PROCEEDINGS OF SCIENCE

Low energy atmospheric neutrino flux calculation with accelerator-data-driven tuning

Kazufumi Sato[a,*]

[a] *Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo Higashi-Mozumi 456, Hida, Gifu, Japan*

E-mail: kazufumi@km.icrr.u-tokyo.ac.jp

We incorporated accelerator-data-driven tuning for hadronic interaction in our atmospheric neutrino flux calculation which has been used for the analysis of atmospheric neutrino oscillations at Super-Kamiokande. This new approach allows us to evaluate the flux uncertainty more directly compared to conventional tuning using atmospheric muons. We tuned the hadronic interaction model in our calculation based on recent hadron production data measured by fixed-target accelerator experiments. The neutrino flux calculated with this new tuning is 5–10% smaller but still consistent with our previously published prediction within its uncertainty. The uncertainty associated with the new tuning was also evaluated based on the measurement errors of the accelerator data. Flux uncertainty was less than 6% in $0.2 < E_\nu < 10$ GeV/c region, which is an improvement over the conventional tuning. We performed the uncertainty evaluation in < 1 GeV/c region where the conventional tuning only provided the conservative uncertainty estimation.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1198

1. Introduction

A collision of a high energy cosmic-ray coming from extraterrestrial origins with Earth's atmosphere causes an air shower, *i.e.* a cascade of hadronic interactions. Consequently, neutrinos are produced through decays of pions and kaons in the air shower. Such "atmospheric neutrinos" have wide ranges of energy (100MeV–O(PeV)) and flight length (10–$O(10^4)$ km), and are promising signals for several physics including neutrino oscillation.

To study for atmospheric neutrinos, the prediction of its flux are necessary. In Super Kamiokande experiment [1], the neutrino flux is calculated by using a 3D Monte Carlo simulation (MC) for air showers developed by *Honda et. al.* [2], which is often called "Honda flux".

The dominant uncertainty of Honda flux arises from the hadronic interaction in the air shower. *Honda et. al.* [3] tuned hadronic interaction model in their MC based on atmospheric μ flux observations [4]. This "μ tuning" suppresses the flux uncertainty down to ~7% in $1 < E_\nu < 10$ GeV region as shown in Fig.11 in [5]. Still, there is relatively large uncertainty in $E_\nu < 1$ GeV and in $E_\nu > 10$ GeV. The former is due that low energy muons lose their energy significantly before reaching to the observation ground, and the latter is due that a neutrino production from kaon decay becomes dominant.

In this article, we tuned the Honda-flux MC based on data measured in accelerator experiments. Several accelerator experiments for precise measurement of hadronic production has been conducted/planned. Such data complements the μ tuning by covering different phase space from μ observations.

2. Accelerator-data-driven tuning

For the tuning, we used several fixed-target accelerator data: HARP [6, 7], BNL E910 [8], NA61 [9], NA49 [10], NA56/SPY and NA20 [11]. These experiments use a proton beam whose momentum ranges from 3 to 450 GeV/c, and provide inclusive differential cross-sections of $\pi^\pm, K^\pm$, and/or proton productions, as summarized in Table 1. In these experiments, several notation to describe the differential cross-sections are used, like $\frac{d^2\sigma}{dp d\theta}$, $\frac{d^2\sigma}{dp d\Omega}$, $\frac{d^2\sigma}{dx_F dp_T}$, etc. To unify the notation, hereafter we use an invariant form notation $E\frac{d^3\sigma}{dp^3}$.

In the MC, the rate of hadron production interaction between cosmic-rays and air nucleus is determined by the air density modeled by NRMSISE-00 and the total production cross section σ_{prod}. Then, the number, momentum magnitude, and direction of outgoing particles are determined according to the number density $E\frac{d^2n}{dp^3}$. The $E\frac{d^2n}{dp^3}$ depends on the incident particle type, the incident particle's momentum magnitude, and the outgoing particle type. The $E\frac{d^2n}{dp^3}$ distributions used in our MC are calculated from JAM model [12] for interactions with the incident particle energy less than 31 GeV/c^2, or DPMJET-III model for higher energies. The σ_{prod} and $E\frac{d^2n}{dp^3}$ are related to $E\frac{d^2\sigma}{dp^3}$ as:

$$E\frac{d^3\sigma}{dp^3} = \sigma_{prod} E\frac{d^3n}{dp^3}. \tag{1}$$

Table 1: List of accelerator data used in this analysis. These data provide the differential cross-section for the interaction $p + A \rightarrow x_{out} + X$. Types of target atoms and the reference number are shown in each cell.

