A THREE-DIMENSIONAL CALCULATION OF THE ATMOSPHERIC NEUTRINO FLUX

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Abstract

We present a fully three-dimensional calculation of atmospheric neutrino fluxes using accurate models of the geomagnetic field, hadronic interactions, tracking and decays. Results are presented for the Super-Kamiokande (SK) and Sudbury Neutrino Observatory (SNO) sites. We see an enhancement of horizontal low energy neutrinos compared with previous one-dimensional calculations.

3D Calculation Outline

- The geomagnetic cutoff is accounted for by starting cosmic rays at the top of the atmosphere and backtracking them in a model of the geomagnetic field. Primaries are rejected if they strike the earth.
- Surviving primaries interact with a model of the atmosphere, producing charged secondaries and neutrinos.
- The charged secondaries are tracked in the geomagnetic field.
- The secondaries are allowed to decay into neutrinos.
- Neutrino type, energy, and direction are recorded for each neutrino that crosses a horizontal surface at the detectors of interest.
- Neutrino flux, and the interaction rates and angular distribution of observed leptons are calculated.

This flux will be compared with the one-dimensional calculation of Barr, Gaisser and Stanev. [1]

Calculation Details

- 518328 protons, 43317 alpha particles and 5 CNO nuclei were started with kinetic energy per nucleon between 0.5 and 100,000 GeV.
- 30 km helical steps were taken for the primaries, 1 km helical steps for secondaries inside the atmosphere.
- Exact detector geometry would make the calculation prohibitively inefficient; The shape of each detector was changed to a flat surface, ± 10 degrees longitude and ± 5 degrees latitude. This was taken into account when computing the flux.
- The flat, horizontal, acceptance shape used allows us to see the recently discovered enhancement at the horizon[4] which would be washed out with an enlarged spherical geometry.
- These primaries resulted in 29398 neutrinos at SNO and 21544 neutrinos at SK.
- The calculation was repeated with various hadronic codes.

Hadronic Codes Comparison

- To compare the results of hadronic packages, we calculate *spectrum weighted moments* Z.
- The values of these factors determine how many charged pions are produced at a given energy, and it is these pions which decay into neutrinos.

$$Z_{p\to\pi^\pm} = \int_0^1 dx \cdot x^{1.7} \frac{dn_{\pi^\pm}(x, E_N)}{dx} \tag{1}$$

where $x = E_\pi/E_N$, and E_N is the total energy of the incident nucleon in the lab system and E_π is the energy of the secondary pion.

Conclusion

- SNO and SuperK are in different geomagnetic environments, and this affects the flux and angular distribution of lower energy atmospheric neutrinos.
- Overall fluxes depend on the choice of hadronic code. CALOR/FRITIOF and GEANT-FLUKA, produce similar spectra, and angular distributions. Fluxes differ by 13% for the SK site and 2% for the SNO site. These differences are small compared with the primary flux uncertainty.
- We see the horizontal enhancement of low energy neutrinos found by Battistoni et. al, [4] and explained by Lipari [5].

Comparison of Hadronic Codes

Hadronic Code	μ^+/μ^- ratio	Z-factor	Effect on ν flux (normalised to CALOR/FRITIOF)
GEANT-FLUKA[2]	1.4	high	0.88
CALOR/FRITIOF[3]	1.24	medium	1.0
BGS[1]	1.3	medium	1.2
GEISHA		low	0.34

Comparison of SNO and SK (CALOR/FRITIOF) and SK (BGS)

Detector	Mean Flux (events/kT/y/sr)	Geomagnetic Deficits from ...
SNO (this work)	5.26	Below, East and North
SK (this work)	4.26	Above and East
SK (BGS)	3.28	

References

[1] G. Barr, T. K. Gaisser and T. Stanev, Phys. Rev. **D39**, 3532 (1989).

[2] GEANT Manual, Application Software Group, CERN program library long write-up W5013, CERN (Geneva) 1994. We use GEANT version 3.21 and the CALOR/GEANT interface 1.04/10 (1997).

