High energy extension of the FLUKA atmospheric neutrino flux

G. Battistoni[1], A. Ferrari[2], T Montaruli[3] and P.R. Sala[4]
(1) INFN, Sezione di Milano, 20133 Milano, Italy
(2) CERN, Geneva 23, Switzerland, on leave of absence from INFN Milano
(3) University of Bari and INFN, 70126 Bari, Italy
(4) ETH Zurich, Switzerland, on leave of absence from INFN Milano

Abstract

The atmospheric neutrino flux calculated with FLUKA was originally limited to 100÷200 GeV for statistical reasons. In order to make it available for the analysis of high energy events, like upward through-going muons detected by ν telescopes, we have extended the calculation so to provide a reliable neutrino yield per primary nucleon up to about 10^6 GeV/nucleon, as far as the interaction model is concerned. We point out that the primary flux model above 100 GeV/nucleon still contributes with an important systematic error to the ν flux.

1. Introduction

The main motivation of FLUKA[6] calculation of atmospheric neutrino flux is the attempt to minimize as much as possible the theoretical uncertainties connected to the shower and hadronic interaction models. The high accuracy of the algorithms adopted in FLUKA and the wide set of experimental data used to benchmark its hadronic and electro-magnetic interaction models have already allowed the use of this simulation models in many applications where the maximum available precision is requested. FLUKA has been successfully used also in cosmic ray physics. For this reason it is also going to be adopted as an option in the CORSIKA code, at least for interactions below 80 GeV[9]. Our results concerning the atmospheric neutrino flux calculations have been presented in [5]. There, the other important factors contributing to the systematic uncertainties which are not connected to the FLUKA code, are the atmosphere description, the accuracy of the geomagnetic model, and, as the most important contribute, the knowledge of the primary flux.

The practical problems arising from our approach is that the demand of computer power for very high energy showers may be very large. This is the reason why so far we have presented calculation results only up to about 100 GeV (useful for the analysis of contained events) due to insufficient statistics at higher energy. The low energy sector was also considered less affected by the uncertainty

pp. 1399–1402

in the primary flux thanks to the high accuracy data from AMS [2] and BESS [12]. This statistical limitation in energy has however prevented the use of FLUKA results for a complete analysis of atmospheric neutrinos, including through–going muons produced by neutrinos with mean energies 50–100 GeV. It has been already shown how this requires the knowledge of neutrino flux up to at least 10^4 GeV. In the high energy sector the existing available calculations are those coming mostly from faster approaches, like those of Bartol[1] and HKKM[10]. Also the new recent HKKM calculation[11] (HKKM2001) stops in practice at about 1 TeV and makes use of extrapolations and/or simplifications.

In order to overcome this limitations, we have performed an extensive simulation run so to extend the FLUKA calculation of atmospheric neutrino fluxes up to 10^4 GeV. This has been done in such a way to consider different possible primary spectra. Results are presented in this paper.

2. The Calculation Model

We have used the same calculation set-up reported in [6], where also some details about the physical model are reported. Here the different strategy is to generate neutrinos avoiding the sampling from a unique primary all-nucleon spectrum and instead prepare parallel simulation runs for many different small energy intervals, summing together the results with a proper weighting scheme so to reproduce any desired input spectrum. In this way we could obtain a statistical uncertainty almost independent on energy. We started from few tens of GeV of primary energy and in order to achieve reliable results at a maximum neutrino energy of 10^4 GeV, we have pushed the maximum nucleon energy up to 10^6 GeV. The relatively high energy allowed some simplification, avoiding the question of solar modulation and geomagnetic cutoff. Furthermore, the angular distribution for non oscillated flux has been recorded in 10 bins in a single hemisphere.

3. Results and Discussion

We have chosen two different primary all-nucleon spectra to present and compare the calculation results. The first one is the 2001 Bartol fit of ref.[8] taking into account the most recent direct measurements, and that was used as reference in our last work[5]. The second one is the previous Bartol fit to all-nucleon flux of ref.[1], which was already used by us for the first (before 2001) FLUKA calculations. The updated flux tables, obtained using the 2001 Bartol fit, are available from our web site [7]. In Fig. 1 we show the angle integrated flux for muon ν and $\overline{\nu}$ for the two primary spectra. It is evident that in the high energy sector the choice between the two different options for the primary all-nucleon spectrum has a large impact. In order to give a quantitative figure of this statement in Fig. 1 we also show, as a function of neutrino energy, the ratio

