\frac{d\sigma_{i\to j}}{dx}\ . \tag{26}$$

Here $x=E_j/E_i$ and the reasoning is of course parallel to the one previously introduced to describe muon generation in Earth's atmosphere with $\alpha=\beta-1=1$ in Eqs. (10) and (11). If j is a decay product of a product particle k, the two-step generation of j is taken into account by a factorized generalization of (26):

$$X_{i\to j}=\left[\frac{1}{\sigma_{i,\rm tot}}\int_0^1 dx\,x^{\beta-1}\frac{d\sigma_{i\to k}}{dx}\right]\left[\frac{1}{\Gamma_{k,\rm tot}}\int_0^1 dx\,x^{\beta-1}\frac{d\Gamma_{k\to j}}{dx}\right]\equiv X_{i\to k}X_{k\to j}\ . \tag{27}$$

Assume an initial ($z=0$) proton beam emitted by the compact object

$$\frac{dN_p^0}{dE}=AE^{-\beta}\ . \tag{28}$$

Neglecting secondary protons the flux at depth z is readily calculated from (25)

$$\frac{dN_p}{dE}=\frac{dN_p^0}{dE}e^{-z/\lambda_p}\ . \tag{29}$$

For reference we first calculate the γ flux[17] in this model to be identified with the beam presumably observed by Čerenkov telescopes and air shower arrays. The photons are the decay products of π^0's produced by the proton flux (29) is the dump:

$$\frac{dN_\gamma}{dE\,dz}=-\frac{1}{\lambda_R}\frac{dN_\gamma}{dE}+\frac{1}{\lambda_p}\frac{dN_p^0}{dE}e^{-z/\lambda_p}X_{p\to\gamma}\ . \tag{30}$$

The solution is easily checked by substitution:

$$\frac{dN_\gamma}{dE}=\frac{dN_p^0}{dE}\frac{e^{-z/\lambda_p}-e^{-z/\lambda_R}}{\dfrac{\lambda_p}{\lambda_R}-1}X_{p\to\gamma}\ , \tag{31}$$

where [see (27)]

$$\begin{aligned}X_{p\to\gamma}&=\langle x^{\beta-1}\rangle_{p\to\pi^0}\langle x^{\beta-1}\rangle_{\pi^0\to\gamma}\\&=\langle x^{\beta-1}\rangle_{p\to\pi^0}\frac{2}{\beta}\ .\end{aligned} \tag{32}$$

For further rough estimates it is reasonable to assume that the radiation length λ_R is not very different from the proton interaction length λ_p, then (31) simplifies to

$$\frac{dN_\gamma}{dE}\simeq\frac{dN_p^0}{dE}\frac{z}{\lambda_p}e^{-z/\lambda_p}X_{p\to\gamma}\ . \tag{33}$$

Stable photinos are produced via gluino production and decay (if $M_{\tilde g}\ll M_{\tilde q}$); therefore

$$\frac{dN_{\tilde\gamma}}{dE\,dz}=\frac{1}{\lambda_p}\frac{dN_p^0}{dE}e^{-z/\lambda_p}X_{p\to\tilde\gamma}\ . \tag{34}$$

Integration over z gives the $\tilde\gamma$ flux emitted by the binary:

$$\frac{dN_{\tilde\gamma}}{dE}=\frac{dN_p^0}{dE}(1-e^{-z/\lambda_p})X_{p\to\tilde\gamma}\ , \tag{35}$$

where

$$X_{p\to\tilde\gamma}=\frac{\sigma_{p\to\tilde g}}{\sigma_{p,\rm tot}}\langle x^{\beta-1}\rangle_{p\to\tilde g}\langle x^{\beta-1}\rangle_{\tilde g\to\tilde\gamma}\ . \tag{36}$$

If on the other hand, the gluino is stable, it is directly produced by protons according to (31) after substitution $\lambda_R\to\lambda_{\tilde g}$ and $X_{p\to\gamma}\to X_{p\to\tilde g}$. Gluinos would be bound in stable gluino hadrons ($\tilde g g$, $\tilde g q\bar q$, or $\tilde g qqq$). Their interaction cross sections should be similar to those of protons. Therefore [as for Eq. (33)],

$$\frac{dN_{\tilde g}}{dE}\simeq\frac{dN_p^0}{dE}\frac{z}{\lambda_p}e^{-z/\lambda_p}X_{p\to\tilde g} \tag{37}$$

with

$$X_{p\to\tilde g}=\frac{\sigma_{p\to\tilde g}}{\sigma_{p,\rm tot}}\langle x^{\beta-1}\rangle_{p\to\tilde g}\ . \tag{38}$$