[3] B. Nilsson-Almqvist and E. Stenlund, Computer Phys. Commun. **43** (1987) 387. The FRITIOF version used here is 7.02 by Hong Pi, 1993. The JETSET version is 7.3 (1991).

[4] G. Battistoni, A. Ferrari, P. Lipari, T. Montaruli, P. R. Sala and T. Rancati, hep-ph/9907408, submitted to Astroparticle Physics (1999).

[5] P. Lipari, "The geometry of atmospheric neutrino production", hep-ph/0002282

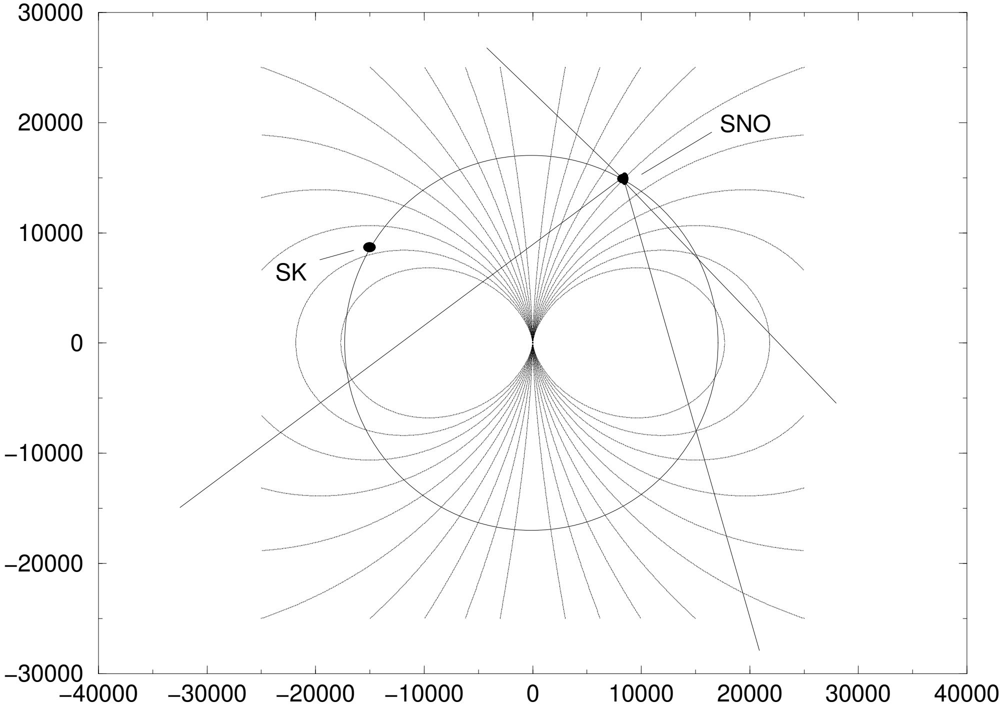

Figure 1: Positions of SNO and SK in the dipole approximation of the earth's magnetic field. At SNO field lines are mostly vertical, while at SK the field lines are closer to the horizontal. There are two directions from SNO's perspective with higher cutoffs, shown as lines that cross the field lines at 90 degrees. These produce the two higher cutoff regions seen in Figure 2.

