PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Upgrade of Honda atmospheric neutrino flux calculation with implementing recent hadron interaction measurement

Kazufumi Sato,[a,*] **Hiroaki Menjo,**[a] **Yoshitaka Itow**[a,b] **and Morihiro Honda**[c]

[a] *Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Aichi, Japan*

[b] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Aichi, Japan*

[c] *Institute for Cosmic Ray Research, the University of Tokyo, Kashiwa, Chiba, Japan*

E-mail: kazufumi@isee.nagoya-u.ac.jp, menjo@isee.nagoya-u.ac.jp, itow@isee.nagoya-u.ac.jp, mhonda@icrr.u-tokyo.ac.jp

We will upgrade atmospheirc neutrino flux calculation by M. Honda (Honda flux), which has been used as a flux prediction in many experiments including Super-Kamiokande and has greatly contributed in the neutrino physics. The dominant uncertainty of the Honda flux arises from insufficient understanding of the hadron interactions inside air showers. Conventionally hadron interaction model in Honda flux has been tuned based on atmospheric muon observation data, but it arises relatively large uncertainties in momentum region below 1 GeV/c and above $O(10)$ GeV/c. Recently several precise measurements for hadron production using accelerator beams have been performed. We incorporate the accelerator-data-driven tuning into Honda flux calculation to complement the muon tuning.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

PoS(ICRC2021)1210

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.* [4] tuned hadronic interaction model in their MC based on atmospheric μ flux observations [3]. 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 will tune 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 will complement the μ tuning by covering different phase space from μ observations and providing information for particle production other than pions.

2. Accelerator-data-driven tuning

2.1 overview

Particle production in hadronic interaction $h_{in} + A_{air} \to h_{out} + X$ is described by an inclusive invariant differential cross-section $E\frac{d^3\sigma}{dp^3}$, where h_{in} (h_{out}) is incident (projectile) hadron, A_{air} is a nucleus in the air, *i.e.* O_2 or N_2, and X represents other nuisance particles. We don't care what kind of particle(s) the X is, so this reaction is "inclusive" and $E\frac{d^3\sigma}{dp^3}$ is independent from X:

$$E\frac{d^3\sigma}{dp^3} = E\frac{d^3\sigma}{dp^3}\left(h_{in}, h_{out}, p_{in}, p_{out}, \theta_{out}\right), \tag{1}$$

where p_{in} and p_{out} are momentum magnitudes of h_{in} and h_{out}, and θ_{out} is an angle between momentum directions of h_{in} and h_{out}. A set of (p_{out}, θ_{out}) may also be converted to (x_F, p_T) which is less dependent on p_{in}, where p_T is a transverse momentum of projectile particle and x_F is a Feynman-X calculated as

$$x_F \equiv \frac{p_L}{p_L^{\max}}, \tag{2}$$

where p_L is a longitudinal momentum of a projectile particle in CM frame of a nucleon-nucleon collision and $p_L^{\max}$ is its theoretical maximum value.

Our aim is to correct the difference of $E\frac{d^3\sigma}{dp^3}$ between the accelerator data and Honda flux MC. To do that, we will apply a weight W to each hadron interaction in the MC, which is defined as:

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

	Beam momentum [GeV/c]										
h_{out}	3	5	6.4	8	12	12.3	17.5	31	158	400	450
$\pi^{\pm}$	Be, C, Al [6]	Be, C, Al [6]	Be [8]	Be, C, Al [6]	Be, C, Al [6]	Be [8]	Be [8]	C [9]	C [10]	Be [11]	Be [11]
$K^{\pm}$	–	–	–	–	–	–	–	C [9]	–	Be [11]	Be [11]
p	Be, C, Al [7]	Be, C, Al [7]	–	Be, C, Al [7]	Be, C, Al [7]	–	–	C [9]	–	Be [11]	Be [11]

$$W \equiv \left(E\frac{d^3\sigma}{dp^3}\right)_{data} \Big/ \left(E\frac{d^3\sigma}{dp^3}\right)_{MC}, \quad (3)$$

where the subscripts *data* and *MC* represent expected values from the measured data and the MC, respectively.

When a primary cosmic ray interacts with a nucleus in the air, the secondary hadrons are produced, and they can interact with another nucleus. Thus, before producing neutrinos it is possible to form a chain of interactions. We apply W to each hadronic vertex on this interaction chain. The product $W_{event} \equiv \prod_i W_i$ will be used as an event weight when counting the number of neutrinos recorded in a detector, where W_i represents the weight applied to the i-th vertex on the chain.