We obtain a depth-independent result for the gluino-to-photon flux ratio of the binary from (33) and (38)

$$\frac{dN_{\tilde g}/dE}{dN_\gamma/dE}=\frac{\sigma_{p\to\tilde g}}{\sigma_{p,\rm tot}}\frac{\langle x^{\beta-1}\rangle_{p\to\tilde g}}{\langle x^{\beta-1}\rangle_{p\to\pi^0}2/\beta}\ . \tag{39}$$

Estimates for the admixture of the photon beam with stable gluinos can be obtained using (39). A similar relation can be obtained for the stable $\tilde\gamma$ scenario from (35), (36), and (33):

$$\frac{dN_{\tilde\gamma}/dE}{dN_\gamma/dE}=\frac{\sigma_{p\to\tilde g}}{\sigma_{p,\rm tot}}\frac{\langle x^{\beta-1}\rangle_{p\to\tilde g}\langle x^{\beta-1}\rangle_{\tilde g\to\tilde\gamma}}{\langle x^{\beta-1}\rangle_{p\to\pi^0}2/\beta}\frac{e^{z/\lambda_p}-1}{z/\lambda_p}\ . \tag{40}$$

Notice that this ratio is also z independent when the linear depth of the star's atmosphere is small compared to λ_p. The average momentum factors of the form $\langle x^{\beta-1}\rangle_{i\to j}$ are model dependent but for a rough estimate it is adequate to say that they are all $\sim 10^{-1}$ for $\beta\simeq 2$. For three-body decay $\tilde g\to\tilde\gamma q\bar q$ we have $\langle x\rangle_{\tilde g\to\tilde\gamma}\simeq\frac{1}{3}$. Up to these factors and an additional factor related to the integration of (40) over the (unknown and varying) line density of the main sequence star in the photino case, we obtain

$$\frac{dN_{\tilde g}/dE}{dN_\gamma/dE}\simeq 3\frac{dN_{\tilde\gamma}/dE}{dN_\gamma/dE}\simeq\frac{\sigma_{p\to\tilde g}}{\sigma_{p,\rm tot}}\ . \tag{41}$$

Eventually detailed calculations of the $\langle x^{\beta-1}\rangle$ factors can be performed using perturbation theory. Also (40) can be integrated over a line density obtained by matching (33) to the observed γ flux. Our main result (41) should not change significantly, however. The production cross section $\sigma_{p\to\tilde g}$ can be calculated perturbatively from $gg\to\tilde g\tilde g$ and similar diagrams. The cross section is given by[18]

$$\sigma_{p\to\tilde g}\simeq 7\sigma_{p\to Q}\ , \tag{42}$$

where Q is a heavy quark of the same mass as the gluino's. The difference comes from larger color charge of gluinos. For light gluinos of order the charm-quark mass, $\sigma_{p\to\tilde g}$ can be an order of magnitude larger than the ~ 1 mb charm cross section. Therefore a 10^{-2}–10^{-3} admixture of $\tilde g$ or $\tilde\gamma$ can be expected [see (41)] for supersymmetric particles of masses ~ 1 GeV. What are the possibilities to detect an admixture that could be as large as 1%?

The possibility that the gluino is the stable supersymmetric particle[19] has not completely been ruled out by accelerator data, although not favored by current models. This scenario is, however, a beautiful example of new particle physics detectable with a cosmic beam. A healthy (stable) $\tilde{g}$ admixture of a cosmic γ beam would produce muons by usual π production and decay in $\tilde{g}$-nucleon interactions in Earth's atmosphere. Gluino hadrons would indeed interact with Earth's atmosphere very much like regular hadrons. This could be readily detected as a deviation from the μ-poor nature of the γ beam. The $\tilde{g}$-quark interaction can also proceed in resonance via $\tilde{g}q \to \tilde{q}$ on quarks in the atmosphere.[20] This is the supersymmetric analog to the Glashow resonance (Ref. 21) $\bar{\nu}_e e \to W$ suggested to detect a $\bar{\nu}_e$ beam interacting with atomic electrons rather than quarks. The resonance peaks at energy