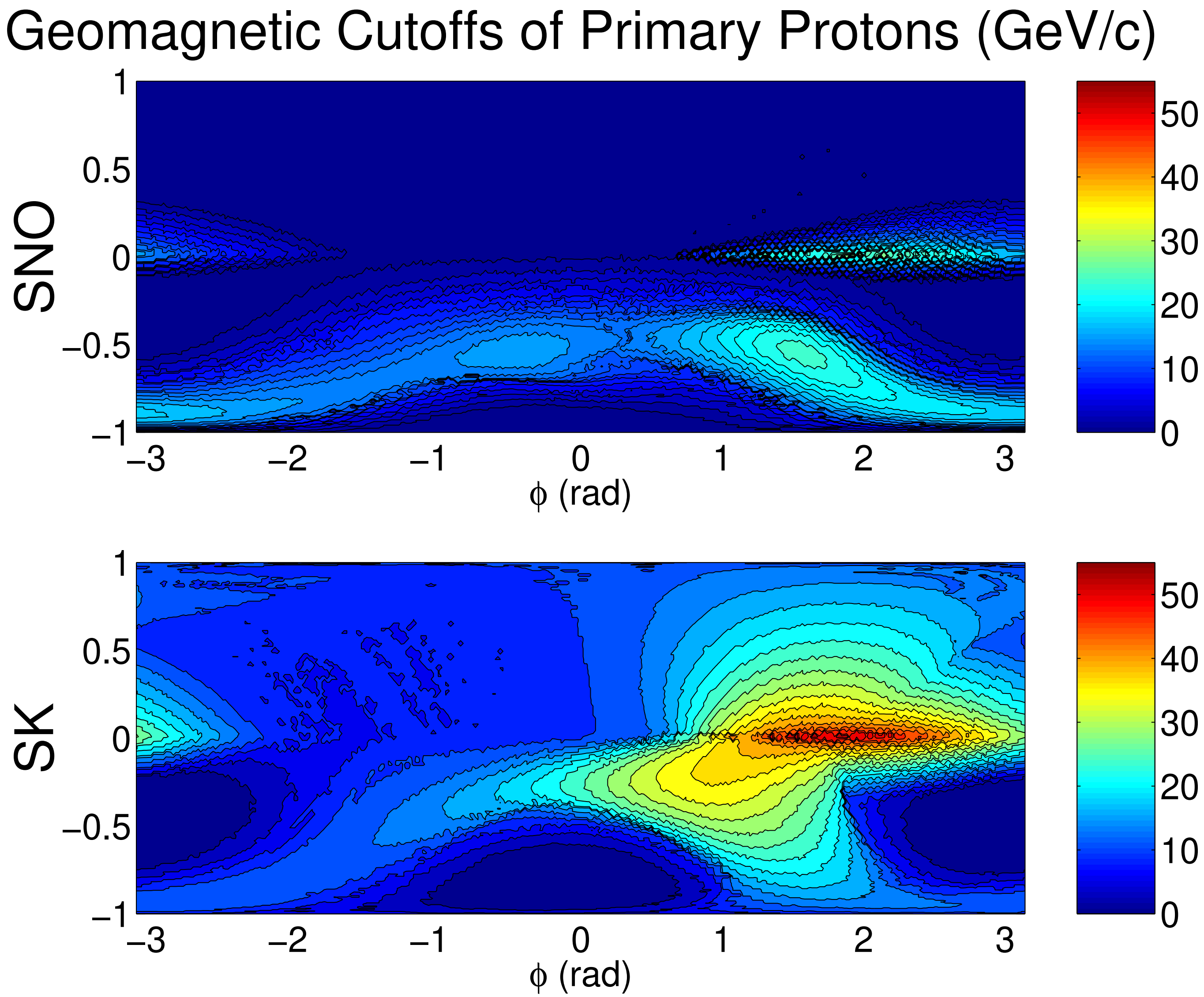

Figure 2: Rigidity cutoffs in the 1-D model for SNO (top) and SK (bottom) sites. The more northerly SNO site has in general much lower cutoffs. The SNO site has the opposite up-down asymmetry to the SK site, and a very much smaller east-west asymmetry. These cutoffs were not used in the calculation, they are merely means to check part of the code, and as an aid to understanding. In terms of cardinal points the x-axis is ordered N-W-S-E-N.

