

# Neutrino Induced Muons in Soudan 2

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## Abstract

The neutrino-induced muon rate underground has been measured at Soudan 2. To discriminate from the intense background of atmospheric muons we consider only the through-going muons which originate from horizontal direction ( $-0.14 < \cos\theta < 0.14$ ). We calculate the horizontal, neutrino-induced muon rate at Soudan 2 from an exposure of  $1.23 \times 10^8$  s as  $\Phi_{\nu\mu} = (3.45 \pm 0.52 \pm 0.61) \times 10^{-13} (\text{cm}^2 \text{sr s})^{-1}$ .

## 1 Introduction:

The Soudan 2 experiment is located near Soudan, Minnesota at a depth of 2100 m.w.e. and has been in operation since 1988. The Soudan 2 detector operates as an iron tracking calorimeter comprised of an array of individual modules each consisting of steel sheets interleaved with proportional drifting tubes (Allison, 1996). The apparatus consists of the central detector measuring  $5 \times 8 \times 14 \text{ m}^3$  with an average density of  $1.6 \text{ gm/cm}^3$  and an enclosing proportional tube detector (Oliver, 1989) which is used to improve the discrimination of  $\nu$ -induced muons and for background rejection for contained-event analyses. A mixture of gaseous argon and  $\text{CO}_2$  is the active component in both detectors. The sampling rate of the central detector is 200 ns and ionization pulse-shape information is recorded. The detectors angular resolution is  $\leq 0.30^\circ$  and has excellent response to through-going muons. The integrated event rate for muons is  $0.2 \text{ Hz}$ .

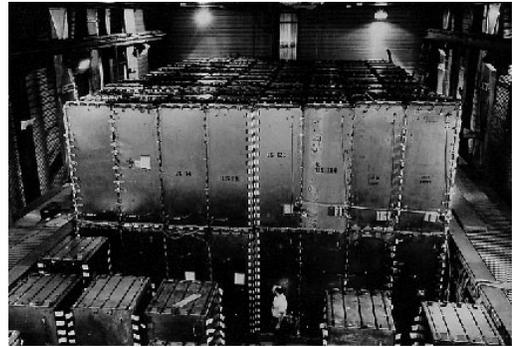


Figure 1: *The Soudan 2 Detector*

## 2 Data Collection and Analysis:

To resolve the neutrino-induced signal we limit our detection aperture to the horizontal direction where the atmospheric muon contribution is significantly reduced. It is the detector's inability to resolve up from down-ward going muons that leads to this exclusive horizontal measurement. Underground muon vertical intensities have been compiled (Crouch, 1987). From Figure 2, two distinct muon spectra are evident; 1) atmospheric muons whose rate decreases as a power law for increasing depth and 2) a relatively flat population of muons for large depth which is considered to be from atmospheric neutrino interactions in the rock near the detector. The atmospheric,  $\nu$ -induced muon component of the underground muon spectra dominates the atmospheric muons for slant depths in excess of 14 km.w.e. of standard rock providing the criteria needed to discriminate from the two populations. This depth corresponds to a zenith angle  $\theta$  of  $\sim 82^\circ$  in Soudan 2 as indicated in Figure 2. In Figure 3, a horizontal muon is presented as evidence for the superior spatial quality that the Soudan 2 detector provides.

