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Horizontal muons in Soudan 2 and Search for AGN neutrinos

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Abstract. Using horizontal muons in Soudan 2, we measure the neutrino induced muon flux and set a limit on the flux of neutrinos from AGN's. A horizontal neutrino induced flux of 5.00 ± 0.55 ± 0.51 $\times 10^{-13}$ $cm^{-2} sr^{-1} s^{-1}$ is measured. The absence of horizontal muons with a large energy loss is used to set a limit on the flux of ν's from AGN's as a function of energy.

1 Introduction

For a deep enough underground detector, horizontal underground muons can be used to study the atmospheric neutrino flux. The Earth provides a natural shield for underground detectors, which, for horizontal directions, eliminates most of the atmospheric muon flux. This data can also be used to look for other possible sources of neutrinos such as a diffuse flux of high energy neutrinos from active galactic nuclei (AGN).

Active galaxies are those which emit abnormally high amounts of energy (optical and/or radio) or those with extreme variations in brightness. Colliding and exploding galaxies also fall into this category. The nuclei of these galaxies may produce both neutral and charged particles. Most of the particles either decay or are absorbed before they can escape the galaxy. This leaves only photons and neutrinos to escape the galaxy and to be detected on Earth. Several models for neutrino production in AGN's have been produced over the years (Stecker, 1991; Szabo and Protheroe, 1994; Protheroe and Kazanas, 1983; Stecker et al., 1992, Stecker2, 1991). Some of these predict high energy neutrino production.

2 The Soudan 2 Detector

The Soudan 2 detector has been described extensively elsewhere (Allison 1996). The detector is located approximately 700 meters below the Earth's surface in a retired iron mine in Soudan, Minnesota.

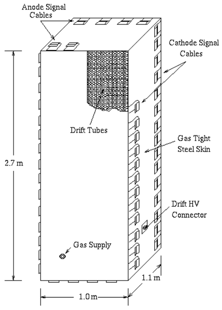

Fig. 1. A single 4.5 ton Soudan 2 module

The main detector is an iron sampling calorimeter using drift tubes as the active medium. The detector is made of 224 modules with dimensions of $2.7 \times 1 \times 1.1 m^3$. Each module has a mass of 4.3 metric tons. The modules are stacked 2 high for a total height of 5.4 m, and 8 wide for a width of 8 m. Figure 1 is a drawing a Soudan 2 module.

The drift tubes are operated in proportional mode. Each end of the tubes is read out by an anode wire and a cathode pad. These establish the x and y coordinates of the hits. Off line, hits are matched in each half tube using pulse height to match the cathode and anode pulses. The z position of the hit is determined by this pulse matching and the drift time in the tube.

The walls of the detector hall are covered with an active shield. This is a two layer proportional tube detector. For most Soudan 2 analyses the shield is used to veto events in the main detector which were initiated by particles interacting in the surrounding rock. Since this analysis uses high energy muons, and therefore long muon tracks, the shield is used to ensure the muons under considerations come from the rock.

The overburden, or the rock above the detector, is used to shield the detector from atmospheric muons. The rock

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overburden reduces the muon intensity from approximately $170/m^2sec$ (Gaisser and Stanev, 1998) at the surface to about $4\times10^{-3}/m^2sec$ in the Soudan cavern. For angles away from the vertical, $\theta > 0$, the overburden increases with $\sec\theta$. Variations in the rock density and the surface terrain cause tracks with the same zenith angle but different azimuthal angles to traverse different amounts of overburden.

The trigger for recording events requires a multiplicity of seven anode pulses or eight cathode pulses on contiguous readout channels. For long muons this trigger is quite efficient. The trigger and its efficiency will be discussed in more detail later.

3 Horizontal Muons at Soudan 2

When a low energy muon neutrino, ν_μ, interacts in the Soudan 2 detector it produces a muon which is contained within the detector and is identified as coming from a neutrino. As the neutrino energy, and therefore the muon energy, increases the muon is no longer contained. The muon may be produced in the detector but exits before it stops or decays. At Soudan, the detector timing is not sufficient to determine whether a muon is entering the detector from the surrounding rock and then stopping in the detector, or if it was created in the detector and exits into the rock. These stopping muons can undergo large multiple scattering, making their direction difficult to determine.

