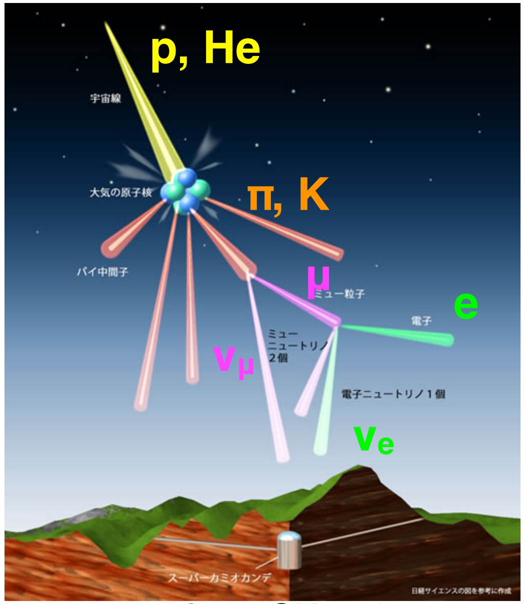
low energy atm. neutrino flux

Sato Kazufumi (ICRR, U of Tokyo)
2 June 2022 @ Neutrino2022

atmospheric neutrino (atm. ν)



from SK web page

primary cosmic-ray particles (p,He,...) hit to air nucleus
→ develop hadronic shower
→ decay of π, μ, K -> **ν**

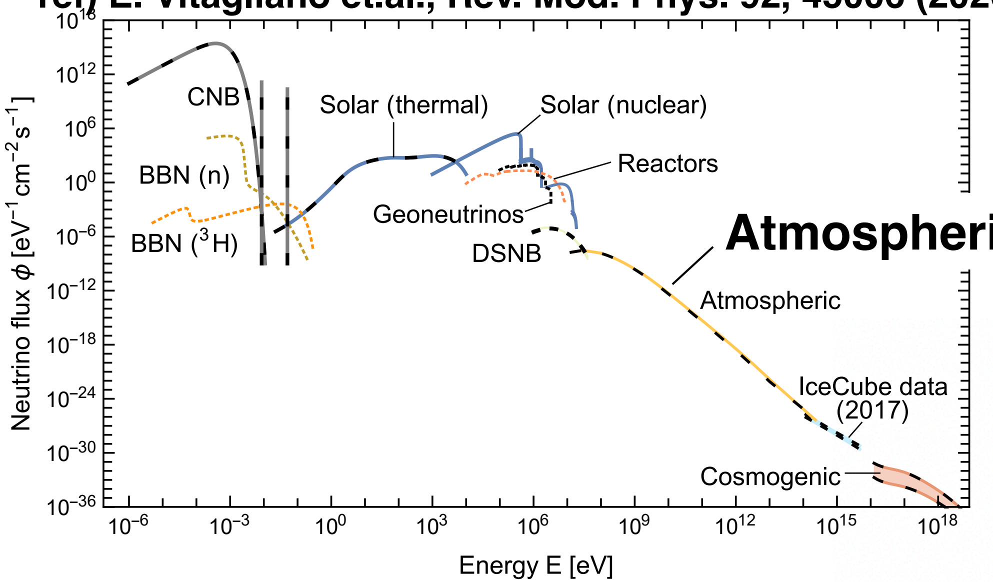
atm. ν's

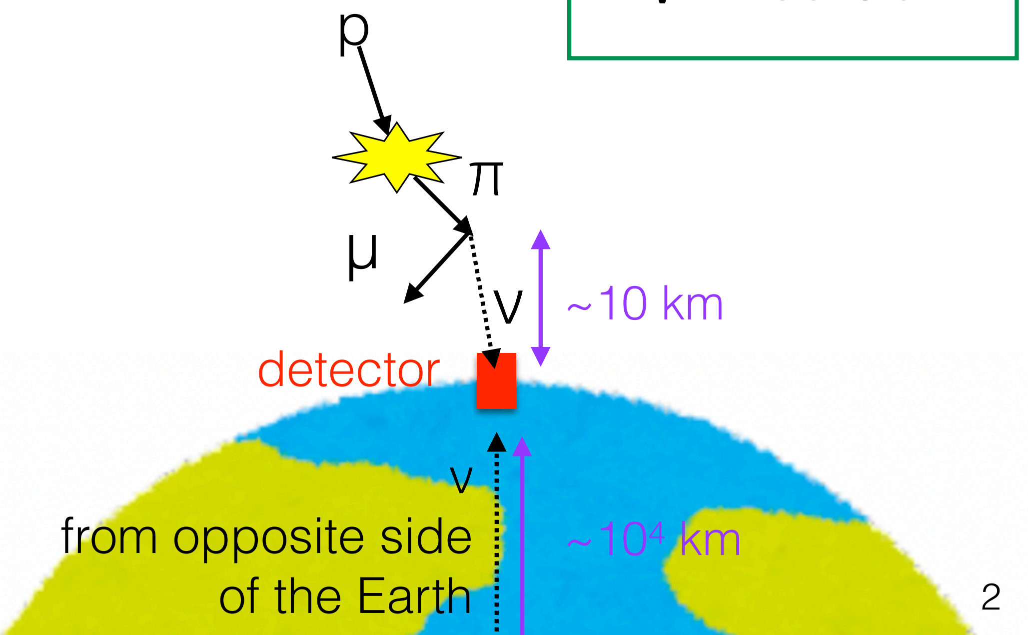
- E_ν : O(10) MeV — O(10) TeV
- flight length L : 10 — O(1e4) km

