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Atmospheric neutrino and muon fluxes

T. Sanuki[a], S. Haino[b], K. Abe[c], M. Honda[c], T. Kajita[c], A. Okada[c], K. Kasahara[d] and S. Midorikawa[e]

(a) University of Tokyo, Tokyo, 113-0033 Japan
(b) High Energy Accelerator Research Organization, Tsukuba, Ibaraki, 305-0801 Japan
(c) Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, 277-8582 Japan.
(d) Institute of Technology, Fukasaku, Ohmiya, Saitama, 330-8570 Japan
(e) Faculty of Software and Information Technology, Aomori University, Aomori, 030-0943 Japan
Presenter: M. Honda (mhonda@icrr.u-tokyo.ac.jp), jap-honda-M-abs1-he22-oral

The muon fluxes at several altitudes are examined with the simulation code used by HKKM04 [1]. This study makes it possible to estimate the uncertainty in the atmospheric neutrino flux calculated by HKKM04, which is less than 10 % in 1–10 GeV. It also provides us a method to calibrate the interaction model, and we find that DPMJET-III [2], the interaction model used by HKKM04, needs to be modified at high energies. We propose a modification of DPMJET-III, and present the results with the modified interaction model.

1. Introduction

Since the evidence of neutrino oscillation was discovered in atmospheric neutrinos, sustained refinement is required for the prediction of atmospheric neutrino flux. As the uncertainty of the primary flux is reduced to $\sim 5\%$ below 100 GeV by the AMS [3] and BESS [4, 5] observations, the interaction model remains as the major source of the inaccuracy in the calculation of the atmospheric neutrino flux.

We note, the muon flux is also measured in a good accuracy ($\lesssim 5\%$) up to a few 100 of GeV [5, 6, 7], and they are considered to be a good calibration source of the atmospheric neutrino flux. Using the muon flux data, we may estimate the uncertainties in the calculation of the atmospheric neutrino flux and refine the accuracy.

The idea is similar to the prediction of the atmospheric neutrino flux directly from the muon flux [8]. However, such high precision observations do not cover all the necessary depths yet. Therefore, we examine the interaction model with available muon flux data and a reliable transportation code.

We study the muon fluxes with the simulation code used in the calculation of the atmospheric neutrino flux[1], then estimate the uncertainties resulted from the interaction model. We also propose a modification for DPMJET-III[2], which is used in the calculation.

2. Phase space in hadronic interaction relevant to muons and neutrinos

In Fig. 1, we plotted the phase space of mesons (π, K) in the cosmic ray – air nuclei hadronic interactions, relevant to the muons and neutrinos with fixed momenta, $P_{\mu,\nu} = 0.1, 1.0, 10, 100$ GeV/c at ground. Note, the distributions are narrow strips for muons with $P_\mu \gtrsim 1$ GeV/c. The meson distributions for neutrino with $P_\nu \gtrsim 1$ GeV/c are wider than those for muons, but could be well reconstructed by the superposition of the meson distribution for muons with neighboring momenta.

For the muons with $P_\mu \lesssim 1$ GeV/c, the meson distribution is largely deformed from that of higher energies. The peak of the distribution moves slowly to the lower projectile momentum, but the distribution has a large overlap with that for muons with $P_\mu = 1$ GeV/c. This is understood by the fact that most of the muons observed with this momentum at the ground are actually produced with higher momenta ($\gtrsim 1$ GeV/c) at the

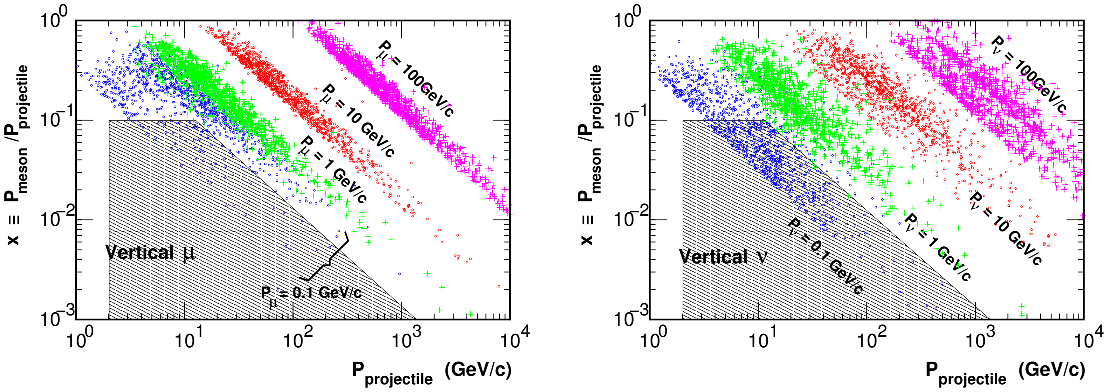

Figure 1. The meson (π, K) distributions in the $(P_{projectile}, x)$ plane of the cosmic ray – air nuclei hadronic interactions relevant to the atmospheric muons and neutrinos with fixed momenta. The left panel is for muons and right for neutrinos, both for the vertical directions.

