1 Introduction

Cosmic rays reveal Nature's particle accelerators. Ever since the pioneering Haverah Park experiment \[1\] discovered that cosmic particles are accelerated up to $10^8$ TeV energy, the origin of the highest energy cosmic rays has been hotly debated. Several recent observations of isolated events with even higher energy is nothing less than paradoxical; they seem to imply aspects of particle physics or astrophysics not revealed in previous experiments. We will outline the puzzle further on.

The energies of such particles exceed by a factor of a hundred million those achieved with man-made accelerators. When colliding with atmospheric nuclei, the center of mass energy is approximately 500 TeV, more than one order of magnitude larger than that of the future Large Hadron Collider at CERN. It may therefore seem reasonable to speculate that cosmic particles, accelerated to such energy, may exhibit new particle physics. In a recurrent scenario they are assumed to be neutrinos which become strongly interacting \[2\ \[3\] at these extremely high energies. The physics behind such interactions, being at scales of several tens or even hundreds of TeV, might be intimately connected to the problem of flavor and fermion masses.

The main point of our paper is to demonstrate that new GeV, not TeV-scale, physics is required to have any impact on the problem at hand. This will follow from...
the fact that cross sections of several tens of millibarn or larger must be associated
with the new physics. It is extremely difficult for such new thresholds to be turned on
up to millibarn cross sections at 10^8 TeV energies without violating s-wave unitarity.
Needless to say that new GeV-scale physics is unlikely to have escaped the scrutiny
of accelerator experiments.

The paper consists of two parts. We first discuss the puzzling features of the
highest energy cosmic rays. Subsequently, we study the possibility that non-standard
neutrino interactions at these very high energies give an explanation of these events.
Our focus on neutrinos is motivated by the fact that - unlike protons - they are largely
unaffected by attenuation, as will be discussed in the next section. We show that,
even in the presence of new interactions at high energies, they cannot provide a real-
izable explanation. This will substantiate our assertion that any new particle physics
relevant to these issues should have been or can be revealed in existing experiments.
We conclude with some comments.

2 The Highest Energy Cosmic Rays: A Paradox

In October 1991, the Fly’s Eye cosmic ray detector recorded an event of energy
3.0^{+0.36}_{-0.30} \times 10^8 \text{ TeV} [4]. This event, together with an event recorded by the Yakutsk
air shower array in May 1989 [5], of estimated energy \sim 2 \times 10^8 \text{ TeV}, are the two
highest energy cosmic rays ever seen. More recent papers [6] report that the Akeno
Giant Air Shower Array, an instrument of over 100 scintillation detectors spread over
a 100 km^2 area, recorded 2 events in the same energy range.

How Nature accelerates microscopic particles to macroscopic energy is still a mat-
ter of speculation. In order to accelerate a particle to energy E in a magnetic field
B, its gyroradius must be contained within the accelerator. In other words, the ac-
celerator’s dimension R has to exceed the particle’s gyroradius E/B. This leads to
the relation

E \leq BR, \quad (1)

where the equality can be satisfied for a totally efficient accelerator. It is generally
accepted, that supernovae in our own galaxy accelerate the bulk of the cosmic rays,
perhaps via shocks driven into the interstellar medium by the supernova explosions.
Although the blueprint of this accelerator is complex, with a typical size of tens of
parsecs and a magnetic field of several microgauss, its maximum energy reach is easily
obtained by dimensional analysis:

E_{\text{max}} = \left(10^5 \text{ TeV}\right) \left(\frac{B}{3 \times 10^{-6} \text{ G}}\right) \left(\frac{R}{50 \text{ pc}}\right). \quad (2)

Our own galaxy is too small and its fields too weak to accelerate particles to energies
exceeding 10^8 \text{ TeV}. This implies that they must be produced outside our galaxy,
possibly near supermassive black holes in active galactic nuclei where magnetic fields
of hundreds of microgauss extend over kiloparsec distances. The highest energy cosmic rays should point at their sources, even if they are charged. The gyroradius of a $10^7$ TeV proton in the $3 \times 10^{-6}$ gauss galactic field is roughly 10 kpc, comparable to the size of our galaxy. So, $10^8$ TeV particles should travel in straight paths from their sources through the galactic and intergalactic magnetic fields.