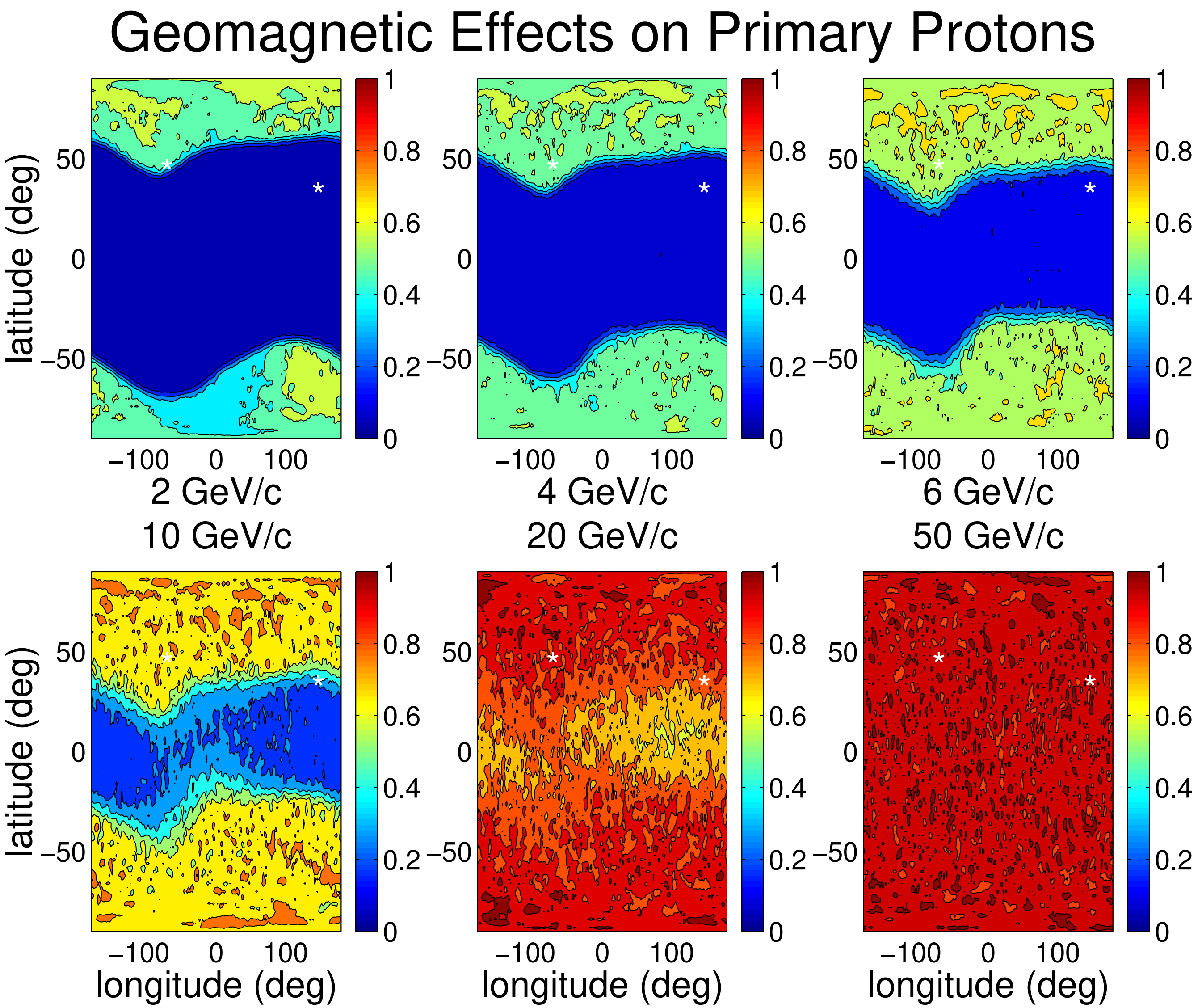

Figure 3: Effect of geomagnetic field on the spectrum of cosmic rays reaching the upper atmosphere. Maps of the intensities of cosmic ray primaries aimed at points on the earth's surface, averaging over all incoming directions, as a fraction of the zero geomagnetic field case, are shown for 2,4,6,10,20 and 50 GeV/c. The two small white crosses mark the positions of SNO and SK.

