DOWNWARD MUON FLUX AT THE SUDBURY NEUTRINO OBSERVATORY

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Abstract

In this paper we present the first results from observing downward-going cosmic ray muons in the Sudbury Neutrino Observatory (SNO). The current analysis is based on data collected over a 5 month time period. The SNO detector is sited at 46.5° N, 81.2° W, under 6150±6m.w.e. of rock with a flat overburden. The observed rate of cosmic ray muons in the detector, a sphere of radius 8.5m, is $67 \pm 2(stat) \pm 3(sys)$ per day. Each muon needs a minimum of ∼4TeV to penetrate the overburden. The rate and angular distribution are consistent with existing data on the muon flux and spectrum at the surface, of muon energy loss mechanisms, of the expected detector performance, and of our knowledge of the local geology. Understanding downward muons is an important step toward the analysis of neutrino-induced muons, which holds the promise of an oscillation signal. We present a zenith angle distribution for through-going muons with $0 < \cos\theta < 1$. This analysis indicates that SNO will have a uniquely large field of view ($-1 < \cos\theta < 0.4$) for neutrino-induced muons.

High Energy Muons in Cosmic Ray Air Showers

Typical primary interaction: $p +^{14}\mathrm{N} \to \pi^{\pm}(K^{\pm})$ + hadrons

"Downward" Muons and Neutrinos from Pion Decays

$$\pi^{+}(K^{+}) \to \mu^{+} + \nu_{\mu} \qquad \pi^{-}(K^{-}) \to \mu^{-} + \bar{\nu}_{\mu}$$

"Upward" Muons from Neutrino Interactions with Rock

$$\nu_{\mu} + \text{rock nucleus} \to \mu + \text{hadrons}; \quad E_{\mu} \sim \text{GeV - 100TeV}$$

Robust Prediction for "Upward" Muons

At high energies the primary cosmic ray flux becomes isotropic in angle, as geomagnetic effects become negligible. The angular distribution of upward muons is thus expected to be largely isotropic, except for an enhancement for horizontal muons due to the increased meson decay path in the atmosphere.

The Problem

Evidence from Super-K indicates that the zenith angle distribution of upward muons is not explainable without invoking the neutrino oscillation scenario suggested by atmospheric neutrino measurements. Ref: Y. Fukuda, Phys. Lett. **B467** (1999) 185.

Motivation for Studying Muons in SNO

Downward Muons

- Demonstrate clean separation from physically more interesting but less frequent upward muons.
- Confirmation that detector and analysis routines perform according to expectations for high energy events.
- Shows whether geological environment is understood.

Upward Muons (1% of downward rate)

Data from previous experiments indicate about half the muon neutrinos oscillate to another flavour.

Best fit oscillation parameters: $\Delta m^2 \sim 0.003$ eV^2; $\sin^2 2\theta \approx 1$

Oscillation Length: $L = 2.48 \frac{E/\mathrm{GeV}}{\Delta m^2/\mathrm{eV}^2}$ km i.e. if $E = 1$ GeV, $L \sim 1000$ km

If this is so, the flux of "upward" muons from below the horizontal will be reduced by oscillation. Those from above the horizontal will be negligibly affected by oscillation.

All previous experiments are at too shallow a depth to distinguish "upward" neutrino-induced muons from above the horizontal from "downward" muons. At SNO's depth we are uniquely capable of being able to see and compare muons from *unoscillated* neutrinos *above* the horizontal against those from *oscillated* neutrinos *below* the horizontal.

Downward Muon Rates at Surface

$$\frac{dI_{\mu 0}(E_{\mu 0}, \cos\theta)}{dE_{\mu 0}} = A \cdot 0.14 \cdot E_{\mu 0}^{-\gamma} \cdot \left(\frac{1}{1 + \frac{1.1 E_{\mu 0} \cos\theta^*}{115\ \mathrm{GeV}}} + \frac{0.054}{1 + \frac{1.1 E_{\mu 0} \cos\theta^\star}{850\ \mathrm{GeV}}} + R_c \right)$$

Ref: T. K. Gaisser, "Cosmic Rays and Particle Physics", Cambridge (1992)

Overall normalization: $A = 0.84 \pm 0.04$ (from Fréjus data: Ch. Berger *et al.* Phys. Rev. **D40** (1989) 2163).

Primary cosmic ray spectral index: $\gamma = 2.7$

"Prompt" muon component $R_c = 0$ (fixed, no sensitivity with present data below 0.01)

These surface muons now need to be transported through the rock to the SNO detector.

Calculating Downward Muon Fluxes at the Detector

Muon Energy Loss in Rock

Muon tracking code: P.Lipari, Astro. Part. Phys. **1** (1993) 195.

Overburden of Rock

Systematic errors in downward muon flux are hard to evaluate due to uncertainty in rock uniformity and in the implementation of density effect parameters for ionization losses. We see a $\pm 10\%$ variation in the azimuthal angle distribution which does not coincide with known geology.

