ELSEVIER

Nuclear Physics B (Proc. Suppl.) 70 (1999) 358–360

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

A new calculation of atmospheric neutrino flux: the FLUKA approach

G. Battistoni[a], C. Bloise[b], D. Cavalli[a], A. Ferrari[a], T. Montaruli[c], T. Rancati[a], S. Resconi[a], F. Ronga[b], P.R. Sala[a]

[a]INFN and Università di Milano, Dipartimento di Fisica, Milano, 20133, Italy

[b]Laboratori Nazionali dell'INFN, Frascati (Roma), 00044, Italy

[c]Università di Bari and INFN, Dipartimento di Fisica Bari, 70126, Italy

Preliminary results from a full 3–D calculation of atmospheric neutrino fluxes using the FLUKA interaction model are presented and compared to previous existing calculations. This effort is motivated mainly by the 3–D capability and the satisfactory degree of accuracy of the hadron–nucleus models embedded in the FLUKA code. Here we show examples of benchmarking tests of the model with cosmic ray experiment results. A comparison of our calculation of the atmospheric neutrino flux with that of the Bartol group, for $E_\nu > 1$ GeV, is presented.

1. Introduction

Atmospheric neutrino flux calculations are affected by the following main sources of uncertainties: knowledge of primary cosmic spectra, their solar modulation and geomagnetic field effects, which are relevant for $E_\nu \leq 10$ GeV; hadronic interaction models and their consequences in the calculation of secondary particle production in the atmosphere.

The FLUKA Monte Carlo code [1] contains very detailed models of hadron–hadron and hadron–nucleus interactions, covering the range from the MeV scale to the many–TeV one and extensive benchmarking against experimental data has been produced. Moreover, so far there is no full 3–D atmospheric neutrino calculation performed with a refined interaction model. Although no fundamental change is expected from this new calculation, the improvement in the quality and precision of predictions would be significant for future generation experiments as, for instance, Icarus at Gran Sasso[2].

2. The interaction model

Different hadronic interaction models are used in FLUKA according to the energy range. In its actual configuration, for incident particle energy below 3 GeV a cascade pre–equilibrium model (PEANUT) is used. Between 3 and 4 GeV, inelastic hadron–hadron collisions are treated according to HADRIN model [3], with a parameterized intranuclear cascade. For energies > 5 GeV, interactions are simulated according to a refined version of the Dual Parton Model [4].

3. Calculation set–up

The main ingredients of the atmospheric shower calculation are: the primary spectra, which are obtained from a NASA code[5] and the superposition model for primary nuclei; the interplanetary modulation according to the actual solar activity for a given day; the vertical rigidities from a NASA compilation interpolated in the Störmer dipole approximation. The superposition model and the treatment of the geomagnetic cutoff will be improved in the next future. The atmosphere (as a proper mixture of N, O and Ar) has been divided in 50 layers of different density, according to a parameterization of the standard atmosphere, down to ~ 0.1 g/cm^2 (~ 70 *km* a.s.l.). Primaries can be injected either at the top of the atmosphere, using an *a priori* geomagnetic modulated spectrum, or at a distance of several Earth radii. The fluxes of various secondary particles can be scored at different heights in the atmosphere and at different geomagnetic locations. This allows us to benchmark

PII S0920-5632(98)00451-4

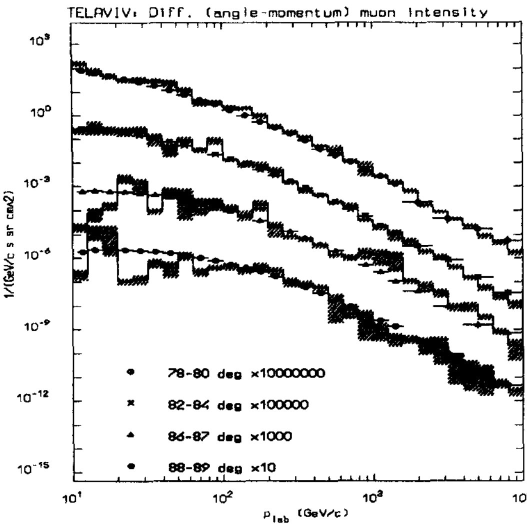

Figure 1. Comparison of FLUKA calculation (histogram) of double differential muon fluxes as a function of momentum and zenith angle at sea level, with the data collected by DEIS[6] (circles). Only a few angular bins are shown for clarity.

