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Simulation of atmospheric neutrino fluxes with CORSIKA

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Abstract. The simulation program CORSIKA originally designed for the four-dimensional simulation of extensive air showers has been modified for the calculation of atmospheric neutrino fluxes. A detailed simulation of the geomagnetic cut-off with GEANT using the International Geomagnetic Reference Field, tables of the geomagnetic field, a description of the solar modulation, an elevation model for the whole Earth, and various atmospheric models for different climatic zones and seasons have been added to standard CORSIKA in order to allow the simulation of low energy primary particles. Different hadronic interaction models are compared on the basis of recent results for the flux and the charge ratio of atmospheric muons. The verified models are used to calculate separately the neutrino fluxes from the lower and upper hemisphere for Super-Kamiokande. The results of CORSIKA confirm the existence of the atmospheric neutrino anomaly.

1 Introduction

The new results of the Super-Kamiokande experiment provide high evidence for the atmospheric neutrino anomaly. Besides the deviation in the integral ratio $R = (\nu_\mu + \overline{\nu_\mu}) / (\nu_e + \overline{\nu_e})$ the dependence of R on the angle of incidence is a convincing proof of the anomaly (Fukuda et al., 1998). After establishing the effect the experiment turns now to a phase of precision measurements in order to identify the oscillation channel (Fukuda et al., 2000) and further effects, like the East-West asymmetry (Futagami et al., 1999). These investigations request the precise knowledge of the theoretical neutrino fluxes. Conventional simulations, done in one-dimensional approximations, neglecting all transversal momenta, the deflection of the charged particles in the atmosphere and most geographical influences, are hardly able to meet the required accuracy.

In this paper CORSIKA (Heck et al., 1998), being originally an air shower simulation code is extended to allow the simulation of low energy primary particles. The results are verified by simulating the fluxes and the charge ratio of atmospheric muons and comparing with experimental results. The results for the fluxes of atmospheric neutrinos at the Super-Kamioka site are compared with the experimental and theoretical results.

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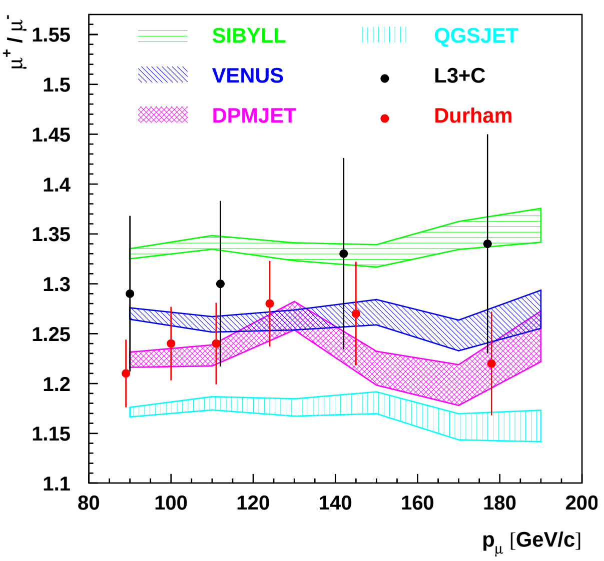

Fig. 1. Simulation of the muon charge ratio at higher energies in comparison with experimental data.

2 CORSIKA and the extensions for the simulation of low energy primary particles

CORSIKA enables fully four-dimensional simulations of extensive air showers. The particle transport includes the particle ranges defined by the life time of the particle and the cross-section with air. Ionization losses, multiple scattering, and the deflection in the local magnetic field are considered. The decay of particles is simulated in exact kinematics, and the muon polarization is taken into account. The difference of CORSIKA from other simulation tools is the optional availability of six different models for the high energy hadronic interaction and of three different models for the low energy hadronic interaction. The threshold between the high and low energy models is set to $E_{Lab} = 80\,\mathrm{GeV/n}$.