What completes the puzzle is that, at this point, one can reasonably argue that the highest energy cosmic rays are not nuclei or protons, nor gamma rays or neutrinos, as long as these particles have standard interactions. We present these arguments sequentially:

- The mean free path of a $3 \times 10^8$ TeV proton in the cosmic photon background is only 8.8 Mpc. Protons of this energy, traveling through the omnipresent 2.7K photon background, will photoproduce pions, and will thus be demoted in energy over a distance of less than 10 Mpc, i.e. much less than the 100 Mpc plus distance from the posited sources. Alternatively, the probability for a proton of this energy to traverse 100 Mpc without an interaction is $1.16 \times 10^{-5}$. A cosmic ray proton needs an energy of $3 \times 10^{10}$ TeV to reach Earth from a 100 Mpc source with the observed energy. Needless to say, achieving energies of this order becomes a challenge, even if the parameters for the standard acceleration mechanisms are stretched [7]. From the previous discussion it is clear that the identification of the highest energy cosmic rays with protons is problematic. The above arguments apply, mutatis mutandis, to nuclei.

- The measured shower profile of the Fly’s Eye event is sufficient to conclude that the event has not been initiated by a photon. Photons with these energies interact in the geomagnetic field, thus starting a cascade well before entering the atmosphere [8, 9, 10]. A Monte Carlo simulation of the atmospheric shower profile of the Fly’s Eye event has been performed [11]. The simulation includes interactions with both the Earth’s magnetic field and nuclei in the atmosphere. They show that a $10^8$ TeV photon encountering the ever increasing geomagnetic field will interact somewhere between 500 and 10000 km above the Earth’s surface. The most probable height is 3000 km. The dipole magnetic field at this distance is roughly 0.1 Gauss. Notice that the shower direction in this event is almost perpendicular to the field lines. In the primary interaction the photon is transformed into a pair of electrons which, subsequently, suffer an energy loss as a result of magnetic bremsstrahlung which is peaked forward at $h\nu/E \sim 0.1$ for $E = 10^8$ TeV and $H = 0.1$ Gauss. The resulting electromagnetic shower consists, on average, of 6 $\gamma$-rays carrying 65% of the primary energy. These $\gamma$-rays of energy $10^7$ TeV will initiate the development of the atmospheric cascade. After further cascading the overall photon energy distribution peaks at $10^5$ TeV. One must take into account that at these energies the electromagnetic cascade is elongated by the LPM effect [11].

The bottom line is that a shower initiated by a $3 \times 10^8$ TeV gamma ray reaches
shower maximum high in the atmosphere at $x_{\text{max}} = 1075 \text{ gr cm}^{-2}$, inconsistent with the observed value of $815\pm45 \text{ gr cm}^{-2}$. As a result of the large number of secondary photons that contribute to the composite air shower, the fluctuations are very small. We conclude that the hypothesis of the event being initiated by a $\gamma$-ray is not consistent with the experimental observations. The same conclusion is reinforced by the Yakutsk event which is recorded by a giant array of 18 km$^2$. The detector consists of scintillators, Čerenkov detectors, muon detectors and antennas for radio frequency detection. The shower is rich in muons and therefore not initiated by a $\gamma$-ray.