	Beam momentum [GeV/c]					
x_{out}	3	5	6.4	8	12	12.3
$\pi^{\pm}$	Be, C, Al [6]	Be, C, Al [6]	Be [8]	Be, C, Al [6]	Be, C, Al [6]	Be [8]
$K^{\pm}$	–	–	–	–	–	–
p	Be, C, Al [7]	Be, C, Al [7]	–	Be, C, Al [7]	Be, C, Al [7]	–

	Beam momentum [GeV/c]				
x_{out}	17.5	31	158	400	450
$\pi^{\pm}$	Be [8]	C [9]	C [10]	Be [11]	Be [11]
$K^{\pm}$	–	C [9]	–	Be [11]	Be [11]
p	–	C [9]	C [10]	Be [11]	Be [11]

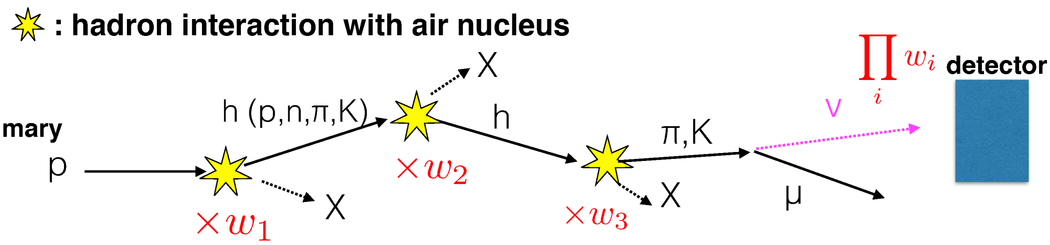

Figure 1: Schematic view of chain interactions associated with neutrino production.

In the accelerator-data-driven tuning, we defined a *weight* to correct the difference between data and MC, as:

$$w \equiv \left(E \frac{d^3\sigma}{dp^3} \right)_{data} / (\sigma_{prod})_{MC} \left(E \frac{d^3 n}{dp^3} \right)_{MC}, \tag{2}$$

where the subscripts *data* and *MC* represent expected values from the measured data and the MC, respectively. We prepared tables of weight w for each particle type (π^+, π^-, K^+, K^-, p, n) of outgoing particle and for various incident momenta from 3 to 1000 GeV/c based on the measured data $\left(E \frac{d^3\sigma}{dp^3} \right)_{data}$ and the value implemented MC $(\sigma_{prod})_{MC} \left(E \frac{d^3 n}{dp^3} \right)_{MC}$. The details of weight derivation was written in [14]. In air showers, neutrinos are produced following a chain of hadron interactions like Fig. 1. We applied the w to each hadronic vertex on this interaction chain in our MC. The product $W_{event} \equiv \prod_i w_i$ was used as an event weight when counting the number of neutrinos hitting the detector, where w_i represents the weight applied to the i-th vertex on the chain.

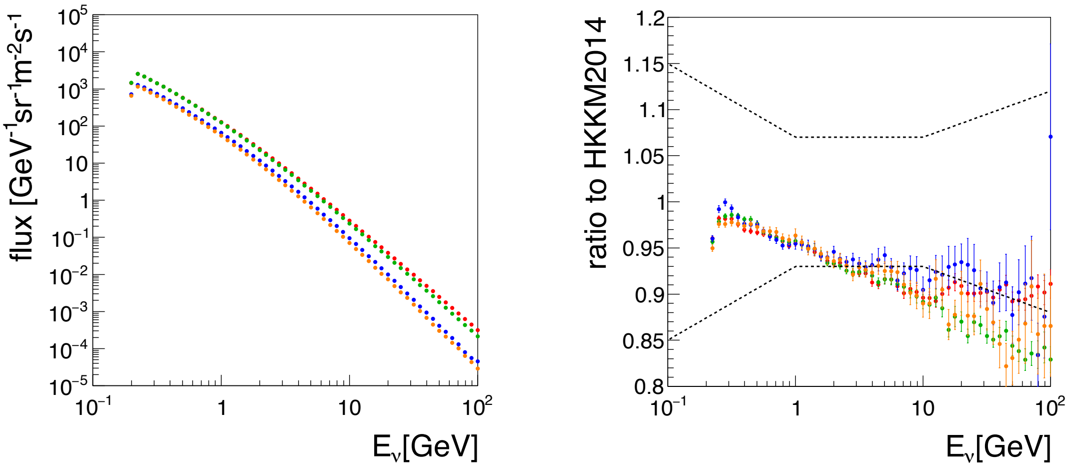

Figure 2: (a) Flux predictions with accelerator tuning. The red, green, blue, and orenge correcspond to ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$, respectively. Thier error bars shows MC statistical error only. (b) Ratio to the "μ-tuned" flux prediction [2]. Dashed line shows the systematic uncertainty reported in [5].