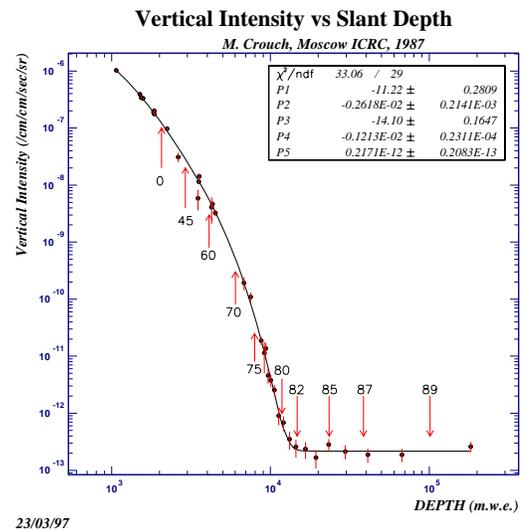


Figure 2: *Vertical intensity vs Slant Depth*

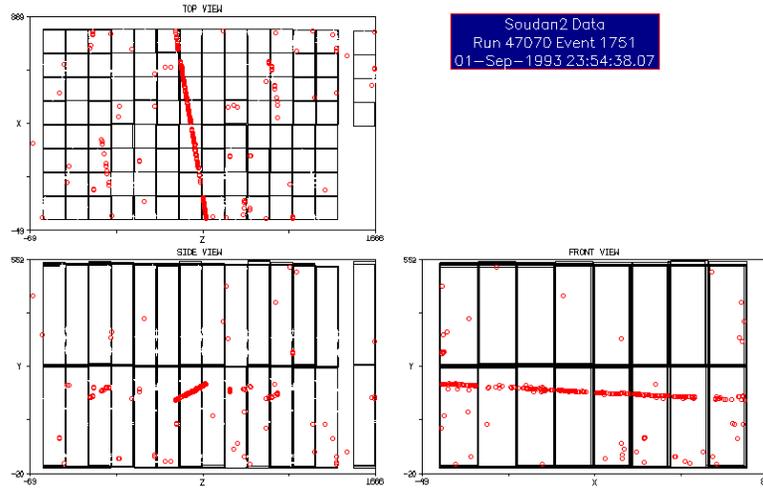


Figure 3: *Horizontal Muon Event: This muon had a zenith angle of  $87^\circ$  and a tracklength of 821 cm.*

**2.1 Horizontal Muon Data:** Muon data from 1686 days was considered which after dead time correction, corresponds to an exposure of  $1.23 \times 10^8$  s. Standard reliability cuts were imposed to extract muon events with  $\theta > 78^\circ$ . A 175 cm track-length cut corresponding to a muon threshold of 600 MeV was also applied. Each muon event was then verified independently by two physicists using visual scanning techniques. From the track direction of each of these events the traversal depth of the muon ( $x$ ) was determined using U.S.G.S. digitized elevation data. The slant depth ( $\rho x$ ) was calculated using an average rock density  $\rho = 2.8 \text{ gm/cm}^3$  and compared to a depth of 14 km.w.e. in standard rock which is necessary for the  $\nu$ -induced muon classification. Reconstruction efficiency is high for most muons with the exception of a small portion which are limited to nearly horizontal events which travel along the south-north or east-west detector coordinate axes. Thus an azimuth cut of  $\pm 8^\circ$  along the cardinal directions was applied. The solid angle subtended for horizontal muons is  $1.77 \text{ sr}$ . The effective detection area for high zenith muons is  $84.86 \text{ m}^2$ . Trigger, filter and scanning efficiencies have been estimated to be 69.1%. Our search has produced 44 events which satisfy the  $\nu$ -induced muon criteria. Expressing the  $\nu$ -induced HMU flux as  $\Phi_{\nu\mu} = \frac{dN_\mu}{dt dA d\Omega \epsilon}$  where  $dt$  is the experimental exposure,  $dA$  is the detection area,  $d\Omega$  is the solid angle and  $\epsilon$  as the detection efficiency and calculate

$$\Phi_{\nu\mu} = (3.45 \pm 0.52 \pm 0.61) \times 10^{-13} (\text{cm}^2 \text{ sr s})^{-1}.$$

The horizontal muon events per azimuth and zenith is displayed in Figure 4. The azimuthal exclusion along the detector axes are evident at  $\phi = 90, 180, 270^\circ$ . Included in this figure is the 14 km.w.e. slant depth contour which is used to determine the  $\nu$ -induced population.

