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Accelerator Sources of High Energy Cosmic Neutrinos

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ACCELERATOR SOURCES OF HIGH ENERGY COSMIC NEUTRINOS*

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This paper reviews some topics of current interest concerning observations of atmospheric neutrinos and searches for high energy neutrinos of extraterrestrial origin.

1. INTRODUCTION

The distinction between "accelerator sources" and "non-accelerator sources" of high energy astrophysical neutrinos is due to Berezinsky [1].The former are neutrinos produced as secondaries in collisions of protons and nuclei accelerated in cosmic ray sources. The interactions may occur either in ambient gas or dense photon fields. In contrast, high energy neutrinos of non-accelerator origin may come from annihilation or decay of dark matter and radiation from black holes or cosmic strings.

Unlike the typical monoenergetic beam produced by a machine, cosmic accelerators generally produce power law spectra of ions at high energy,

$$\phi_p \propto E^{-(\gamma+1)}. \quad (1)$$

The observed high energy cosmic ray spectrum at Earth is characterized by $\gamma \sim 1.7$. In general, a cosmic accelerator in which the dominant mechanism is first order diffusive shock acceleration (first order Fermi mechanism), will produce a spectrum with $\gamma \sim 1 + \delta$, where δ is a small number. The accelerated spectrum may be modified somewhat by propagation effects.

Production of secondary particles (S) is related to the spectrum of accelerated primaries (P) by

$$\frac{\mathrm{d}P_S}{\mathrm{d}E_S} = \frac{\Delta}{\lambda_P}\int_{E_S}^{\infty}\frac{\mathrm{d}n_{PS}(E_S,E_P)}{\mathrm{d}E_S}\phi_P(E_P)\mathrm{d}E_P, \quad (2)$$

where Δ/λ_P is the probability of interaction in traversing a small amount (Δ) of target. If the distribution of secondaries depends only on the ratio of energies, $x = E_S/E_P$ then the integral in Eq. 2 becomes

$$\phi_P(E_S)\int_0^1 x^{\gamma-1}F_{PS}(x)\,\mathrm{d}x \equiv \phi_P(E_S)\,Z_{PS}, \quad (3)$$

where

$$F_{PS} = \frac{1}{\sigma}\int \mathrm{d}^2p_T\, E_S\,\frac{\mathrm{d}\sigma_{PS}}{\mathrm{d}^3p} = E_S\frac{\mathrm{d}n_{PS}}{\mathrm{d}E_S}.$$

For $\gamma > 1$, $F(0)$ does not contribute to the integral, and the scaling approximation made here is an adequate approximation for rough estimates.

This treatment generalises readily to decay chains, such as $p \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$, etc., and it can be applied to cascades in galactic and stellar environments as well as in the Earth's atmosphere. I first discuss (terrestrial) atmospheric neutrinos

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and then some possible sources of astrophysical neutrinos.

2. ATMOSPHERIC NEUTRINOS

The simplest case occurs when all pions, kaons and muons decay. Then

$$\phi_\nu = \frac{\Delta}{\lambda_p} \phi_P(E_\nu) \{ Z_{p\pi^\pm} (Z_{\pi\mu} Z_{\mu\nu} + Z_{\pi\nu}) + \text{kaon terms} \} . \qquad (4)$$

Eq. 4 could apply equally to an astrophysical system (such as a diffuse gas of thickness Δ around an accreting neutron star that somehow accelerates protons) or to the cosmic ray beam interacting in the Earth's atmosphere. In the case of a thick target, the thickness Δ is replaced by the nucleon attenuation length, Λ. The Earth's atmosphere is in this category because its thickness is $\gg \lambda_p$. Another situation in which the target is effectively thick occurs when the accelerated ions are contained by diffusion in turbulent magnetic fields in a region filled with a diffuse gas. If the characteristic time for escape from the region is much longer than the characteristic collision time, then we have effectively a thick target case, even if the line-of-sight thickness of the material is very small. This situation may exist in active galactic nuclei (AGN), [2] and it could have some practical importance that I point out in the last part of this talk.