Quantity	Value	Estimated Error	Fractional Error in Muon Flux
Ionization Parameters			$\pm 20\%$
Density	2950 kg/m^3	$\pm 2\%$	$\mp 16\%$
Mean Z^2/A	6.0	± 0.2	$\mp 10\%$
Depth	6150m	± 6m	$\mp 0.8\%$
TOTAL			$> \pm 28\%$

Total Muon Rate

Predicted daily rate: $50 \pm 15(sys)$ (the systematic errors are very uncertain) within 8.5m impact parameter.

Muon Angular Distribution

Shape very insensitive to rock uncertainties. No credible rock parameters produce downward muons below $\cos\theta = 0.4$.

Data Analysis

Data taken in 126 days of livetime, since November 1999.

40,000 events with more than 300 PMTs triggered.

Data Cleaning: Removal of Instrumental Events

- PMT Flashers
- Light generated in neck of acrylic vessel
- Events associated with water circulation

12,000 events survived coarse instrumental cuts

Event Reconstruction

- Find muon exit point
- Assume light is being emitted at the Cherenkov angle along a line to be determined, and create goodness-of-fit measure based on this geometry

Goodness of fit to be minimized:

$$\text{GOF} = \frac{\chi^2}{N_{good}} = \frac{1}{N_{good}} \sum_{i=1}^{N_{good}} \frac{(t_i - t_i^{fit})^2}{\sigma_t^2}$$

The sum is over the number of PMTs (N_{good}) which have high charge, and times within 10ns of the expected fit value. The timing resolution of the PMTs is taken to be $\sigma_t = 1.6$ns.

- Grid search is made in (θ, ϕ) to maximize the number of in-time tubes.
- Angular resolution from simulations: $\sigma_\theta = 2.1°$; 0.2% of events have reconstructed angle error between 8 and 20°.
- Cut on goodness-of-fit and impact parameter.

Final data sample: 6422 (overall fitter efficiency 77%; >98% for impact parameter <6m).

Measured Total Rate

Method: time difference between events; data sample: 5876

Factor	Contribution to Error
Fit inefficiency	$< 0.9\%$
Contamination	$< 0.4\%$
Size of Fiducial Volume	4%
Statistics	2.4%

Measured total rate: $67 \pm 2(stat) \pm 3(sys)$ muons per day within 8.5m impact parameter.

Conclusion

- The zenith angle distribution of downward muons in SNO is well understood.

- Our angular resolution is good enough to make a clean separation of downward muons from neutrino-induced muons at $\cos\theta \sim +0.4$.

- The measured rate of muons from below $\cos\theta = +0.4$ is similar to that expected. With one year of data the standard oscillation scenario should be statistically distinguishable from no oscillations at 90% C.L.

