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Search for Neutrinos from Active Galactic Nuclei in Soudan 2

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Abstract

Models for AGN neutrino production suggest a measurable muon flux in underground detectors. In this paper we comment on neutrino point sources and discuss our methods for determining an upper limit on the intensity of horizontal, neutrino induced muons with energy above 1 TeV at the Soudan 2 detector. We set a limit of 1.8×10^{-13} $(cm^2\ sr\ s)^{-1}$ for detecting 5 TeV ν-induced muons from AGN.

1 Introduction:

Several authors have discussed astrophysical mechanisms that would lead to measurable sources of high energy neutrinos beyond the atmospheric neutrino background (Stecker, 1991; Szabo, 1992; Mannheim, 1992). These include binary pulsars, early supernova remnants, and active galactic nuclei (AGN). In the case of AGN, a portion of the gravitational energy released by plasma accreting onto a central black hole is converted into non-thermal luminosity which produce high energy protons. Neutrinos (ν) and gamma-rays (γ) are among the particles produced in inelastic collisions of protons with thermal matter or radiation. Neutrinos are not directly measured but instead interact to produce secondary charged muons which can be detected in underground detectors such as Soudan 2 . Atmospheric muons are the principle background to the AGN ν-induced signal and the technique to discriminate among these is described below.

2 Data Collection and Analysis:

We have analyzed muon data from the Soudan 2 experiment spanning 4.6 years, corresponding to an exposure time of 1.23×10^8 seconds, and produced 44 ν-induced muons. The details of this analysis are described elsewhere in these proceedings (HE.4.2.01). The selection criteria was based on a comparison of the muon slant depth to the 14 km.w.e. cutoff needed for the neutrino-induced classification. A horizontal muon flux was calculated to be $\Phi_{\nu_\mu} = (3.45 \pm 0.52 \pm 0.61) \times 10^{-13}$ $(cm^2\ sr\ s)^{-1}$. This value is consistent with the upward-going and horizontal muon fluxes reported in the literature and provides edification for our understanding of the principle background to AGN neutrinos. From these events, we consider a point source and/or an extra-galactic origin.

2.1 Neutrino Point Sources: The Soudan 2 detector has extremely good angular resolution ($\sim 0.25°$) which was verified by the observation of the diminution of the underground muon rate by the moon (SH.3.2.42). Therefore it is well suited for point source searches. The positions of the candidate events are superimposed on the Aitoff projection of our Galaxy in Figure 1.

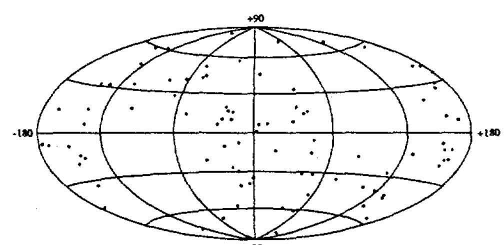

Figure 1: *Aitoff Projection of the Neutrino-induced Muons (Galactic Coordinates)*

The Soudan 2 detection modules operate as time-projection, particle ionization counting chambers whose ADC's sample at a rate of 200 ns. Therefore discerning between down- and up-going muons is not possible.

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The position assuming the muon is up-going is also provided in Figure 1. As expected, these events are fairly isotropic and no point source detections are obvious. Present upper-limits on point sources of ν_μ are exceedingly low, e.g. flux limits for 3C273 have been reported by both IMB (Becker, 1995) and Baksan (Boliev, 1995) to be $\phi_{\nu_\mu} \sim 1.5 \times 10^{-14}$ $(cm^2 s)^{-1}$. Based on the fact that no point in the sky contained five events, we can set a limit of $\phi_{\nu\mu} < 3 \times 10^{-14}$ $(cm^2 s)^{-1}$ from any source in our field of view rendering the detection of point sources at Soudan 2 unlikely. However, if we integrate over all point sources, the diffuse flux of ν_μ may be a tractable measurement.

2.2 AGN Neutrinos: The models predict that AGN ν's dominate the atmospheric background for energies in excess of 10 TeV. As UHE neutrinos traverse the Earth they can undergo charged-current interactions and produce muons. High-energy muons undergo continuous energy loss that slowly degrade ($\sim$ $2\ GeV\ per\ gm/cm^2$) the energy of the muon. With increasing muon energy, the probability that the muon will undergo radiative losses such as bremsstrahlung increases. Radiative processes dominate the energy loss for muons with energies in excess of 1 TeV (Lohmann, 1985). These result in electro-magnetic bursts along the trajectory of the muon. Ultra-high energy muons will likely exhibit this behavior upon traversal of the Soudan 2 detector providing the signature in which to base our search.