The kinematics of pion and muon decay are such that when Eq. 4 applies one has approximately

$$\frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu} \sim \frac{1}{2}. \qquad (5)$$

This is the case for atmospheric neutrinos with $E_\nu < 1$ GeV. The fact that Eq. 5 is apparently significantly violated [3–5] is largely responsible for the great interest in atmospheric neutrinos.

2.1. Contained Events

Although Eqs. 2–5 are qualitatively correct, more detailed calculations are needed for a precise evaluation of the atmospheric neutrino flux. Several complications must be accounted for:

– The primary cosmic ray spectrum is not a simple power law, especially $\lesssim 10$ GeV and $\gtrsim 100$ TeV. Moreover, it depends on location and direction (because of the geomagnetic cutoff) and on the epoch of the solar cycle.

– Muon energy loss, decay and polarization must be accounted for.

– The inclusive cross sections do not have exactly scale-invariant forms. Furthermore, nuclei, as well as nucleons, are involved in the collisions. There have been several calculations in the last few years which use either numerical or Monte Carlo methods to evaluate the neutrino flux at low energy: [6–10].

The results from the two large water detectors [3,4] are completely consistent with each other, after correction for their different locations and small differences in detector threshold. Both find the electron/muon ratio significantly higher than expected [5]. The results of tracking calorimeters [11,12] are consistent with the conventional expectation, but with lower statistics. Several independent calculations agree within 5% for the ν_e/ν_μ ratio. (See [13] for a review.)

It is more difficult to say whether there are too few ν_μ or too many ν_e. This is *not* because there is any mystery or "model-dependence" (in the sense of theoretical model building) involved. It is simply because there are experimental uncertainties in the parameters that go into the calculation of the atmospheric neutrino flux. Some of these are discussed briefly in Ref. [13]. In the calculation of the ν_e/ν_μ ratio, most of the uncertainties cancel.

Interpretation of the contained events depends on two factors in addition to the neutrino fluxes: properties of neutrino interactions in the detectors and the detector calibration. In view of the potential importance of this anomaly, both of these factors also need close scrutiny. A parallel approach is to look for other experimental consequences of assuming that the explanation of the contained event anomaly involves new physics. Several groups [14–16] have emphasized the importance of neutrino-induced upward muons in this connection.

2.2. Upward Muons

In a deep detector, the principle source of energetic upward muons is charged-current interactions of $\nu_\mu\,(\bar{\nu_\mu})$ in the rock below the detector. Atmospheric muons, which dominate the flux of downward muons, are absorbed by the Earth. The flux of ν_μ-induced muons is given by a convolution of the atmospheric neutrino spectrum with the differential cross section for $\nu_\mu + N \to \mu + \ldots$ and with the muon range in rock, $R(E_\mu, E'_\mu)$:

$$N_\mu(>E_\mu) = \int \mathrm{d}E'_\mu \int \mathrm{d}E_\nu\, R(E_\mu, E'_\mu) \times \frac{\mathrm{d}\sigma(E_\nu)}{\mathrm{d}E'_\mu}\,\phi(E_\nu). \quad (6)$$

Since both neutrino cross section and muon range increase with energy, the upward muons probe higher energies than contained neutrino interactions, as shown in Fig. 1.

The quickest way to illustrate the role of upward muons in the atmospheric neutrino problem is to assume a set of oscillation parameters that could account for the observation that ν_e/ν_μ for contained events is larger than expected and see what it would imply for upward muons. For this purpose I use the "allowed region" discussed by the Kamiokande group. [4] For example, for vacuum oscillations of $\nu_\mu \to \nu_\tau$ the oscillation probability is

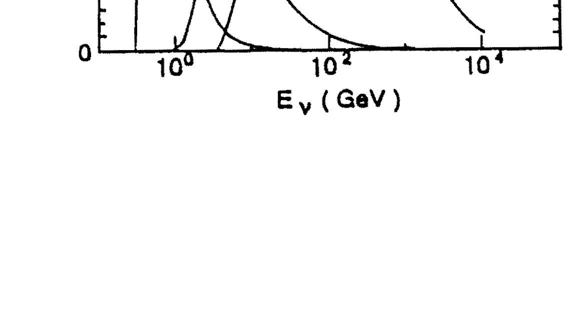
$$P_{\nu_\mu\to\nu_\tau} = \sin^2 2\theta\, \sin^2\left[1.27\,\delta m^2\,\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]. \quad (7)$$

For $\delta m^2 = 0.01$ eV^2 and $L = 10^4$ km, the first node of this function occurs at $E_\nu = 80$ GeV, in the peak of the response function (Fig. 1) for ν_μ-induced muons.

