Improvement of Atmospheric Neutrino Flux at Low Energies Below 1 GeV.

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***Abstract*. We have calculated the atmospheric neutrino flux based of the modified DPMJET-III interaction model, and could achieve a good accuracy with the muon calibration above 1 GeV [?]. However, the uncertainty of atmospheric neutrino flux below 1 GeV is still large. In this paper, we introduce an interaction model named PHITS [?] which agrees well with the HARP experiment [?]. The PHITS reproduce the muon flux at the balloon altitude better than the DPMJET-III [?] interaction model. The preliminary calculation of the atmospheric neutrino flux and the new application of our calculation code (ATMNC3) are presented.**

***Keywords*: Atmospheric-Neutrino PHITS ATMNC3**

I. INTRODUCTION

We have calculated the atmospheric neutrino flux, using the observed muon fluxes at the sea or mountain level, and balloon altitudes as the calibration source of the hadronic interaction model [**?**]. The study support the use of DEPMJET-III [**?**] as the interaction model, with a modification at higher energies. However, the calibration of the interaction model with muon fluxes observed at the sea or mountain level does not work effectively for the interactions relevant to the atmospheric neutrinos below 1 GeV. The balloon altitude observation of muon flux is an ideal resource for such a study. However, the statistics is poorer than that at the sea or mountain level.

On the other hand, HARP [**?**] experiment largely improved the knowledge of the hadronic interaction at 12 GeV/c for p-Air (p-N_2 and p-O_2) interactions, which are relevant to the low energy atmospheric neutrino fluxes. Here, we introduce the PHITS interaction model [**?**], which show a little better agreement with the HARP experiment than the DPMJET-III and is usefull much lower than 100 MeV. We could reconstruct the muon flux at the sea and mountain level with PHITS as well as the DPMJET-III. The agreement of observation and calculation with PHITS interaction model at balloon altitude is a better than that with the DPMJET-III. The atmospheric neutrino flux is calculated with the PHITS, and is compared with that of our former calculation.

We have named our code for the calculation of the atmospheric neutrino flux as ATMNC3 (Atmospherics Muon and neutrino calculation Code 3-dimension version). Hare after, we refer the code as ATMNC3. The ATMNC3 treats the primary and secondary cosmic rays in a 3-dimensional manner without improper assumptions or approximations. The code is useful for the calculation of particle spectra at the satellite orbit. Also the expected experimental data by new satellites will be the new resource for the ATMNC3.

II. PHITS INTERACTION MODEL

The PHITS (Particle and Heavy-Ion Transport code System)[**?**] is originally developed for the designing of the radiation shield, and is a integrated software including the interface to the visualization. However, we call the hadronic interaction model used in the code as PHITS also.

The PHITS interaction model is designed to describe the heavy Ions interaction, but it also describe the proton and light nuclei pretty well. We compare the result of HARP experiment [**?**] and the results of PHITS for p-Air interactions in Fig**??**, assuming the air composition as 79 % N_2 and 21 % O_2. We also plotted the results of DPMJET-III in the same figure with dashed lines for the comparison.

We find both interaction models does not agree well with the HARP experiment in large angle bins at high momenta. We note, however, the secondary particle with high momentum ($P \gtrsim 0.5 P_{proj}$) does not affect the calculation result too much due to the small multiplicity. Taking into account the multiplicity and the steep spectra of the primary cosmic rays, the secondary particles with the momenta of $0.1 \sim 0.3$ of the projectile, are important in the calculation of secondary cosmic rays. We may say both the PHITS and DPMJET-III agree with the HARP experiment in the "important momentum region" for the calculation of atmospheric muon and neutrino fluxes. In the comparison of PHITS and DPMJET-III, the PHITS shows a little better agreement with HARP experiment than the DPMJET-III.