An analytical prediction of the underground muon spectrum at Soudan which includes radiative muon energy loss processes has been developed (Uretsky, 1997). Using this recipe, we superimpose his predictions onto the measured muon flux ( $\theta > 78^\circ$ ) in Figure 5. His spectrum is normalized by a factor of  $9.35 \times 10^{-5}$ .

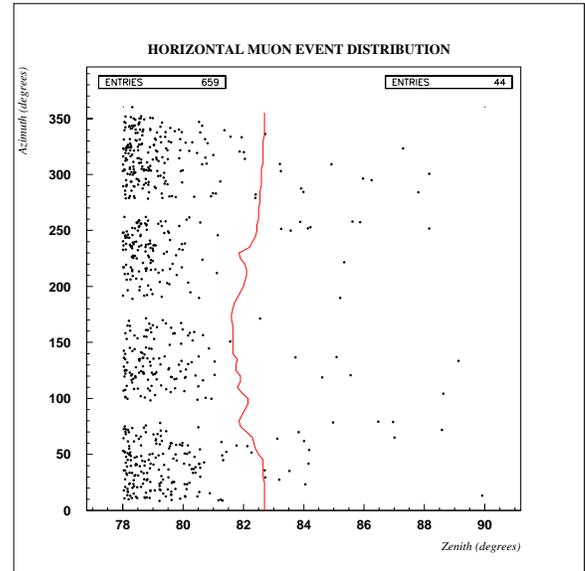


Figure 4: *The muons falling to the right of the 14 km.w.e. contour are considered as  $\nu$ -induced.*

We note the excellent agreement of Uretsky's fit for  $\theta \leq 82^\circ$  with the atmospheric portion of our measurement rendering support for our claim that beyond  $\cos\theta > 0.9$  the events are not atmospheric muons.

**2.2 Data Comparisons:** Several underground experiments have reported upward-going muon fluxes averaged over the full range of zenith angles corresponding to the upward hemisphere. The horizontal muon flux is enhanced relative to other zenith angles due to the secant theta effect. Therefore the horizontal rate should be slightly higher than the upward-going rates. We have considered up-going muon fluxes from Baksan (Boliev, 1991) and Kamiakande (Mori, 1991) by averaging only the horizontal points from the up-going data to give  $3.72$  and  $3.30 \times 10^{-13} (cm^2 sr s)^{-1}$  respectively.

Two underground experiments have reported exclusive horizontal muon fluxes. In particular, Frejus (Rhode, 1996), and LVD (Aglietta, 1998) report horizontal intensities as  $3.67 \pm 0.66$  and  $8.3 \pm 2.6 \times 10^{-13} (cm^2 sr s)^{-1}$  respectively. We speculate that the LVD results are tainted by backgrounds. From these flux values, and given the relative uncertainties associated with the measurement of the muon flux underground, we feel our results are consistent.

### 3 Conclusion:

We have analyzed muon data from the Soudan 2 experiment which spans 4.6 years and corresponds to an exposure time of  $1.23 \times 10^8$  s. The analysis produced 44 events which were classified as neutrino-induced muons by establishing their slant depth. 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.

### References

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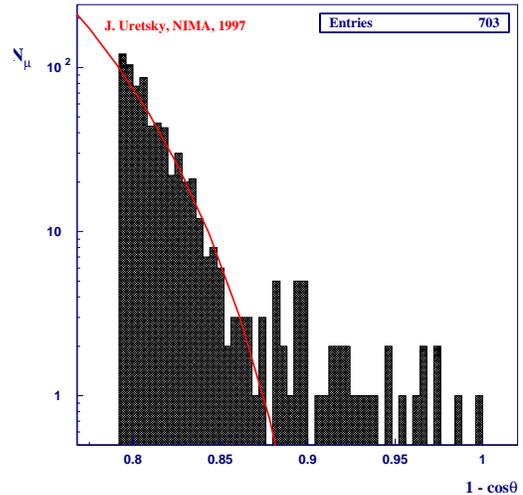


Figure 5: *Horizontal Muon Spectra*