Calculations of the flux of neutrino-induced upward muons are generally consistent with observation. Given the uncertainties involved, both in the calculations and in the data, this does not necessarily eliminate the possibility of neutrino oscillations at a level consistent with the contained events. In fact, I will argue below (Fig. 2) that the size of the expected effect is comparable with the uncertainties for $\delta m^2 \gtrsim 10^{-2}\,\mathrm{eV}^2$.

Uncertainties in the calculated neutrino flux arise from two sources, the primary cosmic ray spectrum and the inclusive cross sections for production of pions and kaons. The latter is particularly important at high energy since decay of

FIGURE 1.



kaons is the dominant source of ν_μ around 100 GeV and above. Measurements of the primary cosmic ray spectrum typically quote a systematic error of 15% in the normalization. The uncertainty from the input inclusive cross sections is of comparable magnitude. [17] The neutrino spectra in the literature [18–20] show differences that reflect these levels of uncertainty in the input to the calculations. Examples are given in Table 1, which shows the flux averaged over the upward hemisphere.

Table 1. $\frac{dN}{d\ln E_\nu}$ ($\nu_\mu + \bar{\nu}_\mu$, $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$)

	10	100	1000 GeV
Volkova[18]	6.0 $\times 10^{-4}$	6.1 $\times 10^{-6}$	4.5 $\times 10^{-8}$
Mitsui[19]	6.3	6.2	4.1
Butkevich[20]	7.3	6.9	4.2
Ref. [17] (preliminary)	6.9	7.2	4.7

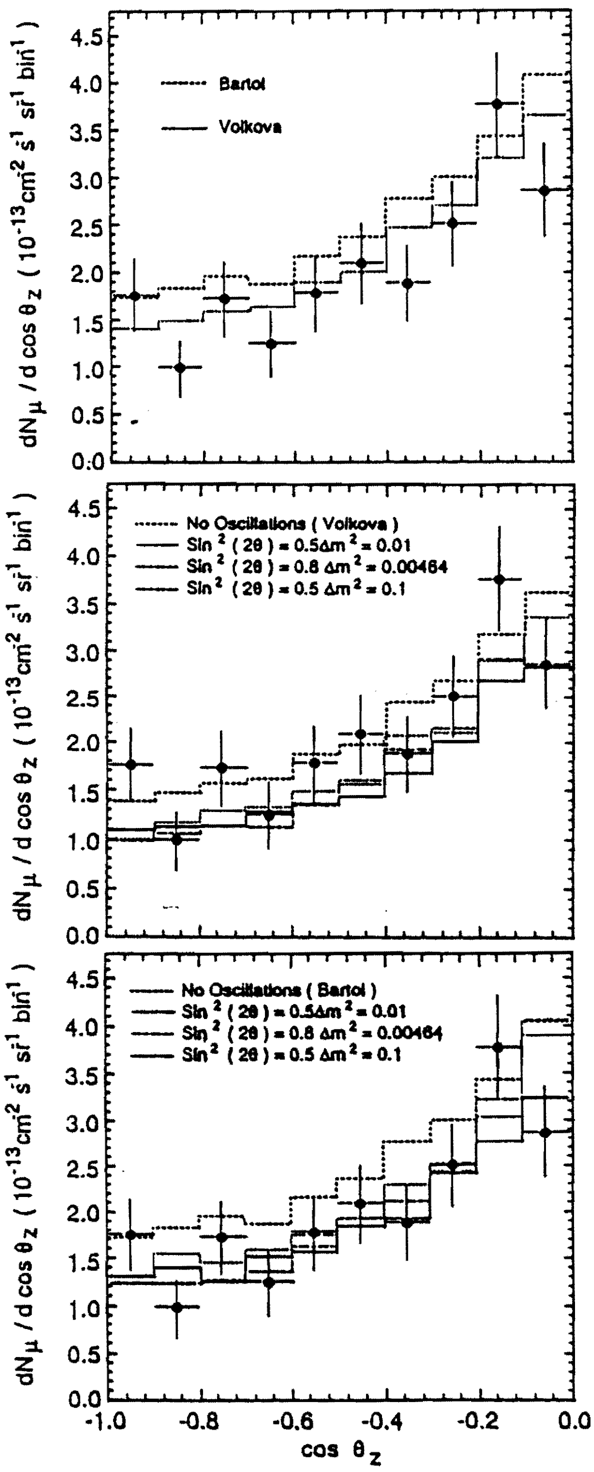
The IMB group point out that the fraction of upward muons that stop in the detector is relatively insensitive to uncertainties in the calculation because the flux normalization cancels. They find [15] that the measured fraction of stopping muons rules out a portion of the $\delta m^2, \sin^2\theta$ plane for $\delta m^2 < 10^{-2}\ eV^2$ and large mixing angle. The constraint on the δm^2 parameter from the fraction of stopping muons comes from the absence of a distortion of the muon energy spectrum. The relevant neutrino energies are illustrated in Fig. 1. For example, if $\delta m^2 \sim 10^{-3}\ \mathrm{eV}^2$ the transition probability (7) is relatively large for $E_\nu \sim 10$ GeV (and $L \sim 10^4$ km) but negligible for $E_\nu \sim 100$ GeV. In this case one would have a significant distortion of the upward muon spectrum and hence an anomaly in the stopping fraction provided the mixing angle is sufficiently large. On the other hand, if $\delta m^2 \gtrsim 10^{-2}$ then both the high and low energy portions will be affected similarly.

