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

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@ ICRC2021

- tune the **Honda flux simulation** by using **accelerator hadron measurements**

Honda flux simulation

atmospheric neutrino : signal for physics (oscillation, etc...)

→ the **prediction of its flux** is necessary

Honda flux MC

developed by M. Honda (U of Tokyo, ICRR)

[PRD 92, 023004 (2015) and references in it]

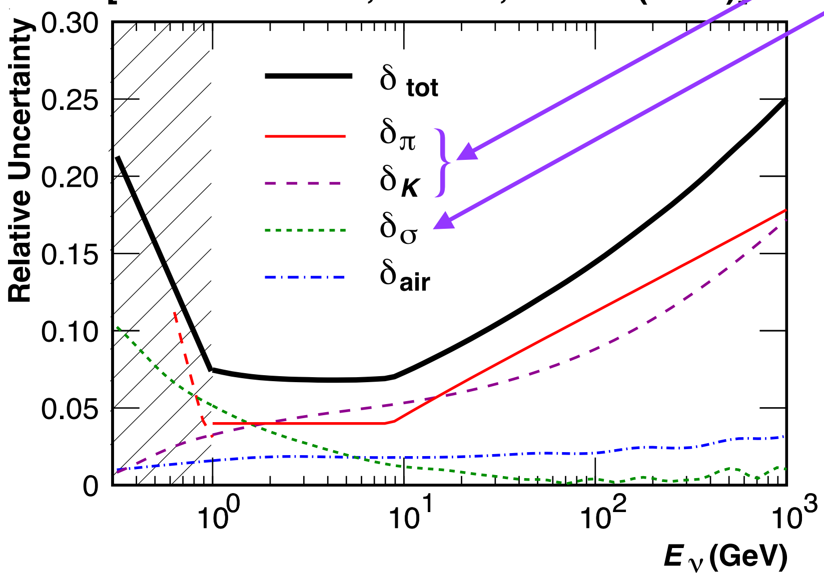
- full MC simulation for air shower

→ provides $\boldsymbol{\nu_\mu}$, $\boldsymbol{\bar{\nu}_\mu}$, $\boldsymbol{\nu_e}$, $\boldsymbol{\bar{\nu}_e}$ **flux** at any detector position

- **3D** simulation
  - air density model **NRLMSISE-00**
  - geomagnetic model **IGRF**
  - precise primary particle flux based on **AMS02** data
- has been widely used (e.g.: Super-Kamiokande analysis)
- FORTRAN code

uncertainty of atm. ν flux

uncertainty of Honda flux
(except primary flux err ~5%)
[M. Honda et. al, PRD75, 043006(2007)]



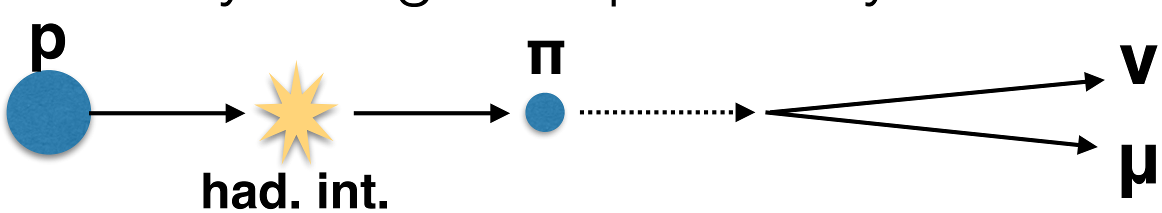
hadron production
hadronic cross-section

- ***hadronic interactions in air shower***

→ ***dominant!***

- Hadronic Model
  - **JAM** (E<31GeV)
  - **DPMJET-III** (otherwise)

- tuned by using atm. μ data by Honda-san

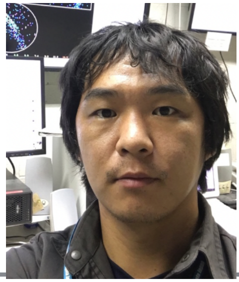


limitation of tuning

- low E_ν (<1GeV): E deposit of μ
- high E_ν (>10 GeV): K contribution

activity of Nagoya ISEE CR group

K. Sato



H. Menjo

Y. Itow

accelerator-data-driven tuning

- several beam experiments are conducted

  HARP, BNL E910, NA61/SHINE …

- present precise $\frac{d\sigma}{dp d\Omega}$ of hadron production
- mainly for long-baseline ν experiment