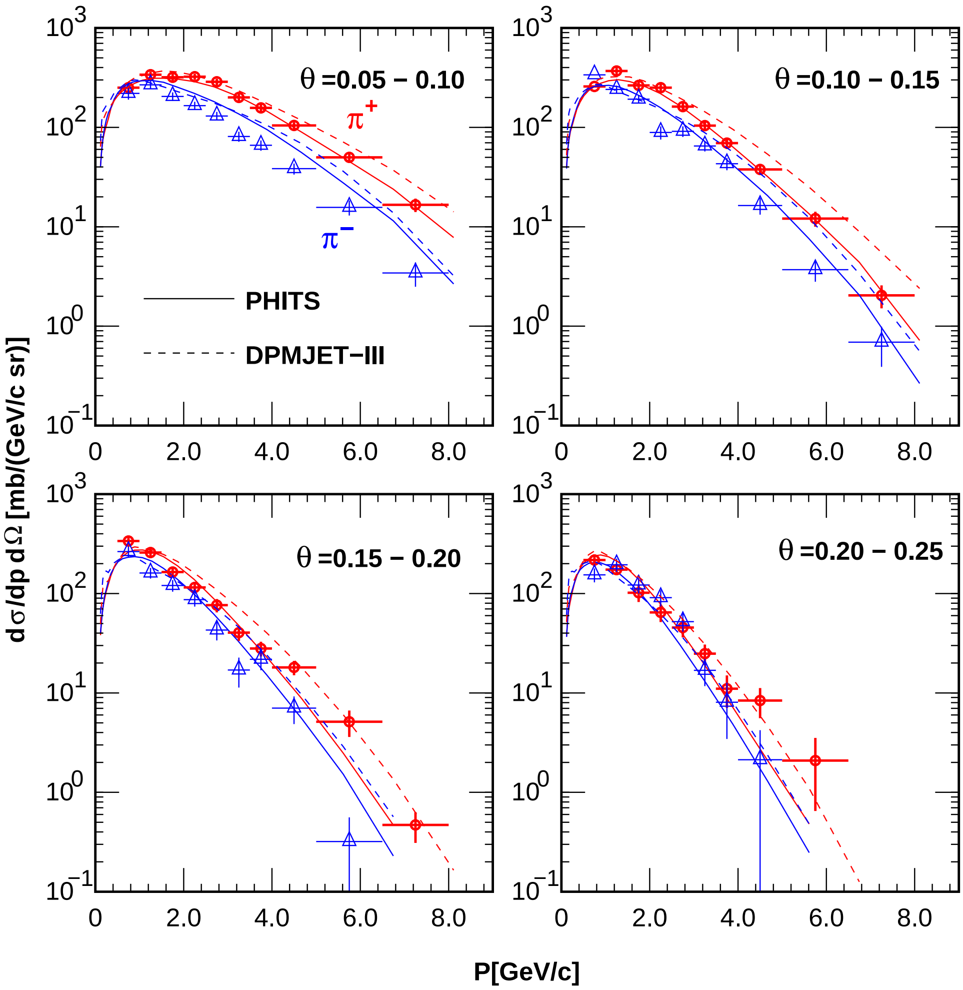

Fig. 1. Comparison of interaction models and HARP data. The dashed lines are for the DPMJET-III

III. Comparison of Calculated and Observed for Atmospheric Muons

Next, we calculated the atmospheric muon fluxes at the three different cites, at Tsukuba (sea level) [**?**], at Norikura (2770m asl) [**?**], and at Fort Sumner (Balloon altitude) [**?**]. Note, PHITS is originally designed to describe the transportation of low energy particles, there is an upper limit of useful energy for the projectile of the hadronic interactions. The energy is different for the kind of particle, but it works fine below 50 GeV for all the particles. In the calculation with PHITS interaction model, we limit the use of it for the hadronic interactions below 32 GeV/c, and above that, we used the "modified DPMJET-III" as the former calculations.

The observed muon flux data are divided by the calculations, and are shown in Fig. **??** for Tsukuba and Fig. **??** for Norikura.

In the former study, we find the agreement of the observation and calculation with DPMJET-III agree well each other at the momenta above 1 GeV/c at the sea level and mountain level. However, they disagree each other below 1 GeV/c. We find the same feature is seen in the comparison of observation and calculation with PHITS.