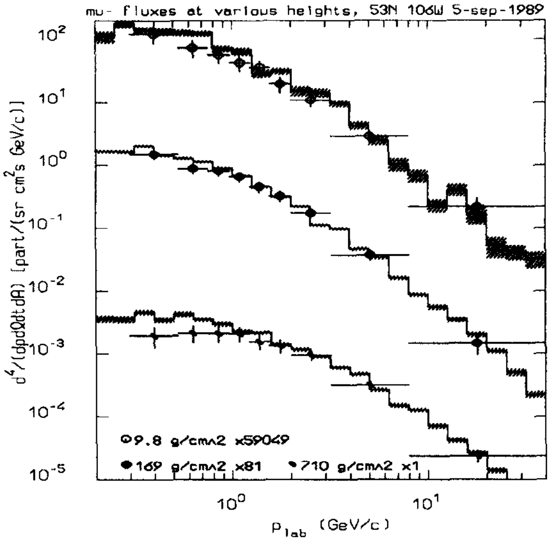

Figure 2. Comparison of negative muon fluxes at different heights in the atmosphere between MASS data (circles) [7] measurement and our calculations (histogram) Only 3 data sets are shown for clarity.

our model with respect to the existing data on the detection of charged and neutral particle in atmosphere. Of particular interest are the data on atmospheric muons. As an example, we show in Fig. 1 part of the comparison of FLUKA calculation with the double differential muon fluxes measured by the DEIS spectrometer[6], at sea level, near the horizontal direction. A further important comparison is that with the negative muon flux measurements at various heights in the atmosphere performed by the MASS experiment[7]. In Fig.2 we show the result of this comparison at three heights (9.8, 169 and 710 g/cm^2), with different scale factors. Extensive benchmarking will give the clue to a proper evaluation of the systematic error in the prediction of ν flux.

4. The ν spectrum

We have performed a direct comparison (for $E_\nu \geq 1$ GeV) of the FLUKA results concerning the neutrino fluxes with an existing and widely used calculation by the Bartol group[8]. They have performed a 1–D Monte Carlo simulation using the TARGET interaction model. This is mainly a parameterization of accelerator data for hadron–nucleus collisions. We have compared secondary hadron multiplicity and their x_F distributions as predicted by the two models in proton-Air collisions. TARGET and FLUKA provide similar results for pions, but there are noticeable differences on K production. In particular, TARGET predicts a strong enhancement of K^+ production in the forward region, while a relative depletion in the same kinematic region appears for K^-. This is relevant for the $\nu_\mu/\bar{\nu}_\mu$ at high energy. The FLUKA predictions at high x_F, for light nuclear targets, seem to give a reasonable account of the data taken by the NA56/SPY experiment[9].

For the flux comparison, the same primary input spectrum of Bartol has been used[10]. In Fig. 3 the muon and electron neutrino fluxes averaged over the solid angle are compared to Agrawal et al.[8]. The results of HKHM [11] are shown as well, although they use a different input primary spectrum. The main difference among the three calculations is in the $E_\nu < 10$ GeV region. Our

Table 1
FLUKA/BARTOL ratios of the muon and electron ν fluxes , of $\bar{\nu}/\nu$, and of ν_e/ν_μ for $\cos\theta$=1.