→ **incorporate these measurement into Honda flux**

Maybe the measurement data is insufficient but…

- can **reduce uncertainty** by combining the muon study
- can reveal **which phase space is important for atm. ν** production, and **feed back to the beam experiment**
- common treatment of sys. error between **T2K-SK**

tuning (weighting method)

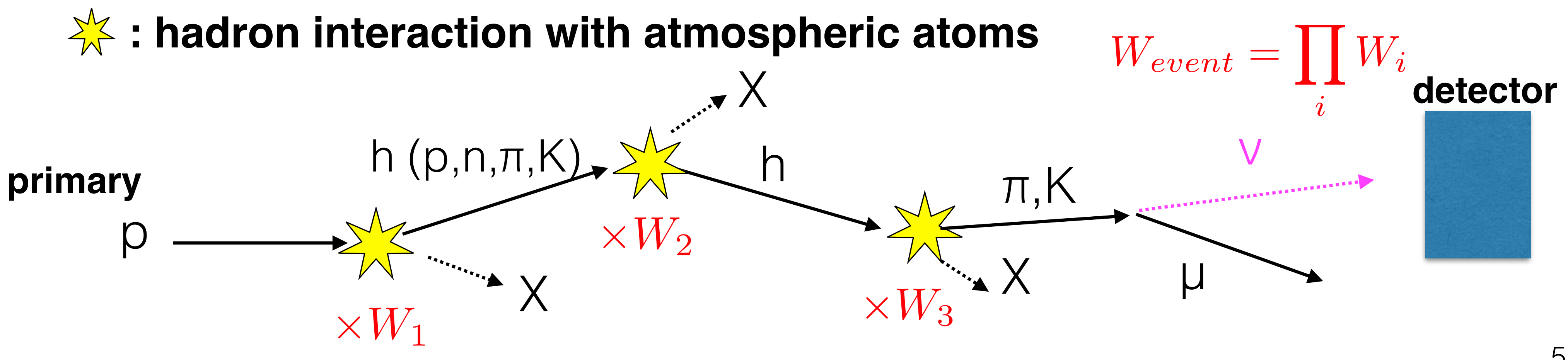
What we want to do:

- correct difference of differential cross-section between data and MC

  → apply the *weight*

$$W = \frac{\left(E\frac{d^3\sigma}{dp^3}\right)_{data}}{\left(E\frac{d^3\sigma}{dp^3}\right)_{MC}}$$

for each hadron interaction in Honda flux MC



accelerator data

- HARP p+(Be,C,Al) → (π±,p)+ X
  PRC80, 035208 (2009), PRC 82, 045208 (2010)
  PRC77, 055207 (2008)

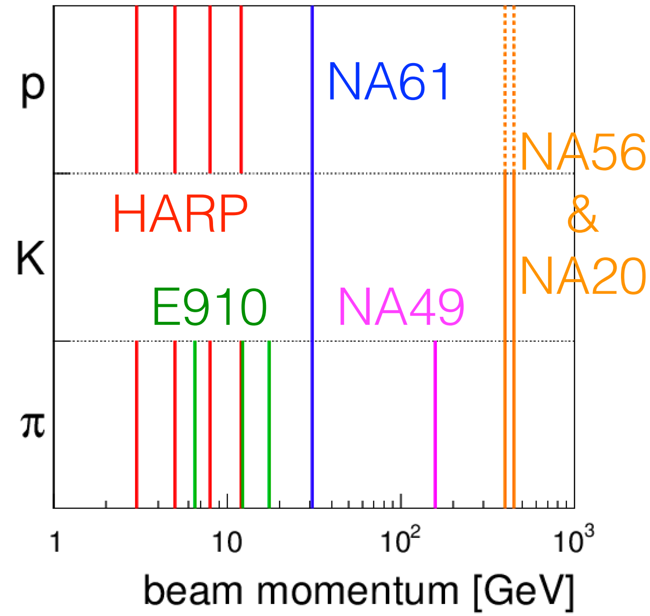
- BNL E910 p+Be → π± + X
  PRC 77, 015209 (2008) and its Erratum