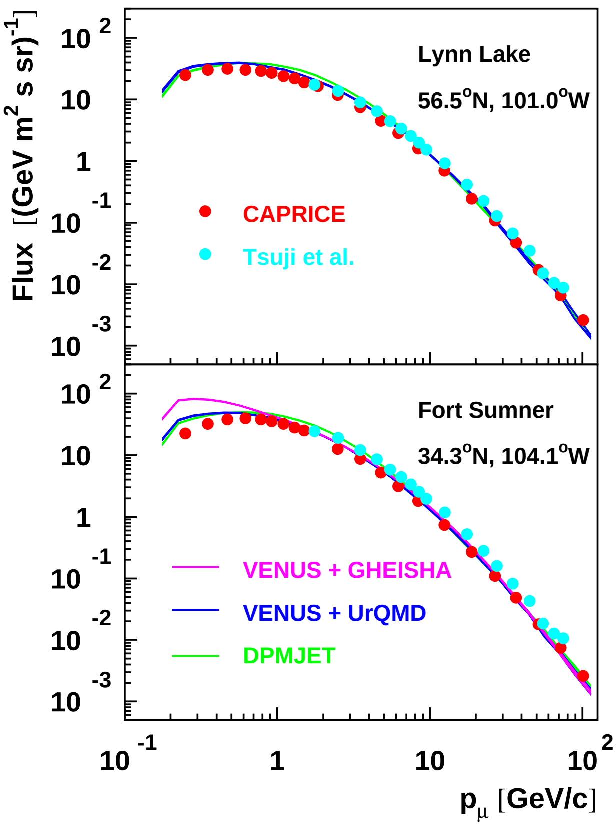

Fig. 2. The differential muon flux compared with experimental results. The results of Tsuji et al. are corrected for the altitude.

In order to simulate primary particles at very low energy, CORSIKA has been extended by a description of the geomagnetic cut-off and the solar modulation. For most places on Earth the geomagnetic cut-off is stronger than the visible influence of the solar modulation. Therefore the geomagnetic cut-off is simulated in a detailed microscopic calculation as described in Wentz et al. (2001) while the solar modulation is handled by the parameterization of Gleeson and Axford (1968).

In order to simulate all possible angles of incidence the “curved” version of CORSIKA is used, where the curvature of the Earth’s atmosphere is approximated by sliding plane atmospheres. The flux, the composition, and the spectrum of the primary cosmic rays are compiled from the recent results of the prototype mission of the AMS experiment (Alcaraz et al., 2000).

The geographical influences for the different places on the Earth are taken into account by various parameter tables. In the computational procedure each primary particle is first randomly distributed over the whole Earth. After the check for the geomagnetic cut-off the correct atmospheric model for the geographical latitude and season, the values of the local magnetic field and the elevation over sea-level are set, before the interaction of the particle in the Earth’s atmosphere is calculated. All neutrinos passing the area around Kamioka are selected and used in the further analysis. This complete way of the simulation avoids various error sources in the relative normalization between different simulations for different angles of incidence, different solid angles, etc.

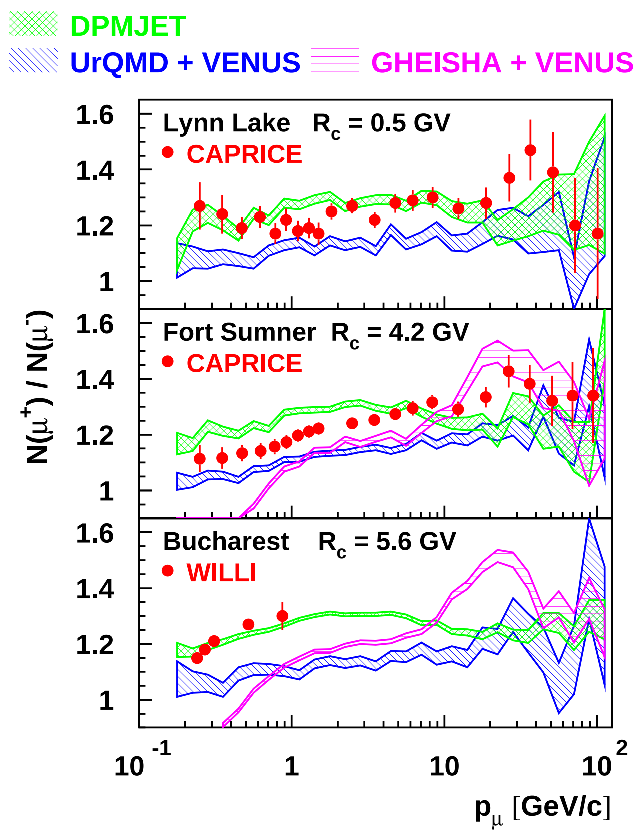

Fig. 3. The charge ratio of muons as simulated by CORSIKA compared with experimental results.

