Atmospheric neutrinos and cosmic ray flux

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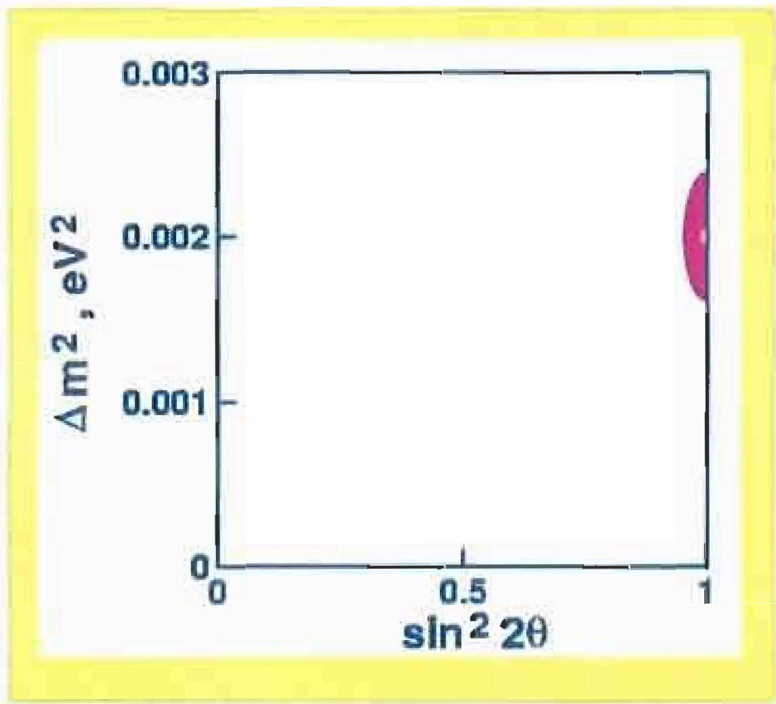
Neutrino oscillations are very well established on the basis of sub- and multi-GeV neutrino data.

Detailed new atmospheric neutrino calculations are needed to improve substantially the derivation of the oscillation parameters.

How well can we do ?

The current status of muon to tau oscillations is great and even large increase of statistics will not help much. The problem are the systematic errors from uncertainties of the atmospheric neutrino flux.



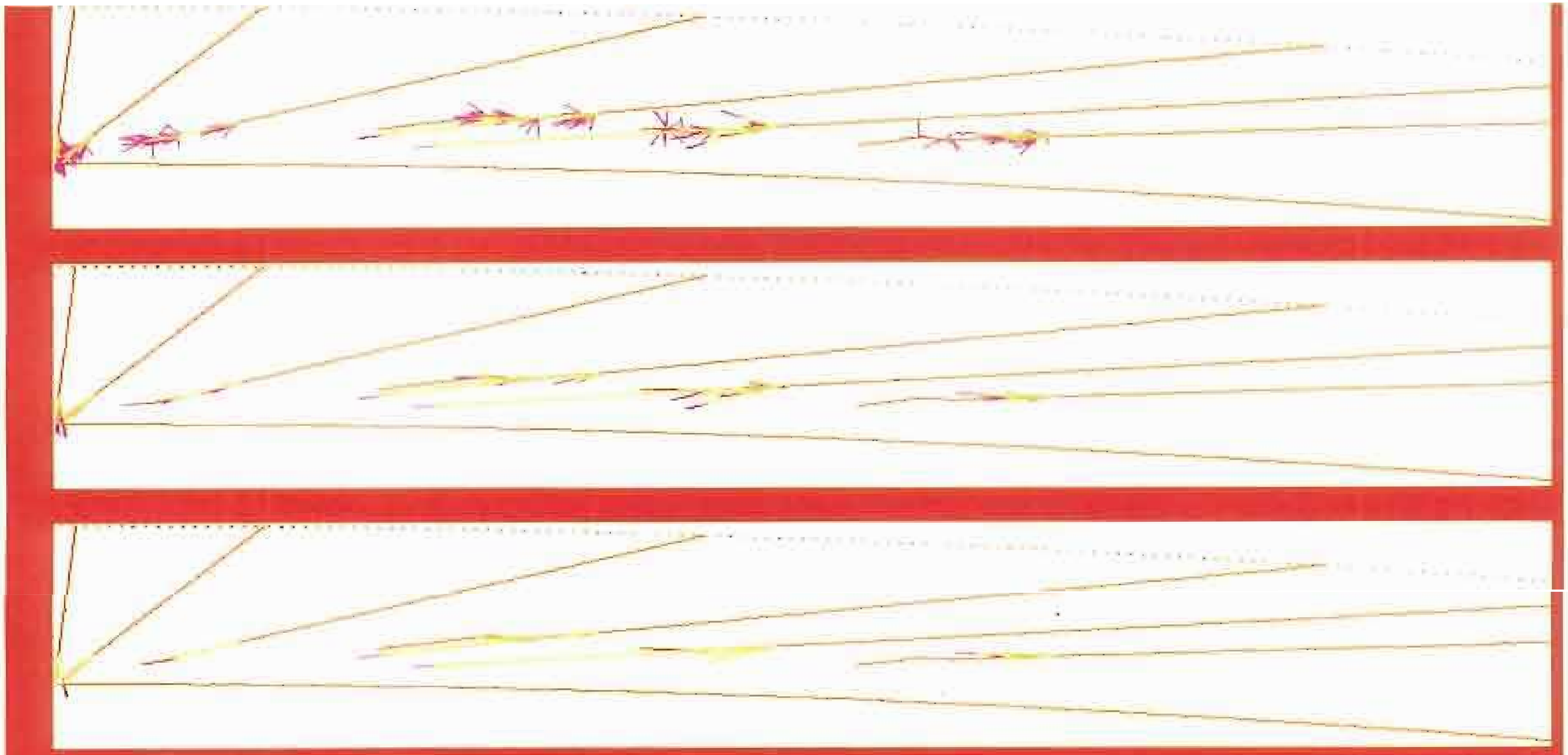
Which of the inputs Can be significantly improved so calculations become much more stable. Can the methodology be improved too ?