2.2 Derivation of $\left(E\frac{d^3\sigma}{dp^3}\right)_{data}$

To derive $\left(E\frac{d^3\sigma}{dp^3}\right)_{data}$ used in Eq. (3), we use several beam data: HARP [6, 7], BNL E910 [8], NA61 [9], NA49 [10], NA56/SPY and NA20 [11]. These experiments cover beam momenta from 3 to 450 GeV/c, and provide inclusive differential cross-sections $\frac{d^2\sigma}{dpd\Omega}$ of $\pi^{\pm}, K^{\pm}$, and proton productions, as summarized in Table 1. Based on Honda flux MC, hadronic interactions involved in atmospheric neutrino production is dominantly caused by protons when the neutrino energy is less than 10 GeV. We thus use only proton-incident beam data in this study.

The beam data have a finite binning, and the beam momenta are discrete. To derive $\left(\frac{d^3\sigma}{dp^3}\right)_{data}$ as a smooth function, we parameterized the data with fitting. The fitting function is defined as

$$f_{IDCS}^{data} \equiv f_{BMPT} \times (A/A_0)^{\alpha} \times f_{pd/pp} \quad (4)$$

for pion and kaon productions. The f_{BMPT} is introduced in [11]. Since the f_{BMPT} has a symmetric form with respect to x_F, it is considered appropriate for describing $p + p$ collision. The $(A/A_0)^{\alpha}$ explains a difference of nuclear effect between different nucleus, where A and $A_0(= 2)$ are atomic masses of target and reference nucleus, and α is defined in [11] as

$$\alpha = (a + bx_F + cx_F^2) \times (1 + dp_T^2). \quad (5)$$

Table 2: Reduced χ^2 of fitting.

h_{out}	beam momentum section [GeV/c]					
	3–5	5–8	8–12.3	12–17.5	17.5–31	31–450
π^+ (NDF)	1.43 (549)	1.63 (732)	1.72 (889)	1.80 (554)	1.96 (471)	1.79 (691)
π^- (NDF)	1.41 (510)	1.53 (683)	1.51 (838)	1.57 (528)	1.25 (504)	2.10 (716)
K^+ (NDF)	–	–	–	–	–	0.80 (103)
K^- (NDF)	–	–	–	–	–	1.34 (89)
p (NDF)	1.02 (119)	1.66 (179)	1.50 (215)	2.24 (293)		1.26 (200)

The $f_{pd/pp}$ is introduced to explain the difference between nucleon-nucleon collision and nucleon-nucleus collision. Based on DPMJET-III simulation [13], we defined it as

$$f_{pd/pp} \equiv \exp\left(\sum_{i=0}^{2}\sum_{j=0}^{2} a_{ij} x_F^i p_T^j\right), \tag{6}$$

where a_{00} is fixed to 0. For proton production, we use

$$f_{IDCS}^{data} \equiv A(1 + Bx_F + Cx_F^2)(1 - x_F)^{bp_T^d}(1 + ap_T + \frac{(cp_T)^2}{2})e^{-ap_T} \times (A/A_0)^{\alpha}\,. \tag{7}$$

Parameters for Eq. (4) and (7) are determined by fitting the data. Because it is difficult to find a proper parameterization over whole beam momentum range, we divided the data into small sections based on their beam momentum as written in Table 2. The fitting was conducted for each section separately.

First we determined parameters of the α function by fitting HARP $\pi^\pm$ production data for Be, C, and Al targets. We calculated the ratio of $\frac{d^2\sigma}{dpd\Omega}$ of C or Al data to Be data. Using Eq. (4) the ratio is written as

$$R_{C(Al)/Be} = \left(\frac{d^2\sigma}{dpd\Omega}\right)_{C(Al)} / \left(\frac{d^2\sigma}{dpd\Omega}\right)_{Be} = \left(\frac{A_{C(Al)}}{A_{Be}}\right)^{\alpha}, \tag{8}$$

thus we could determine parameters of α directly. The α was derived for each section. For data with beam momentum > 12 GeV/c and for kaon and proton production data, α derived from HARP 12 GeV π^+ data were used with assuming the dependence of α on the particle types and beam momentum is small.

We then fitted Eq. (4) (or Eq. (7) for protons) for each section, by minimizing the χ^2:

$$\chi^2 \equiv \sum_i^{data} \frac{\left(\frac{d^2\sigma}{dpd\Omega}_i - < \frac{p_{out}^2}{E_{out}} f_{IDCS}^{data} >_i\right)^2}{\sigma_i^2} + \sum_j^{beam}\left(\frac{\Delta_j^2}{\sigma_j^2}\right), \tag{9}$$

