Final atmospheric neutrino oscillation results from Soudan 2

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Abstract. The final set of Soudan-2 data has been prepared including both events with their vertex within the detector and upgoing stopping muons originating in neutrino interactions within the rock surrounding the detector. This data set was analyzed for effects of atmospheric neutrino oscillations. The resulting probability of no oscillations was found to be $3.2 \times 10^{-5}$. The improved 90% CL contour in $\sin^2 2\theta \times \log_{10}(\Delta m^2)$ is given, and found to be independent of the choice of 1D or 3D neutrino flux model. The Soudan 2 allowed contour includes, but is broader than, the 90% CL contours reported by SuperK and MACRO.

1. Introduction
Soudan 2 was a 963-ton iron tracking calorimeter located 2070 mwe underground in Soudan, MN. It took data between 1989 and 2001, accumulating an exposure of 5.9 kty (within fiducial volume). The detector design provided fine granularity, good particle identification, together with good energy and angular resolution. The iron calorimeter was surrounded by a 1700-m$^2$ active shield that enabled identification of non-neutrino background in the atmospheric-neutrino analysis. The calorimeter was turned off in Summer 2001 and dismantled in Summer 2004.

2. Data samples old and new
As reported previously [1], a neutrino oscillation analysis of the Soudan-2 data was completed, and an allowed region in the oscillation parameter space determined, using selected Fully Contained Events (FCE) and Partially Contained Events (PCE). All of these events have their vertices contained within the Soudan-2 central detector. There were 430 FCE without shield hits, 516 FCE with shield hits (used to determine the background), and 58 PCE, yielding 437 neutrino events. A sample of 3624 Monte Carlo (MC) events, representing 6.09 times the detector exposure, was incorporated blindly into the data stream.

This analysis includes a new data category of charged-current $\nu_\mu$ interactions that occur in the rock beneath the Soudan-2 cavern, and only the outgoing muon is detected as a stopping non-interacting track in the Soudan-2 detector. These upgoing stopping tracks (UpStops) appear as one-prong PCEs, and can be confused with downgoing one-prong PCEs (InDowns), however with careful scrutiny they can usually be distinguished one from another. The UpStop tracks (vertex in the rock) have multiple Coulomb scattering increasing upward, and hits at the top - if any - are consistent with muon decay. InDown tracks (vertex within the detector) have scattering increasing toward the bottom, and hits at the top - if any - are consistent with a recoil proton. Only a small number of events were assigned to an Ambiguous category.
Monte Carlo simulation of the InDown events is the same as that used in Ref. [1] for all neutrino interactions with their vertices within the Soudan-2 detector. However, additional software development was needed to simulate neutrino interactions in the rock [2].

A major source of non-neutrino background was interactions of cosmic-ray muons in the rock yielding upgoing pion tracks together with other particles that produced veto-shield hits. Without any cuts on $n_{\text{all}}$, the number of all veto-shield hits in the event, an excess of data over Monte Carlo was observed at low values of track range. This excess was mostly eliminated after requiring that $n_{\text{VS}} = n_{\text{track}}$, where $n_{\text{VS}}$ denotes the number of veto-shield hits associated with an incoming (or outgoing) track.

All events were then required to satisfy the following conditions: (i) $\cos \theta_z < +0.05$, (ii) $n_{\text{VS}} = n_{\text{track}}$, and (iii) range > 260 g/cm$^2$ (2 pion interaction lengths). Numbers of events in the resulting event samples are shown in Table 1, both for the data and the simulation.

### Table 1. Event tally of the data and simulation samples. MC event counts are normalized to the data exposure of 5.9 kty.

| Scanned as | No-osc. MC Truth | Data |
|------------|------------------|------|
| InDown     | 12.4±1.4         | 0.3±0.1 | 16 |
| UpStop     | 1.8±0.5          | 53.3±1.8 | 26 |
| Ambig      | 0.8±0.3          | 3.4±0.4 | 2 |

3. Results

Like the other in-detector PCEs, the InDowns have sufficient neutrino energy determination to permit using the $\log(L/E)$ variable. Fig. 1a shows the $\log(L/E)$ distribution for data (crosses) compared to the no-oscillation MC (shaded histograms). We observe a good agreement between the two distributions and no evidence for oscillations in this sample of $\nu_\mu$ atmospheric neutrinos incident from above (avg. $E_\nu = 2.4$ GeV).