The answers of these questions are not obvious.

There are however problems related to the much heavier numerical work involved.

- including the charge particles bending in the geomagnetic field means a new calculation for each experimental location site.
- the number of showers calculated depends on the ratio of the `experiment's' surface and the surface of the whole atmosphere. The `detector' can not be much smaller than several hundred kilometers in radius. This may bias the calculation toward an effectively different geomagnetic latitude of the real detector.
- how to deal with Earth's surface profile ?

Bartol's 3D calculation



Red box: Displays of six separate cascades from the 3D simulation. The primaries are protons and are injected at 80km. The blue tracks are neutrinos, green are muons and black are nucleons. The three panels show the same events with different threshold energies.

Bartol's 3D calculation (G.Barr, T.K. Gaisser, P. Lipari, S. Robbins and T. Stanev)

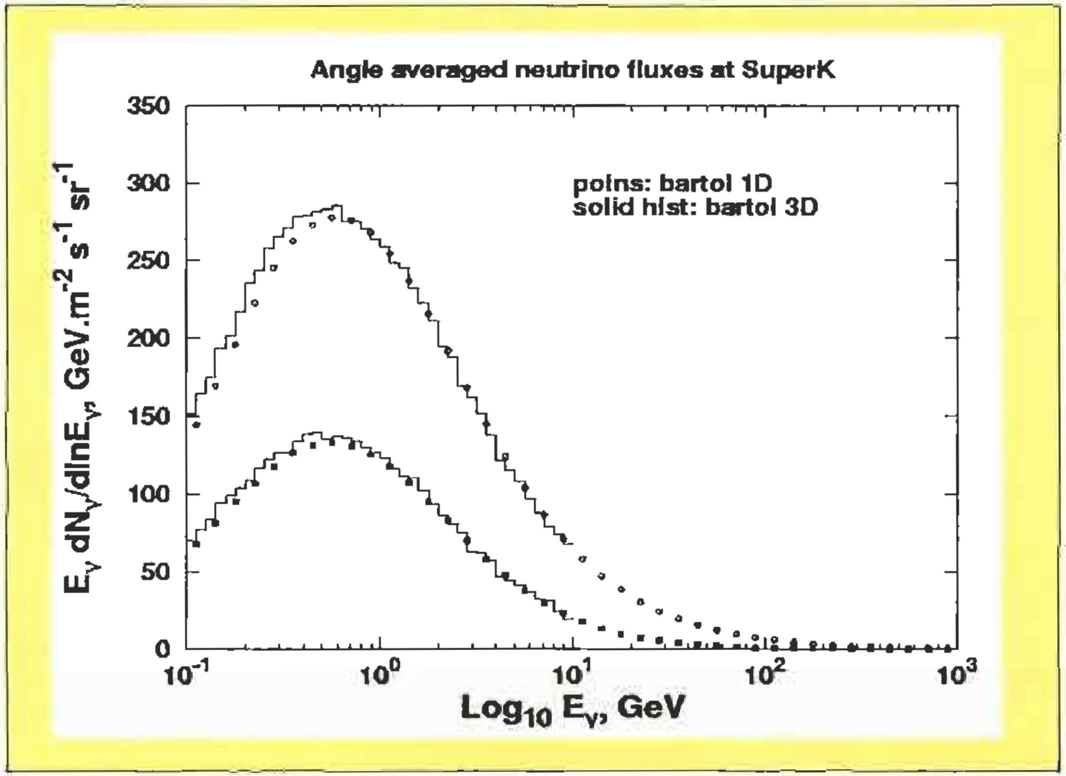
- Fixed primary energy in logarithmic steps. This allows re-weithing without repeating the whole calculation.
- Free protons, bound protons and neutrons are treated separately
- Calculation is done in a global coordinate system with origin at the center of the Earth
- The bending in the geomagnetic field is done crudely and repeated in detail if the generated neutrino passes within 1000 km of detector center
- At the same time backtrack the primary to see if it could have passed through the geomagnetic field

Bartol's 3D calculation

Currently only neutrino fluxes up to 10 GeV are available for solar min/max and the locations of Kamioka and Soudan.
To check the procedure we simultaneously do two 1D versions:
- one in the old style, combining neutrino yields with cosmic ray fluxes
- a pseudo 1D calculation where the transverse momenta and magnetic field are set to 0

