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Uncertainty Estimates for Atmospheric Neutrino Fluxes

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Abstract: Starting from a survey of experimental measurements, we assign uncertainties to the two most critical inputs to the calculation of fluxes of unoscillated atmospheric neutrinos, the hadron production and the primary cosmic ray fluxes. We then propagate these uncertainties through the entire flux calculation to arrive at estimates of the uncertainties in the fluxes of neutrinos and of various ratios of neutrino fluxes. We find that there is indeed a significant cancellation of flux uncertainties when these ratios are made. The uncertainties as a function of neutrino energy will be presented.

Introduction

Cosmic ray produced neutrinos have been used to make precise measurements of neutrino oscillation parameters [1]. As the size and quality of these data samples gets better, the challenge of improving the computations of the unoscillated fluxes and the experimental input to them becomes greater. This paper focuses on evaluating the uncertainties in the calculated fluxes, most importantly by assigning uncertainties to accelerator hadron production measurements and the primary cosmic ray flux measurements and propagating them through the neutrino flux calculation.

To obtain the precision to do oscillation studies, the experiments use various ratios of fluxes to reduce the sensitivity of the oscillation analysis to the prediction of the fluxes. This study investigates to what extent uncertainties are reduced by taking ratios and attempts to find the origin of the remaining uncertainties in the flux ratios. More details of this study are given in Ref. [2].

Hadron production uncertainties

Hadron production uncertainties are the most serious source of uncertainties in computing atmospheric neutrino fluxes. Ultimately, measurements would be desirable with: primary energy varying from 2 GeV to the highest energies possible; over the whole secondary particle phase space; with p, n, π and K projectiles and secondaries; on target nuclei of the appropriate A. In practice, the measurements are rather sparse.

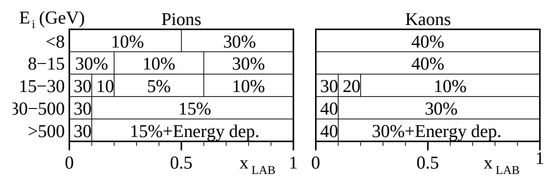

Figure 1: Uncertainty assignments for different phase space regions for $\pi^{\pm}$ and $K^{\pm}$ production.

The uncertainties are incorporated by dividing the phase space for meson production from protons on light-nuclear targets into regions (see figure 1) and assigning an uncertainty to that region based on the experimental errors and/or the degree to which extrapolation from neighbouring regions in x_F, p_T or target type is required [3]. The measurements used to obtain these uncertainties are those which were available at the time the fluxes for the current atmospheric neutrino analyses were made. There are more recent measurements from HARP [4], E910 [5], NA49 [6] and MIPP [7].

The effects of these uncertainties is propagated through the calculation by assigning a weight to

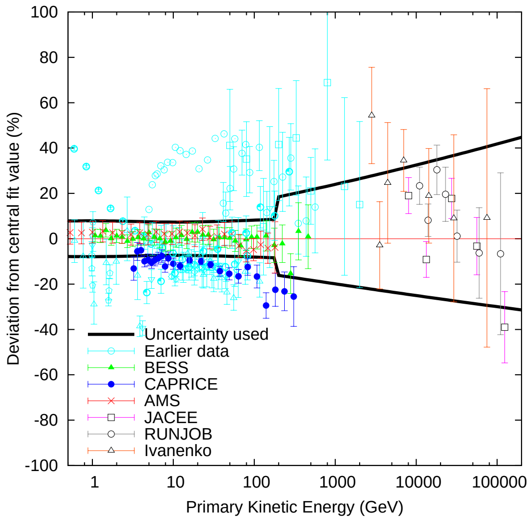

Figure 2: Variation of measured proton fluxes from a fit with equation (1) to show the uncertainties allowed in this study.

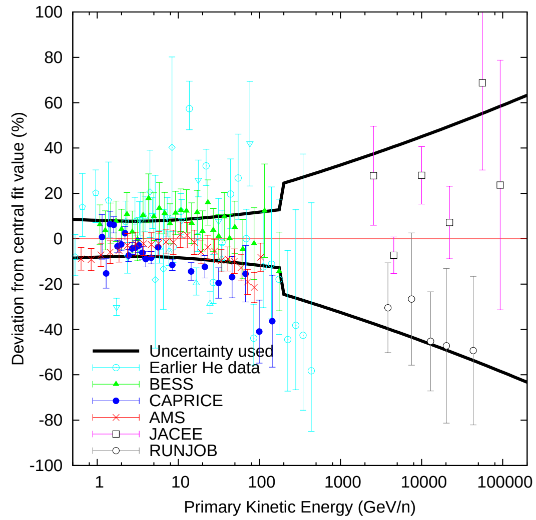

Figure 3: Variation of measured helium fluxes from a fit with equation (1).

each neutrino based on the parent energy, x_F and meson type of the first meson produced in the chain of direct descendants within the shower starting from the primary cosmic ray. The simulation from Ref. [8] is used. The additional uncertainties associated with neutrons being more poorly measured than protons, scattering and multiple interactions (important at high energy) are not included, they are beyond the scope of this study.