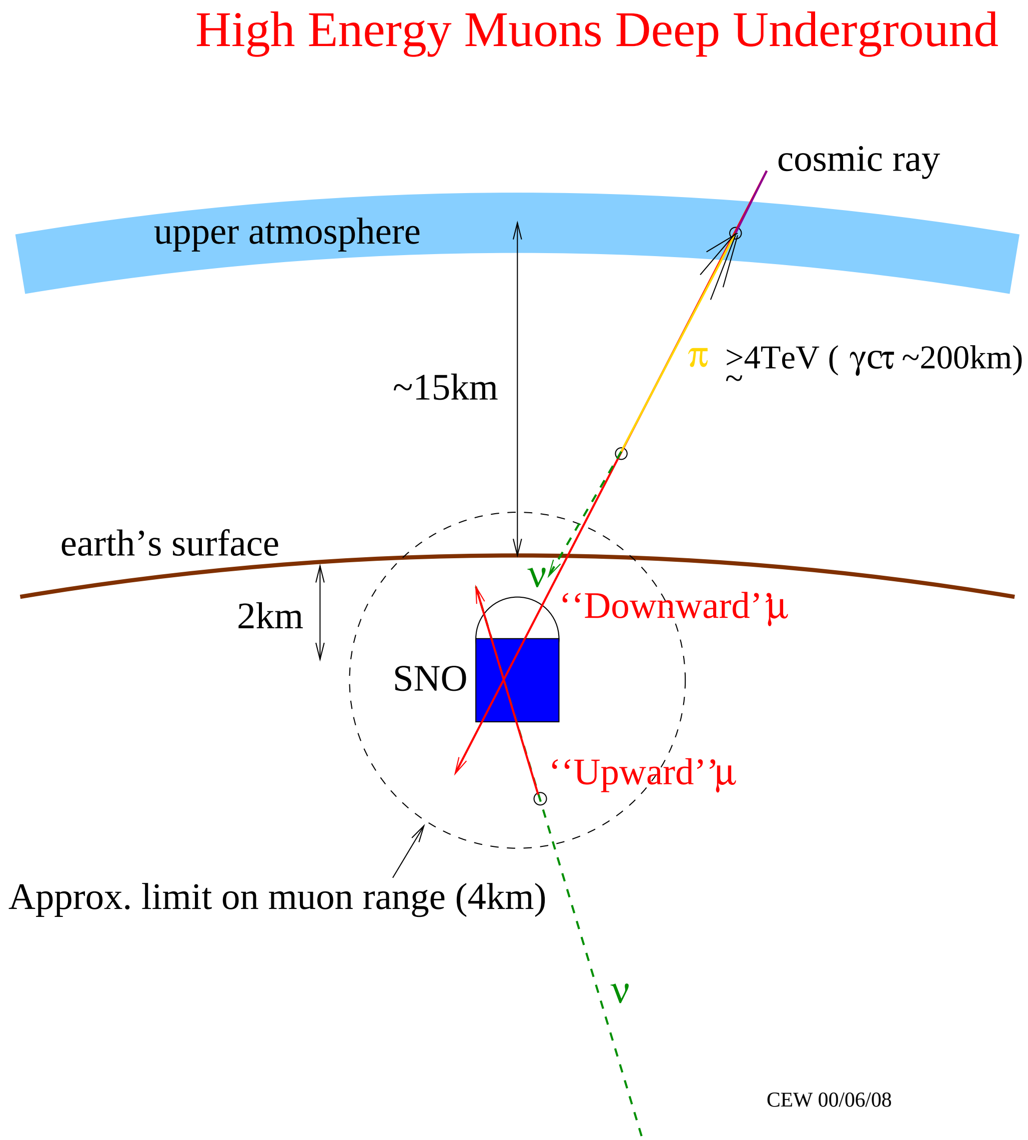

Figure 1: Sketch of the proton + air nucleus $\rightarrow \pi \rightarrow \mu$ production and decay chain which leads to muons being observed deep underground in SNO. Pions decay in flight in the atmosphere to produce observable muons and neutrinos.

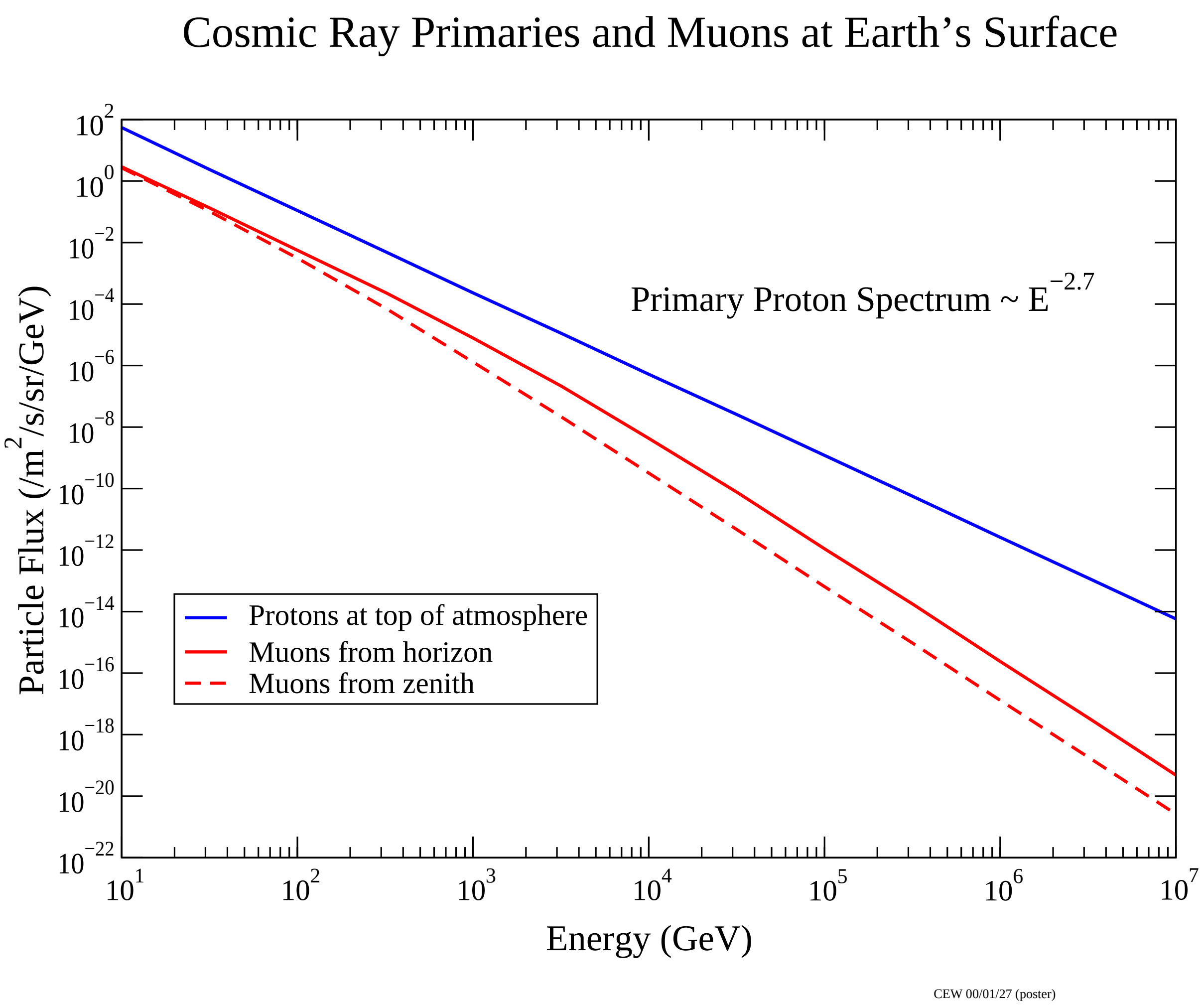

Figure 2: Spectra of cosmic ray primaries (protons and some heavier nuclei) and secondary muons. All pions lower than 100GeV decay in the atmosphere so at these energies, the muon spectrum has the same shape as the primary, $E^{-2.7}$. At higher energies the pion decay probability falls as $1/E$, so the muon spectrum becomes $\sim E^{-3.7}$. Ref: Gaisser *ibid.*; L. V. Volkova, Sov. J. Nucl. Phys. **31** (1980) 784.