- Neutrino origin is also inconsistent with the observed shower profiles. At these energies the atmosphere is transparent to neutrinos. The ratio of the neutrino-air and proton-air cross sections is, in the absence of new physics, approximately $10^6$ at this energy. The particle physics is sufficiently precise to bracket its value in the range $10^5 \sim 10^7$. This is so even when the energies are so high as to probe very small values of $x$. The average $x$ is given by:

$$<x> = \frac{1}{\sigma} \int_0^1 dx \ x \frac{d\sigma}{dx}.$$ (3)

It is essential not to neglect the $x$-dependence of the $W$ propagator in the expression for $d\sigma/dx$ which gives the main contribution to average $x$:

$$\frac{d\sigma}{dx \ dy} = \frac{G_F^2 s}{\pi} \left( \frac{M_W^2}{M_W^2 + s \ x \ y} \right)^2 x q(x) ,$$ (4)

where $s$ is the square of the center of mass energy. If we assume that the quark distribution function is given by $q(x) \sim 1/x^{1+\epsilon}$, with $\epsilon \sim 1/2$ from perturbative QCD, we obtain

$$<x> \approx O(1) \times \frac{1}{\sigma} \frac{G_F^2 M_W^2}{16 \pi} \sqrt{(M_W^2/s)} ,$$ (5)

with average $Q^2$ of the order $M_W^2$. Thus, for $E_\nu \approx (2 - 3) \times 10^8 \text{ TeV}$ one expects $<x> \approx (10^{-7} - 10^{-8})$. However, the fact that this values of $x$ are well below the currently measured range, does not represent an obstacle to bound the neutrino cross section. For instance, in Reference [12] various methods of extrapolation at low $x$ are used in order to establish a range for the neutrino cross section. At these energies the charged current cross section varies from approximately $2 \times 10^{-5}$ to $3 \times 10^{-4}$ mb for different structure functions. These are still very small values.

With a cross section reduced by at least a factor $10^5$ compared to protons, neutrinos should interact in the earth, not the atmosphere, with relatively flat distributions. Although nothing can be made of an odd single event interacting in the atmosphere, the neutrino scenario is inconsistent with 5 events, or more depending on how one counts, all interacting at the top of the atmosphere.

We conclude that the highest energy cosmic rays are neither protons or photons, nor neutrinos. While the data itself rules out photons, both protons and neutrinos
are disfavored by a problematic factor of $10^5$ which represents the probability that a proton reaches us without attenuation from 100 Mpc source, and the ratio of the neutrino to proton interaction cross sections in the case of neutrinos. This is the paradox. Its resolution may involve new astrophysics, or new particle physics at energies which exceed those of existing accelerators by two orders of magnitude. In what follows we will argue that the second possibility is unlikely if we restrict the primary to be a known particle experiencing non-standard interactions. As mentioned earlier, neutrinos are the most promising candidates within this option due to the absence of attenuation effects.

3 Is New Particle Physics the Solution?

Going the particle physics road is attractive. What if, for instance, neutrinos became strongly interacting so as to initiate air showers? Transforming the energy of $10^8$ TeV to the center of mass, yields approximately 450 TeV. At such energies physics associated with scales as large as $10 - 100$ TeV may be relevant and even dominant. As mentioned above, this energy scales might be associated with new particle physics, the generation of flavor and fermion masses, dynamical supersymmetry breaking, etc. The possibility that these new interactions might cause neutrinos to become strongly interacting at these energies has been raised in several opportunities. For instance, it is the underlying physics behind the neutrino compositeness proposal of Reference [2]. More recently, a model of spontaneously broken family symmetry [3], with a typical scale of hundreds of TeV and designed to generate flavor, was suggested as a possible origin of a very large neutrino coupling at high energies, thus offering a potential explanation for the Ultra High Energy Cosmic Ray (UHECR) events. We will now show that these proposals fail, dramatically. In order to resolve the puzzle of the highest energy cosmic rays the new physics scale cannot exceed several GeV. On the one hand, s-channel unitarity prevents us from turning on suddenly, at $10^8$ TeV, a threshold associated with a cross section characterized by a typical scale of about 1 GeV. More sophisticated proposals might get around the unitarity bound at the cost of giving a very small effect. We will study below various specific examples covering these possibilities.