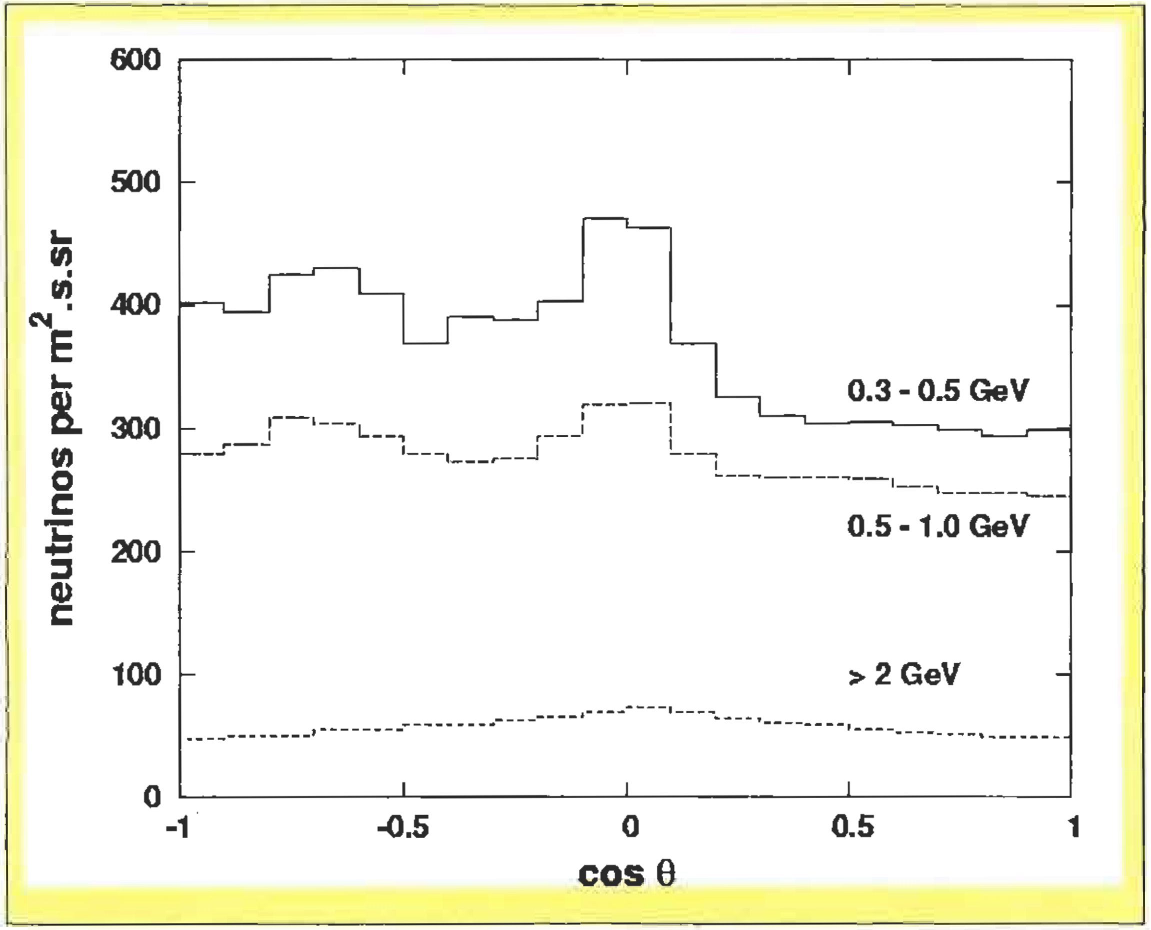
These two agree well with each other

Angle averaged neutrino fluxes , comparison of 3D To 1D calculation



The calculated fluxes are identical at energies above about 5 GeV. In the sub-GeV range the 3D version gives higher flux, as expected.

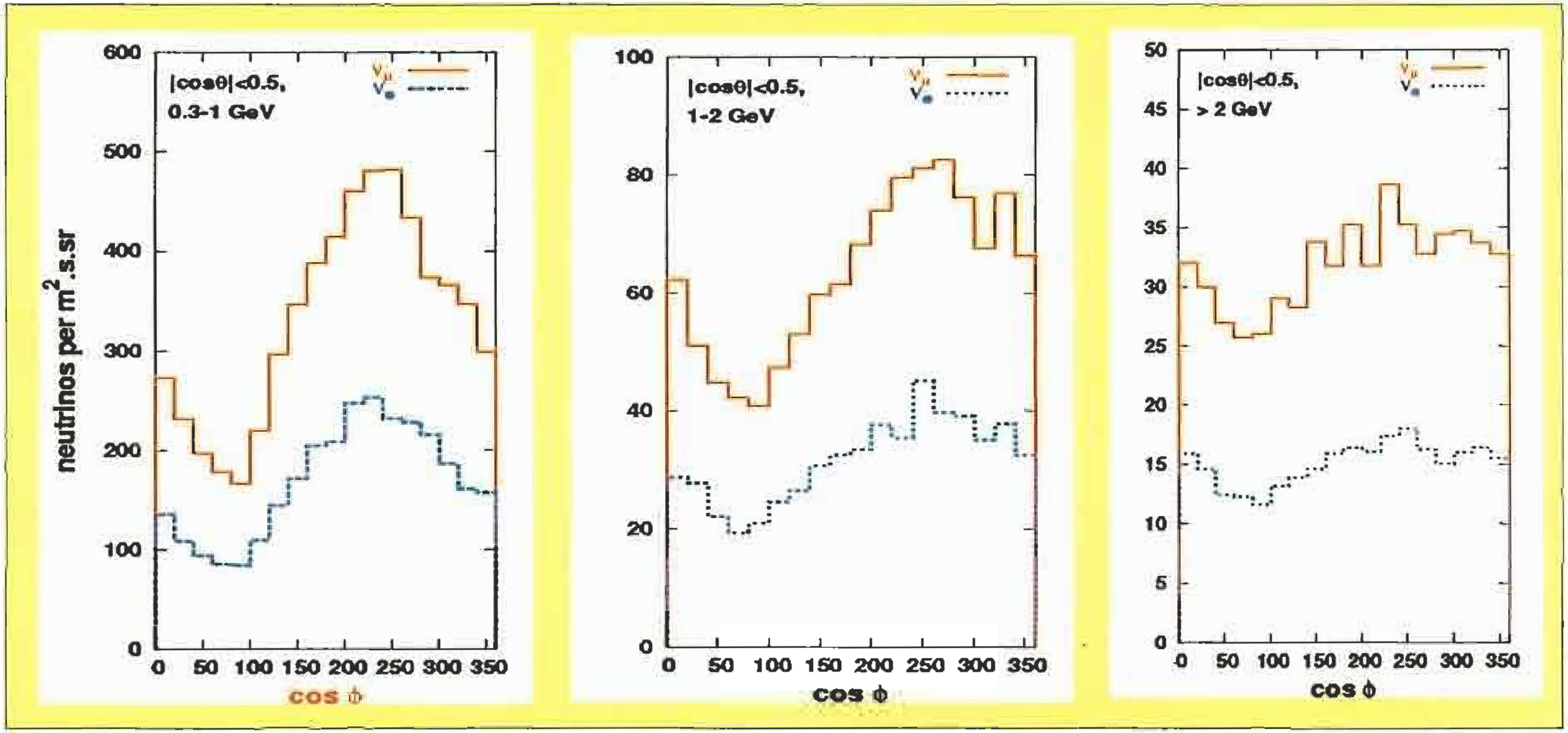
Bartol's 3D calculation: angular distributions