High energy neutrinos will produce high energy muons in the rock. These muons will have enough energy to traverse the entire detector. Since the timing of the experiment is not sufficient to determine the direction of a track there is a twofold ambiguity in the direction for each measured track.

As the zenith angle of the track increases, the path length of the particle through the Earth increases as $\sec\theta$. This path length is known as the slant depth. In the vertical direction, there is a large background to neutrino induced muons from atmospheric muons. The $\sec\theta$ factor coupled with the steeply falling muon energy spectrum, causes the muon flux in the detector to fall steeply with angle. As θ increases the atmospheric muons are effectively attenuated by the surrounding rock. Above a sufficiently high zenith angle, the only muons seen in the detector are neutrino induced. To determine at what point the neutrino induced muons dominate the atmospheric muons, we refer to the Crouch curve. Figure 2 shows the slant depth at the Soudan 2 detector as a function of the zenith angle.

M. F. Crouch compiled underground muon intensities in 1986 (Crouch, 1987). He constructed a curve for muon vertical intensity as a function of slant depth in standard rock. Figure 3 shows the data and the fit. The fit he made to this data displays two distinct spectra. The first is an atmospheric muon spectra which falls exponentially with slant depth. The second is due to neutrino-induced muons and is only visible above the muon spectra for slant depths greater than 14 km.w.e. This curve has been updated by the Particle Data Group (Groom, 2000) and the flux for the neutrino induced muons has been increased for horizontal muons. Based on the Crouch curve and the calculation of the average slant depth at Soudan 2, a cut on the zenith angle of a track near 82° selects a sample of neutrino-induced muons with little background from the atmospheric muons.

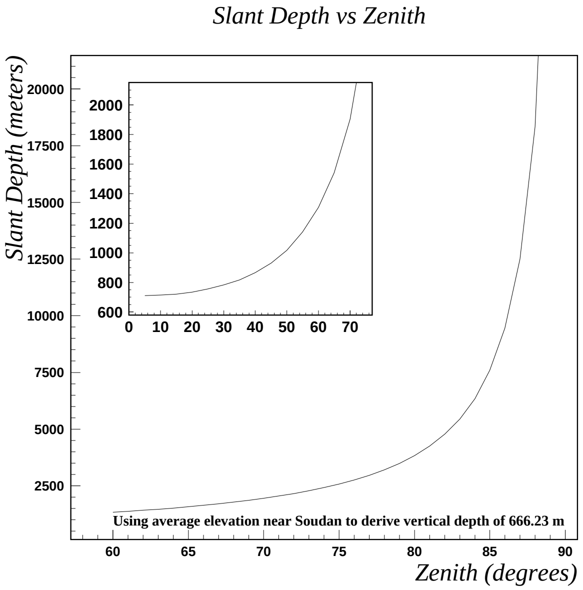

Fig. 2. Slant depth versus zenith angle.

The amount of rock around the Soudan 2 detector must be measured relative to standard rock which has an average density of 2.62 gm/cm^3. The average density of rock near Soudan 2 is higher, near 2.7 gm/cm^3, but varies with zenith and azimuthal angles. The geology of the region is such that the iron deposits are almost vertical. This results in different average densities for tracks at the same zenith angle but different azimuthal angles. That, combined with the uneven surface terrain, meant that in order to ensure that each particle has traversed the 14 km.w.e. minimum to screen atmospheric muons, the slant depth must be calculated for each track and based on both the zenith and the azimuthal angle of the track.

4 Results

The events are analyzed by a software package which recognizes horizontal muons and discriminates against certain noise topologies which confuse the pattern recognition. A scan of all tracks greater than 78° eliminates multiple muons and other horizontal tracks associated with vertical muons. The slant depth cut reduces this to 85 events with a slant depth greater than 14 km w.e. Figure 4 shows the (θ,ϕ) distribution of about 80% of the events. The contour denotes the slant depth cut.