3. Flux prediction with the tuning

We simulated the neutrino flux with applying the weight in Eq. (2). The result is shown in Fig. 2 (a). The flux is almost consistent with the one previously reported in Ref. [2] considering its systematic error, though it has a tendency to be ~5–10% smaller. The predictions of flavor ratio $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ and neutrino-antineutrino ratios $\bar{\nu}_\mu/\nu_\mu$ and $\bar{\nu}_e/\nu_e$ were also calculated with accelerator tuning, as shown in Fig. 3. The new tuning method did not have a significant impact for these predictions.

4. Flux uncertainty

The flux uncertainty associated with the accelerator tuning was evaluated based on the measurement errors of the accelerator data if the proper data was available. Otherwise, we used a DPMJET-III [13] implemented in CRMC [15] for the uncertainty estimation. We considered several uncertainty sources as summarized in Fig. 4. The total flux uncertainty was evaluated to be 6–7% in < 1 GeV/c ν region. In that region, the conventional muon tuning only provided the conservative uncertainty estimation. Up to 10 GeV/c, the accelerator-data-driven tuning put reasonable and smaller uncertainty compared to the conventional muon tuning. The largest uncertainty below 8 GeV/c came from the error bars of the accelerator $\frac{d^2\sigma}{dp d\theta}$ measurement. In higher energy region, such error was suppressed due to the precise measurements provided by NA61 and NA49. Instead, incompleteness of fitting function to describe incident momentum dependence was the largest uncertainty source. These uncertainties will be able to reduce more precise measurements with low energy beam (< 10 GeV/c) and/or measurements with more various beam energy around $O(10)$ GeV/c–$O(100)$ GeV/c, which will be provided by the future accelerator experiments.

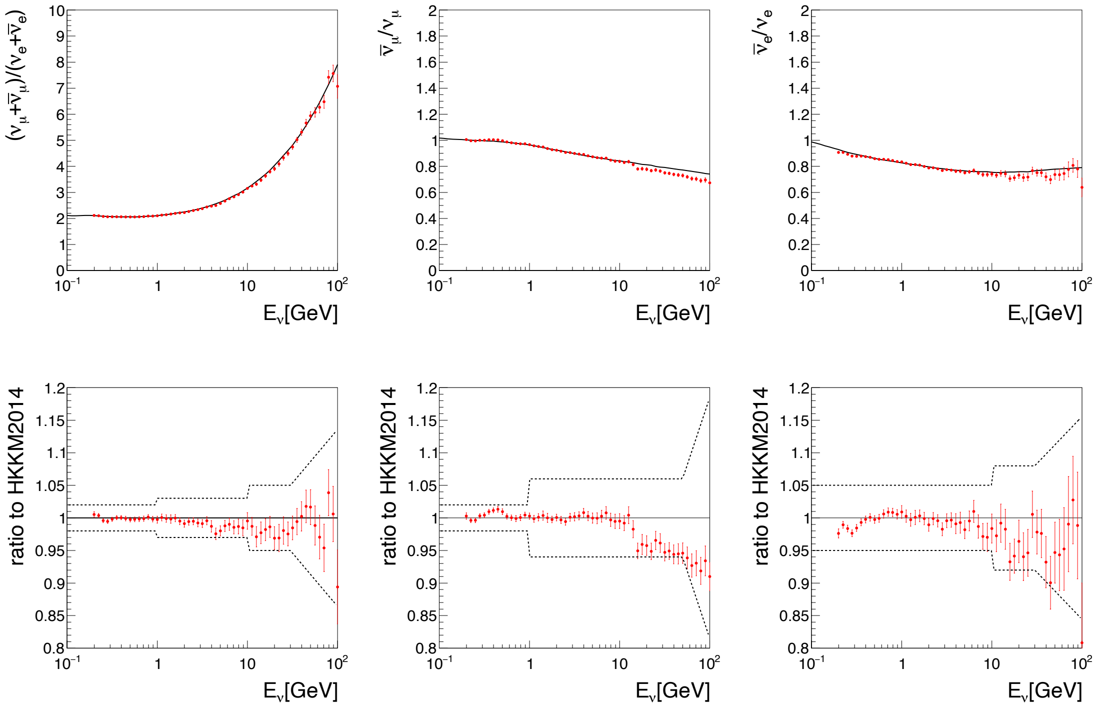

Figure 3: Flux ratio predictions with accelerator tuning. On the top panel, flavor ratio (left), $\bar{\nu}_\mu/\nu_{mu}$ ratio (middle), and $\bar{\nu}_e/\nu_e$ ratio (right) are shown. The red dots show our accelerator tuning predictions, while the black line is the "μ-tuned" predictions [2]. On bottom panel, the ratio of the accelerator tuning to the muon tuning are shown. The dashed lines are uncertainties of flux ratios used in Super-Kamiokande analysis.