It should be mentioned that the IMB constraint from the stopping fraction is based on use of a single neutrino flux calculation. [18] It therefore reflects a particular assumption about the slope of the primary cosmic ray spectrum and other factors that could affect the shape of the neutrino spectrum. One example of such a factor is the uncertainty in the production of kaons, because kaons contribute about 50% of the throughgoing signal but only about 25% of the stopping muons. Nevertheless, as Table 1 illustrates, the uncertainty in shape is less than the uncertainty in normalization. For example, while the absolute values are spread over a 20% range, the variation in the ratio of flux at 100 GeV to that at 10 GeV is much less.

To explore the region of $\delta m^2 > 10^{-2}$, one needs to look at the throughgoing muons. If $\delta m^2 \sim 10^{-2}\ \mathrm{eV}^2$, then an oscillation effect has the possibility of distorting the angular distribution, since horizontal ν_μ ($L \lesssim 1000$ km) may not be affected as much as upward muons ($L \sim 10^4$ km). For larger δm^2, only the overall rate will be affected. These features are illustrated in Fig. 2 [21] in which the Kamiokande data for upward muons [16] is compared to various calculations. The first panel shows the distributions calculated with two different neutrino spectra [17,18] with no neutrino oscillations. The next two panels show the distributions expected for three different sets of oscillation parameters for each of the two neutrino spectra.

We [21] are currently investigating the quantitative implications of these graphs to obtain the excluded regions in the $\delta m^2, \sin^2 2\theta$ plane. It is interesting to note that the combination of neutrino flux [18] and cross section [22] often used [14–16] gives the lowest predicted flux of upward muons.

FIGURE 2.



3. POSSIBLE POINT SOURCES

Many authors have discussed candidate point sources of $\gtrsim$TeV neutrinos, especially in connection with reported observations of air showers from point sources. Possible sources include accreting X-ray binaries[23–25], compact binary systems with interacting winds[26], a neutron star engulfed by a giant companion[24,27] and young supernova remnants [28–31].