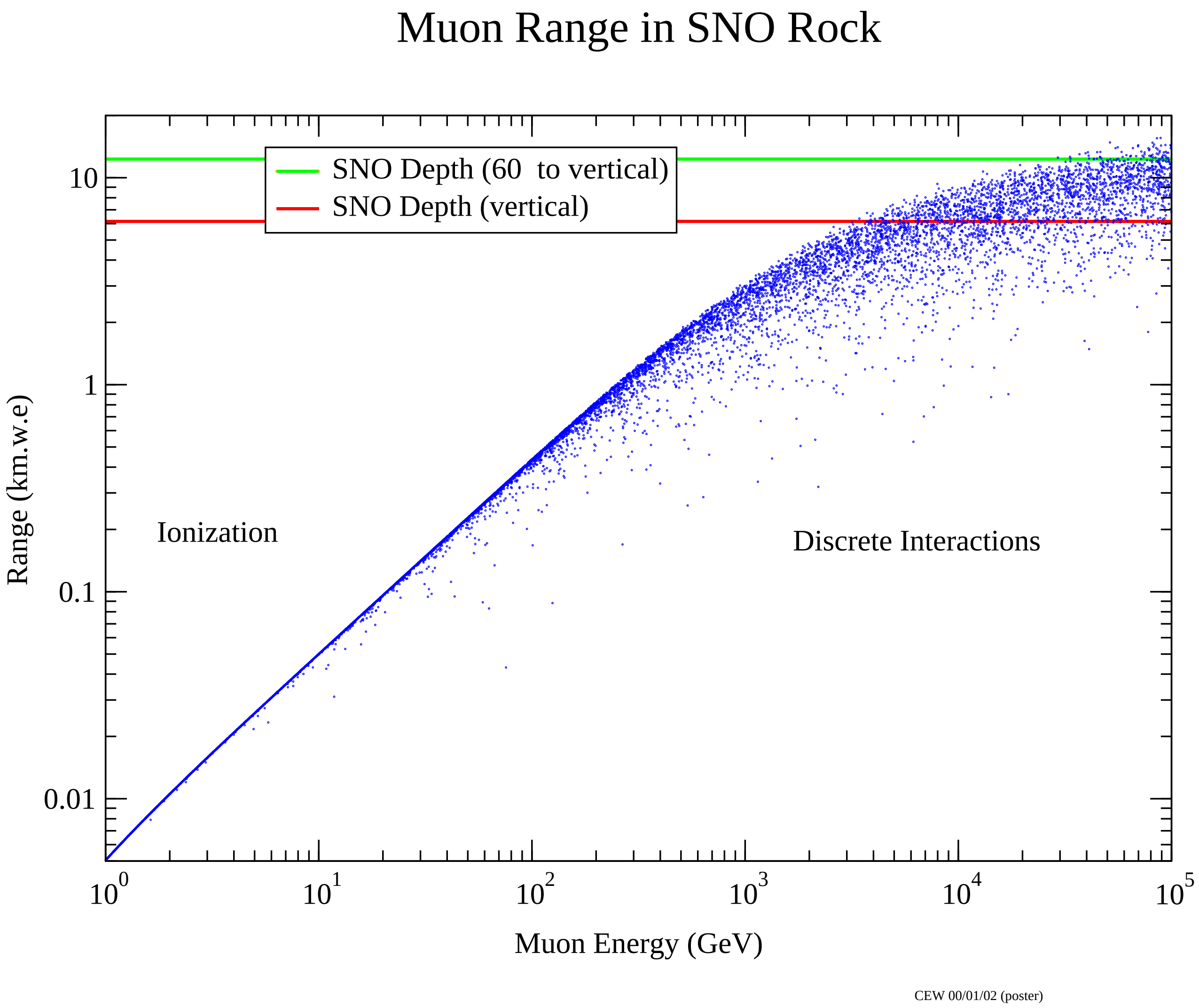

Figure 3: The range of muons in SNO rock, calculated using the code of Lipari. The linear ionization region and the asymptotic discrete interaction region are shown. The overburden of SNO is shown for vertical and slant ($\cos\theta = 0.5$) directions.