higher altitude, but they lose the energy in air before reaching the ground. Most of the muons, created by the mesons (π, K) in the hatched area, decay in air before reaching the ground.

The meson distribution for neutrinos with $P_\nu \lesssim 1$ GeV/c shifts to lower projectile momenta without changing the shape largely. Therefore, the meson distributions for the neutrino in these momenta are not reproduced by the superposition of those for muons. The interactions relevant to the neutrinos with $P_\nu \lesssim 1$ GeV/c are not calibrated by the muon flux at the ground level.

There is another limitation at higher energies, since the contribution of K-meson is largely different for muons and neutrinos. At 100 GeV/c, the K-meson contribution is more than 50 % to the neutrinos, while it is still less than 10 % to the muons, for vertical directions. In Fig. 1, we find 2 clusters in the meson distribution for 100 GeV/c neutrinos. Each cluster stands for π and K contributions.

3. Comparison of calculated muon flux with observed data

In the left panel of Fig. 2, the calculated muon fluxes by HKKM04 are compared with the accurate measurements at Tsukuba (BESS-TeV) [5], Mt. Norikura(BESS) [6], and CERN (L3+C) [7]. Note, the muon fluxes are calculated for different sites separately, and the difference is shown in the ratio.

We find the agreement of the calculated muon fluxes by HKKM04 with the observed data are $\lesssim 5\%$ in 1 – 30 GeV/c region. Therefore, we may conclude the uncertainty of HKKM04 calculation in 1 – 10 GeV is less than 10 % in the absolute value, assuming the experimental uncertainty of ~ 5 % in the muon observations. However, the difference is larger for $P_\mu \lesssim 1$ GeV and $P_\mu \gtrsim 30$ GeV.

We have modified DPMJET-III, to get a better agreement between calculations and observations. As the modification we change the average energy of the secondary mesons which have the same valence quark as the projectile. The magnitude of change is determined for each kind of quark as a function of the projectile energy. We also assume the iso-symmetry that the magnitudes of change for u-quark and d-quark in $p + air$ interactions are the same as those for d-quark and u-quark in $n + air$ interactions respectively. In $p, n + air$ interactions, the magnitudes of change for π^+ and K^+ are the same, that for K^0 is the $1/2$ of π^-, and no change is applied to K^-. The nucleon average energies are also changed to balance the total energy. The magnitudes of change are tuned to minimize the difference between calculations and observations. Note, the

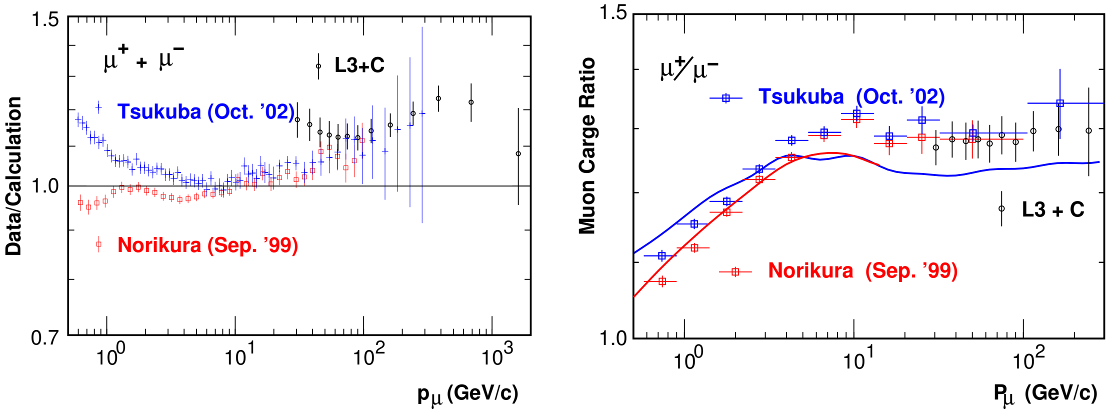

Figure 2. The comparison between calculated muon flux with DPMJET-III and observed data. The total flux is compared in left panel taking the ratio, and the charge ratio in right panel.