Low energy neutrino fluxes peak at the horizon. The effect is especially strong below 500 MeV, although in the case of Kamioka it is masked by the strong geomagnetic effects.

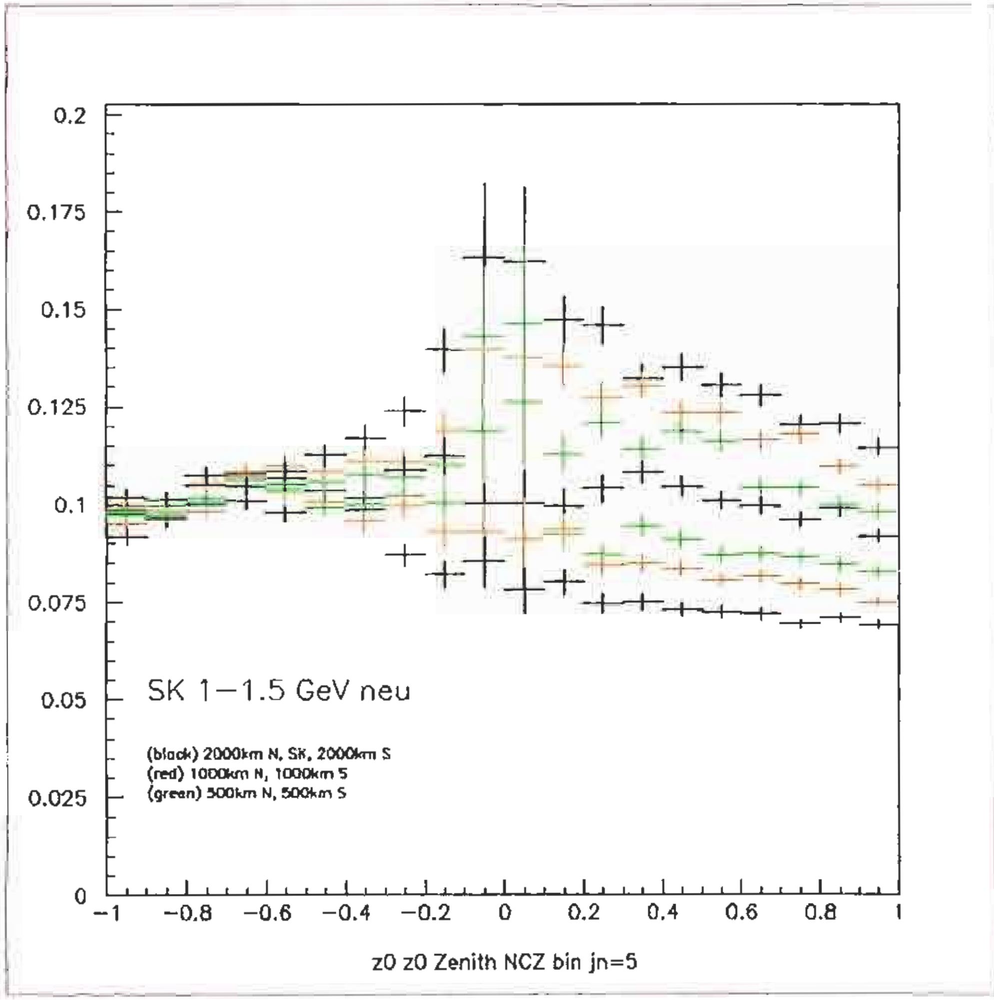
The angular distribution above 2 GeV is identical to the 1D calculation.

Bartol's 3D calculation: East-West effect



The East-West effect in neutrinos is also predicted.