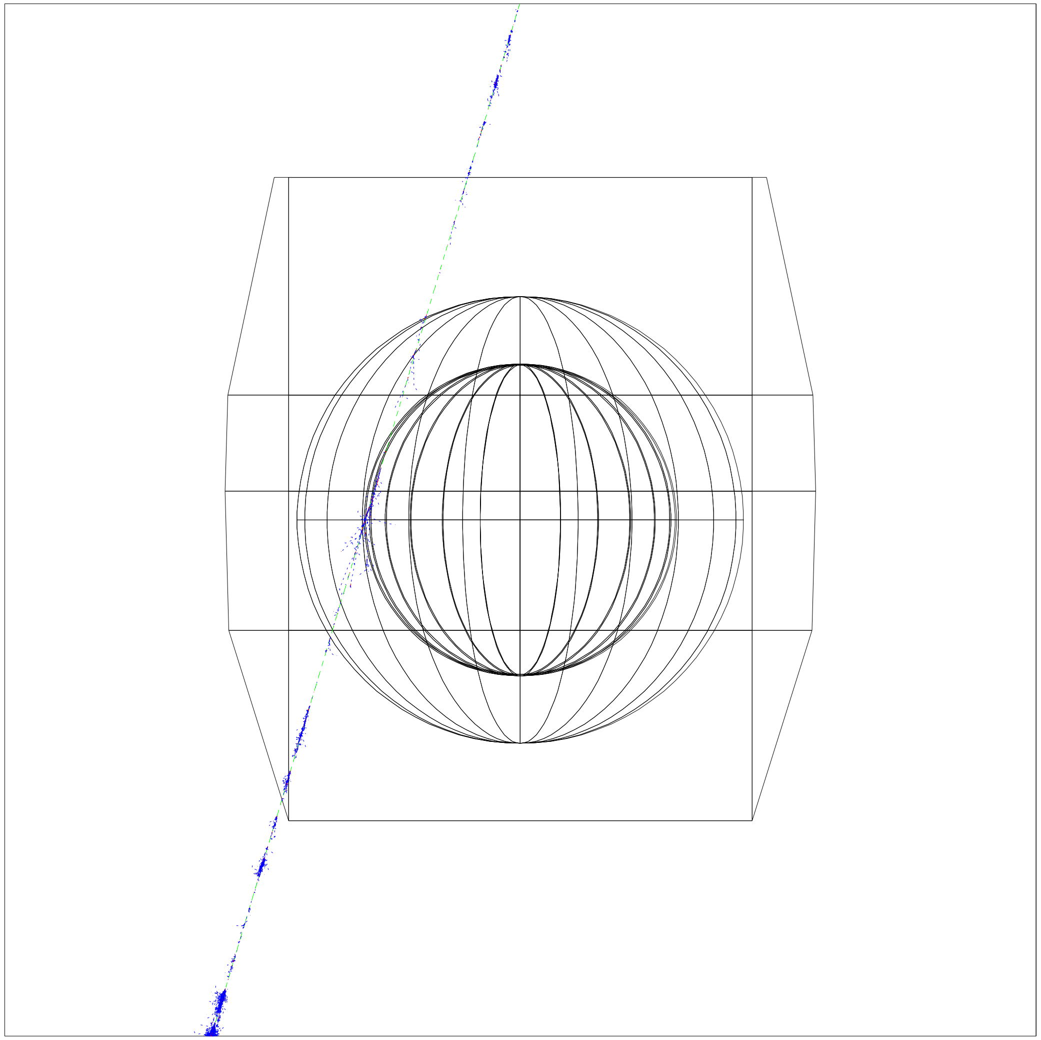

Figure 4: A GEANT simulation of a muon traversing the SNO cavity. The ionization track is shown in green, while the gamma rays are shown in blue and $e^{\pm}$ in red. The inner sphere is the D_2O, the outer sphere is where the PMTs are, and the barrel shape is the cavity in the rock.