To estimate the amount of background from atmospheric muons we integrated under the Crouch curve, without the constant term, for slant depths greater than 14 km w.e. This results in an estimate of 0.1 event of background in the sam-

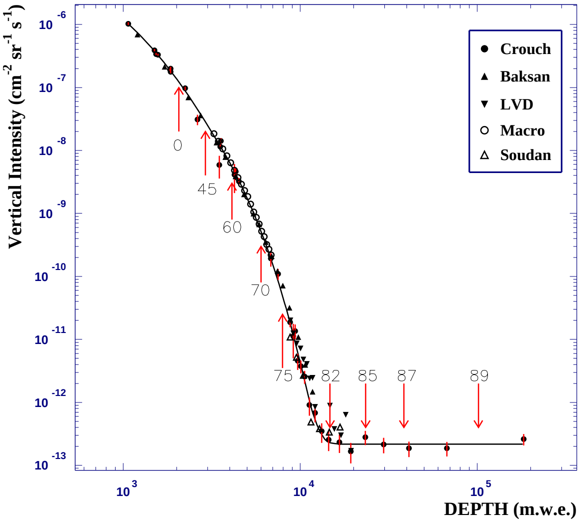

Fig. 3. Crouch curve expressing the underground muon intensity as a function of slant depth. Arrows indicate the average depth at different zenith angles at the Soudan 2 detector.

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The neutrino induced muon flux, Φ_μ, can be expressed as

$$\Phi_\mu = \frac{dN_\mu}{dt\, dA\, d\Omega\, \varepsilon}, \tag{1}$$

where dt is the time exposure of the detector in seconds, dA is the effective area of the detector in cm^2 for the appropriate angles, $d\Omega$ is the solid angle subtended by the detector in steradians for the appropriate angles, and ε is the detection efficiency for the muons in the detector.

The exposure time is calculated from the start and end times of every run used in the analysis. The calculated exposure for this analysis, including corrections for the detector duty cycle and electronics dead time during data taking, is 2.00×10^8 sec.

The effective area of the detector depends on the zenith and azimuthal angles of the particle. To understand the effective area for this analysis, Monte Carlo muons were uniformly generated in the relevant zenith angle range and the effective area for each track calculated. For zenith angles greater than 78° the average area is 88.70 m^2. For $\theta > 82°$ the average effective area is 84.86±0.33 m^2.

If the terrain over the detector were flat and homogeneous, the slant depth cut would be equivalent to a cut on the zenith angle of $\sim 82°$. In that case the solid angle covered by the detector could be calculated as

$$d\Omega = -2 \int_0^{2\pi} \int_{82°}^{90°} d\cos\theta\, d\phi. \tag{2}$$

Since the terrain is far from flat, there are directions for which the slant depth passes the cut at $\theta = 81°$ and others where the slant depth does not pass the cut until $\theta = 83°$. Because of this the solid angle calculation is not a simple integral. The slant depth was calculated for $\theta \geq 81°$ in bins of 0.05° in θ and 5° in ϕ. Figure 5 shows which (θ, ϕ) combinations pass the slant depth cut. The weighted sum of the bins which pass the slant depth cut are used to calculate $d\Omega$. All bins with $\theta > 83°$ pass the slant depth cut. From this the solid angle is calculated to be 1.77 sr.

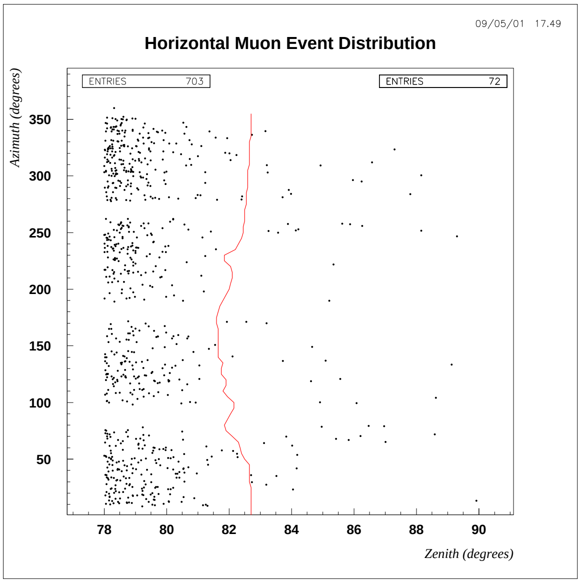

Fig. 4. Angular distribution of horizontal muon candidates. About 80% of the data is shown. The line represents the 14 kmwe cut.