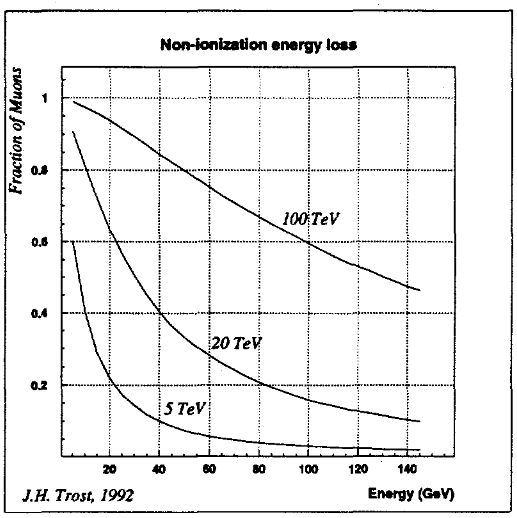

Figure 2: *The fraction of 5, 20, 100 TeV Monte Carlo muons in Soudan 2 that undergo radiative losses.*

The determination of the detection of efficiency for ultra-high energy muons in Soudan 2 is essential. A GEANT model of the Soudan 2 detector was used to estimate the detection efficiency for high-energy muons passing through the detector. Muons of energies 5, 20 and 100 TeV were propagated through the detector and energy deposition was recorded to determine the fraction of muons which undergo stochastic (non-ionization) energy loss. In Figure 2 the integral distribution is presented from which the detection efficiency for these muons is derived. For example, 95% of the 100 TeV muons which were generated, experienced at least 20 GeV of energy loss; similarly, ~20% of 5 TeV muons underwent a loss of 20 GeV or more. The high energy muon detection efficiencies are given as 60, 91, and 99%, respectively and are presented in Table 1.

2.3 AGN Neutrino Limit: The AGN ν-induced muon flux can be expressed as

$$\Phi_{\nu\mu} = \frac{dN_\mu}{dt dA d\Omega \epsilon}$$

where dt is the experimental exposure, dA is the detection area, and $d\Omega$ is the solid angle subtended in this experiment, and ϵ is the detection efficiency. The efficiency for detecting ultra-high energy muons are included in Table 1. In addition, the detection efficiency established in the atmospheric neutrino analysis for through-going muons (69.1%) is also included in the calculation. Based on the observation of *zero* events with radiative energy loss in excess of 5 GeV we set a preliminary 90% confidence limit on AGN ν induced muons at Soudan 2 as 1.80, 0.46, and 0.21×10^{-13} cm^{-2} sr^{-1} s^{-1} respectively. This AGN ν_μ-induced muon limit uses $dN = 44$ events, an exposure of $dt = 1.23 \times 10^8$ s, $dA = 84.86$ m^2, and $d\Omega = 1.75$ sr.

Table 1: *Preliminary AGN-Muon Flux*

5	20	100	Muon Energy (TeV)
60%	91%	99%	Detection Efficiency
1.80	0.46	0.21	$\times10^{-13}$ $(cm^2 srs)^{-1}$

In Figure 3, the various neutrino spectra from Gaisser (Gaisser, 1995) are presented. Both the Soudan limit (X) and the reported Fréjus limit (Daum, 1995) are superimposed onto the plot. Despite comparable detection methods and the longer exposure of the Soudan measurement, the Fréjus limit remains out of reach. It is worth considering the relative similarities of the two detectors as a check on their limits; eg. detector type, size, and slant depth in the horizontal direction are similar. Yet from only 44 events, which is coincidently the size of Soudan's, they extract limits for the neutrino spectra which seem too restrictive for their exposure. In contrast, Soudan 2 has produced results that are based only on observed data and cannot approach their limits. Our limits appear to be less significant that the Fréjus limits, but we believe they are accurate.

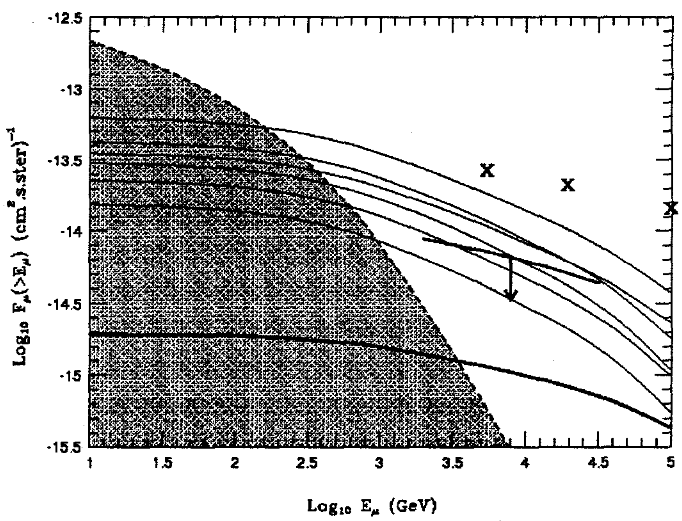

Figure 3: *Horizontal* ($-0.3 < \cos\theta < 0.3$) *muon fluxes generated by the isotropic neutrino background as in the models of Szabo & Protheroe (thin solid lines) and by Stecker etal.(thick solid line). The 90% C.L. upper limit for Soudan (X) and of the Fréjus experiment are shown. The dashed line is the spectrum from atmospheric muons.*

3 Conclusions:

In response to predictions for neutrino production from AGN we have conducted a search at Soudan for muons which exhibit large radiative losses along their trajectory as signature for an extra-galactic origin. From the 1.23×10^8 second exposure, we find *zero* events and calculate limits for 5, 20, & 100 TeV muons that are provided in Table 1.

4 Acknowledgments:

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