3 Simulation results for atmospheric muons

A verification of the calculation results for neutrino fluxes, and especially for the used interaction models can be done by studying atmospheric muon fluxes. In addition to the total muon flux which is biased by the error in the total primary flux the charge ratio of muons provides an independent test. Fig. 1 shows the results for a simulation of high energy muons with four different high energy interaction models in comparison with experimental data (Fletcher, 1994; Kalmykov et al., 1997; Baxendale et al., 1975; Hebbeker et al., 2000). VENUS (Werner, 1993) and DPMJET 2.5 (Ranft, 1999) agree best with the experimental results and are therefore used in all further simulations.

For the simulation of the low energy hadronic interaction there are three different, selectable models in CORSIKA. Beside GHEISHA (Fesefeldt, 1985) and UrQMD (Bleicher et al., 1999), DPMJET can be used with some modifications, too.

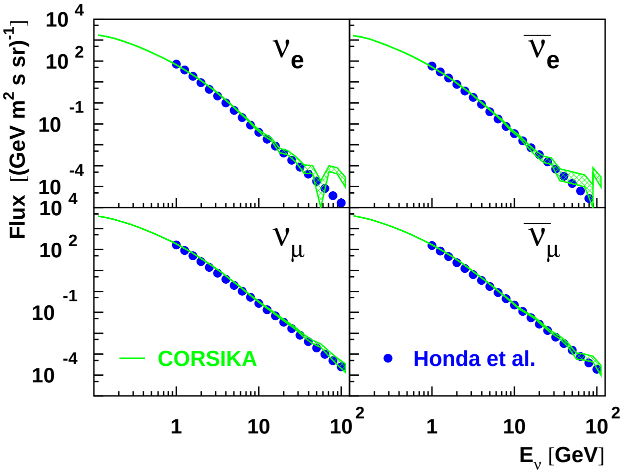

Fig. 4. Vertical neutrino fluxes in Kamioka.

Fig. 2 and Fig. 3 show the differential muon flux and the charge ratio for selected places on Earth where the results can be compared directly with experimental results (Kremer et al., 1999; Tsuji et al., 1998; Vulpescu et al., 2001). While the data for the differential muon flux exclude only GHEISHA as reliable interaction model, the muon charge ratio provides a more decisive test. GHEISHA is again far from reality but also UrQMD gives in all cases a low charge ratio, while the result of DPMJET show a good agreement with the experimental results. The deviation for Fort Sumner has to be questioned because the geomagnetic cut-off in Fort Sumner and Bucharest is nearly equal. Therefore the differences in the experimental values and the continuous increase of the charge ratio in the CAPRICE measurement for Fort Sumner far beyond the geomagnetic cut-off seem to indicate experimental problems in this particular measurement.

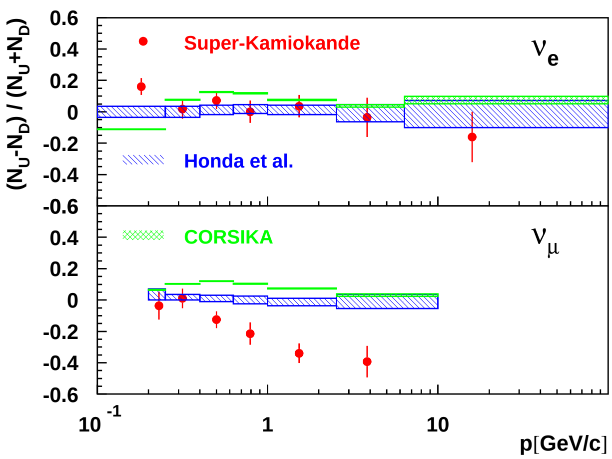

Fig. 5. The up-down asymmetry of the neutrino fluxes in Kamioka. The experimental angular resolution is taken into account.

The influence of the geomagnetic cut-off can be seen in the comparison of the CAPRICE results for Lynn Lake with the WILLI results for Bucharest. The charge ratio of muons is nearly constant unless the geomagnetic cut-off clips the high excess of low energy primary protons, as seen in the results for Bucharest. This effect is nicely reproduced by CORSIKA using DPMJET as interaction model, while using UrQMD the effect is covered by problems of the model.