The exact position of the 250 km radius detector is quite important at the position of Kamiokande

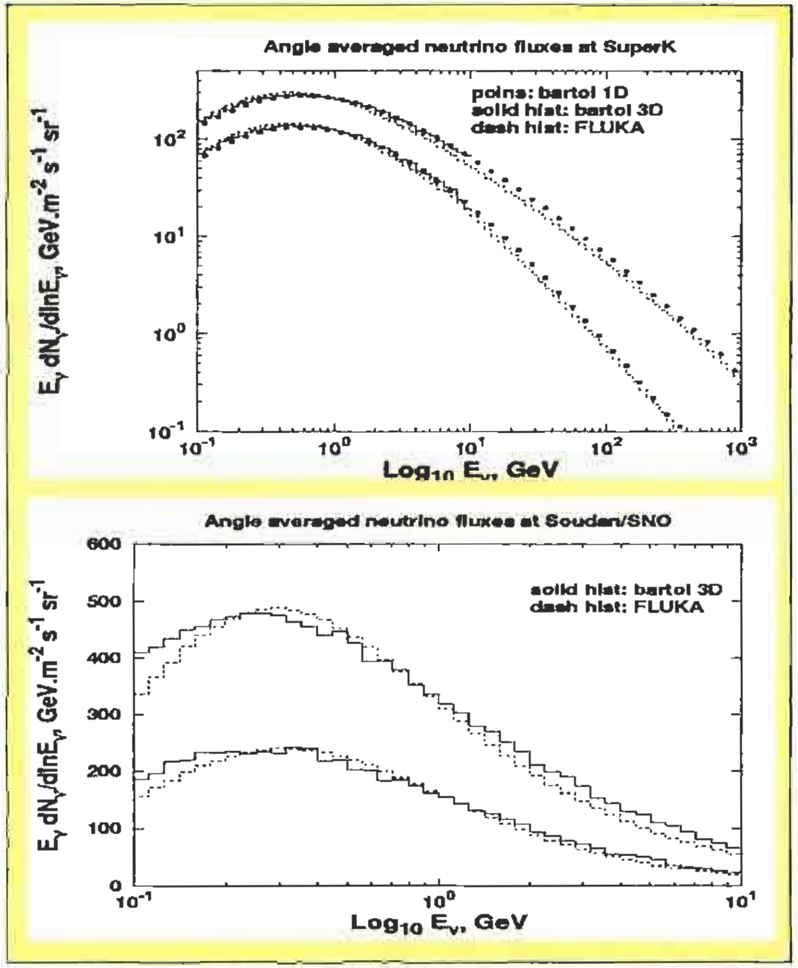


These are the angular distributions of all neutrinos of energy 1.5 to 2 GeV when the detector is moved 500, 1000 and 2000 km North and South of Kamioka.

Moving the detector East and West does not generate visible differences.

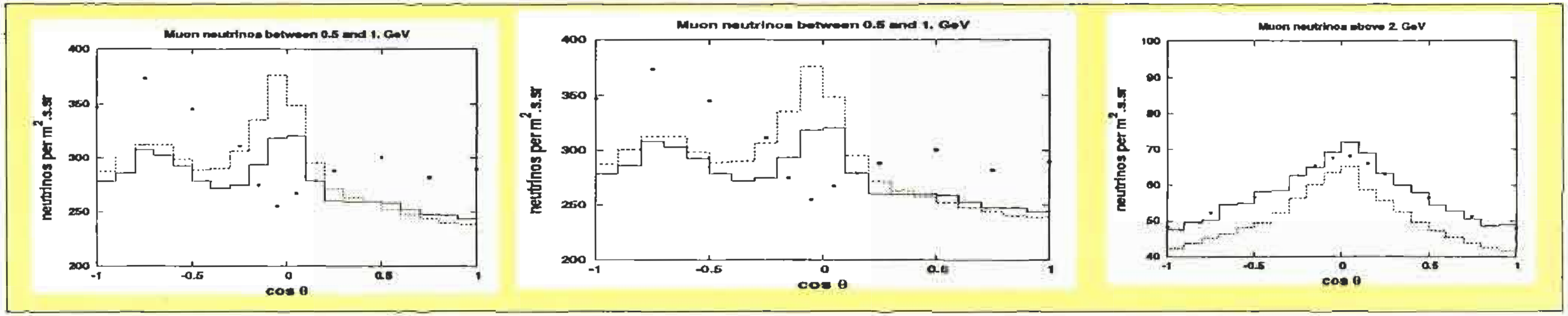
Note that the difference is substantial for downgoing and horizontal neutrinos.

Comparison to FLUKA



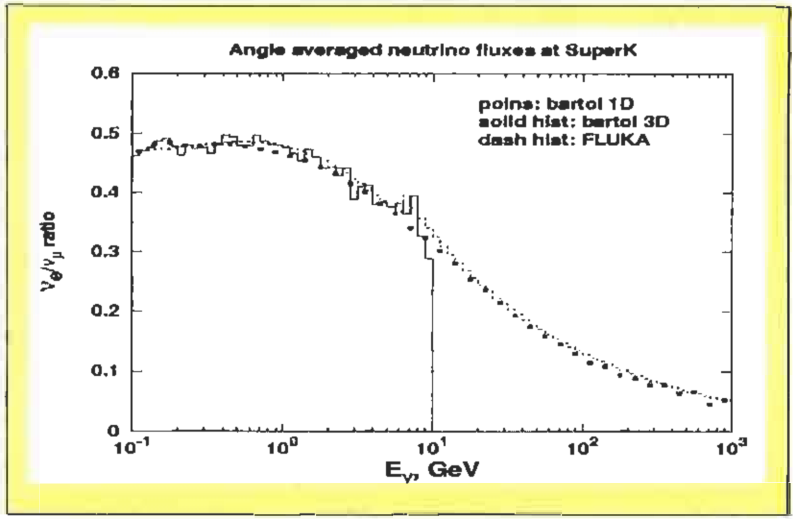
Bartol's 3D fluxes are slightly higher than FLUKA below 200 MeV and lower around 500 MeV. This is easy to see at Soudan/SNO. The reason must be the different cosmic ray spectrum used, because FLUKA has lower pion multiplicity than TARGET. At high energy Bartol's flux is always above FLUKA's by about 20%.