There are two approaches to computing the signal expected from such sources. The first starts from observations (or limits) on photon signals from candidate sources. If the photons are products of decay of neutral pions, then one expects a comparable flux of ν_μ. To be certain that the photons are from pion decay (rather than from electron bremsstrahlung without accompanying neutrinos), we use limits or observations on photons in the 100 TeV range, i.e. from air shower experiments. Typical limits for steady emission from point sources [32–35] are in the range

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}\ln E_\gamma} = E_\gamma\,\phi_\gamma \lesssim 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \qquad (8)$$

for $E_\gamma \sim 100$ TeV. The implied limit on the corresponding neutrino flux is

$$\phi_\nu \lesssim \left(\frac{E_\nu}{E_\gamma}\right)^{\gamma+1} \times \frac{\phi_\gamma}{(1-A_\gamma)}, \qquad (9)$$

where A_γ is the fraction of photons absorbed at the source. We can integrate this neutrino flux with the charged current neutrino cross section and muon range[36] to obtain a limit on the upward muon rate. For spectral index γ in the range 1.1 to 1.3, inserting the limit of Eq. 8 into Eq. 9 leads to the result that

$$\mathrm{Flux}(\uparrow\mu) \lesssim \frac{0.2\ \mathrm{events}}{10^4\,m^2\,yr} \times \frac{1}{(1-A_\gamma)}. \qquad (10)$$

A source producing at this limit and having $A_\gamma \gtrsim 0.98$ would be detectable in DUMAND in the sense of giving at least 10 events per year. (The exact number depends on "details" such as the location of the source relative to the detector, which determines the fraction of the time it is sufficiently below the horizon to produce a signal).

The photon absorption factor A_γ could be much larger (e.g. in the case of the neutron star swallowed by a giant star), but this would be at the expense of requiring still greater power at the source. #1 This leads to the other approach to estimating likely neutrino fluxes from various sources. It is straightforward to calculate the power in accelerated protons required to give a detectable signal of neutrino-induced muons independent of any model of photon reabsorption. The result depends on the distance to the source, the assumed spectral index and the fraction of the accelerated proton beam that interacts. Estimates [38,37] show that a power of about 10^{39} to 10^{40} erg/s of accelerated protons is required for a source at the distance of the Galactic radius to produce a detectable signal in DUMAND, assuming a fully absorbed proton beam. This could be a young supernova remnant or a young pulsar. A system accelerating particles with a power of 10^{38} erg/s (e.g. an X-ray binary accreting at the Eddington limit for a solar mass star with a large efficiency for converting accretion energy into high energy particles) would have to be relatively nearby ($\sim$ 1 kpc) to be detectable.

4. NEUTRINOS FROM AGN

There is great interest at present in the possibility of Active Galactic Nuclei as potential neutrino sources. [39,40] The idea that accretion onto a massive black hole may be the central engine of AGN [41,42] and that accelerated particles are the means of transferring energy has a long history, as described in Refs. [40,1]. The current flurry of activity was stimulated by the paper of Stecker et al. [43] which emphasized the large neutrino flux implied by the model at ultra-high energies. Although the initial estimates were too high [2,38], the revised estimates [2,44] still predict fluxes at an interestingly high energy and intensity. The recent discovery that the extragalactic source Markarian-421 emits TeV gamma rays [45] adds to the excitement.

The basic idea [43,44,2] is to build a self-consistent model in which accretion produces a shock at which particles are accelerated to high energy. They interact in intense ambient radiation fields to initiate electromagnetic cascades which in turn are the source of the ambient radiation. The largest potential signal is predicted to be from the diffuse background of high energy neutrinos from all sources, although individual AGN's may be detectable in detectors of sufficient size. A comprehensive review of the subject may be found in [39,40]. Here I want to make just one rather detailed point, which has an important practical implication.

The effective threshold energy for photoproduction in the intense UV photon field in the acceleration region is

$$E_c \sim 10^7 \text{ GeV}. \qquad (11)$$

If (as assumed by Stecker et al. [44]) only those protons with this energy and above interact, then resulting neutrino spectrum will follow the presumed power law dependence of the accelerated proton spectrum for $E_\nu \gtrsim E_c/10$. Below this energy the spectrum will be $dN/dE_\nu \sim$constant.

On the other hand, if (as argued by Szabo

#1 It is shown in Ref. [38] that the power of a hidden source cannot be increased indefinitely without making the object so hot and bright as to violate observations.

and Protheroe [2]) the lower energy protons remained trapped within the central region by diffusion in turbulent magnetic fields, then eventually the whole accelerated proton beam will photoproduce on photons of higher energy. The line-of-sight optical depth may be small for protons with $E < E_c$, but in this scenario they eventually will interact. Since diffusion in ambient magnetic fields must be assumed to make the acceleration mechanism work in the first place, this picture seems quite plausible to me. It has the important consequence that the neutrino spectrum continues to rise at low energy. The neutrino spectra that result from these two assumptions are shown in Fig. 3.