$\nu_\mu + \bar{\nu}_\mu$			$\nu_e + \bar{\nu}_e$			$\bar{\nu}_\mu/\nu_\mu$	$\bar{\nu}_e/\nu_e$	$\frac{\nu_e+\frac{1}{3}\bar{\nu}_e}{\nu_\mu+\frac{1}{3}\bar{\nu}_\mu}$
0.4-1 *GeV*	1-2 *GeV*	2-3 *GeV*	0.4-1 *GeV*	1-2 *GeV*	2-3 *GeV*	$0.4 \leq E_\nu \leq 1$ *GeV*		
0.86	0.84	0.89	0.83	0.80	0.84	1.02	0.94	0.98

result predicts an harder spectrum and a lower total neutrino flux in that region. The comparison of some significant numbers is given in Tab. 1 for the vertical direction ($cos\theta = 1$). At present we are investigating the precise origin of this difference. At energies exceeding a few GeV we do not expect significative differences deriving from a 3–D calculation.

REFERENCES

1. A. Fassò, A. Ferrari, J. Ranft and P.R. Sala, Proc. of the *3rd Workshop on Simulating Accelerator Radiation Environment, SARE-3*, KEK-Tsukuba, May 7–9 1997, H. Hirayama ed., KEK report 97-5, p. 32 (1997); A. Ferrari and P. R. Sala, Proc. of the *Workshop on Nuclear Reaction Data and Nuclear Reactors Physics, Design and Safety*, ICTP, Trieste, Italy, 15 April – 17 May 1996, in press.
2. P. Cennini et al. (ICARUS coll.) ICARUS II, Experiment proposal Vol. I & II, LNGS-94/99-I&II
3. K. Hänssgen and J. Ranft, Comp. Phys. Commun. **39** (1986) 37.
4. A. Capella et al., Phys. Rev. Lett. **58** (1987) 2015.
5. HIZ, (O'Neill, 1996), private communication by L. Pinsky, Houston University.
6. O.C. Allkofer, et al., Nucl. Phys. B 259, 1985, 1-18.
7. R. Bellotti et al., Phys. Rev **D53** (1996) 35.
8. V. Agrawal et al., Phys. Rev. **D53** (1996) 1314.
9. NA56/SPY, talk By R. Arsenescu at TAUP97, these proceedings.
10. private communication by T. Stanev.
11. M. Honda et al., Phys. Rev. **D52** (1995) 4985.

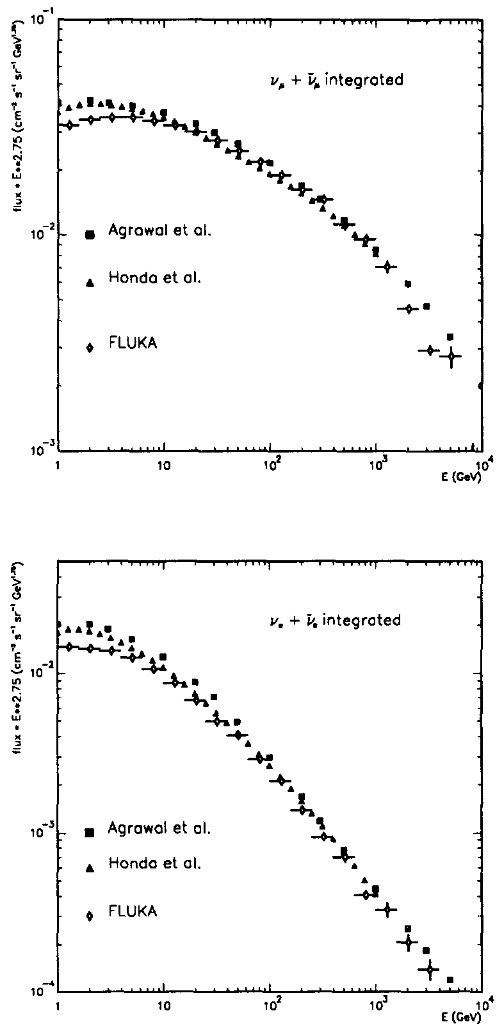

Figure 3. Muon and electron neutrino fluxes $\times E^{2.75}$ averaged over solid angle from the present calculation compared to Bartol[8] and to HKHM [11] ones.