Comparison to FLUKA



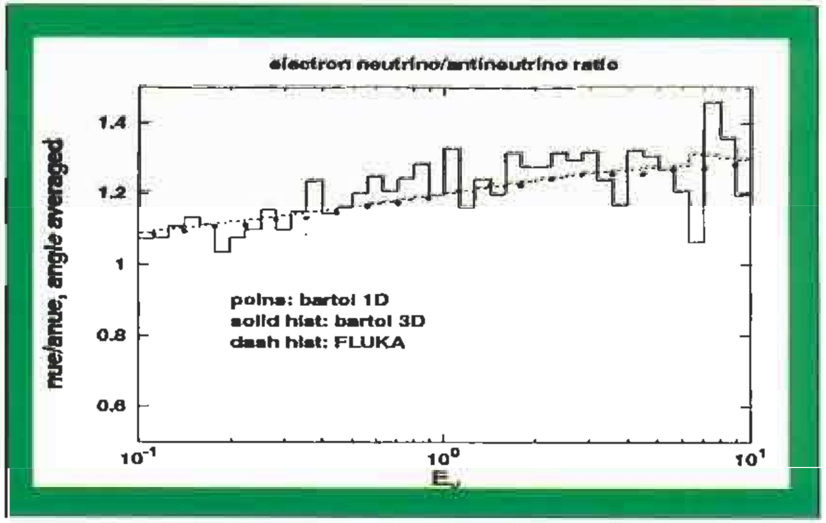
There is one more significant difference between these two calculations which is in the exact form of the angular distribution. We are investigating the reasons for this disagreement. `Bartol' has paid special attention to the exact form of weighting of neutrino events around the horizon - see ICRC (Tsukuba) paper. A few events at very small cosθ can introduce huge fluctuations in the flux values, although this is not likely with the large FLUKA statistics.

Comparison to FLUKA

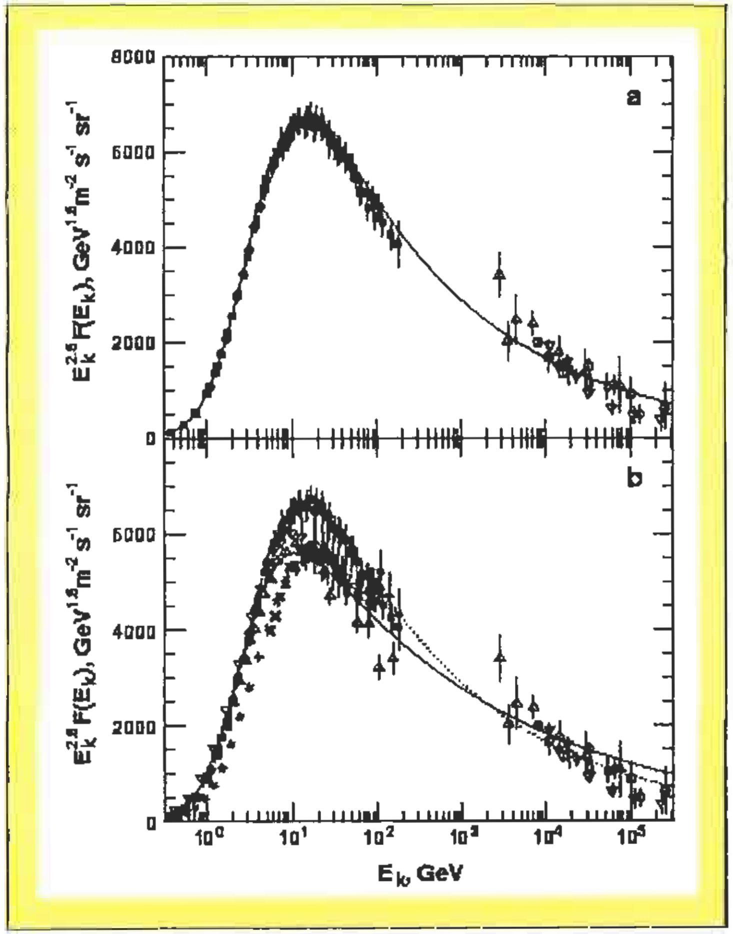


Other important quantities agree well. Note, however, that nue/numu ratio in 3D calculations is slightly higher than in 1D, at least below 10 GeV.

Electron neutrino to antineutrino ratios appear to be very similar, although Bartol's statistics has to be considerable increased to study it in more detail.