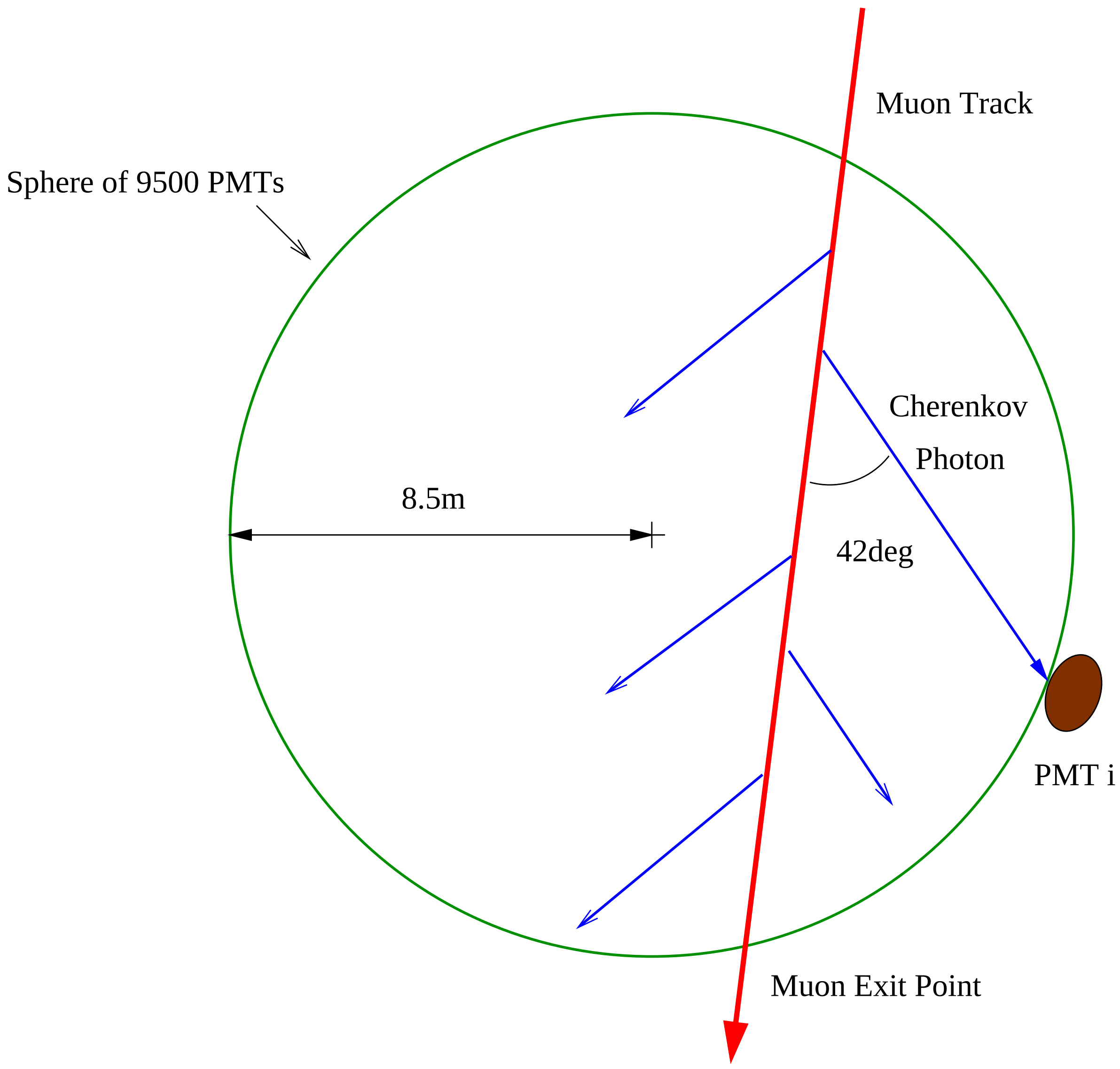

Figure 5: Geometry for reconstructing through-going muon events in SNO. The ith hit PMT has measured time t_i and time deduced from fitted muon track t_i^{fit}.

