Systematic uncertainties in the prediction of the atmospheric ν fluxes

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This contribution is a critical discussion of the systematic uncertainties in the calculation of the atmospheric neutrino event rates, and on their effect in the interpretation of the data.

1. Introduction

The data on atmospheric neutrinos [1] show strong evidence of the existence of new physics beyond the standard model, that reveal its existence with the "disappearance" of ν_μ and $\overline{\nu}_\mu$ that travel sufficiently long distances. This result is essentially independent from the details of a calculation of the fluxes, since it can be deduced from the observation of a suppression of the rates of μ–like compared to e–like events and of up–going compared to down–going ones. These ratios can be predicted in the "standard model" on the basis of very simple considerations, with an uncertainty much smaller that the detected effects. However to establish the exact nature of the physics involved, (and to determine the parameters that describe this physics) one needs to compare the data with a calculation, and then systematic uncertainties in the prediction play a more important role. Several elements enter a "standard model" calculation of the atmospheric ν rates: the primary cosmic ray (c.r.) fluxes, geomagnetic effects, the hadronic cross sections, the model for c.r. shower development, and the ν cross sections (we do not consider here the detector acceptance and efficiency).

2. The Primary Cosmic Ray spectra

The description of the primary c.r. spectrum has been until recently a major source of uncertainty. The situation has improved dramatically with new more precise data of the Caprice [2], AMS [3] and BESS [4] experiments. For energy below $E_0 \sim 200$ GeV/nucleon the fluxes are now known with an accuracy $\sim$ 5–10%. For larger energies, that are relevant relevant for the calculation of up–going μ fluxes, the uncertainties are still important.

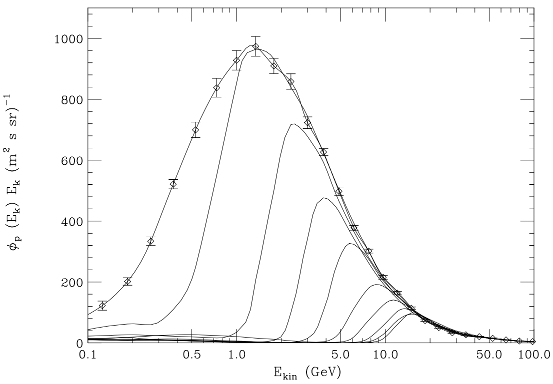

Figure 1. AMS measurements of the vertical p c.r. flux in different regions of magnetic latude. (points and error bars are shown only for the highest latitude measurement.

The AMS detector has also measured essentially simultaneously the cosmic ray fluxes at different positions over the Earth surface, allowing a quantitatively confirmation of the algorithms used for the description of the geomagnetic effects. According to these algorithms for large rigidity the fluxes of the primary c.r. are equal for all positions on the surface of the Earth, while the flux of lower rigidity particle is suppressed near the geomagnetic equator. The isotropy of the c.r. fluxes, together with the assumption of spherical symmetry insures that the ν fluxes are up–down symmetric. The geomagnetic suppression of the low rigidity primary c.r.fluxes is at the orgin of a small ν up–down asymmetry that must be taken into account. For SK this "geomagnetic asymmetry" has *opposite* sign with respect to the detected one; for Soudan it has the same sign.

An interesting result of AMS has also been the measurement of fluxes of sub–cutoff particles generated in the atmosphere and trapped for up to several seconds in near Earth's orbits. These particles give a negligible contribution ($\ll 1\%$) to the atmospheric ν rates.

3. Hadronic Interactions

The modeling of hadronic interactions is also important for the calculation of the ν fluxes [5]. The main effect appears to be in the absolute normalization of the calculated fluxes. This is a reflection of the approximate Feynman scaling of the inclusive cross sections for particle production above $\sim$ 10 GeV of primary energy. At lower energy the difference between different models is perhaps even larger. This has some important consequences for the estimate of the "geomagnetic" up/down asymmetry, since the difference between the "up" and "down" primary fluxes is convoluted with a ν yield that depends on the hadronic interaction model. This is illustrated in fig. 2 for two models of the hadronic interactions. As an example the up/down asymmetry observed by Soudan, when interpreted with the Bartol model is attributed entirely to the geomagnetic contribution, while interpreted with Fluka should be considered in part as generated by oscillations, and accordingly the estimated value of Δm^2 would be smaller.

In the near future we can expect some progress, thanks to the new HARP [8] experiment currently taking data at CERN.