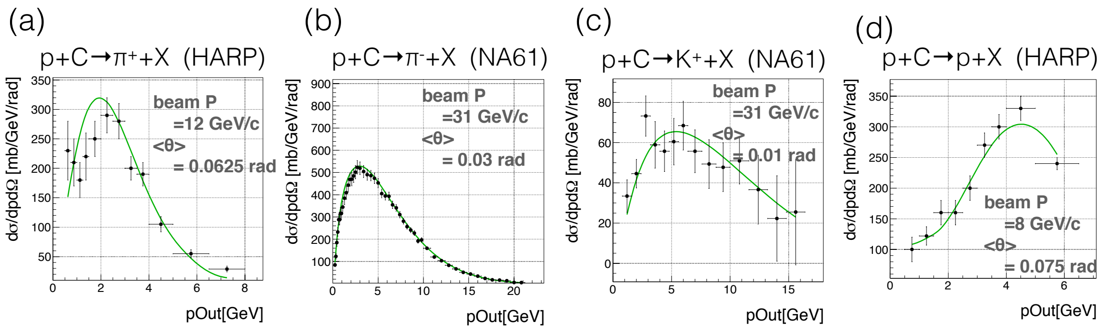

Figure 1: Examples of the fit result. Each example is taken from the fit result for the beam momentum section of (a) 8–12.3 GeV/c (b) 31–450 GeV/c (c) 31–450 GeV/c (d) 5–8 GeV/c.

where $\frac{d^2\sigma}{dpd\Omega}_i$ is the measured data of the i-th bin, $< \frac{p_{out}^2}{E_{out}} f_{IDCS}^{data} >_i$ is a fitting function averaged inside the i-th bin, and the $\sum_j^{beam}\left(\Delta_j^2/\sigma_j^2\right)$ explains the uncertainty of overall scale where summation is taken for all beam data. The reduced χ^2 is around 2 or less in all the sections, as summarized in Table 2. Some examples of fitting are shown in Fig. 1.

2.3 Derivation of $\left(\frac{d^3\sigma}{dp^3}\right)_{MC}$

In Honda MC, hadronic production is calculated based on JAM [12] model if the incident particle's kinetic energy is below 31.6 GeV, otherwise based on DPMJET-III [13] model. We evaluated the $\left(\frac{d^3\sigma}{dp^3}\right)_{MC}$ by running Honda MC. We generated $N_{gen} = 4.8 \times 10^8$ hadron interactions for each of the following incident momenta: p_{MC} = 11, 12, 14, 16, 17.5, 20, 25, 31, 33, 50, 75, 100, 158, 200, 300, 450 GeV/c, and every 0.5 GeV/c between 3–10 GeV/c.

2.4 Derivation of weight W

From the $\left(\frac{d^3\sigma}{dp^3}\right)_{data}$ and $\left(\frac{d^3\sigma}{dp^3}\right)_{MC}$ derived above, W in Eq. (3) was calculated for each p_{MC}. We represented W as a function of a Feynman-X x_F and a transverse momentum p_T. For any p_{in}, two W's are interpolated as

$$W(p_{in}, x_F, p_T) = \frac{W(p_{MC2}, x_F, p_T) - W(p_{MC1}, x_F, p_T)}{\log p_{MC2} - \log p_{MC1}} \times (\log p_{in} - \log p_{MC1}) + W(p_{MC1}, x_F, p_T), \tag{10}$$

where p_{MC1} and p_{MC2} are the two p_{MC}'s closest to a given p_{in}. For interactions with $p_{in} > 450$ GeV/c, we use W for $p_{in} = 450$ GeV/c with assuming that Feynman scaling is well conserved in such high energy interaction. For $p_{in} < 3$ GeV/c for pion or proton production or $p_{in} < 31$ GeV/c for kaon production, we set $W = 1$. For a given (x_F, p_T), we required that at least one of the beam data used for the fitting cover the (x_F, p_T), otherwise $W = 1$. Some examples of the weights are shown in Fig. 2.

3. Result of tuning

We simulated the neutrino flux with applying the weight W. The preliminary result is shown in Fig. 3. The flux is almost consistent with the one previously reported in Ref. [2] within its

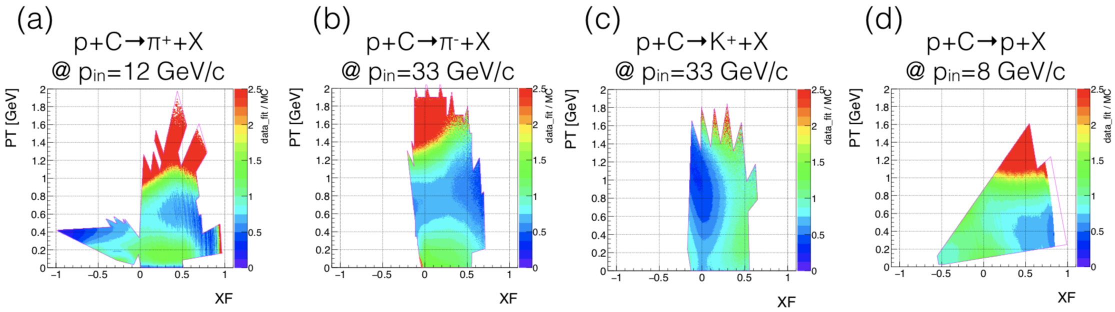

Figure 2: Weight W in Eq. (3) as a function of x_F and p_T. In uncolored region W is set to 1.