References

[1] S. Fukuda *et. al.* (Super-Kamiokande), Nucl. Instrum. Meth. A501 (2003) 418.

[2] M. Honda *et. al.*, Phys. Rev. D 92, 023004 (2015).

[3] T. Sanuki *et. al.*, Phys. Rev. D 75, 043005 (2007).

[4] S. Haino et al. (BESS), Phys. Lett. B594, 35 (2004). T. Sanuki et al., Phys. Lett. B541 234 (2002); Erratum B581 272 (2004). K. Abe et al. (BESS), Phys. Lett. B564, 8 (2003).

[5] M. Honda *et. al.*, Phys. Rev. D 75, 043006 (2007).

[6] M. Apollonio et al. (HARP), Phys. Rev. C 80, 035208 (2009). M. G. Catanesi et al. (HARP), Phys. Rev. C 77, 055207 (2008).

[7] M. Apollonio et al. (HARP), Phys. Rev. C 82, 045208 (2010)

[8] I. Chemakin *et. al.* (E910), Phys. Rev. C 77, 015209 (2008); Erratum C 77, 049903 (2008).

[9] N. Abgrall et. al. (NA61/SHINE), Eur. Phys. J. C 76, 84 (2016).

[10] C. Alt et. al. (NA49), Eur. Phys. J. C 49, 897 (2007).

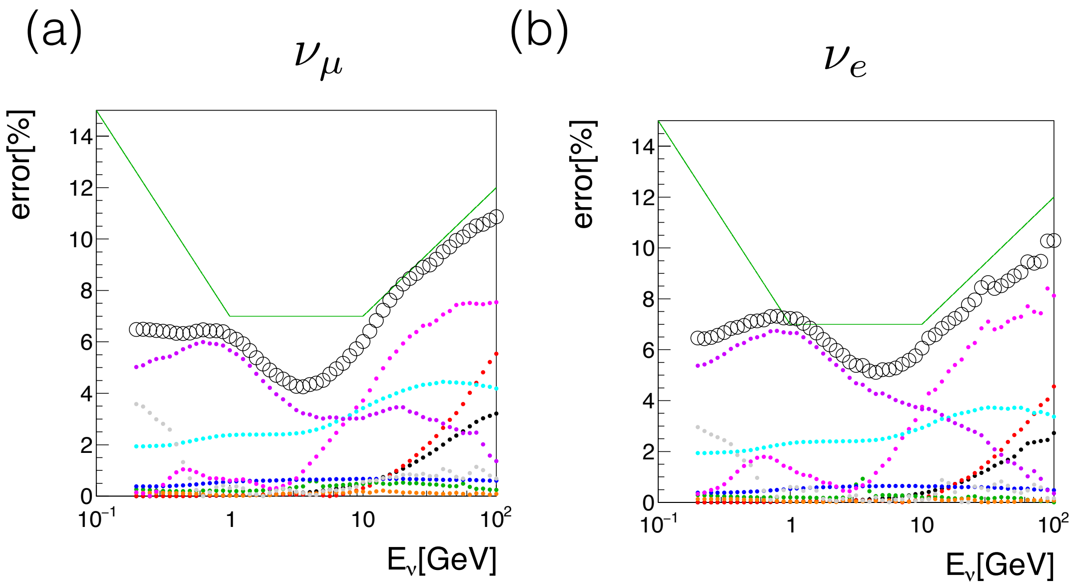

Figure 4: Systematic uncertianties in accelerator tuning for (a) ν_μ flux and (b) ν_e flux. The open circle shows the total systematic uncertainty. The solid line shows the uncertainty evaluated for the muon tunig[5]. The dots show the uncertainties come from each uncertainty source. Violet: measurement error of accelerator data, cyan: overall normalization uncertainty of measurement data, magenta: incompleteness of fitting function, red and black: related to Fyenman scaling, blue, orange and green: related to atom number dependence.

[11] M. Bonesini et.al., Eur. Phys. J. C 20, 13 (2001).

[12] K. Niita et al., Radiat. Meas. 41, 1080 (2006)

[13] S. Roesler, R. Engel, and J. Ranft (2000), hep-ph/0012252.

[14] Proceedings, 37th International Cosmic Ray Conference (ICRC 2021), PoS(ICRC2021)1210.

[15] R. Ulrich, T. Pierog, C. Baus. "The Cosmic Ray Monte Carlo Package, CRMC (v2.0.1)". Zenodo (2021). https://doi.org/10.5281/zenodo.4558705