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Atmospheric Neutrinos in Soudan 2

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Soudan 2 has measured neutrino oscillation parameters using atmospheric νs. We have added the upward stopping μs and downward going ν induced μs to the oscillation fits.

1. Introduction

The neutrino oscillation analysis of the Soudan 2 atmospheric ν data [1] did not include *UpStop* and *InDown* events. *UpStop* events are upward-going stopping μs which arise from charged-current ν_μ and $\overline{\nu}_\mu$ interactions occurring in the rock surrounding the cavern. *InDown* events are ν_μ and $\overline{\nu}_\mu$ interactions in the detector yielding downward going, exiting μs with 3 or fewer hits arising from hadrons at the vertex. Approximately 65% of these InDown events are quasi-elastic interactions with low energy protons. Interactions having more than 3 hits at their vertex were included in the Partially Contained (PC) sample analyzed previously.

Whereas through-going μ samples originate from a broad high-energy ν spectrum having a mean $E_\nu$near 100 GeV, UpStop events originate predominantly from interactions below 20 GeV. Consequently they provide different constraints for oscillation scenarios. MACRO[2] has provided the most detailed treatment to date of UpStop and InDown events. In that experiment it was not possible to separate the two categories, so they were analyzed as a combined sample. Clearly it is advantageous to separate the samples, since comparison of their zenith angle distributions can provide additional discrimination between values of Δm^2.

2. Separation of UpStop and InDown Events

Events were classified as UpStop candidates if they satisfied: 1) The track was μ-like, devoid of kink or scatter; 2) The length was greater than 1 m; 3) The μ endpoint occurred in a live detector region; 4) Track ionization and straggling were consistent with the hypothesis of an upward-going μ which ranges to stopping. That is, near the edge of the detector the track was straight and lightly ionizing while, near the interior end, the track exhibited multiple scattering and/or heavy ionization; and 5) Associated hits at the track endpoint, if any, had to be consistent with an electron shower from μ decay. An anode versus cathode view of an UpStop data event is shown on the left in Fig. 1 where multiple scattering can be discerned as the μ ranges to stopping. Endpoint decay hits, the three matched hits modestly displaced from the μ endpoint in Fig. 1, are observed in some events (with higher probability for μ^+ than for μ^- since the former do not undergo nuclear absorption within iron nuclei).

InDown events were required to satisfy criteria 1-3 above and: 4) The μ track was straight and lightly ionizing at its interior end; 5) Associated hits near the interior end of the track, if present, must have been consistent with hits from a proton or $\pi^\pm$ track, lying in a straight line and heavily ionizing. These features are exhibited by the InDown data event shown on the right in Fig. 1. At the vertex, the μ is accompanied by a track of 2 hits for which the ionization is relatively heavy. This pattern is typical of a recoil proton. This event is a candidate quasi-elastic $\nu_\mu\ n \to \mu^- p$. There were a few events which could not be resolved as UpStop or InDown, the direction of the track being undetermined. Such events, though rare, were retained as an *Ambiguous* category.

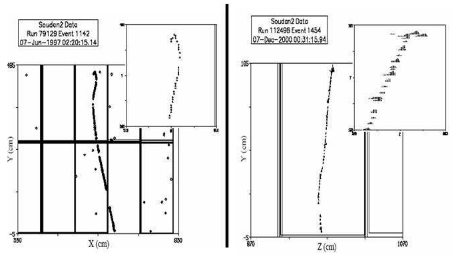

Figure 1. On the left is an UpStop data event recorded in the anode-cathode matched view (side view of the calorimeter). On the right is an InDown data event recorded in the cathode versus time view (calorimeter front view).

3. Event Processing and Simulation

Both UpStop and InDown data events were selected in the PC event sample, and were processed as described in Ref. [1]. The Monte Carlo (MC) sample of the contained-vertex InDown events were included in the data processing. However, additional simulations were needed for the ν interactions in the rock surrounding the cavern, which give rise to UpStop events.

The GEANT MC program together with modified Soudan 2 software provided the UpStop simulation (UpStop-MC). A total of 68.7 million ν interactions in green stone rock were simulated. Since high energy charged-current (CC) events can project μs to the cavern from more remote rock than low energy events, the dimensions of the primary rock volumes were chosen to increase with increasing E_ν.

The PC selection filter required candidate tracks to penetrate to the fiducial region while not being through-going. Additional requirements were imposed in order to reject downward-going cosmic ray μs. A total of 7662 UpStop-MC events passed the filter and trigger. However, only 34% of these events yielded a potentially interesting topology in the detector. Consequently additional cuts were applied to the true kinematic variables which rejected those events which were certain not to pass the subsequent analysis cuts. These cuts (a final-state μ with cosine zenith angle, cos $\theta_z < +0.05$, and energy E_μ at the detector within the range 350 MeV $< E_\mu <$ 3500 MeV) were designed to ensure that the event had an upward going μ that stopped within the fiducial volume. A sample of surviving events was then scanned by physicists, using scanning rules identical to those used for PC data event scanning. The MC sample contained 25 times more events than the data.