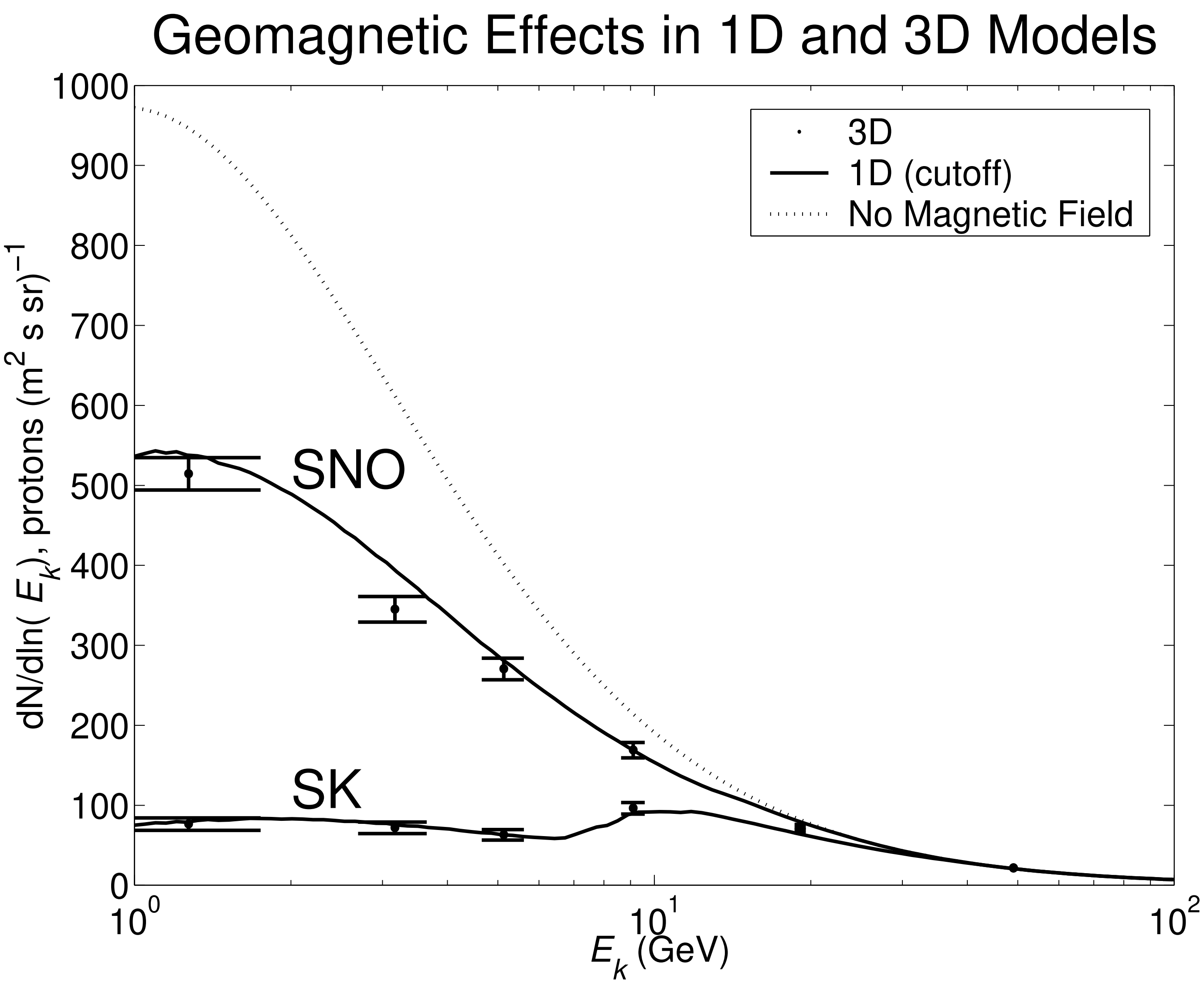

Figure 4: Effect of geomagnetic field on the flux of cosmic rays reaching the upper atmosphere. The results of both BGS (1D) and this work (3D) are presented.

