Update of the atmospheric neutrino flux simulation ATMNC for next-generation neutrino experiment

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Abstract. Atmospheric neutrino flux calculation ATMNC has greatly contributed to the physics of neutrino experiments including Super-Kamiokande. Since next-generation large-scale experiments, such as Hyper-Kamiokande, are expected a large improvement of statistical errors, it is desirable to reduce systematic errors associated with uncertainty of the flux calculation. The dominant uncertainty of the ATMNC calculation arises from insufficient understanding of the hadron interactions inside air showers caused by cosmic rays. In order to improve the accuracy of the hadron interaction model, many precision measurements for hadron production using accelerator beams have been performed or planned. In this report, we discuss a strategy to update ATMNC calculation to reduce its uncertainty by incorporating such measurements.

1. Introduction

ATMNC is a simulation code to calculate a flux of atmospheric neutrino developed by M. Honda [1]. It provides a full Monte Carlo (MC) simulation of air showers induced by the primary cosmic rays, and calculates energies and directions of neutrinos, which is the end product of the shower, at a given detector location. The \(\nu\) flux calculated by ATMNC has been used in several neutrino physics experiments such as Super-Kamiokande (SK) [2], and contributed to their physics results with a sufficient accuracy compared to their statistical uncertainties. In experiments in the next generation such as Hyper-Kamiokande [3], a statistics will be largely improved. Thus, it is desirable to reduce the uncertainty of the ATMNC calculation accordingly.

The dominant uncertainty of ATMNC calculation arises from the hadron interaction inside the air shower. To suppress the uncertainty, Honda et al. [4] apply a correction to hadron interaction based on atmospheric \(\mu\) flux data, but the \(\nu\) flux in low energy of \(< 1 \text{ GeV}/c\) still has relatively large uncertainty (\(~15\%\) at 0.5 GeV/c). Many accelerator experiments for precise measurement of hadron production are conducted or planned mainly for long-baseline \(\nu\) experiments [5, 6, 7]. We started a study to incorporate such measurements into ATMNC. We plan to refer a method of the hadron interaction correction used in T2K [8]. This will enable to handle the hadron uncertainty in common way between the T2K and SK experiments, that will be useful for the T2K-SK combined analysis. Though the accelerator data may be insufficient at present, they are independent from the \(\mu\) study and will compensate the phase space where the
The study does not cover. Thus the combination study of the $\mu$ data and the accelerator data will reduce the hadron uncertainty of ATMNC. In addition, this study will reveal that which phase space is important for atmospheric $\nu$ simulation, and provide feedback to future accelerator experiments. We will give a brief review of the T2K method in Section 2. In Sections 3 and 4, we show some preliminary simulation results which will be a basis for further study.

2. Review of T2K weighting method

We will install a weighting method used in the T2K beam simulation [8] into ATMNC. Based on a difference between the accelerator data and the MC, T2K applies two kinds of weights for each hadron interaction in their simulation: weights for hadron production cross-section $\sigma$, and for differential multiplicity $\frac{dn}{dpd\theta}$. These two parameters change a hadron interaction rate. The ratio of the interaction rate of the data to the MC is calculated as

$$W_{\sigma} = \frac{\sigma_{\text{data}}(\vec{x})}{\sigma_{\text{MC}}(\vec{x})} \exp\{-L(\langle \sigma_{\text{data}} \rho \rangle - \langle \sigma_{\text{MC}} \rho \rangle)\}$$

for the difference of $\sigma$, where $\rho(\vec{x})$ is a number density of nuclear targets in air at position $\vec{x}$, $L$ is a flight length, and $\langle \sigma \rho \rangle$ represents an average value of $\sigma \rho$ along the particle’s track. The subscripts $\text{data}$ and $\text{MC}$ represent a measured value in the accelerator data and an expected value in the MC, respectively. For the difference of $\frac{dn}{dpd\theta}$, the ratio is calculated as

$$W_{\frac{dn}{dpd\theta}} = \frac{(\frac{dn}{dpd\theta})_{\text{data}}}{(\frac{dn}{dpd\theta})_{\text{MC}}} \prod \sigma_{\text{MC}}^i \times W_{\frac{dn}{dpd\theta}}^i$$

Each MC event is weighted by $\prod_i W_{\sigma_i} \times W_{\frac{dn}{dpd\theta_i}}$, where $i$ represents the $i$-th hadron interaction in the event.

3. Requirement for beam data

The first step of our study is to reveal the requirement for the accelerator data. The $\sigma$ and $\frac{dn}{dpd\theta}$ depend on a type of incident particle and its momentum. Using ATMNC, we investigated incident particles of hadron interaction in air shower. We found that protons cause $\sim70\%$ of all the hadron interactions, as shown in Fig. 1(a). The simulation also shows that a peak momentum of incident protons to produce sub-GeV and multi-GeV $\nu$s distributes around 5–100 GeV, as shown in Fig. 1(b). Thus, the accelerator experiments with a 5–100 GeV/c proton beam are important for our study. Experiments listed in Table XII in [8] provides the $\sigma$ measured with such proton beam. As for $\frac{dn}{dpd\theta}$, measurements by [5, 6, 7] will be useful, which provides the data with 6.4–31 GeV/c proton beam.

4. Test of weighting method

We are now implementing the T2K-style weights into ATMNC. The weight is designed to be applied to the output of ATMNC so that we do not need to iterate the AMTNC simulation to modify the weight. Of the abovementioned two weights, we finished the coding of the weight for cross-section $\sigma$, and tested the weighting. The $\sigma$ used in ATMNC and those measured in several measurements are shown in Fig. 2(a). We calculated the weight in Eq. (1) assuming the $\sigma_{\text{data}}$ to be the red lines in Fig. 2(a). The expected $\nu_\mu$ flux with and without the weight is shown in Fig. 2(b). We found that the change of flux spectrum is $<3\%$ as shown in Fig. 2(c). We will implement the weighting for differential multiplicity and evaluate quantitatively how the measured uncertainty of accelerator data propagate to the $\nu$ flux uncertainty. This study will be a basis for our final goal of reducing uncertainty of ATMNC.

5. Summary

We are studying to incorporate the accelerator measurements into ATMNC flux calculation using T2K-style weighting method. It will enable a common treatment of systematic uncertainty...
between SK and T2K. It will compensate the conventional $\mu$ flux study to reduce ATMNC uncertainty related to hadron interaction. We revealed that the accelerator data with a 5–100 GeV/c proton beam is important for sub-GeV–multi-GeV $\nu$ flux. The implementation of the weighting method is ongoing.

Figure 1. (a) Fraction of incident particle types causing hadron interactions in air shower. Color represents kinds of incident particles, as indicated in the plot. (b) Incident proton momentum of hadron interaction v.s. $\nu_\mu$ momentum.

Figure 2. (a) Hadron production cross-section. The black line shows the default value used in ATMNC. The points are from the accelerator measurements in [9, 10] or references in [8]. The red and green lines interpolate the high and low measurement values, respectively. (b) MC expectation of $\nu_\mu$ flux. The green (red) points show the flux with the weight in Eq. (1) where the green (red) line in (a) is used as the $\sigma_{\text{data}}$. The brack points shows the flux without any weight (the points are almost overwrapped with the red and green points). (c) Ratio of the flux with weight to that without weight. Meaning of green and red color is the same as (b).

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