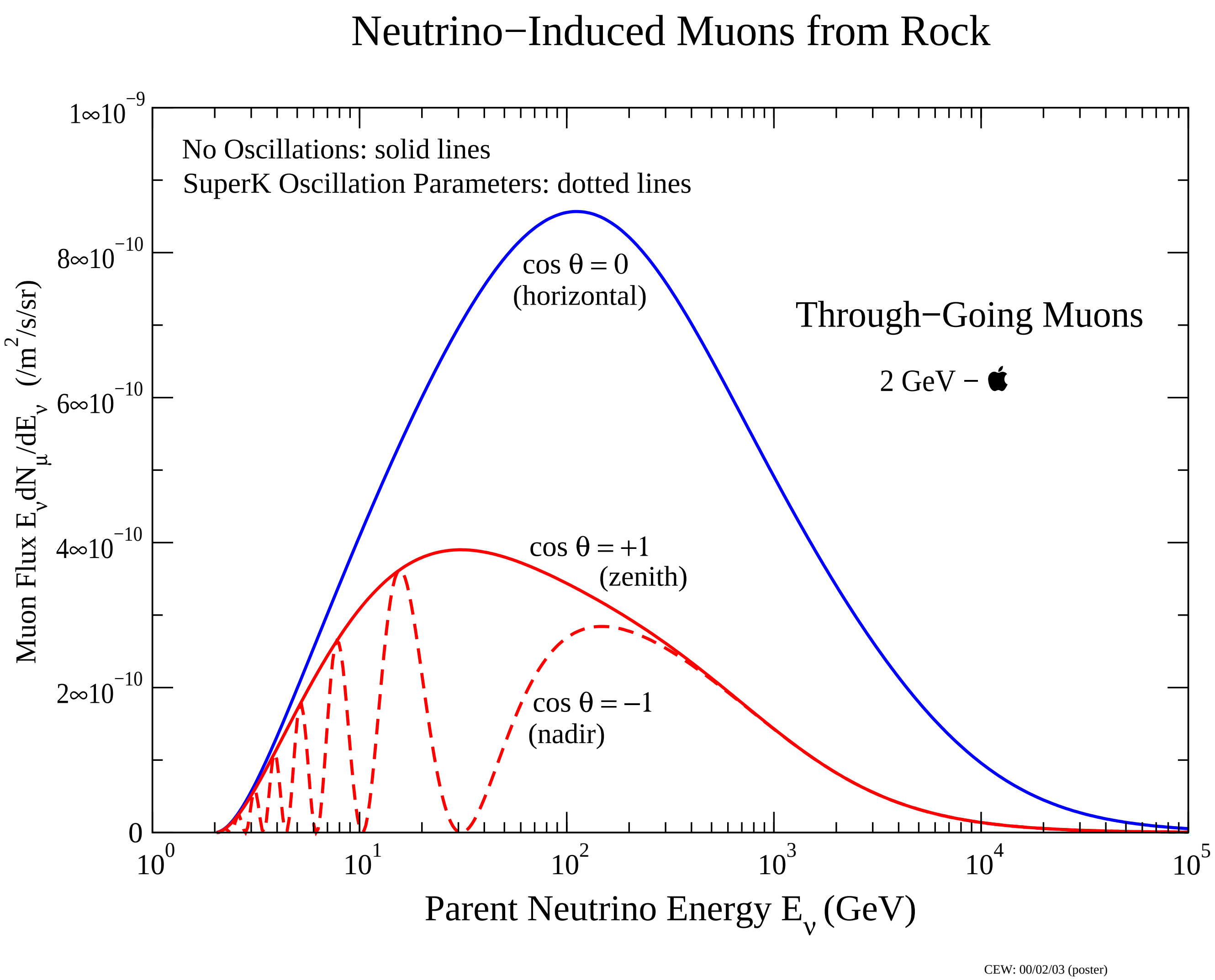

Figure 6: The parent neutrino energies for rock-generated muons which reach SNO. The through-going muons, with which we are concerned here, originate with neutrinos in excess of 2GeV. Hence the parent cosmic rays mostly had an energy in excess of the geomagnetic cutoff for any incoming angle. The effects of neutrino oscillations, which only affect muons arriving from beneath the horizontal, are shown for the standard Super-K parameters. Ref: Gaisser and Stanev, Phys. Rev. **D30** (1984) 985; Volkova *ibid.*