In this talk, focus on E_ν < 100 GeV

natural neutrino source

ref) E. Vitagliano et.al., Rev. Mod. Phys. 92, 45006 (2020)



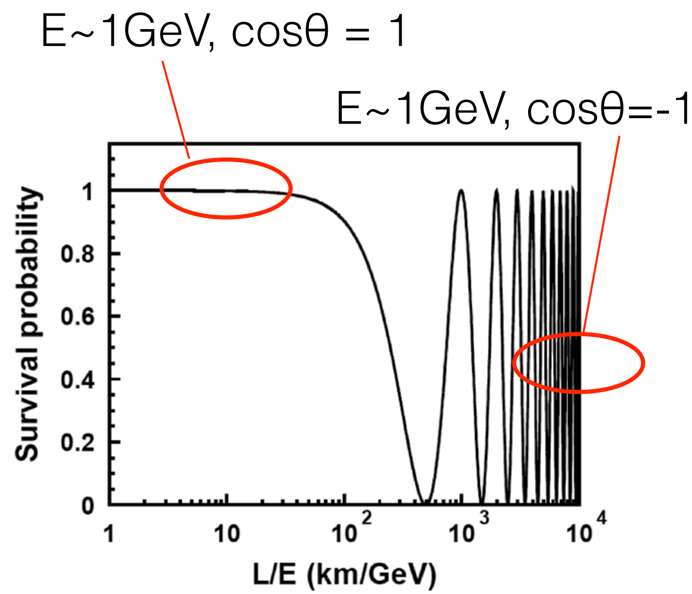


physics of low energy neutrinos

As a physics target

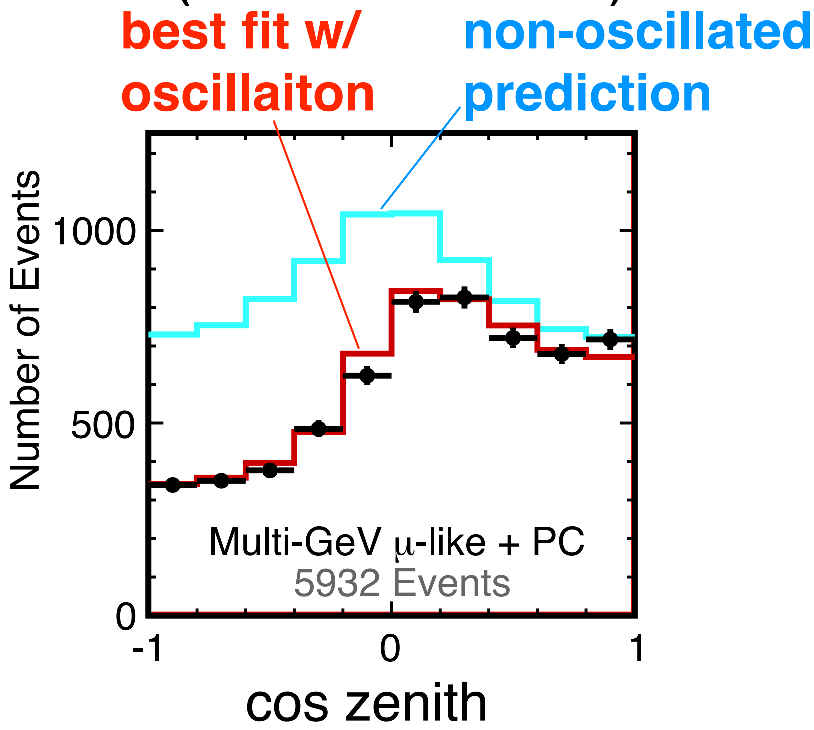
★ discovery of **ν oscillation** in 1998
- ν_μ deficit in large L/E region