Cosmic ray flux: hydrogen

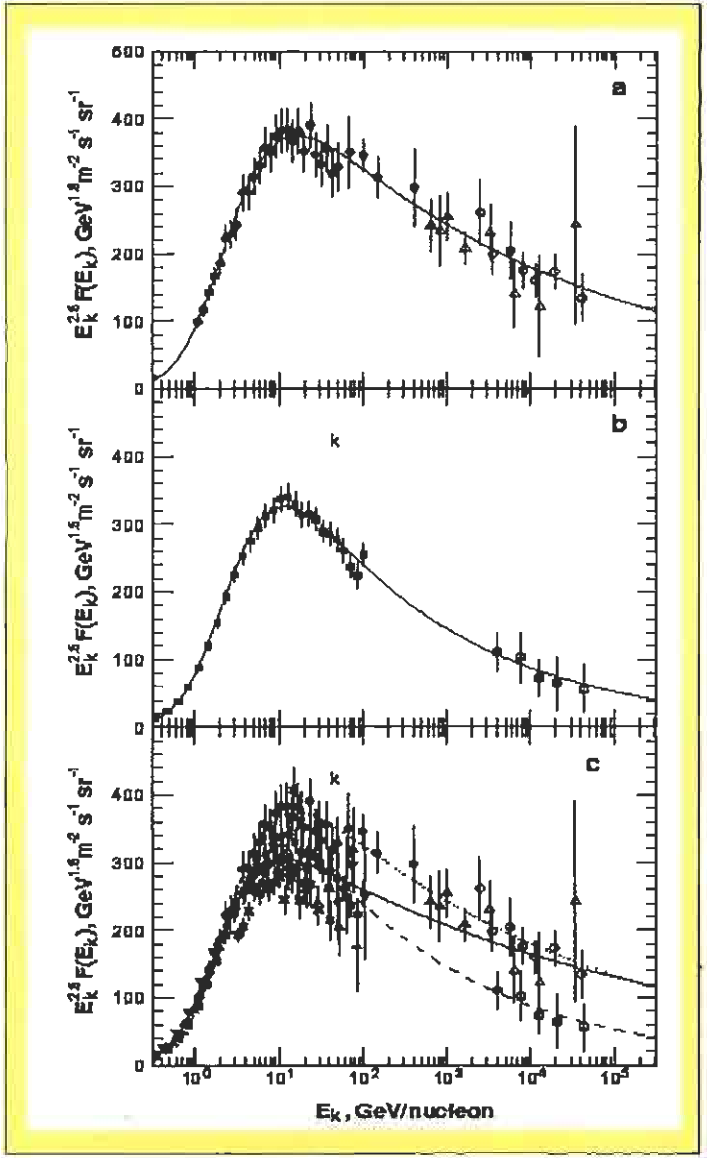


Cosmic ray flux measurements have improved considerably during the recent 10 years (BESS, AMS, Atic, Caprice) but there are still at least two ambiguities:

- fluxes at about 10 GeV are different by about 20% between two groups of measurements: (BESS,AMS) and Caprice.
- the extension of the H (proton) flux to high energy depends on the values at 10 GeV and the TeV measurements of JACEE and Runjob, which are not identical either.

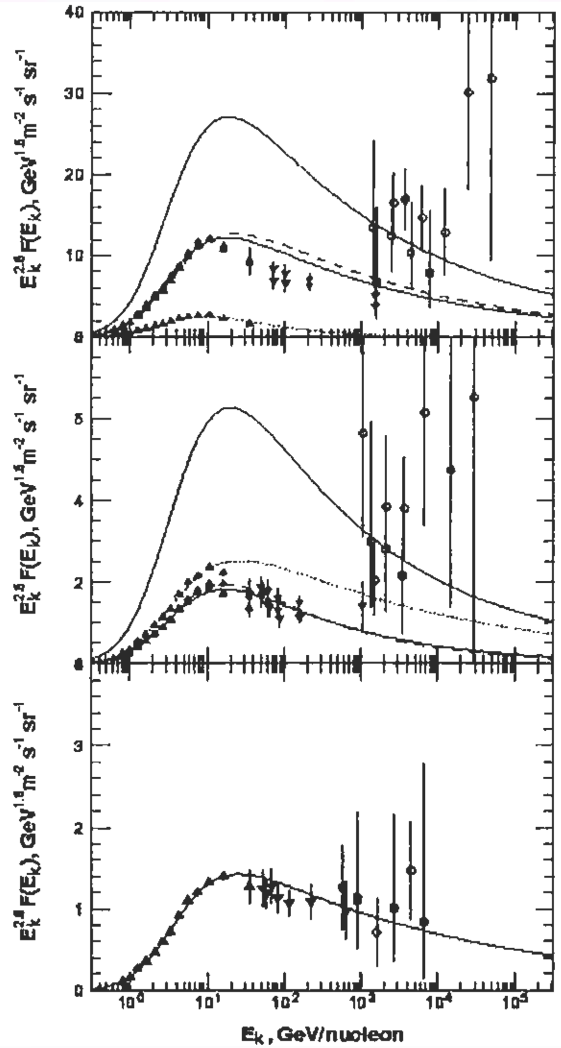
Since the Hydrogen flux dominates in terms of energy/nucleon, the two fits shown cause similar level of uncertainty in the all nucleon flux.

Cosmic ray flux: helium



The situation with the He flux is worse. In the GeV region the difference between the measurements is bigger – even BESS and AMS do not agree. In the TeV range there is a huge disagreement between JACEE and Runjob. Fits using JECEE data generate flat energy spectra with indices of about 2.65. Fits using Runjob generate spectra with indices similar to these of the proton fits – 2.70 to 2.75. Helium is the second most important element and this adds to the uncertainty in the all nucleon flux.