Primary flux uncertainties

The flux uncertainties are less complicated to incorporate due to recent high quality measurements. They are incorporated in a similar way to the hadron production by including more variables which can affect the neutrino weight. The uncertainties are obtained using the form of the parameterisation of Gaisser, Honda, Lipari and Stanev [9]

$$\Phi(E_p) = a\left[E_p + b\exp\left(c\sqrt{E_p}\right)\right]^{-d} \qquad (1)$$

as a function of primary energy E_p by assigning ranges by which the parameters a, b, c and d can be adjusted while still covering the measured fluxes. Two separate sets of uncertainties are used for (a) protons and (b) all nuclei. The bands are compared with the measured fluxes in figures 2 and 3.

Results

To investigate how the uncertainties affect the neutrino fluxes and flux ratios, the neutrino weight is used to compute the fluxes with a 1-sigma excursion on each of the variables representing the uncertainties one-by-one. The total changes in fluxes and flux ratios are obtained by combining in quadrature.

Figure 4 gives examples of the uncertainties obtained as a function of neutrino energy. It shows the total uncertainty in the absolute $\nu_\mu + \overline{\nu}_\mu$ fluxes and the ratio of the upward fluxes ($\cos\theta_z < -0.7$) to horizontal fluxes $|\cos\theta_z < 0.3|$ where θ_z is the zenith angle. Figure 4 also shows the breakdown of uncertainties by the variables and a key showing which regions of hadron production phase space correspond to each variable: A–I represent changes in charged pion production and are assumed to affect π^+ and π^- together; Chg represents a 5% allowable difference between π^+ and π^- production applied uniformly over phase space; W–Z represent changes in kaon production, (varied indepen-

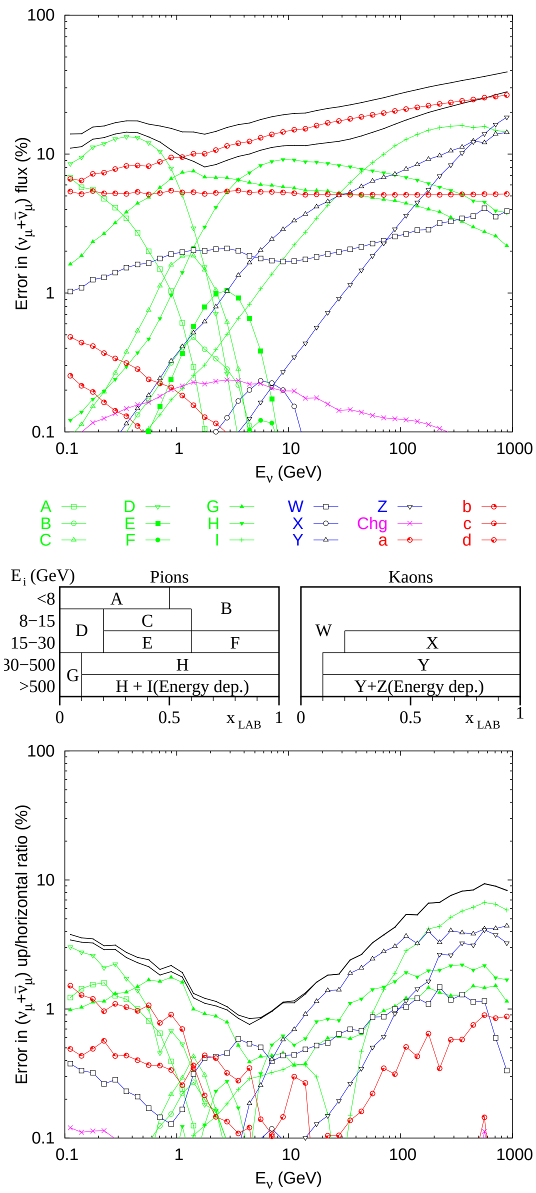

Figure 4: Comparison between the uncertainties in an absolute neutrino flux and a flux ratio (the up-horizontal ratio). The highest line represents the total uncertainty and the lower solid black line the uncertainty due to all hadron production effects only. The lines with symbols give a breakdown of the uncertainties. The key gives the correspondence between the hadron uncertainties and the phase space regions.