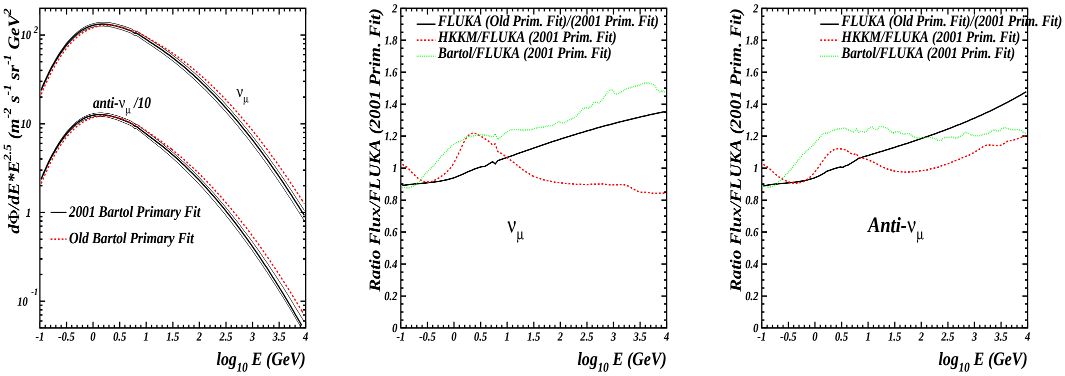

Fig. 1. *Left*: angle integrated (and without oscillations) atmospheric ν_μ and $\bar{\nu}_\mu$ FLUKA fluxes for the 2 choices of primary spectrum considered here, weighted by $E^{2.5}$. *Center*: ν_μ flux ratio vs. energy with respect to the FLUKA + 2001 primary fit of: 1) the FLUKA+Old Bartol primary fit (solid line), Bartol flux (dotted green line) and HKKM2001 flux (dashed red line). *Right*: the same for $\bar{\nu}_\mu$. *Right*: the same for $\bar{\nu}_\mu$.

of the flux calculated using the old Bartol fit with respect to the one obtained with the 2001 fit (solid line) for ν_μ and $\bar{\nu}_\mu$. In the same plots we also show the ratio of the Bartol and HKKM2001 flux with respect to FLUKA with the 2001 primary fit.

The difference introduced by using the 2 primary spectra evidently results from a different weight given to the high energy primary measurements. The highest energy point in the recent high precision experimental measurements from AMS and BESS is at 100 GeV. Higher energy points in the TeV region (essentially from JACEE[4] and RUNJOB[3]) have much larger error bars. There are indeed suspicions that the multi–TeV proton component could be underestimated in the 2001 fit. Assuming to consider the 100 GeV point as a pivot from which a simple power law spectrum ($E^{-\gamma}$) is used to extrapolate to the high energy region, we obtain the results shown in Fig. 2, by varying the spectral index γ from 2.6 to 3.0. We also show the flux ratios.

4. Conclusions

The FLUKA atmospheric neutrino spectrum calculation has been extended up to 10^4 GeV, so that it can be used for the analysis of upward going muon experiments. Above 1 TeV, the uncertainty in the primary flux seems to be the most important contribution: it may exceed 20%. In principle this has no impact on the essential feature of experimental analysis, namely the deformation of the angular distribution of upward going muons as induced by oscillations. How-

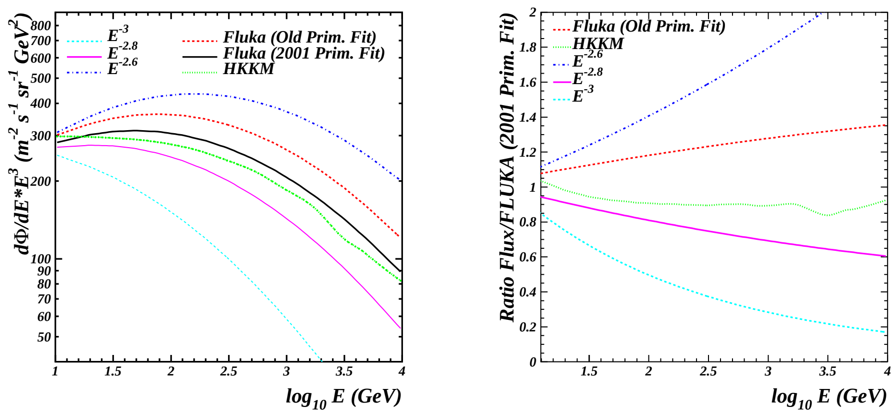

Fig. 2. *Left*: Angle averaged ν_μ FLUKA fluxes weighted by E^3, including also the case of simple power law primary spectra with different spectral indexes, ranging from 2.6 (upper curve) to 3.0 (lower curve). The HKKM2001 flux is also shown. *Right*: ratios of the different cases with respect to the present FLUKA result.

ever, also the absolute normalization has some importance, at least to achieve a better internal consistency. As a first guess, considering the event rate of upward–going muons observed by MACRO and Super–Kamiokande, the results that we obtain using the 2001 Bartol fit seems to exhibit a too low normalization (of the order of 15÷20 %, if we include oscillations), although this has to be confirmed by detailed analysis performed by the experimental collaborations. Within the statistical uncertainty of the 2001 primary fit, our results are very close to those of the HKKM2001 calculation. A less steep primary spectrum at high energy, as that of ref.[1], would probably provide a better absolute normalization.

5. References

1. Agrawal V. et al., 1996, Phys. Rev. D53, 1314
2. Alcaraz J. et al. (AMS Collaboration) 2000, Phys. Lett. B490, 27
3. Apanasenko A.V. et al. (RUNJOB Coll.), 2001, Astrop. Phys. 16, 13
4. Asakimori K. et al. (JACEE Coll.), 1998, Ap.J. 502, 278
5. Battistoni G. et al., 2003, Astrop. Phys. 19, 269
6. Fassò A. et al., full reference list available in http://www.fluka.org
7. FLUKA neutrino flux web page: http://www.mi.infn.it/~battist/neutrino.html
8. Gaisser T.K. et al, 2001, Proc. of the 27th ICRC
9. Heck D. et al, 2003, These proceedings
10. Honda M. et al., 1995, Phys. Rev. D52, 4985
11. Honda M. et al., 2001 Phys. Rev. D64, 053001 and private communication
12. Sanuki T. et al, 2001, Ap. J. 545, 1135