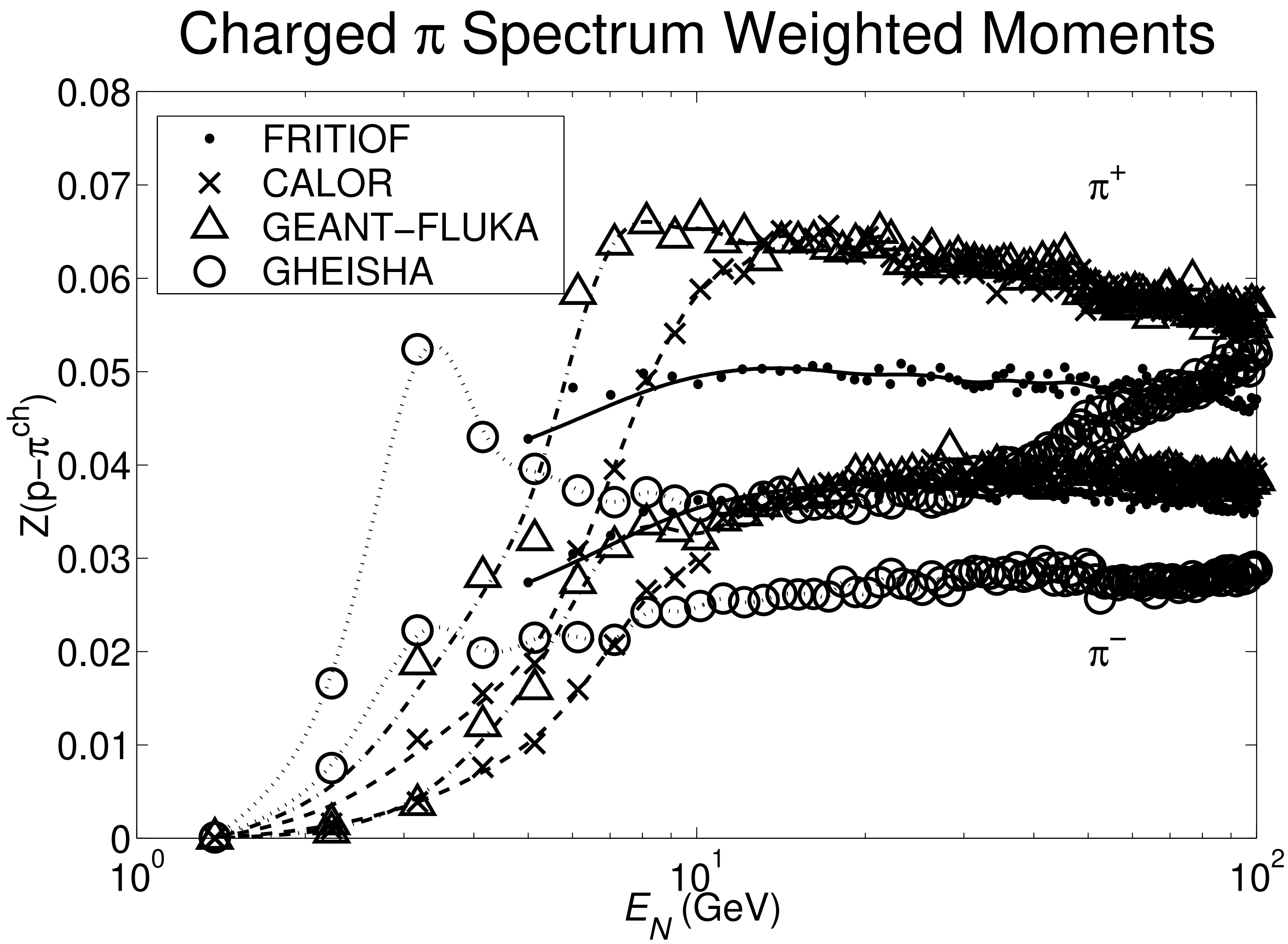

Figure 5: Spectrum-weighted moments for the production of charged pions as a function of proton total lab energy, for different common hadronic codes. For each calculation the higher of the two data sets represents π^+ production, and the lower, π^-. In our work we have primarily used CALOR below 10 GeV/c and FRITIOF above 10 GeV/c, a combination with a spectrum-weighted moment which closely resembles that in BGS.