The proton-proton cross section at $10^8$ TeV energy is roughly 100 mb [13]. The interaction length of a proton in the atmosphere corresponding to this interaction cross section is $40 \text{ g cm}^{-2}$, i.e. the full atmosphere represents 20 interaction lengths. As the interaction length is inversely proportional to the cross section, the atmosphere is only 2 interaction lengths for a particle with a cross section of 10 mb. So, in order for five cosmic rays to initiate showers near the top of the atmosphere, their interaction cross section must be several times 10 mb, or not much smaller than the 100 mb value for protons.

The new particle physics scenarios we consider here are chosen partly because of the attention each of them has attracted in relation to the UHECR question. They
also span a wide range of models making our conclusions quite general. Our aim is to show that, with very few and constrained exceptions, extensions of the standard model of electroweak interactions at scales above a few TeV cannot be the physics behind UHECR and that the energy scale necessary to explain the highest energy cosmic rays is not far above 1 GeV in most cases. To illustrate this point we will study three different classes of models: s-channel resonances, composite neutrinos and the t-channel exchange of a gauge boson strongly coupled at high energies.

We first study the effects of an s-channel $\nu q$ scalar resonance $S$ in the $\nu N$ cross section. This is very similar to the study of the effects of leptoquarks in UHECR in Reference [14]. The production cross section, in the narrow width approximation, is given by

$$\sigma(\nu N \to SX) = \frac{\lambda^2 \pi}{4M_S^2} \times q(x = \frac{M_S^2}{s}, Q^2 = M_S^2),$$

where $\lambda$ is the coupling of $S$ to quarks and leptons. In Figure 1 we plot this cross section as a function of the neutrino energy, for various values of $M_S$ and for $\lambda = 1$.[1] For reference, we plot the SM $\nu N$ charged current cross section, computed using the CTEQ4D set of parton distribution functions [15]. These are extrapolated down to values of $x$ as low as $10^{-8}$ by using the double logarithmic approximation [16]. The uncertainties associated with the use of this procedure are irrelevant for the purpose of the calculation of the neutrino cross sections due to new physics effects, since we are interested in enhancements of several orders of magnitude. Also plotted in Figure 1 is the $pp$ cross section, which sets the scale a model must match in order for the neutrinos to interact in the atmosphere. We observe that in order to obtain a neutrino cross section of this size at the highest energies the mass scale of the exchanged particle has to be $O(1)$ GeV. Of course, such a mass is in flagrant conflict with all low energy data. The idea behind this simple exercise is to show the difficulty of generating a $\simeq 100$ mb cross section at $E_\nu \simeq 10^{12}$ GeV. New particle physics scenarios which extrapolate from and extend on established particle physics, cannot generate neutrino cross sections far above their SM values. In what follows, we will arrive at the same conclusion in two completely different and seemingly promising type of models.

We next consider the possibility that neutrinos are composite with a scale $\Lambda_c$ somewhere between 10 TeV and several hundred TeV. If the neutrino constituents are colored, they will experience strong interactions with quarks and gluons above the scale $\Lambda_c$. This is essentially the scenario proposed in [2], where it was suggested that the cross section is determined by the scale of the strong interactions, $\Lambda_{QCD}$, as opposed to the scale of compositeness. This would lead to a large cross section of the order of several millibarns, and perhaps to an explanation of the UHECR events. We will show that this is not the case. We first notice that the size of the neutrino must be determined by $\Lambda_c$ and that no color can leak out of a $\sim 1/\Lambda_c$ radius. In order to resolve the constituents, the wavelength of an exchanged particle must be sufficiently