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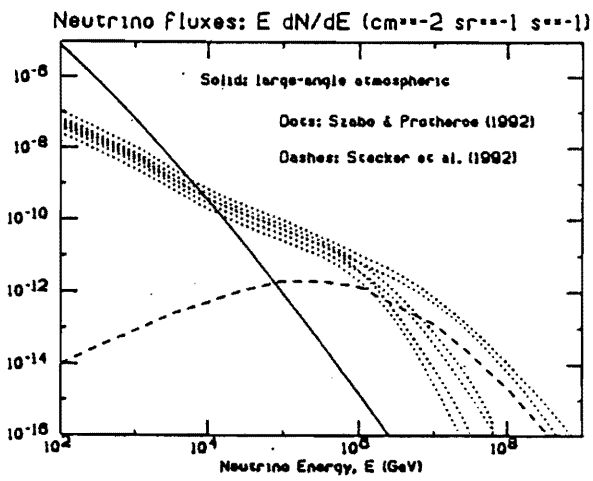
FIGURE 3.



I have used the neutrino cross sections of Owens [46] together with results Lipari & Stanev [47] for muon propagation (which is valid up to ultra-high energies) to estimate the diffuse flux of horizontal muons that would be produced by the neutrino spectra of Fig. 3. In Fig. 4 I compare the predicted integral rates of AGN muons with $E_\mu > E_{\rm min}$ with muons induced by atmospheric neutrinos.

The Frejus group [48] have measured the rates of horizontal muons ($|\cos\theta| < 0.3$) and displayed the results as a function of muon energy loss in the detector. They make a cut at energy loss of 2 GeV/m, which corresponds approximately to $E_\mu > 2$ TeV in the detector. They quote a 90% c.l. upper limit of 2.3 events, which ruled out the prediction of Ref. [43]. To compare the Frejus limit with the fluxes in Fig. 4, I estimate their exposure factor as
$4.5\ \mathrm{yrs} \times 3.5\,\mathrm{sr} \times 60\ \mathrm{m}^2 \sim 3 \times 10^{14}\ \mathrm{m}^2\,\mathrm{sr\,s}$.
This leads to an upper limit of $0.8 \times 10^{-14}\ \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$ on the flux of muons with $E_\mu > 2$ TeV at the detector. This upper limit is plotted at 2 TeV in Fig. 4. #2

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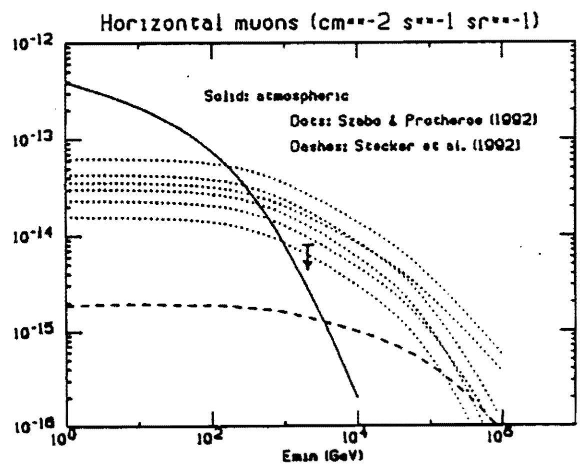
FIGURE 4.



The conclusion is that, although the revised estimate of Stecker *et al.* [44] is now well below the Frejus limit, that same limit gives an interesting constraint on the models of Szabo & Protheroe

#2 To check my estimate of the exposure factor, I calculate the expected flux of horizontal ($|\cos\theta| < 0.3$) muons ($E_\mu > 2$ TeV) produced by atmospheric neutrinos. From the solid line in Fig. 4 it is 0.9, which is in agreement with the 1.1 expected in the Frejus Monte Carlo.

[2]. This is a consequence of the reasonable assumption made in Ref. [2] that protons are confined in the inner AGN until they fully interact (apart from a fraction which escape the central region after being converted to neutrons[49]).

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