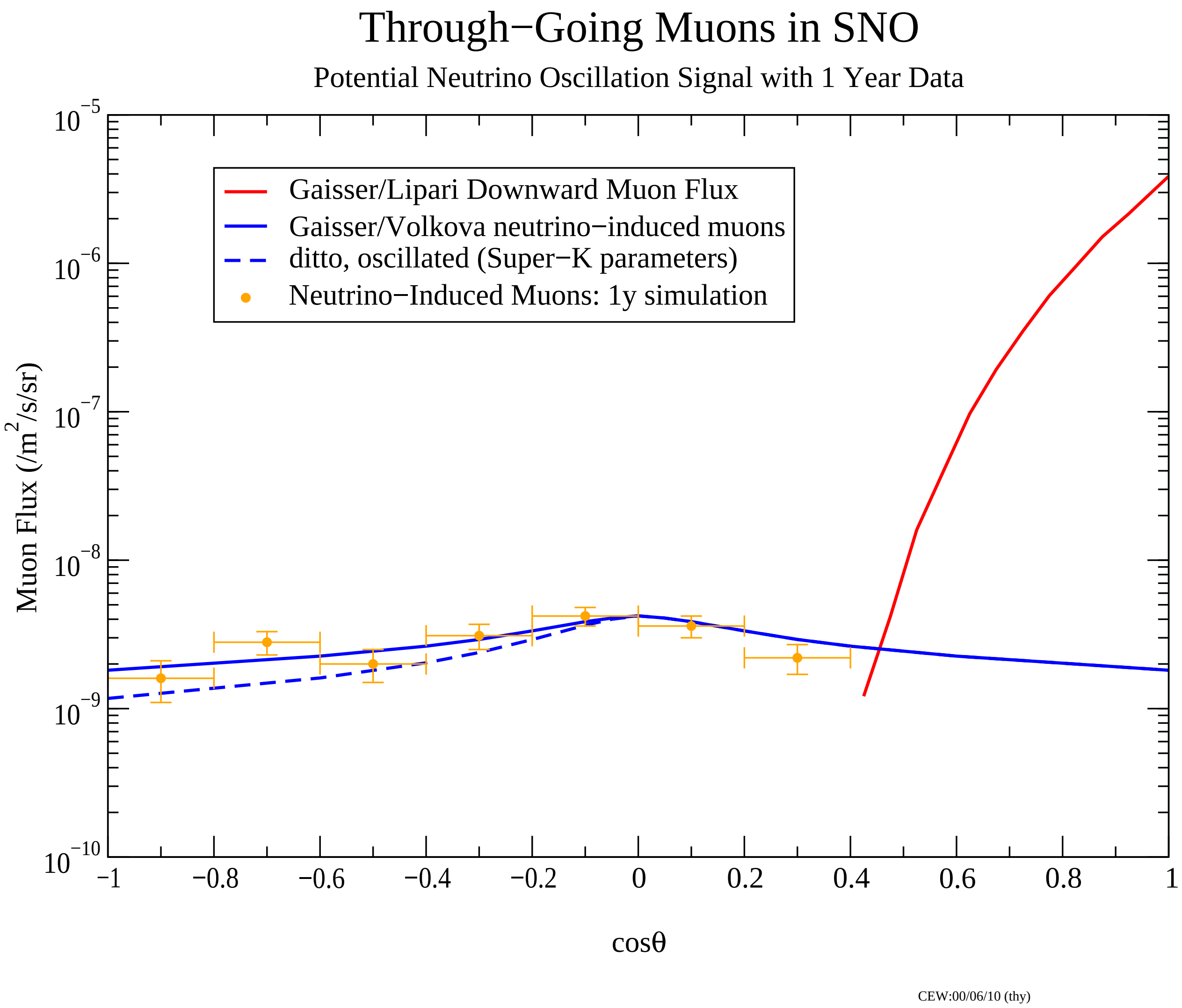

Figure 7: A complete theoretical angular distribution for through-going muons detected by SNO. Only the neutrino-induced muons from below the horizontal can be affected by any expected neutrino oscillation scenario. The "Super-K" parameters plotted here are $\sin^2 2\theta = 1$, $\Delta m^2 = 0.003\mathrm{eV}^2$. The orange points show a simulation of one year of SNO data if there are no oscillations. Ref: Gaisser, Lipari, Volkova *ibid.*

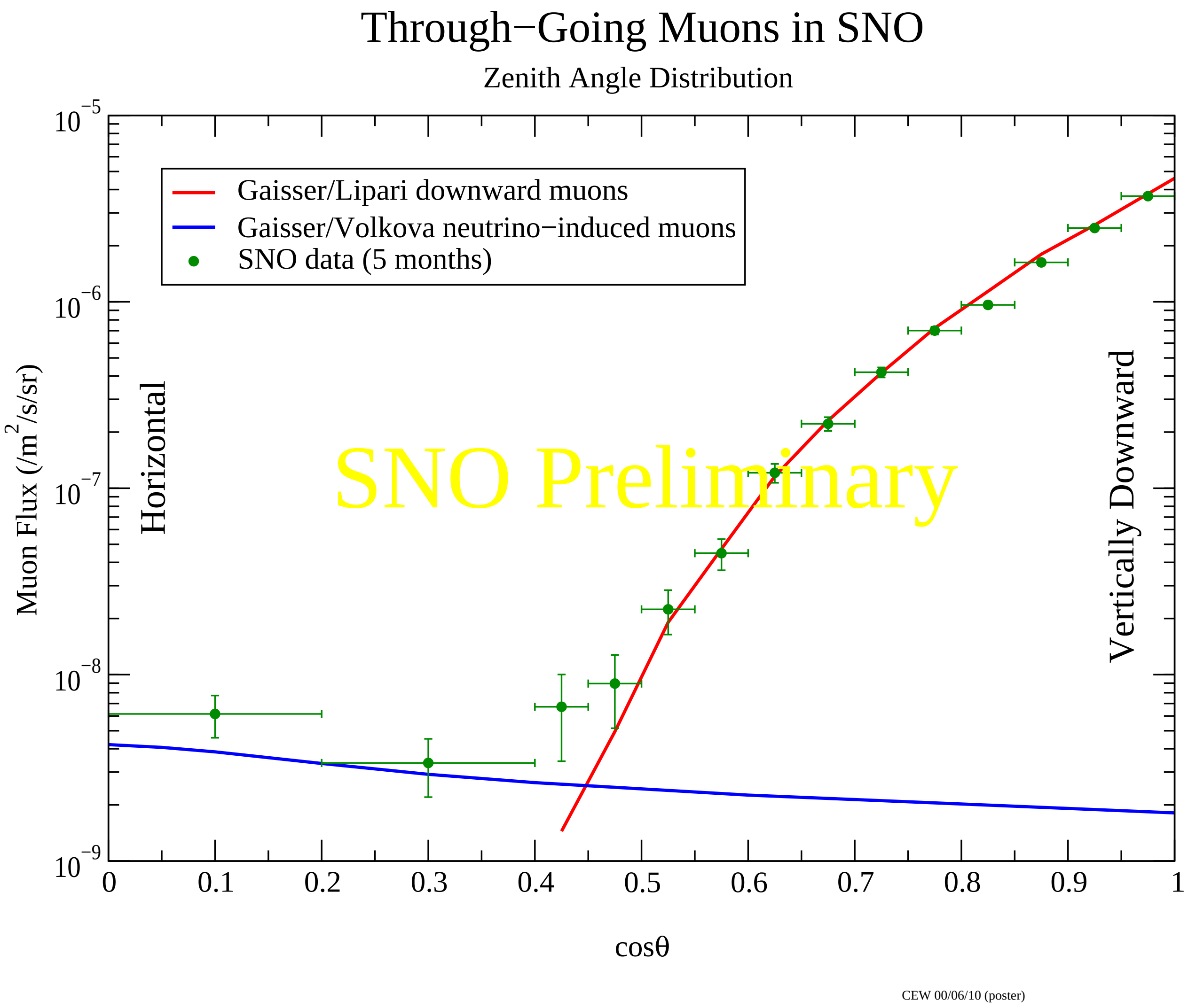

Figure 8: Zenith angle distribution of through-going muons. The theoretical calculations are for downward muons (red) and upward neutrino-induced muons (blue). For $\cos\theta > 0$ the standard neutrino oscillation scenario has no effect on muons coming from above the horizontal. The downward flux calculation has been normalized to the measured total rate. The upward flux has an overall uncertainty of 25% from that in the primary flux. The measured upward flux has an uncertainty of 10% due to fitter ability to distinguish through-going from stopped muons.