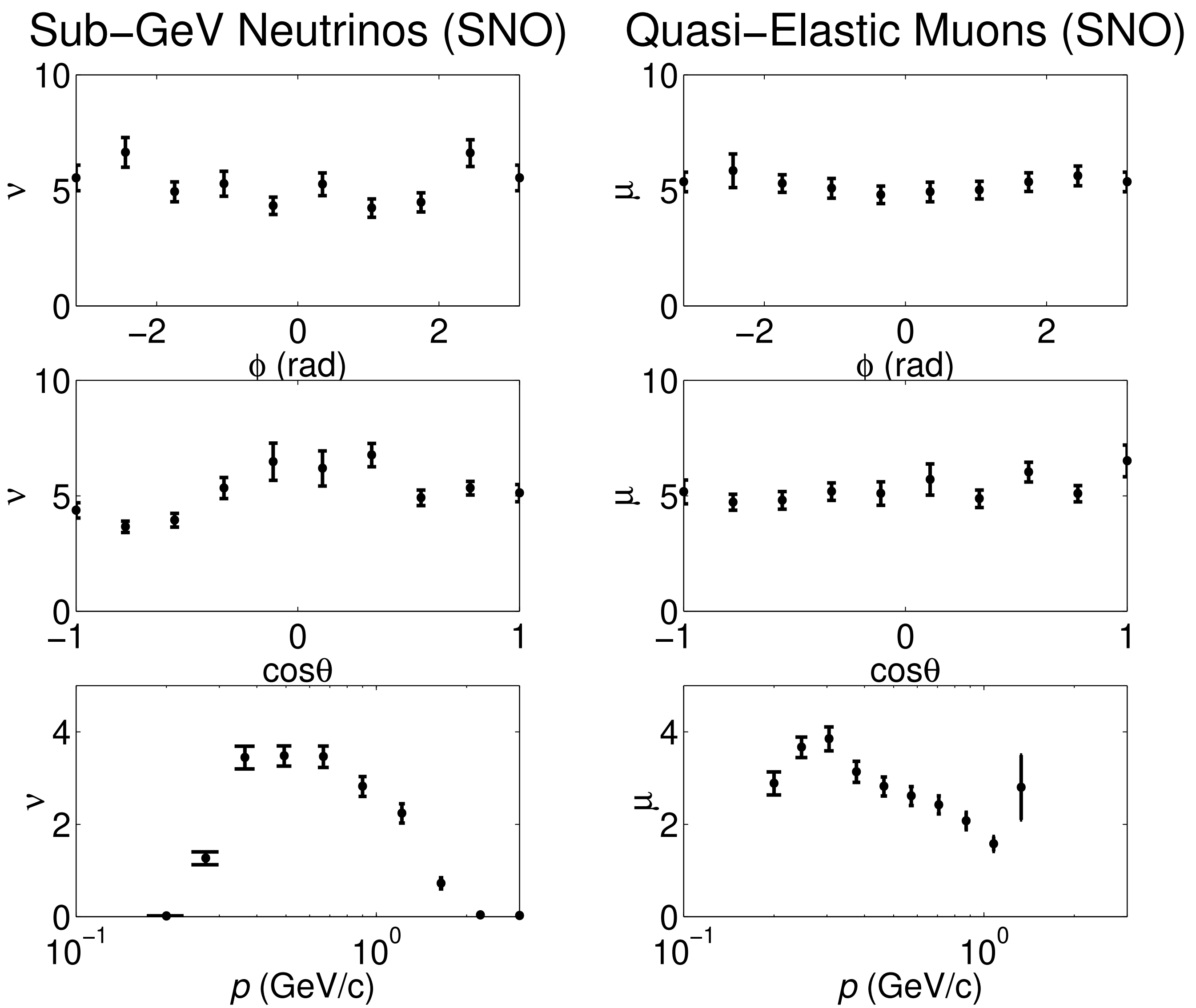

Figure 6: Right: angle and energy distributions of "sub-GeV" muons (0.2 - 1.33 GeV/c) produced by quasi-elastic scattering on water nuclei at the SNO site. Left: the same, but for parent neutrinos. Units: number/(kT·sr·y). In terms of cardinal points the azimuthal angle ϕ is ordered N-W-S-E-N.