- NA61 p+C → (π±,K±,p) + X
  EPJ. C 76, 84 (2016)

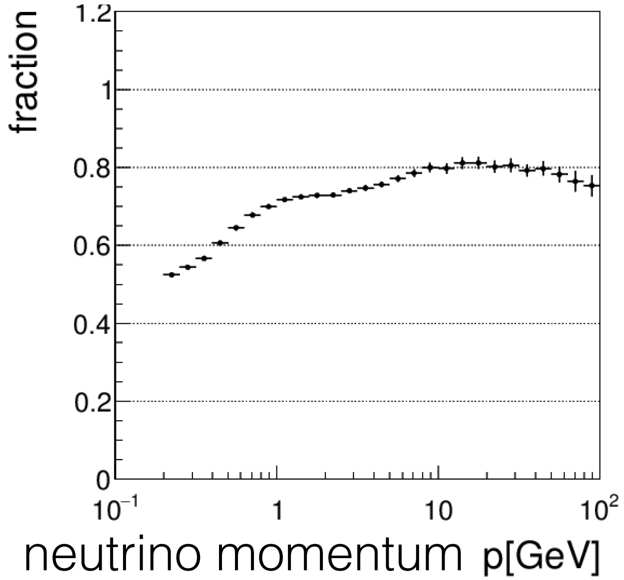
- NA49 p+C → π± + X
  EPJ. C 49, 897 (2007)

- NA56, NA20 p+Be → (π±,K±,p)+ X
  from M. Bonesini et. al. EPJ C20, 13, (2001)

beam P and particle type



coverage of phase space related to ν_μ production



- These beam data cover
  > 70% of phase space for >1GeV ν production

parameterization

data : discrete beam P & finite binning → parameterization

fitting function

$$E\frac{d^3\sigma}{dp^3} = f_{BMPT} \times \left(\frac{A}{A_0}\right)^{\alpha} \times f_{pd/pp}$$

$Ed^3\sigma/dp^3$ of p+p

for π,K : BMPT parameterization

for p :

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

$$f = A(1 + Bx_F + Cx_F^2) \times (1 - x_F)^{bp_T^d}$$
$$\times \left(1 + ap_T + (cp_T)^2/2\right) \exp(-ap_T)$$

dependence of atomic mass derived from HARP data

difference of p+p and p+A_0

$= \exp(\sum_{i=0}^{2}\sum_{j=0}^{2} a_{ij}x_F^i p_T^j)$ for π, K,

= 1 for p

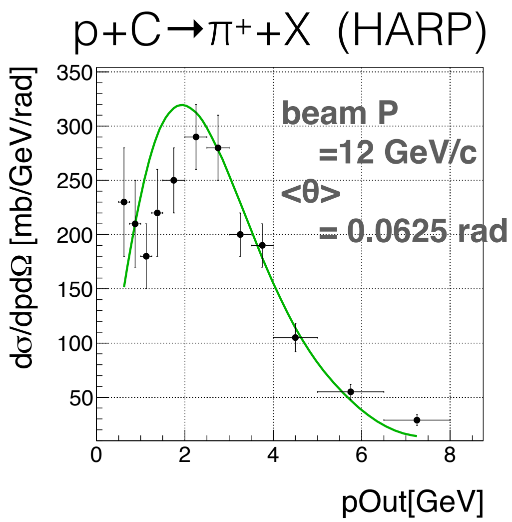
parameterization

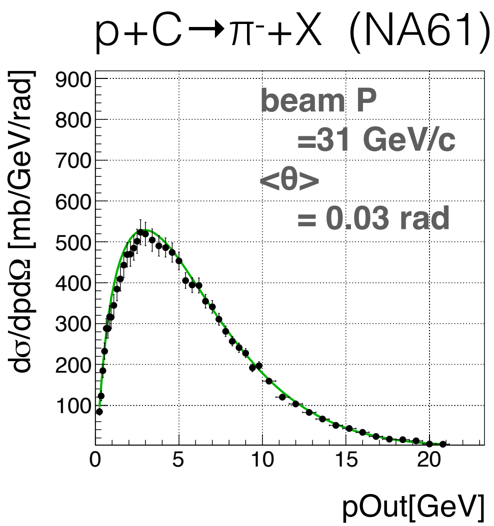
difficult to parameterize beam energy dependence
→ divide into small E sections. fitting for each section.