For the UpStop events, there is no adequate determination of the event energy (avg. $E_\nu = 6.2$ GeV), and we therefore examine only the angular distribution in cosine of the zenith angle, $\cos \theta_z$ (see Fig. 1b), which indicates disagreement between the no-oscillation MC and data.

For the $\nu$ oscillation analysis, the complete Soudan 2 atmospheric neutrino data sample was divided according to momentum and energy resolution. The $L/E$ distributions included high-resolution FC tracks, $\nu_\mu$-flavor FC multiprongs, $\nu_\mu$-flavor PCEs (including InDowns), and low-resolution FC tracks; an $L$ distribution was used for the UpStop events. The $\nu_\tau$-flavor events, neutral-current events, low-resolution FC multiprongs and InDown/UpStop-ambiguous events were used for normalization only. Of the 488 events used in Ref. [1], 167 were high-resolution events; all 44 new InDown and UpStop events have high resolution.

Soudan-2 data were analyzed using a bin-free likelihood analysis within the framework of two-neutrino oscillations, as described in Ref. [2]. The parameter space in $\sin^2 2\theta \times \log_{10}(\Delta m^2)$ was divided into a $15 \times 80$ grid. At each grid-square, the summed negative log-likelihood was calculated, the minimum value of $\mathcal{L}$ among all the squares was found, and $\Delta \mathcal{L} = \mathcal{L} - \mathcal{L}_{\text{min}}$ plotted. The non-neutrino background FC events were included in $\mathcal{L}$. The overall normalization and the amount of background in six subsamples were treated as statistical ‘nuisance parameters’. The resulting $\Delta \mathcal{L}_{\text{data}}$ surface exhibited two minima differing only by $\Delta \mathcal{L}_{\text{min}} = 0.18$, one at $\Delta m^2 = 1.7 \times 10^{-3}$ eV$^2$, and one at $\Delta m^2 = 5.2 \times 10^{-3}$ eV$^2$, both with $\sin^2 2\theta = 0.97$.

Confidence levels were calculated using the Feldman-Cousins method [3]. 1000 MC ‘experiments’ were simulated at each grid square, incorporating statistical and systematic errors. The resulting 1000 $\Delta \mathcal{L}_{\text{MC}}$ values at each grid square were histogrammed, and $\Delta \mathcal{L}_{90}$ found such that 90% of the events had $\Delta \mathcal{L}_{\text{MC}} < \Delta \mathcal{L}_{90}$. The square was then included in the allowed 90%
Figure 1. Distribution in log($L/E$) for the InDown and UpStop events. The crosses represent the data, and the light (dark) shaded histogram shows the expected InDown (UpStop) Monte Carlo distribution for no oscillations.

Figure 2. The 90% C.L. allowed region using all Soudan-2 data (solid line), and using the FCE and PCE samples only (dashed line).

CL region if $\Delta L_{\text{data}} < \Delta L_{90}$. The resulting 90% CL contour is shown in Fig. 2 by the solid line. The dashed line indicates the larger contour obtained using the FC and PC events only [1]. The new value for probability of no oscillations in Soudan 2 data is $3.2 \times 10^{-5}$, based on a simulation of 500,000 experiments.

We also compared contours obtained using three different 1D and 3D atmospheric-neutrino flux models [4]-[6]. We find that change in the flux model results in no change in the fit parameters and only minor differences in the contour shapes. The resulting value for the neutrino flux normalization of Ref. [5] to Soudan 2 data is $0.91 \pm 0.07$.

The Soudan-2 90%-CL contours are compatible with, but are broader than the published results of the SuperK [7] and MACRO experiments [8].

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