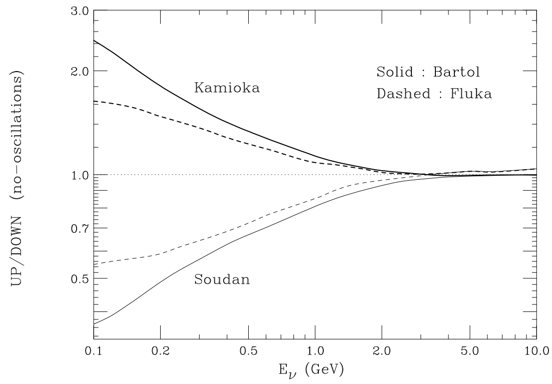

Figure 2. Predictions for the no–oscillation up/down ratio for ν (no smearing) with the Bartol [6] and Fluka [7] models. Note that the sign of the asymmetry depends on the detector location.

4. Three–dimensional effects

The first generation calculations of the atmospheric ν fluxes have used the so called "1D" approximation, that is the ν's are considered as exactly collinear with the primary particle. This was motivated by a fundamental inefficiency of a montecarlo calculation of the fluxes since all showers, reaching any point on the Earth, can contribute to the flux at any given point. The 1D approximation has been recently found insufficient. In fact 3D calculations that take into account the angle $\theta_{0\nu}$ between ν and primary particle predict an enhancement of the ν flux on the horizontal plane. This enhancement, that is most important for large $\langle\theta_{0\nu}\rangle$ (small E_ν), can be understood as a simple geometrical effect [7,9]. The enhancement is difficult to observe directly because of the poor experimental angular resolution of the existing detectors, however since it implies a different pathlength distribution for the ν's, and it can in principle have non–trivial consequences for the interpretation. Preliminary analysis of SK suggest that inclusion of the 3D effects results in small variations in the allowed region in parameter space [1].

The importance of the 3D effects can be observed in an analysis of the azimuth distributions of atmospheric events. These distributions (in contrast to the zenith angle ones) do not give information about oscillations (or other forms of new physics), but allow a test the calculation independently from the presence of new physics. The azimuth distributions show an excess of east–

going over west–going particles. This reflects the geomagnetic effects on the primary radiation, however also the bending of the muons in the geomagnetic field (neglected in a 1D calculation) introduces significant corrections to the size of the asymmetry. This can be understood observing that positively (negatively) charged particles are bent upward (down–ward) and viceversa for west–going particles. Since $\mu^+ \to \nu_e \overline{\nu}_\mu$, $\mu^- \to \overline{\nu}_e \nu_\mu$, and $\sigma_\nu > \sigma_{\overline{\nu}}$, the net effect is an enhancement (suppression) of the asymmetry for e–like (μ–like) events [10] in better agreement with the data [11].

5. The ν fluxes at high energy

The fluxes of atmospheric ν's at high energy can be studied using "up–going" μ–events. These measurements are valuable because give information about the ν_μ survival probability for large E_ν. This is important for the discrimination between the oscillation hypothesis and alternative mechanisms (FCNC, ν decay, violations of the equivalence principle) that are characterized by different energy dependences of the probability, and the discrimination between the $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{\rm sterile}$ hypothesis, since in the first case the transition probability is suppressed by the matter effects that grow in importance $\propto E_\nu$.

The key observable for this study is the shape of the muons angular distribution, that is significanly distorted is the standard oscillation scenario, and less so in the other models. A critical question is the uncertainty in the calculation of the "standard model" shape. The vertical/horizontal ratio is larger than unity since, for simple geometrical reasons, inclined mesons and muons decay more easily than vertical ones The main sources of uncertainty on the shape of the distribution are the energy spectrum of the primary radiation, and the K/π ratio. A quantitative analysis indicates that the prediction of the shape is robust. After integration over half hemispheres, the vertical/horizontal ratio has a systematic uncertainty:

$$\frac{\delta(V/H)}{(V/H)_0} \simeq 0.25\ \delta\alpha \oplus 0.12\ \frac{\delta(K/\pi)}{(K/\pi)_0} \simeq 3.3\% \qquad (1)$$

where the first contribution arises from the error on the slope α of the primary flux, and the second from the K/π ratio. For the final analysis the two terms have been combined quadratically, estimating a 25% systematic uncertainty for K/π and $\delta\alpha \simeq 0.05$.

6. Summary

The main lessons of critical studies of the uncertainties on the atmospheric ν fluxes performed by several groups, has been the confirmation that the evidence for new physics in the data is robust. For the two–flavor oscillation scenario, that is the simplest and probably most successful explanation of the data, no large theoretical bias in the parameter dermination has been found. The uncertainty of $\sin^2 2\theta$ is currently controled by the measurements of the up/down asymmetry of the SK multi–GeV μ–like events and is dominated by statistical errors. Theoretical (and experimental) systematic uncertainties play a more important role in determining the extension (and exact position) of the allowed interval for Δm^2.

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