*Normally, leptoquark scenarios have $\lambda \ll 1$
small. In $\nu q$ scattering, this implies that the exchanged gluon can only interact with the neutrino constituents if its momentum transfer is of the order of $\Lambda_c$, or larger. To estimate the neutrino cross section we assume that the preons inside the neutrino have $\mathcal{O}(1)$ momentum fractions. Thus the $\nu N$ cross section is approximately given by

$$\frac{d\sigma}{dx\,dy} \simeq 2\pi\alpha_s \frac{s}{Q^4} \left[1 + (1 + y)^2\right] xq(x) \ ,$$

for momentum transfers satisfying $Q^2 > \Lambda_c^2$. In Figure 2 we plot the neutrino cross section for several values of $\Lambda_c$. For any reasonable values of $\Lambda_c$ the cross section is nowhere near the $\simeq 100$ mb landmark it should reach at $E_\nu \simeq 10^{12}$ GeV. The plot of the cross section for $\Lambda_c = 1$ GeV illustrates the fact that this is the relevant energy scale to enter the millibarn regime, as one would expect. Of course, the neutrino compositeness scale is bound by experiments to be at least a few TeV [17]. The failure of the argument in [2] can be traced back to the fact that color is confined in $r_\nu \simeq 1/\Lambda_c$, and therefore the factor of $Q^4$ in the denominator in (7) represents an unsurmountable suppression. This feature of s-wave unitarity prevents the sudden appearance of a very large effect. The statement that the interaction scale should be of about 1 GeV is very general and can be applied to models where exotic particles are chosen to be the primary sources of UHECR. These must carry color in order to hadronize and thus have a large cross section in the atmosphere, regardless of their mass or other quantum numbers.

Finally, we consider the very intriguing scenario of Reference [3], where fermions transform under a spontaneously broken generation symmetry taken to be $SU(3)$. The generation group is assumed to be dual to $SU(3)$ color. The massive gauge bosons in this model couple to generation number with a coupling $\tilde{g}$, satisfying the duality condition

$$\tilde{g}g = 4\pi \ .$$

These gauge bosons, dubbed “dual gluons”, induce flavor changing neutral currents (FCNC) at tree level. Experimental bounds on FCNC processes force their mass scale to be at or above the 100 TeV range. It was pointed out in [3] that neutrino interactions could become strong at very high energies via the exchange of dual gluons, which become strongly coupled due to the condition (8). This fact explains why there would be no large effects induced at low energies. The $\nu N$ cross section induced by the exchange of a dual-gluon is given by

$$\frac{d\sigma}{dx\,dy} = \frac{\pi F}{2\alpha_s(Q^2)} \frac{s}{(Q^2 + M_D^2)^2} xq(x) \left\{1 + (1 + y)^2\right\} \ ,$$

where $M_D$ is the mass of the dual gluon and $F$ is a factor of order one coming from the group structure of the generation symmetry. For instance, for $SU(3)$, we have $F = 2$ as long as we consider only first generation fermions in the initial state. The $\nu N$ cross section mediated by dual gluon exchange is plotted in Figure 3 for several
values of the dual gluon mass. It is apparent that for the desired mass range of 100 TeV the effect on the cross section is negligible, even when compared to the SM $\nu$ cross sections. This is the case despite the very large enhancement coming from the running of $\alpha_s$ in the denominator, a consequence of (8). The main reason for the relative suppression is the value of $M_W/M_D$. This is somewhat upset by the fact that the dual-gluon cross section rises linearly with $E_\nu$ up to very large energies before saturating. Even with this feature, the cross section at $E_\nu \approx 10^{12}$ GeV is about one hundred times smaller than the SM one. We see that a dual gluon mass of 50 GeV, in obvious conflict with experimental bounds on FCNC, is required in order to yield a sufficiently large cross section at the highest neutrino energies. This mechanism avoids the need for a $O(1)$ GeV scale, given the extreme strength of $\tilde{\alpha}(Q^2)$ at very high energies. Even with this coupling the model produces an insignificant enhancement of the SM neutrino cross section because of the scale of 100 TeV. On the other hand, one could in principle imagine a completely unrelated model where the dual gluon has no FCNC interactions and then is allowed to be lighter. However, the induced contact interactions, even when flavor diagonal, are constrained to be governed by a scale above a few TeV [17]. Although at these mass scales the effect of dual-gluon exchange is large compared to the SM $\nu$ cross sections, it is still several orders of magnitude smaller than needed to explain the UHECR excess.