4 Atmospheric neutrino fluxes for Kamioka

CORSIKA with DPMJET including the described extensions has been used to simulate the atmospheric neutrino fluxes for Kamioka. Fig. 4 shows the results for the vertical neutrino fluxes in comparison with the calculation results of Honda et al. (1995). The agreement in the spectral shape and the absolute normalization is impressingly good.

For the further comparisons of the simulations with the experimental results of Super-Kamiokande, the CORSIKA results have been processed further with a straight forward geometrical simulation of the detector. The scattering angle between the neutrino and the detected charged lepton and the corresponding energy difference are taken into account. The cylindrical shape of the detector and the ranges of muons are used to discriminate between the fully and partially contained events. The data are weighted for the linear increase of the neutrino cross-sections, but data are normalized in absolute scale to the Honda simulations, where necessary.

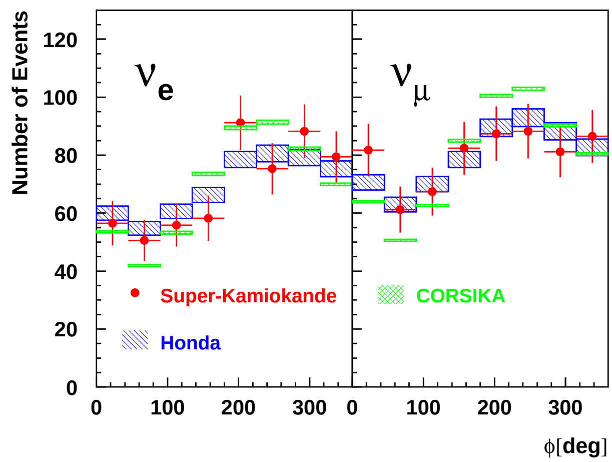

Fig. 6. Azimuthal dependence of the neutrino fluxes in Kamioka.

The CORSIKA result for the ratio between upward and downward neutrino fluxes reveals a substantial difference to previous calculations (Fig. 5). The flux of upward traveling neutrinos is about 15 % higher than the downward flux predicted by CORSIKA. This is a direct consequence of the difference in the geomagnetic cut-off between Kamioka and its antipode region in the South Atlantic. Kamioka is relatively near to the geomagnetic equator and has a high geomagnetic cut-off of 12.1 GV. The average cut-off for the areas where the upward traveling neutrinos result is less than half, giving rise to the primary cosmic ray flux between 6 and 12 GeV proton energy. In the experiment, this up-down asymmetry is obscured by the low angular resolution for neutrinos with energies less than 1 GeV, but it should be observable for intermediate energies by the Super-Kamiokande detector.

The East-West effect is shown in Fig. 6 by the azimuthal distribution of the flux. The agreement of the CORSIKA simulation with experimental results is on the same level as the agreement with the simulation of Honda.

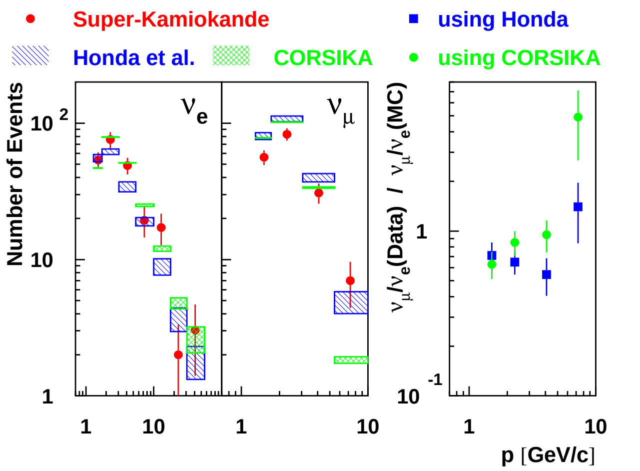

Fig. 7. Differential spectra of neutrino counts. The right figure presents the ratio of the experimental ratio $\nu_\mu/\nu_e(data)$ to the theoretical ratio $\nu_\mu/\nu_e(MC)$ of Honda (■) and CORSIKA (●).

The preliminary results of CORSIKA for the differential spectra of neutrino counts and the ratio between the neutrino flavors are presented in Fig. 7. The observed difference is magnified for a direct comparison of the CORSIKA results with the results of Honda in Fig. 8. Especially the difference in the ratio $\nu_e/\overline{\nu_e}$ is remarkable. This ratio is directly coupled to the ratio μ^+/μ^-, the quantity where CORSIKA is explicitly verified and therefore the confidence for this result should be high.