The trigger and reconstruction efficiencies have been calculated using a Monte Carlo simulation. The overall efficiency for horizontal muons greater than 82 degrees is found to be 0.556.

Combining the acceptance and efficiency with the event statistics results in a neutrino induced muon flux of

$$\Phi_{\nu_\mu} = 5.00 \pm 0.55^{stat} \pm 0.51^{sys} \times 10^{-13}\ \frac{1}{cm^2\ sr\ sec}. \tag{3}$$

5 AGN Neutrino Search

Many of the models for neutrino production in Active Galactic Nuclei predict large and potentially measurable fluxes of high energy neutrinos (Stecker, 1991; Szabo and Protheroe, 1994). These very high energy neutrinos would then produce high energy muons with energies from a few TeV up to 100's of TeV. In this energy range the dominant energy loss process for the muons in iron is pair production, followed by bremsstrahlung (Lohmann, 1985). This sort of electromagnetic energy loss can produce large showers of energy in the Soudan 2 detector which is easily detected and measured.

To understand what these high energy muon events look like in the Soudan 2 detector another Monte Carlo simulation was performed. high energy muons were propagated through the Soudan 2 detector and the amount of energy they deposited in was tabulated. Three different muon energies were studies; 5, 20 and 100 TeV. Where only 60% of the 5 TeV muons lose 5 GeV or more, 91% of the 20 TeV muons

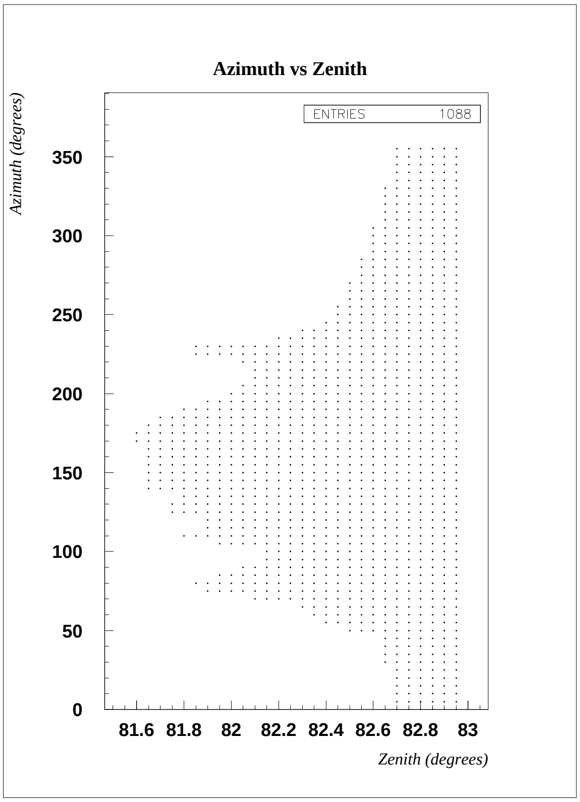

Fig. 5. Angular acceptance of the slant depth cut.

and 99% of the 100 TeV muons lose at least 5 GeV in the detector.

The muons identified for the horizontal muon flux measurement are subjected to a cut on the amount of energy loss they experienced in the detector. None of the events experience an energy loss of 5 GeV or greater.

Based on the observation of no events, the detection efficiency for high energy muon energy loss and the efficiency in the horizontal muon analysis, we calculate limits for the AGN neutrino flux as a function of energy. Those limits are 0.23, 0.15, and 0.14 $\times 10^{-13} cm^{-2} sr^{-1} sec^{-1}$ for muon energies of 5, 20 and 100 TeV respectively.

Energy(TeV)	High Energy μ Efficiency	Limit($cm^{-2}sr^{-1}sec^{-1}$)
5	60%	0.23×10^{-13}
20	91%	0.15×10^{-13}
100	99%	0.14×10^{-13}

Table 1. Efficiency for high energy muons to experience at least 5 GeV of energy loss in the Soudan 2 detector and the resulting AGN neutrino flux limits.

As a final check for a point source of horizontal muon events, the galactic coordinates of the 85 candidates are placed on an Aitoff projection of the galaxy (figure **??**). Both possible directions of the tracks are plotted. No clustering of as many as three points within the angular resolution of Soudan 2 is found.

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