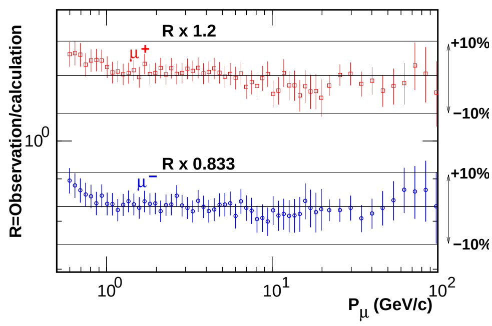

Fig. 2. Comarison of observed muon flux data at Tsukuba with the calculation with PHITS

The muons below 1 GeV/c are mostly produced at higher momenta at high altitude, and arrive the sea or mountain level after suffering from the large energy loss. Therefore, the information of the hadronic interaction is diluted. We consider the agreement above 1GeV/c is important in the comparison of observed and calculated muon flux at the sea or mountain level.

On the other hand the muons at balloon altitude reflect the hadronic interaction of the cosmic rays and the air nuclei more directly. Although the statistics is small, we

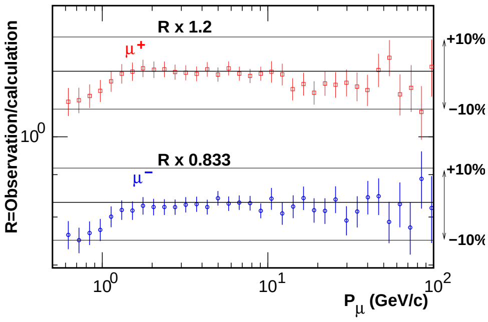

Fig. 3. Comarison of observed muon flux data at Norikura with the calculation with PHITS

consider the muon spectra data at the balloon altitude is important.

In Fig. **??**, we show the comparison of observation and calculation of the muon flux at balloon altitude at Fort Sumner. The agreement of calculation and observation below 1 GeV/c is better than the former calculation in this comparison.

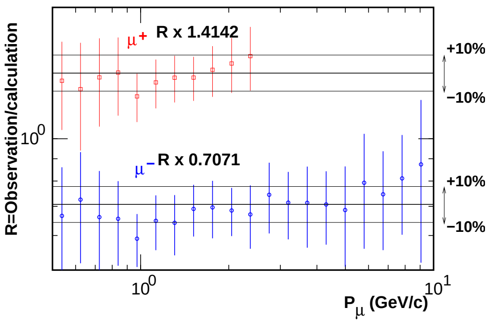

Fig. 4. Comarison of observed muon flux data at Fort Sumner with the calculation with PHITS

IV. ATMOSPHERIC NEUTRINO FLUX (PRELIMINARY)

We are calculating the atmospheric neutrino with PHITS interaction model. Here, we present a preliminary results; the comparison of the atmospheric neutrino fluxes with the PHITS interaction model and the former ones. The comparison is made for the vertical down-going neutrinos at Kamioka and at Sudbury. The atmospheric neutrino flux calculated with PHITS are divided by the former ones calculation with the "modified DPMJET-III" and shown in Figs. **??** and **??**.

We find that the calculation with PHITS interaction model gives a higher atmospheric neutrino flux below 1 GeV both in the calculation for Kamioka and Sudbury. This feature may have the same origin as the agreement of atmospheric muons observed at balloon altitude at Fort Sumner.

Since we are still in the stage of the calibration of our calculation with PHITS interaction model, these results are still preliminary, and the difference of the flux calculated with PHITS from the former calculation is to be considered as the systematic error of our calculation

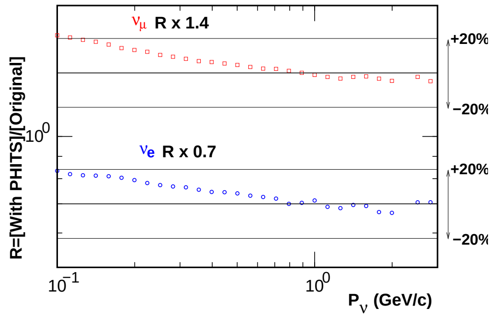

Fig. 5. Comparison of the atmospheric neutrino flux calculation with PHITS interaction model and our former ones for Kamioka.