We conclude that it is highly unlikely that neutrino initiated air showers involving new neutrino interactions are responsible for the apparent excess of events in UHECR. We have shown that the needed scale is, in most cases, of $O(1)$ GeV which is not an allowed energy scale for new neutrino interactions. One type of models that gets around this general constraint, does so by having an increasingly strong coupling at high energies. Even in these cases, the scales that are still allowed by low energy constraints (e.g. a few TeV in Fig. 2) are already too high to provide a large enough effect.

4 Some Final Remarks

We have studied the possibility that the UHECR excess is initiated by known particles with non-standard interactions at very high energy. We concentrated on neutrinos as they do not suffer from the attenuation that forces protons, for instance, to come from local sources. We found that, even in the presence of important new physics effects at the high energies at hand, neutrino initiated air showers are not viable. We have also shown that the energy scale associated with the interactions responsible for the UHECR should be, in most cases, in the vicinity of 1 GeV. Thus, models postulating exotic primaries must arrange for them to form hadrons, which in turn can interact with the desired cross sections in the atmosphere. An exception to this is the model of Reference [4], where the energy scale needed is of the order of 100 GeV due to the large enhancement given by the strength of the coupling at high energies. However, in this as well as in all other cases, the necessary energy scales are well below the limits
allowed by observation. We conclude with a few comments about possible alternative explanations.

As it can be read from Figure 1, leptoquarks [14] as well as typical supersymmetric models, which are associated with TeV-scale physics, are irrelevant to cosmic ray issues. At $10^8$ TeV supersymmetric particles interact with universal electroweak cross section, i.e. cross sections similar to those of Standard Model neutrinos [18].

The scenario where the highest energy cosmic rays are light gluinos does not violate our no-go argument [19]. Their mass is indeed in the GeV-range. But most importantly, they form various supersymmetric hadrons which interact with the atmosphere with cross sections governed by the 1 GeV scale. This scenario can be tested by existing accelerator experiments [20].

Topological defects [21] are an example of new particle physics not covered by our exclusion argument because they are, essentially, a new astrophysical source and do not represent new particle dynamics.

Scenarios involving exotic primaries, possibly avoiding our arguments, require yet additional assumptions in order to be relevant. While large cross sections with hadrons are required, those with photons must be suppressed in order to avoid significant attenuation in the cosmic microwave background. If not, the new particle has properties similar to protons and can only come from local sources. Heavy stable colored particles fall in this category [22]. On the other hand, heavy quasi-stable particles [23] decaying locally, for instance in the halo, are not affected by attenuation.

In sum, a particle physics explanation of the UHECR is not viable unless new interactions and new matter with the right properties are invoked. On the other hand, it is possible that the cosmic ray paradox may have an alternative solution which can hardly be raised to the level of new astrophysics. There may be mechanisms by which $10^8$ TeV energy is reached locally, not in sources beyond 100 Mpc. Such speculations have been disfavored. We mention them for completeness: galactic winds exceeding the size of our galaxy [24] possibly reaching out into the local cluster, and pinball enhancement of the particle energy between several galactic supernovae [25].

Acknowledgments

The authors thank Chris Quigg for useful comments and discussions. This research was supported in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881 and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.
References

[1] M. A. Lawrence, R. J. O. Reid, and A. A. Watson, *Journ. Phys. G* **17** (1991) 733.

[2] G. Domokos and S. Nussinov, *Phys. Lett.* **B187** (1987) 372; G. Domokos and S. Kovesi-Domokos, *Phys. Rev.* **D38** (1988) 2833.

[3] J. Bordes, Chan Hong-Mo, J. Faridani, J. Pfaudler and Tsou Sheung Tsun, [hep-ph/9705453](http://arxiv.org/abs/hep-ph/9705453).

[4] D. J. Bird *et al.*, *Phys. Rev. Lett.* **71** (1993) 3401.

[5] N. N. Efimov *et al.*, *ICRR Symposium on Astrophysical Aspects of the Most Energetic Cosmic Rays*, ed. by M. Nagano, F. Takahara, World Scientific (1991).