$$E \simeq \frac{M_{\tilde{q}}^2}{2\xi_q \xi_{\tilde{g}} M_p} . \tag{43}$$

Here M_p and $M_{\tilde{q}}$ are the proton and (presumably heavy) scalar-quark masses, and $\xi_q, \xi_{\tilde{g}}$ are the typical momentum fraction of quarks in the proton and gluinos in the gluino hadron, respectively. The resonance peak (43) is of course broadened by the momentum distribution of the quarks and gluinos and the energy spectrum of the incident $\tilde{g}$'s. A spectacular signature is nevertheless expected as the muons produced via a heavy $\tilde{q}$ resonance would have an angular spread resulting from the decay transverse momentum:

$$\theta \le \frac{M_{\tilde{q}}}{E} . \tag{44}$$

For $M_{\tilde{q}} \simeq M_W$ we obtain a resonance for $E \simeq 10$ TeV incident energy using (43). From (44) an angular spread of the muons of several degrees is expected. Such a spread could never be accounted for by standard cosmic-ray processes. Indeed the average angular spread of muons from conventional sources is well approximated by

$$\theta\,(\text{mrad}) \simeq \frac{\pi}{\sqrt{E_\mu}\,(\text{TeV})} . \tag{45}$$

This allows a muon array to be used as a telescope; muons are collinear with the parent cosmic beam to accuracy (45). The observation of muons with a 3-degree spread[3] at 10-TeV incident energies has prompted the speculation that Cygnus X-3 emits gluinos.[16,22] This would, however, require a $\tilde{g}$ flux in excess of the γ flux which is in contradiction with our estimates based on standard supersymmetry. Nevertheless even the estimated flux would be observable in the class of experiments described in the following section.

If on the other hand, the photino is the lightest supersymmetric particle,[16] its admixture in a photon beam at the level 10^{-3} or less [a heavier gluino mass would further suppress the $\tilde{\gamma}$ flux estimated in (41) by gluino production and decay in the source] would be more difficult to detect. They interact with Earth via processes such as $\tilde{\gamma}q \to \tilde{g}q$ which are neutrinolike:

$$\sigma \simeq \frac{\pi\alpha\alpha_s s}{M_{\tilde{q}}^4} \tag{46}$$

except for very small values of $M_{\tilde{q}}$. The process would be difficult to disentangle from direct neutrino emission by the source under realistic experimental conditions. Again observation via resonance $\tilde{\gamma}q \to \tilde{q}$ could be contemplated. More promising here is the observation of the Glashow resonance $\tilde{\gamma}e \to \tilde{e}$. It has a larger cross section, and is only smeared by the $\tilde{\gamma}$ flux and not by the quark momentum distribution, but unfortunately occurs at a resonance energy increased by a factor $\xi^2 M_p / M_e$ relative to (43). Here the $\tilde{\gamma}$ flux is unfortunately depleted. Statements regarding a large resonant cross section $\sigma = (4\pi / M_{\tilde{e}}^2)\, B(\tilde{e} \to e\tilde{\gamma})$ are misleading as the beam is not monochomatic or tunable. The width of the resonance is narrow $\Gamma \simeq \alpha M_{\tilde{e}}$ and therefore the relevant integrated cross section is again as estimated by (46).

V. FEASIBILITY OF THE EXPERIMENT

We have identified several physics possibilities where new physics can generate an anomalous muon component at a level 10^{-2} or even above. The examples cited include new γ interactions, some composite models for quarks and leptons, stable gluinos. At a level 10^{-5} routine but interesting high-energy physics occurs, e.g., onset of a large prompt muon component of heavy-quark origin. At some level QED deviations related to interference of scattering occurring on more than one atmospheric atom are anticipated,[23] the so-called Landau-Pomeranchuk-Migdal (LPM) effect. Although not expected to be large in a sparse medium such as air, study of this effect is important, for it could seriously affect lepton detection at future accelerators. We will now argue that experiments probing these issues are not only feasible, they are a not-too-far-reaching extension of present cosmic-ray facilities such as the Akeno array in Japan. Reaching the desired energy is not a problem. We will indeed see further on that experimental requirements dictate telescopes and/or arrays working in the 1–100 TeV region of primary photon energy. The problem is statistics [given the flux of Eq. (1)] and the signal-to-noise ratio (S/N) as the photon beam has to be tagged in a uniform background of cosmic-ray showers with typically 10^2 times the photon beam flux.