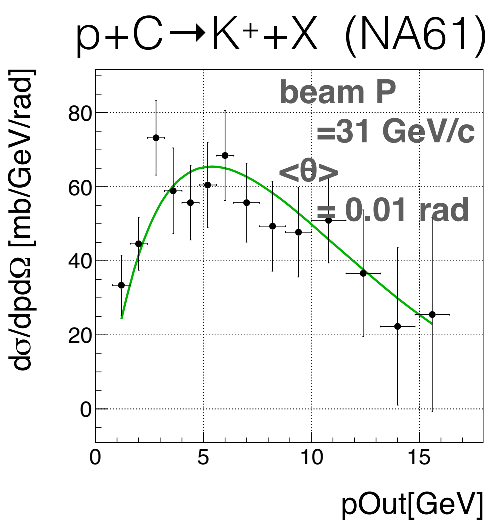
fitting reduced chi-square

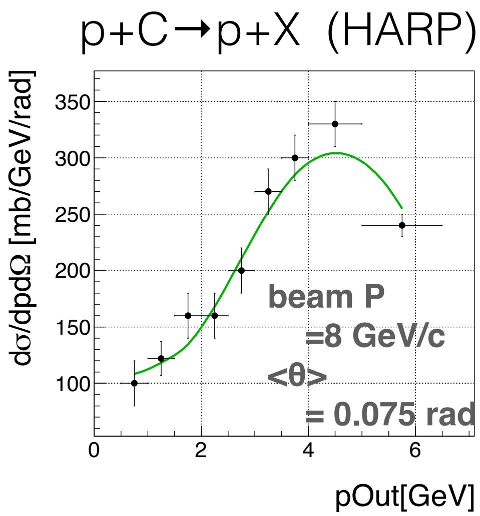
p_{beam}	3 ⟷ 5	5 ⟷ 8	8 ⟷ 12	12 ⟷ 17.5	17.5 ⟷ 31	31 ⟷ 450 [GeV]
π^+	1.43	1.63	1.72	1.80	1.96	1.79
π^+	1.41	1.53	1.51	1.57	1.25	2.10
K^+			--			0.80
K^-			--			1.34
p	1.02	1.66	1.50	2.24		1.26