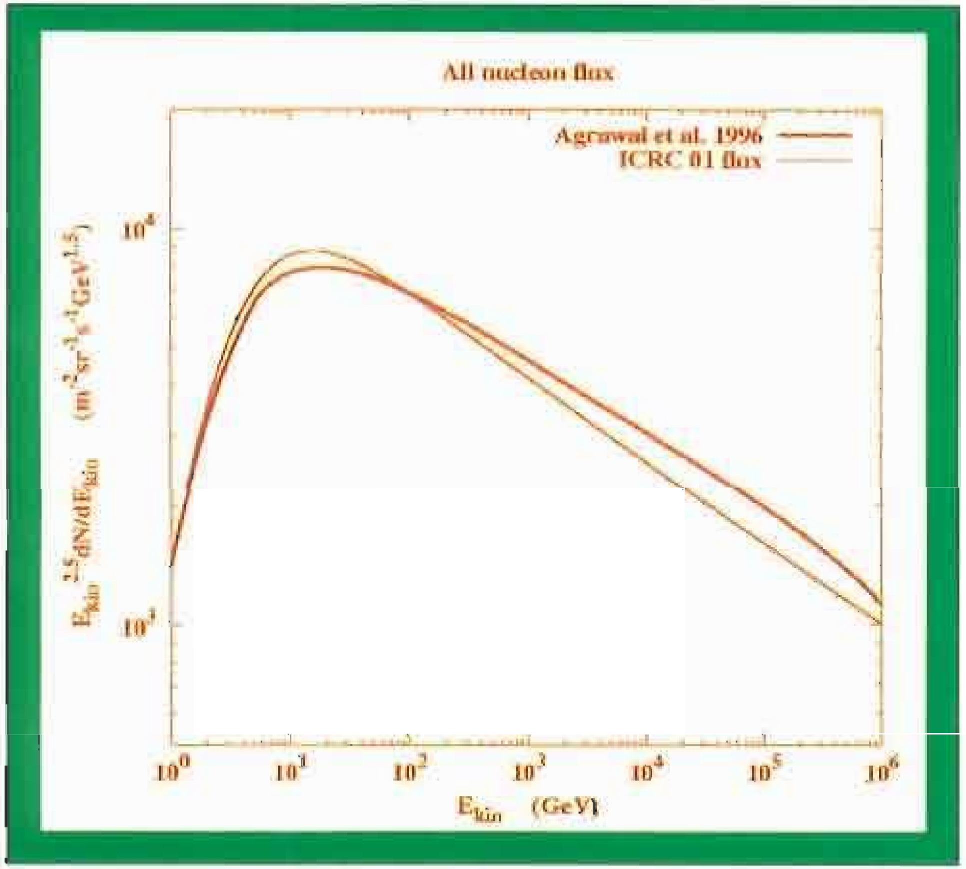
Cosmic ray flux: heavy nuclei



The situation is worst for the heavier elements (CNO, Mg-Si, and Fe from top down) where various TeV measurements show much higher fluxes than expected from the more precise GeV experiments. It is important to note that most GeV measurements give the fluxes of individual elements, while the high energy data are for wide groups of charges.

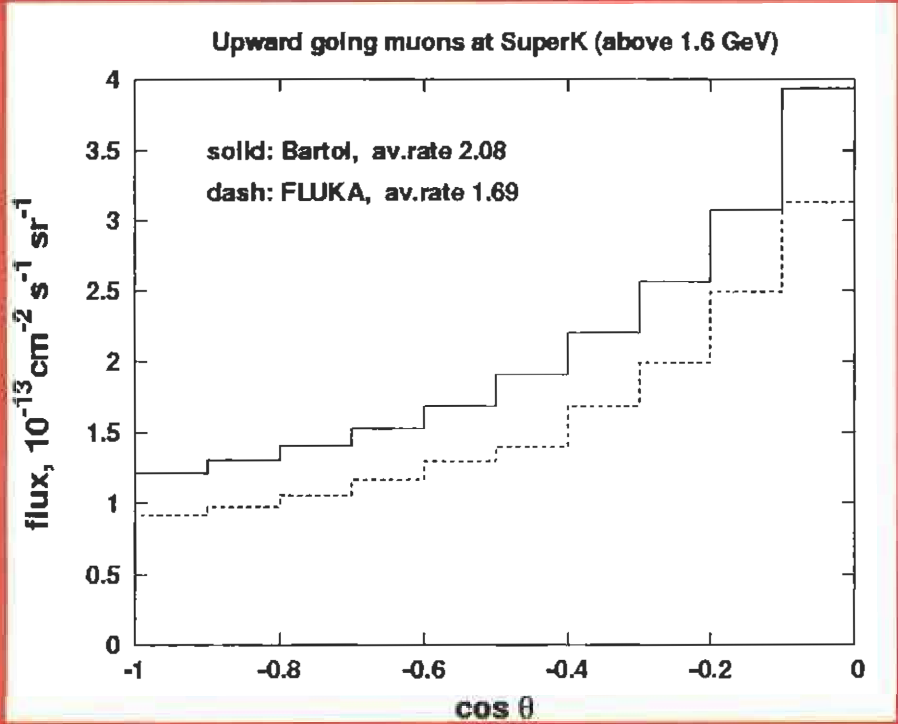
These inconsistencies do no affect drastically the all nucleon flux, but alter the energy dependence of the proton to neutron ratios, thus the neutrino to antineutrino ratio.

Cosmic ray flux: all nucleon flux



As an example for different possible fits we show the all nucleon spectrum used by Agrawal et al (1996) and the fit of Gaisser et al (2001), which uses the high proton fluxes measured by BESS and AMS.
Agrawal et al flux is used in the current version of the Bartol 3D calculation;
2001 flux is used by the FLUKA group. One can immediately recognize the reason for the high FLUKA neutrino flux at about 500 MeV.

What am I afraid of ?



The figure shows the angular distribution of upward going muons of energy above 1.6 GeV at Kamioka. The two histograms have slightly different shape with average rate difference of 20%.

Could it happen that SuperK measures 10% more upgoing neutrino induced muons that are predicted ?

These differences are energy dependent and will also change the stopping/troughgoing ratio.

These differences are due to the combination of steeper flux with lower pion production in FLUKA compared to the Agrawal et al flux and TARGET 2.1.

HOPES for better future.

There are at least two new data sets that are bound to improve the extension of the cosmic ray flux models: BESS-TeV and ATIC. These experiments cover the very important reagion between 100 GeV and TeV using different technique.

HARP, NA48 at CERN, as well as the corresponding Fermilab experiments, will produce high quality data on hadron interactions with light nuclei in the range from 2 to 200 GeV. This will hopefully decrease significantly the uncertainty in the hadronic interaction models.

The final solution of the oscillation parameters may take more time than we hope for.