The two essential components of tagged photon experiments are obvious: (i) an array of scintillation counters with fast timing or of Čerenkov telescopes giving an observation of electromagnetic showers with good angular resolution; (ii) an array of shielded counters identifying the muon content of the showers. The idea of simultaneously detecting electrons and muons is, of course, as old as cosmic-ray physics. In the case of γ primaries the case for a dual measurement is even more compelling.

Table II summarizes some properties of air showers obtained from fits to data obtained with the Akeno air-shower array.[24] For completeness we also list here the Greissen distribution which describes the density of muons in a hadron shower with N_e electrons. The density of muons at a distance R (m) from the core is given by

TABLE II. Properties of hadron- and photon-induced air showers at Akeno (depth 920 g/cm^2).

Primary energy (TeV)	1	10^2
γ flux from Cyg X-3 using (1) ($\text{km}^{-2}\ \text{yr}^{-1}$)	10^7	10^5
Number of electrons in hadron shower		3800
Number of muons in hadron shower ($E>1$ GeV)	30	1525
Number of muons in γ shower		40

$$\rho\ (\text{muons/m}^2)=18R^{-3/4}\left[1+\frac{R}{R_0}\right]^{5/2}\left[\frac{N_e}{10^6}\right]^{3/4} . \quad (47)$$

The parameter R_0 depends on the zenith angle and varies from 350—500 m for $\theta=0°$—45°.

From Eq. (1) we conclude that at 1 TeV energy even a "modest" (100 m)^2 array (telescope) can accumulate 10^5 γ rays. The number of muons at sea level is however insufficient to perform a realistic experiment as can be seen from Table II. At 100 TeV this problem is no longer an issue but it takes a (1 km)^2 array to accumulate the 10^5/year statistics to hope to take a detailed look at photoproduction under difficult experimental circumstances.

Clearly statistics is not completely in the realm of science fiction, especially as one can conceive arrays triggering on multiple sources. What about the signal-to-background ratio? Present detectors (e.g., Čerenkov telescopes) achieve a nominal value

$$\frac{S}{N}=10^{-2} . \quad (48)$$

This is clearly insufficient to hope to detect traces of new particle thresholds in the tagged photon beam. This number can be greatly improved in the future when the detailed emission time structure of sources like Cygnus X-3 is well known. The binary 4.8 hour and candidate 19, 34 day, 12 month(?), and 5 year burst(?) repetition rate of the source can be used to enhance S/N possibly by 10^2 using phase information. The μ-poor property of γ showers further enhances the signal by another factor 10^2 but not more as at that level γ showers photoproducing a π in the primary interaction are virtually indistinguishable from a hadron-induced background cosmic-ray cascade. With possible improvements in angular resolution $S/N\simeq 10^2-10^3$ can possibly be achieved.

Clearly one cannot have it both ways and when new physics appears, the muon-poor property of photon showers can no longer be used as tag. This inevitably results in a reduced S/N ratio and one will have to rely exclusively on the characteristic time structure of the emission to identify the beam. It is even conceivable that new physics is associated with particles which do not keep time over the galactic distances which separate us from the source. A particle emitted with a time structure of characteristic width Δt will preserve this pattern over a distance L provided its γ factor satisfies (Refs. 2 and 4) $\gamma>(L/2c\Delta t)^{1/2}$. Photons satisfy this relation and, conversely, when one tracks a pulsar phase with $\Delta t \lesssim$ seconds it is difficult to imagine that anything but photons are carrying the radiation. It is, however, clear from our previous discussion that photons will always be a significant component of the beam and therefore can be used to identify periods of activity even in the presence of phenomena altering the muon-poor nature of the emission.

Preliminary data[25] from the Haleakala Čerenkov telescope suggest however emission from Cygnus in bursts with a typical duration of one minute. During these bursts $S/N\simeq 1$ rather than 10^{-2} [Eq. (48)]. Tagging such bursts could therefore yield data at the 10^4-10^5 signal-to-noise level.

It is exciting to contemplate the feasibility of such experiments as a not-too-far-fetched extrapolation of present facilities (e.g., Akeno). Even if no other than routine particle-physics results are ever obtained, imagine their power as a telescope.

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*Present address: National Laboratory for High Energy Physics (KEK), Oho-machi, Tsukuba, Ibaraki 305, Japan.

†Permanent and present address: Bartol Research Foundation of the Franklin Institute, University of Delaware, Newark, DE 19716.

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