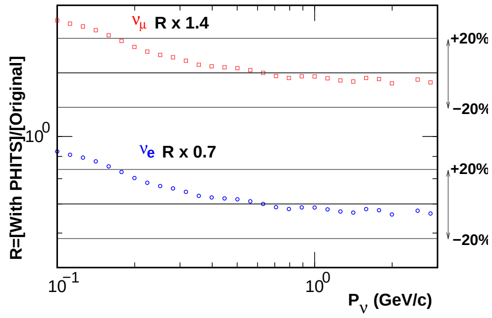

Fig. 6. Comparison of the atmospheric neutrino flux calculation with PHITS interaction model and our former ones for Kamioka.

when we calibrate it with the available atmospheric muon data.

V. PARTICLES AT THE SATELLITE ALTITUDE AS NEW CALIBRATION RESOURCE

The PHITS interaction model is original developed for the low energy particle transportation in the shielding material. And, it is useful down to much lower energies than 100 MeV. With this PHITS interaction model, we may use the ATMNC3 code to predict the sub cutoff particles at the satellite orbit. In the Fig. **??**, we plotted the result of the preliminary result of the calculation of the particle spectra at satellite orbit.

Note, originally ATMNC3 cannot handle the electro-magnetic cascade in the air, since it is not directly related to the atmospheric muon or neutrino spectra, and consume much computation time. However, the electron is an important particle to observe at the satellite orbit. We integrated the electro-magnetic cascade code in the ATMNC3. and plotted the electron and positron energy spectra in Fig. **??** also. As the simulation of the electro-magnetic cascade is a computation-time consuming computer process, we can switch off it when we are interested in the atmospheric neutrinos and muons rather than in the electrons and gamma rays.

It is interesting that the positron flux is larger than the electron flux below the rigidity cutoff. This is due to the direction dependent rigidity cutoff for protons and direction dependent escape probability of electrons and positrons. Consider a proton entering the atmosphere from the west direction tend to produce electrons and

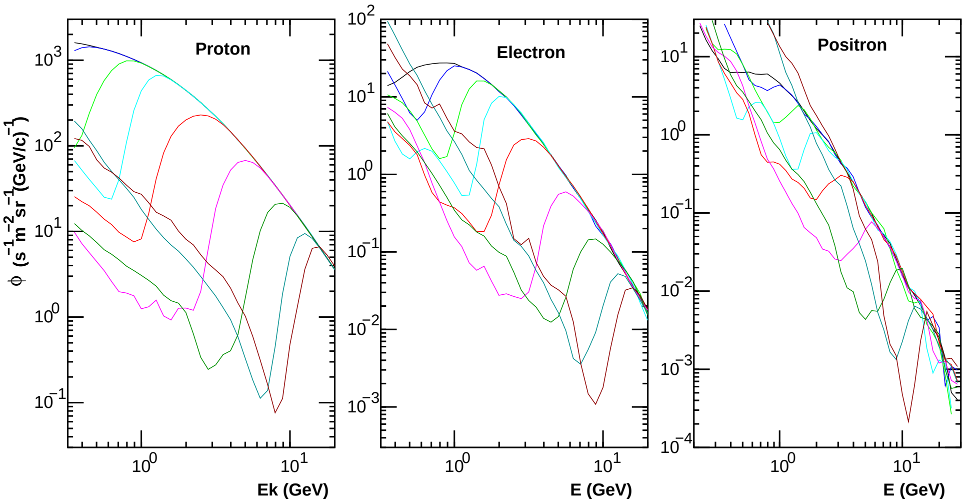

Fig. 7. The energy spectra of protons, electrons, and positrons at the satellite altitude (550km) for the rigidity cutoff of 0–0.6, 0.6–1, 1–1.5, 1.5–2, 2–4, 4–7, 7–10, and 10–14 GV. The rigidity cutoff could be read from the bending point of each line.

positrons after the hadronic interactions and electro-magnetic cascading running to the east direction. The geomagnetic field bend such a positron to upward direction, while it bend such a electron to the downward direction. Therefore, the escape probability of positrons produced by protons with near the cutoff rigidity is larger than that of electrons in average.

We are expecting that the observation at satellite orbit will be icreased in the quality and in the quantity, by the PAMALA, FERMI, AMS, etc experiments. Those data could be used to calibrate our calculation in the low energy region where the atmospheric muons are not useful for calibration of the ATMNC3.

VI. Acknowledgements

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