[6] N. Hayashida *et al.*, *Phys. Rev. Lett.* **73** (1994) 3491.

[7] G. Sigl, D. N. Schramm and P. Bhattacharjee, *Astropart. Phys.* **2** (1994) 401.

[8] B. McBreen and C. J. Lambert, *Proc. 17th Int. Conf. on Cosmic Rays*, Paris, 1981, ed. by Ch. Ryter, V.6, p.70.

[9] F. A. Aharonian, B. L. Kanewski and V. A. Sahakian, *Journ. Phys. G: Gen. Phys.*, **17** (1991) 1989.

[10] H. P. Vankov and P. V. Stavrev, *Phys.Lett.* **B226** (1991) 178.

[11] F. Halzen, R. Vazquez, T. Stanev and H.P. Vankov, *Astropart. Phys.* **3** (1995) 151.

[12] R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, *Astropart. Phys.* **5** (1996) 81. For an update see C. Quigg, FERMILAB-CONF-97/158-T.

[13] M. M. Block, F. Halzen and B. Margolis, *Phys. Rev.* **D45** (1992) 839.

[14] R. W. Robinett. *Phys. Rev.* **D37** (1988) 84; M. A. Doncheski and R. W. Robinett, PSU-TH-184, [hep-ph/9707328](http://arxiv.org/abs/hep-ph/9707328).

[15] H. L. Lai *et al.*, *Phys. Rev.* **D55** (1997) 1280.

[16] L. V. Gribov, E. M. Levin and M. G. Ryskin, *Phys. Rep.* **100** (1983) 1; D. W. McKay and J. P. Ralston, *Phys. Lett.* **B167** (1986) 103. The use of more singular structure functions at low $x$ give a somewhat higher cross section. For a complete discussion see Reference [12].

[17] F. Abe *et al.* (CDF Collaboration), FERMILAB-PUB-97-171-E; K. Ackerstaff *et al.* (OPAL Collaboration), CERN-PPE-97-101.

[18] M. Drees, private communication.

[19] D. J. H. Chung, G. R. Farrar and E. W. Kolb, FERMILAB-PUB-97-187-A, [astro-ph/9707036](http://arxiv.org/abs/astro-ph/9707036).
[20] I. F. Albuquerque et al. (E761 Collaboration), *Phys. Rev. Lett.* **78** (1997) 3252; J. Adams et al. (KTeV Collaboration), RUTGERS-97-26.

[21] P. Bhattacharjee, C. T. Hill and D. N. Schramm, *Phys. Rev. Lett.* **69** (1992) 567. For a discussion on monopole initiated air showers see: T. W. Kephart and T. K. Weiler, *Astropart. Phys.* **4** (1996) 217; C. O. Escobar and R. A. Vázquez, IFT-P.050/97, astro-ph/9709148; as well as Reference [22].

[22] R. N. Mohapatra and S. Nussinov, hep-ph/9708497.

[23] V. Berezinsky, M. Kachelrieß and A. Vilenkin, astro-ph/9708217; P. H. Frampton, B. Keszthelyi and Y. J. Ng, astro-ph/9709080.

[24] J. R. Jokipii, *Astro. Journal* **313** (1990) 301.

[25] W. I. Axford, in *Proceedings of the 1990 Kofu Symposium on “Astrophysical Aspects of the Most Energetic Cosmic Rays”*, eds. M. Nagano and F. Takahara, World Scientific, p. 406 (1991).
Figure Captions

**Figure 1:** Neutrino cross section as a function of the neutrino energy, for the case of scalar s-channel exchange. For comparison the standard model charged current neutrino-nucleon cross section, as well as the total pp cross section, are shown in dashed lines.

**Figure 2:** Neutrino cross section as a function of the neutrino energy, for the case of neutrino compositeness.

**Figure 3:** Neutrino cross section as a function of the neutrino energy, in the dual gluon model of Reference [3].
Figure 1
Figure 2
Figure 3