5 Conclusion

CORSIKA, recently extended for the simulation of low energy primary particles including the precise description of all geographical influences, is now a program which allows the accurate simulation of neutrino fluxes in the energy range of the atmospheric neutrino anomaly. Various interaction models in CORSIKA can be checked by simulations of low energy muon fluxes. The muon charge ratio turns out to be the most critical test for the interaction models. The study proves that DPMJET has to be favored as the most reliable hadronic interaction model for the simulation of low energy neutrino fluxes.

The CORSIKA results for atmospheric neutrino fluxes are in a good overall agreement with the simulation of Honda, which are usually used for the interpretation of the atmospheric neutrino anomaly. Nevertheless the precise handling of all geographical factors reveals also deviations, mainly based on the difference in the geomagnetic cut-off between Kamioka and its antipode region which results in different

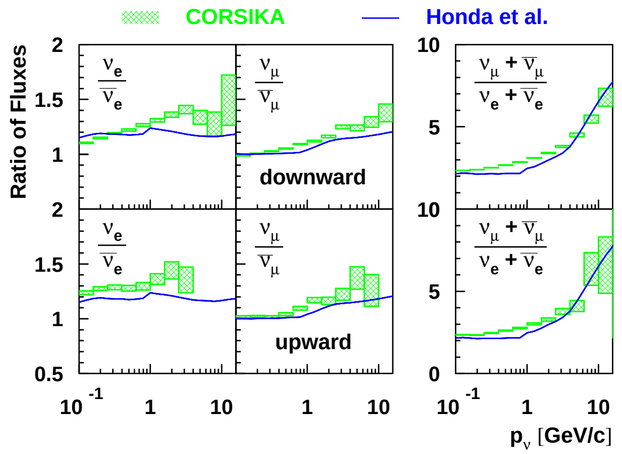

Fig. 8. Ratios between the vertical neutrino fluxes for downward (upper spectra) and upward (lower spectra) going neutrinos.

fluxes for up- and downward going neutrinos in the Super-Kamiokande detector. In conclusion, CORSIKA confirms the atmospheric neutrino anomaly but a more detailed analysis with an accurate detector simulation will presumably lead to modified oscillation parameters.

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References

J. Alcaraz et al., Phys. Lett. B 472, 215–226, 2000.

J.M. Baxendale, C.J. Hume, M.G. Thompson, Jour. Phys. G 1, 781–788, 1975.

M. Bleicher et al., J. Phys. G: Nucl. Part. Phys. 25, 1859–1896, 1999.

H. Fesefeldt, Report PITHA-85/02, RWTH Aachen, 1985.

R.S. Fletcher et al., Phys. Rev. D 50, 5710–5731, 1994; J. Engel et al., Phys. Rev. D 46, 5013–5025, 1992.

Y. Fukuda et al., Phys. Rev. Lett. 81, 1562–1567, 1998; Phys. Lett. B 433, 9–18, 1998; Phys. Lett. B 436, 33–41, 1998.

S. Fukuda et al., Phys. Rev. Lett. 85, 3999–4003, 2000.

T. Futagami et. al. Phys. Rev. Lett. 82, 5194–5197, 1999.

L.J. Gleeson and W.I. Axford, Astrophys. Jour. 154, 1011–1026, 1968.

T. Hebbeker. et al., Proc. 30th Int. Conf. High Energy Phys., Osaka, July, 27th - Aug., 2nd, 2000.

D. Heck et al., Report FZKA 6019, Forschungszentrum Karlsruhe, 1998.

M. Honda et al., Phys. Rev D52, 4985–5005, 1995.

N.N. Kalmykov, S.S. Ostapchenko, and A.I. Pavlov, Nucl. Phys. B (Proc. Suppl.) 52B, 17–28, 1997.

J. Kremer et al., Phys. Rev. Lett. 83, 4241–4244, 1999.

J. Ranft, preprint hep-ph/9911213, 1999.

S. Tsuji et al., J. Phys. G: Nucl. Part. Phys. 24, 1805–1822, 1998.

B. Vulpescu et al., J. Phys. G.: Nucl. Part. Phys. 27, 977–991, 2001.

J. Wentz et al., these proceedings, 2001.

K. Werner, Phys. Rep. 232, 87–299, 1993.