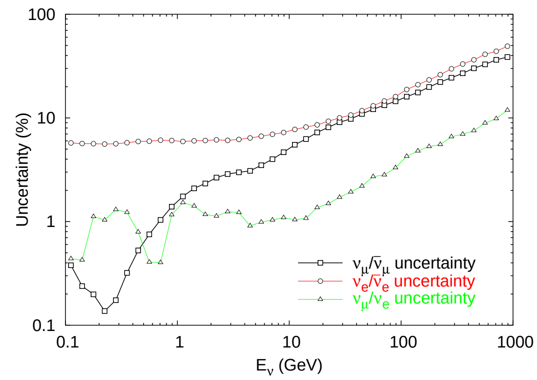

Figure 5: Uncertainty in the neutrino flavour ratios.

dently for K^+ and K^- and combined in quadrature on the figure for each of the four regions); a–d represents the primary flux uncertainties for the parameters in equation (1) (combined in quadrature for protons and nuclei).

The plots show that the uncertainties are at around the 20% level for the absolute fluxes whereas the ratio has an uncertainty in the range between 1% and 10% depending on neutrino energy i.e. there is a considerable reduction in uncertainty by taking a flux ratio. The components which affect the uncertainties are different for the absolute fluxes and the flux ratios indicating that the cancellation in the ratios occurs differently for the uncertainties considered. The components are found to be different again for other ratios (see Ref. [2]). The dominant uncertainty in the absolute fluxes at low energy is region D (low x_F pion production) and at high energy is the primary flux spectral index d whereas in the ratio, the effect of D is still important at low energy, but the cancellation of the spectral index uncertainty d at higher energies is more complete. Kaon production becomes important in the ratio at higher energy.

Figure 5 gives the flux ratios of neutrino flavours and shows that the cancellation of the large uncertainties in the absolute fluxes works here as well. At low energy, where most of the muons decay in the atmosphere, the uncertainty cancellation in the ν_μ/ν_e and $\nu_\mu/\overline{\nu}_\mu$ ratios is very good, since each muon provides neutrinos to both the numerator and denominator of the ratio with roughly equal ener-

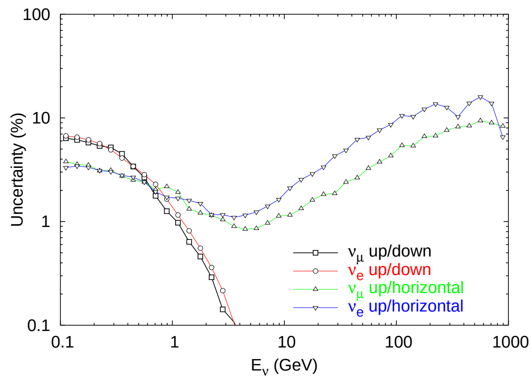

Figure 6: Uncertainties in up/down and up/horizontal ratios.

gies on average. This is not so for the $\nu_e/\overline{\nu}_e$ ratio and the uncertainty at low energies is 5%, reflecting the uncertainty in the ratio of π^+ to π^- production inserted into the study. At higher energies the uncertainties in all three flavour ratios increase because (a) some of the muons hit the Earth and the cancellation described above is less exact and (b) kaon production which is less well measured becomes more important.

The uncertainties in up/down and up/horizontal neutrinos is given for both muon-type and electron-type neutrinos in figure 6. The ratios for the two flavours behave very similarly. At high energy, the uncertainty in up/down ratio cancels completely because the primaries are all above the energy where geomagnetic effects are important and by geometry, the upward and downward directions are equivalent. The up/horizontal uncertainties do not exhibit the same high degree of cancellation because, due to the change in slant depth which affects the altitude where the interactions take place, the meson reinteraction probabilities are higher for vertical cosmic rays than horizontal ones.

Summary

An estimation of the uncertainties in the atmospheric neutrino fluxes has been carried out. Uncertainties were assigned for the interaction within the simulated cosmic ray shower which produces the first meson in the chain between the primary and the neutrino. Primary flux uncertainties are also included. It is shown that the uncertainties which are $> 20\%$ for absolute fluxes are reduced when taking flux ratios. The components of the uncertainties cancel to different extents in the ratios of the fluxes. The effects of whether the muons hit the Earth's surface, whether the geomagnetic field effects are the same in numerator and denominator of the ratio and the local atmospheric density where the meson decays or interacts all play a role in determining how well the flux uncertainties cancel.

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