☞ success to parameterize reduced X^2 = 1~2



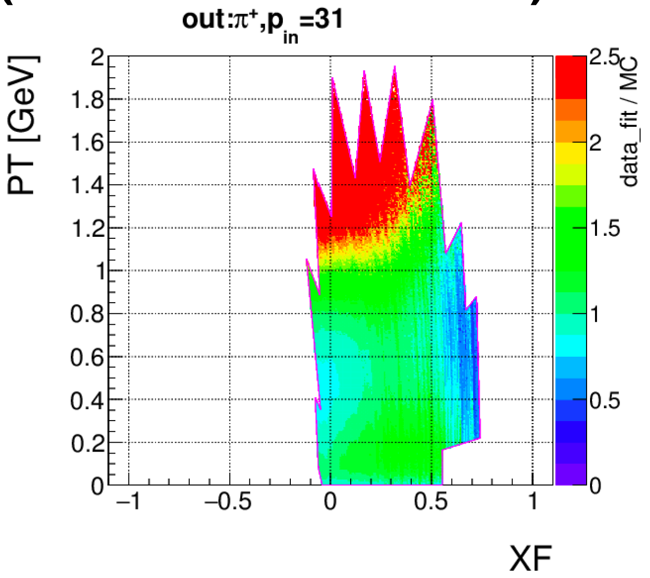






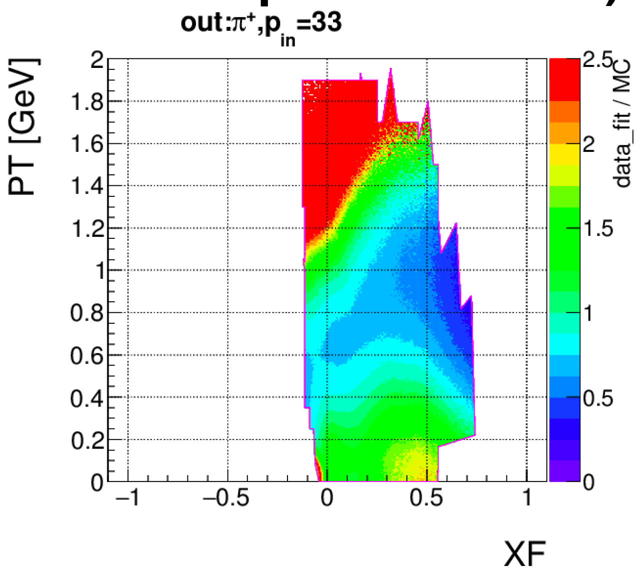
weight table

for p(31 GeV) + Air → π⁺ + X
(MC uses JAM model)



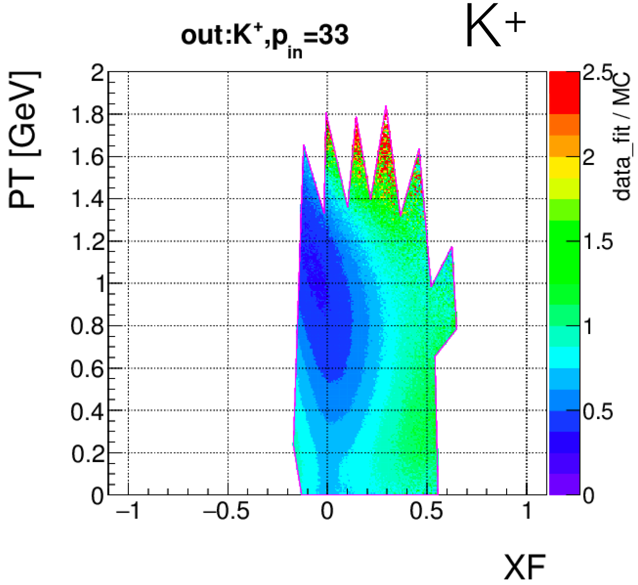
- make a *table* of weight $W = \frac{\left(E\frac{d^3\sigma}{dp^3}\right)_{data}}{\left(E\frac{d^3\sigma}{dp^3}\right)_{MC}}$
- prepare 35 tables in p_{in} =3--400 GeV
- MC uses JAM (E<31GeV), dpmJet3 (>31)
  - JAM is in better agreement with data

for p(33 GeV) + Air → π⁺ + X
(MC uses dpmJet3 model)

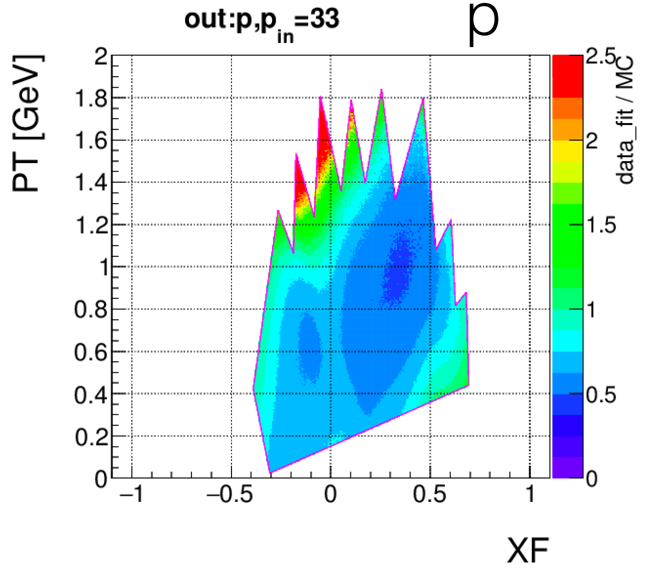


for p(33 GeV) + Air → (K⁺, p) + X
(MC uses dpmJet3 model)