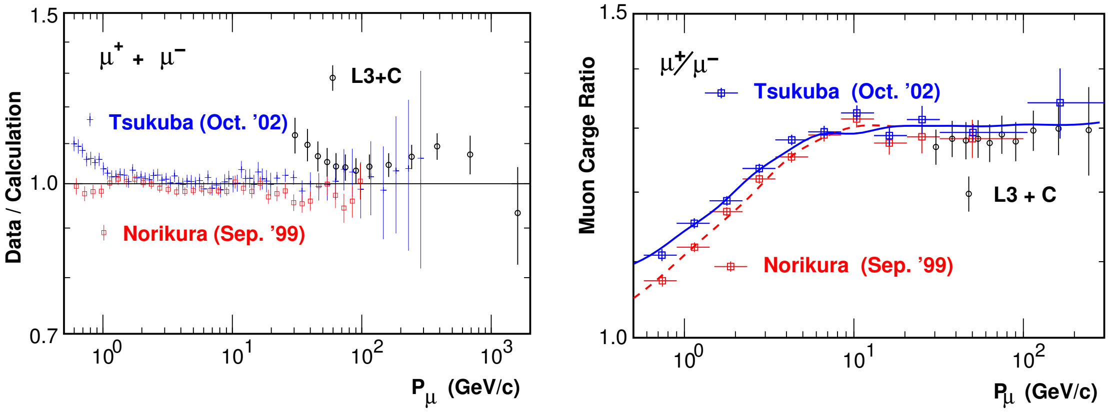

Figure 3. The comparison between calculated muon flux with the modified interaction model and observed data. The total flux is compared in left panel taking the ratio, and the charge ratio in right panel.

muon flux observed by L3+C in $\lesssim$ 50 GeV is higher than that by BESS. We used the BESS data in this energy region, since they are not suffered from the overlaying material.

In Fig. 3, the muon fluxes calculated with the modified interaction model are compared with the observed data, showing a better agreements in 1 – 300 GeV/c. Note, we have used the air density structure measured by the meteorological office in the calculation with the modified interaction model for Tsukuba and Norikura. Then the calculated muon fluxes are much closer to the observed data consistently in GeV region.

4. Summary

We have studied the muon flux with the calculation code used in HKKM04, and find that the uncertainties of the atmospheric neutrino fluxes are around 10 % for the absolute values in 1 – 10 GeV/c. Some modifications are necessary for DPMJET-III, since the model fails to reproduce the observed muon flux at higher energies. Applying a modification to DPMJET-III, the agreement of calculation and data for the muon flux becomes better in a wider momentum range. We consider the modified interaction model make the prediction of the atmospheric neutrino flux more reliable than that of HKKM04 in wider energy range. The neutrino fluxes calculated with the modified interaction model and DPMJET-III are compared in Fig. 4.

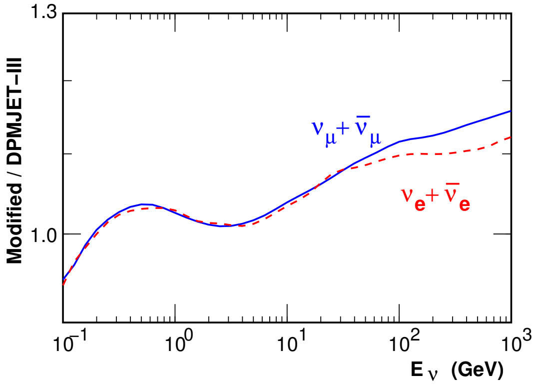

Figure 4. The ratio of all direction averaged neutrino flux calculated with the modified interaction model to that calculated with DPMJET-III.

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References

[1] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, Phys. Rev. D70:043008 (2004).
[2] S. Roesler, R. Engel, and J. Ranft, Proc. 27th ICRC, Hamburg, 1, 439 (2001); Phys. Rev. D 57, 2889 (1998).
[3] AMS Collaboration: J. Alcaraz et al., Phys. Lett. B 490, 27 (2000).
[4] BESS Collaboration: T. Sanuki et al., Astrophys. J., 545, 1135 (2000).
[5] BESS Collaboration: S. Haino et al., Phys. Lett. B594 35 (2004).
[6] BESS Collaboration: T. Sanuki et al., Phys. Lett. B541, 234 (2002).
[7] L3 Collaboration: P. Achard et al. Phys. Lett. B598 15 (2004).
[8] D.H. Perkins, Astropart. Phys. 2, 249 (1994).