The atmospheric ν flux used to generate the UpStop events was the 1D calculation of the Bartol group [4], modulated by the solar cycle as described in Ref. [1]. Other fluxes were simulated by applying correctional weights to the generated events. For consistency with Ref. [1], the numbers and plots in Sects. 4 and 5 were weighted to correspond to the updated 1D Bartol-96 flux [5]. Our analysis used the latest 3D fluxes from the Bartol group [6] and Battistoni *et al.* [7]. The ν cross sections were from our NEUGEN3 MC; the target nuclear composition was that of Soudan rock, described in Ref. [8]. The effect of Pauli blocking in elastic and quasi-elastic reactions was accounted for.

4. Event rates and backgrounds

For the UpStop events, potential backgrounds include Cosmic-ray μs which enter the detector in an upward direction due to scattering, and charged hadronic tracks, especially pions, produced at large angles in interactions of cosmic-ray μs in the rock surrounding the detector. Unlike experiments under mountains, the flat overburden ensures that the flux of cosmic ray μs becomes less than the flux of ν-produced μs significantly above horizontal angles [8]. Thus the background from the first source is negligible. The second source was studied using observed hadrons in the detector, as well as through comparison of shield data with MC events. Cuts on the track range, zenith angle and shield were used to make the hadronic background source negligible as well. Potential backgrounds in the InDown events would exist if the top of the detector had poor or non-existing drifting for any period of time. Great care was taken to remove any data set where this was even a remote possibility.

The numbers of candidate data ν events which survive are listed in Table 1, where the MC numbers have been scaled to an exposure of 5.90 kton-years. Comparison of the data with the ν MC predictions, the sum of columns 2 and 3, shows that the observed InDown rate is consistent with the prediction, whereas the UpStop data rate appears suppressed by a factor of approximately two.

Table 1. Numbers of data and MC events which pass all cuts. The no oscillation MC event rate is normalized to the measured e-flavor event rate of Ref. [1] assuming no oscillations.

Assigned as	*No-osc. MC Truth*		*Data*
	InDown	UpStop	
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

5. Energy and Angular Distributions of UpStop/InDown νs

The ν energy, E_ν, for MC UpStop and InDown events is shown in Fig. 2. The UpStop events have an average E_ν of 6.2 GeV. In contrast, the InDown events have lower E_ν values with an average of 2.4 GeV. For the UpStop events however, the whole of the hadronic shower energy plus a fraction of the μ energy is missing. Thus, whereas L can be calculated accurately from $cos\theta_z$, E is essentially undetermined. The average difference between $\log_{10}(L/E)_\nu$ and $\log_{10}(L/E)_\mu$ is 0.69, spanning four bins used in the oscillation analysis. Therefore $\log_{10}(L/E)$ is not a useful variable for analysis of oscillations in these events. The left plot in Fig. 2 shows the distribution of cosθ_z for upward-stopping μ data events. The distribution decreases steadily toward the nadir. Fig. 2 also includes the simulated UpStop-MC (light shading) and the misidentified contained-vertex PC-MC (dark shading) distributions, for the no-oscillation case. Significant disagreement between the ν UpStop events and the no-oscillation expectation is apparent toward the nadir, which is consistent with the loss of upward-going μ-flavor events due to oscillations.

6. Summary and Discussion

The oscillation analysis is a bin free likelihood analysis based on the prescription of Feldman and Cousins [9]. A detailed description of the method can be found in Ref. [1]. Comparison of this experiment's revised 90% CL allowed region with the most recent Super-K [3][10] and MACRO [11] allowed regions is shown in Fig. 3. This result is in good agreement with both experiments. The two new data sets in this analysis provide additional support for the hypothesis of atmospheric neutrino oscillations. The flux of upward-stopping ν-induced μ events is observed to be suppressed by about 2, while downward-going μ events are not suppressed. An oscillation analysis using the method described in Ref. [1] and adding this new data gives a more restrictive

90% confidence allowed region of Δm^2 and $\sin^2 2\theta$. The probability of the no oscillation hypothesis is reduced by more than a factor of 10 to 3.2×10^{-5}.

The data have been analyzed using three models of the atmospheric flux at the northern geomagnetic latitude of this experiment. The models include two recent 3D flux calculations and an older 1D calculation. The oscillation parameters are found to be essentially independent of the flux calculation.

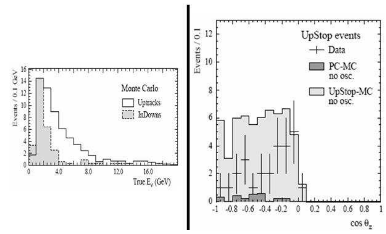

Figure 2. (Left) Distribution of cosθ_z for the UpStop events (crosses) and the expected no-oscillation MC (histogram). Light and dark-shaded areas show the estimated contributions from UpStop and InDown events for no oscillations. and (Right) Comparison of the primary E_ν spectra for UpStop and InDown events.

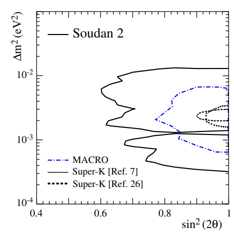

Figure 3. The Soudan 2 90% confidence allowed region in $\sin^2 2\theta$, Δm^2 (solid line) compared with the allowed regions of MACRO (dot-and-dashed line) [11], and of the Super-K zenith angle [3] (dotted line) and L/E [10] (dashed line) analyses.

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