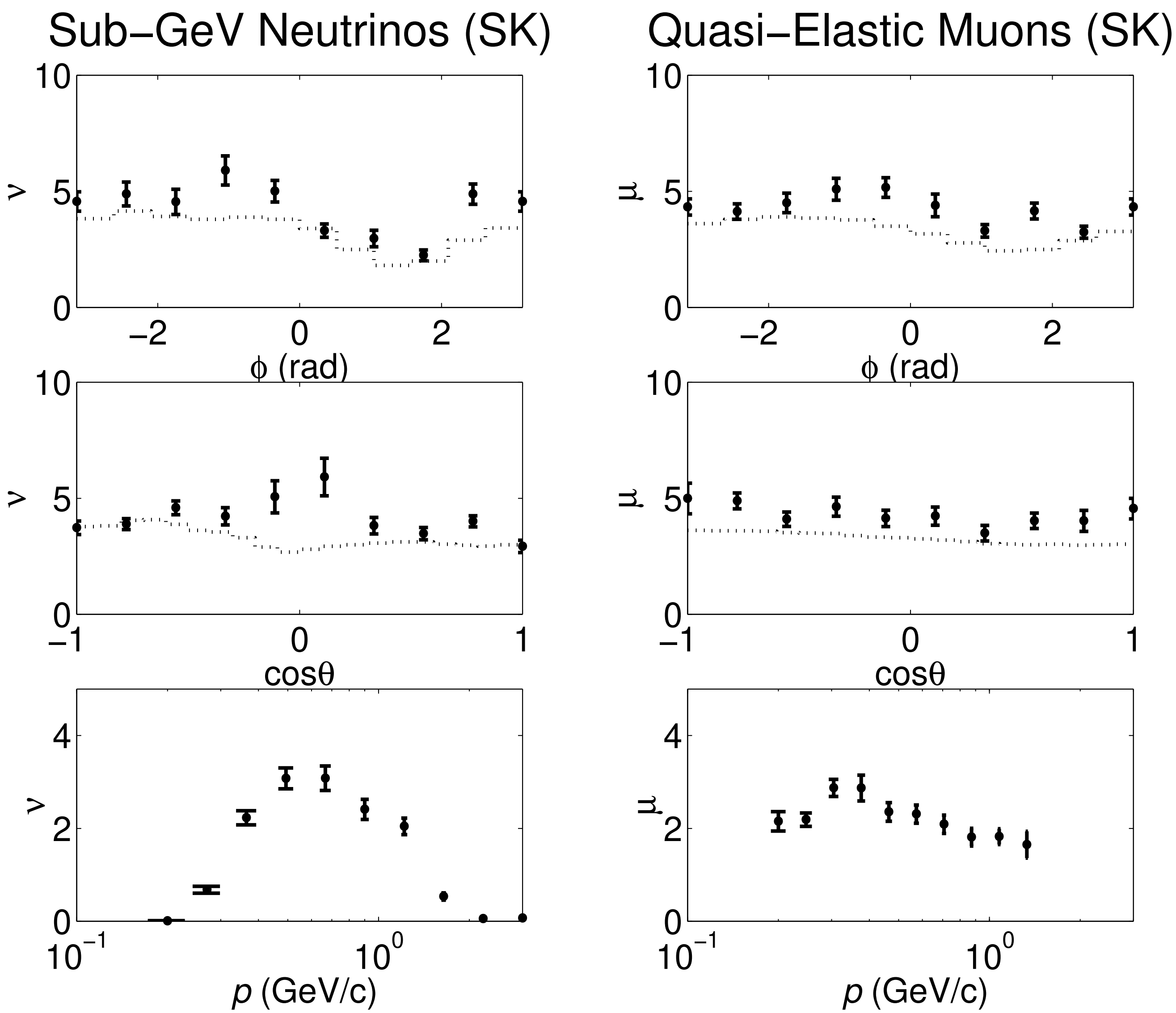

Figure 7: Right: angle and energy distributions of "sub-GeV" muons (0.2 - 1.33 GeV/c) produced by quasi-elastic scattering on water nuclei at the SK site. Left: the same, but for parent neutrinos. Units: number/(kT·sr·y). In terms of cardinal points the azimuthal angle ϕ is ordered N-W-S-E-N. The dotted line is the BGS flux. Note the horizontal enhancement ($\cos(\theta)$=0) in the neutrino flux, associated with a full three-dimensional calculation.