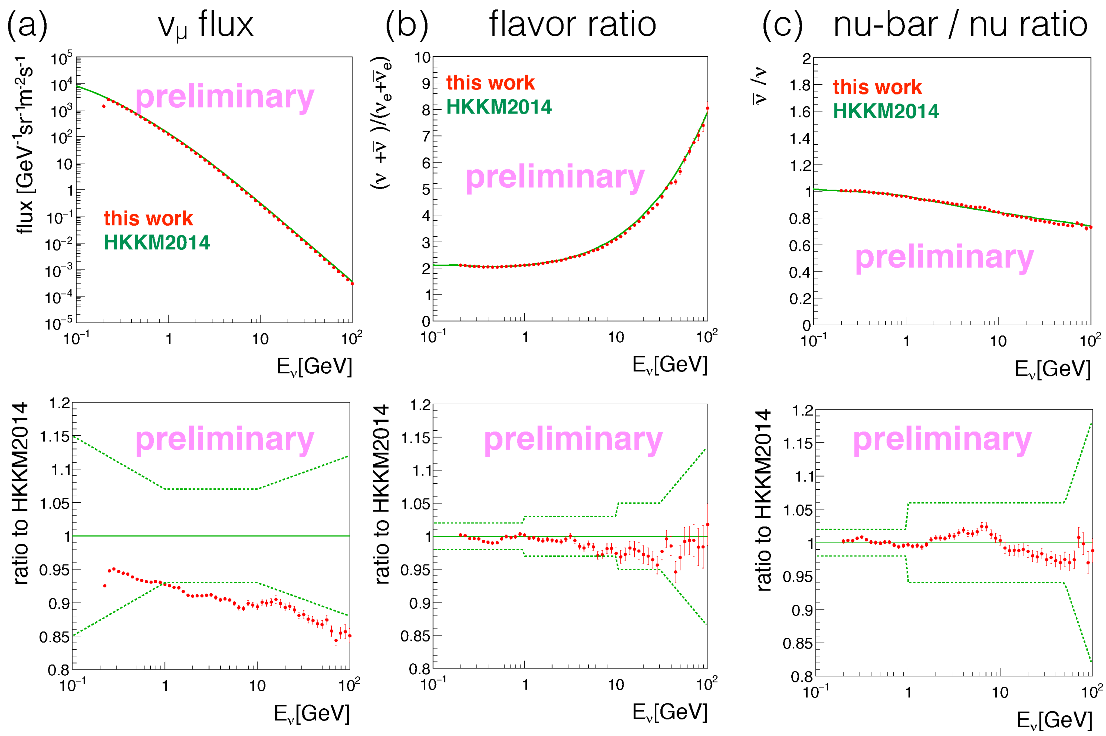

Figure 3: Result of accelerator tuning (preliminary). Red dots shows our result of accelerator-driven tuning. Thier error bars shows MC statistical error only. Green solid line shows "μ-tuned" simulation reported by *Honda et. al.* [2], and dashed line represents its systematic error. Top plots show (a) ν_μ flux. (b) flavor ratio $((\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e))$. (c) $\bar{\nu}_\mu/\nu_\mu$ ratio. Bottom plots show their ratios to [2].

systematic error, though it has a tendency to be ~5–10% smaller. The ν_μ/ν_e ratio and $\bar{\nu}_\mu/\nu_\mu$ ratio are also shown in the figure. They are also consistent with Ref. [2] within a few %.

4. Summary

We are implementing the accelerator-data-driven tuning into Honda flux MC. Several hadron production measurements in beam experiments with beam momentum from 3 to 450 GeV/c have been considered. We constructed a function to describe differential cross-sections and succeeded in fitting the beam data with the function. It allows us to evaluate "weight" to correct the difference of the differential cross-sections between data and MC. Though the neutrino flux prediction was modified ~10% smaller with applying the weight to the MC, still the modified flux is in agreement with the previous Honda flux within its uncertainty.

The accelerator-data-driven tuning should complement the conventional tuning using atmospheric muons. The combined analysis of the accelerator tuning and the muon tuning is a topic for future study and will be able to reduce the systematic uncertainty of the flux prediction.

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] 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).

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

[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).

[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.