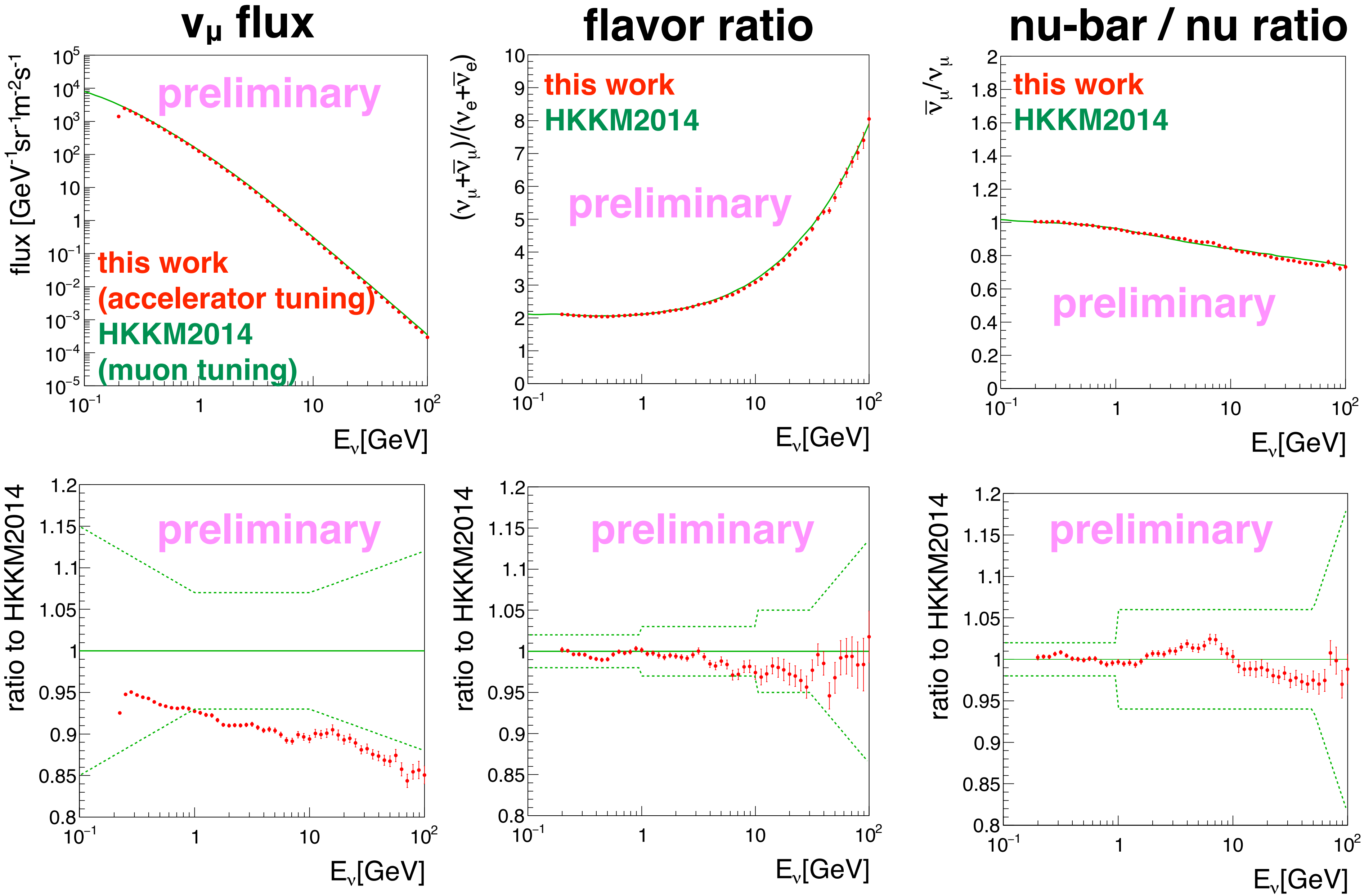
K⁺



p



result of weighting



with accelerator tuning : 5-10% smaller flux
small effects on flavor ratio, ν / ν ratio

→ **almost consistent**

Summary

Nagoya group acitivity

- upgrading **Honda flux MC**
  - preparing manuals
  - Fortran → C++ interface
  - **implementing accelerator-data-driven tuning**

- correct the difference of $d^3\sigma/dp^3$ between data and MC
  - data from NA61, NA49, HAPR, BNL-E910, NA56/SPY...
    - success to parameterize in 3--450 GeV/c beam P.
      - reduced chi2 < ~2

- preliminary result
  - **consistent** with the conventional flux
    - tendency to be ~5--10% smaller
- future plan
  - combined analysis of **accelerator tuning and μ tuning**

  → reduce systematic uncertainty