★ sensitivity for **δ_{CP}** and **Mass ordering** in future big ν detectors

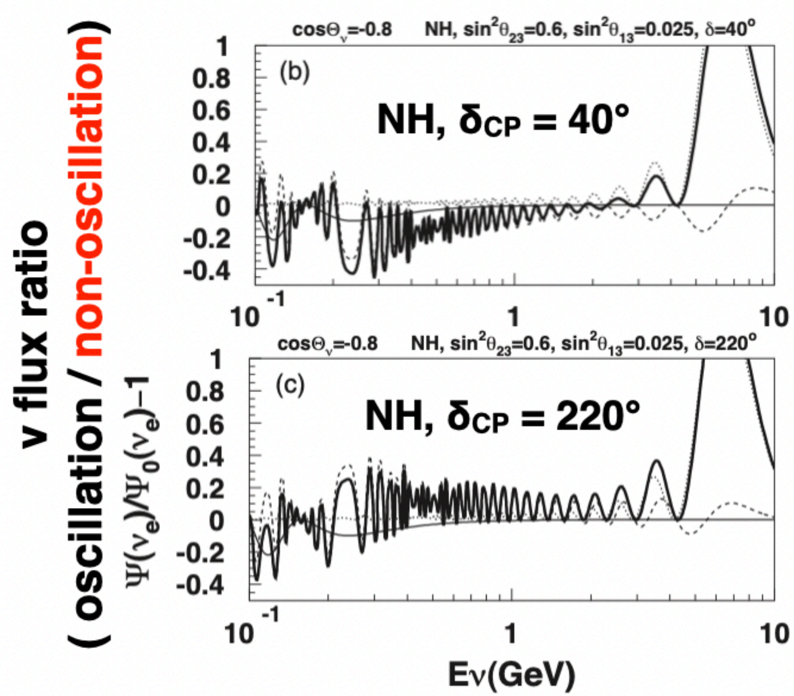


ν oscillation observed in SK

(from IPMU News vol. 15)



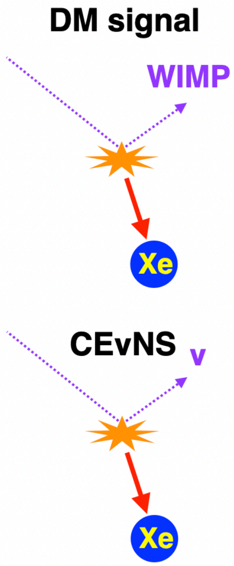
from HK design report



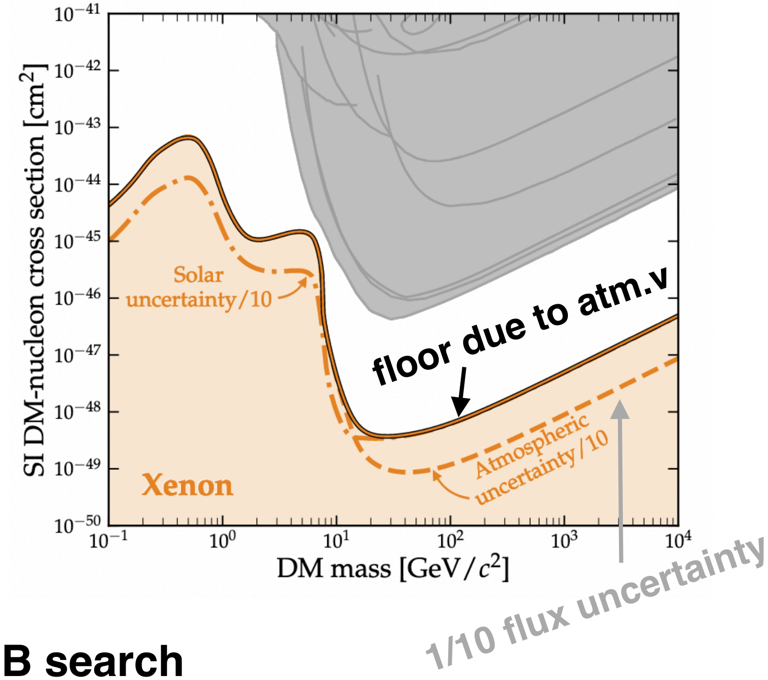
physics of low energy neutrinos

As an important background

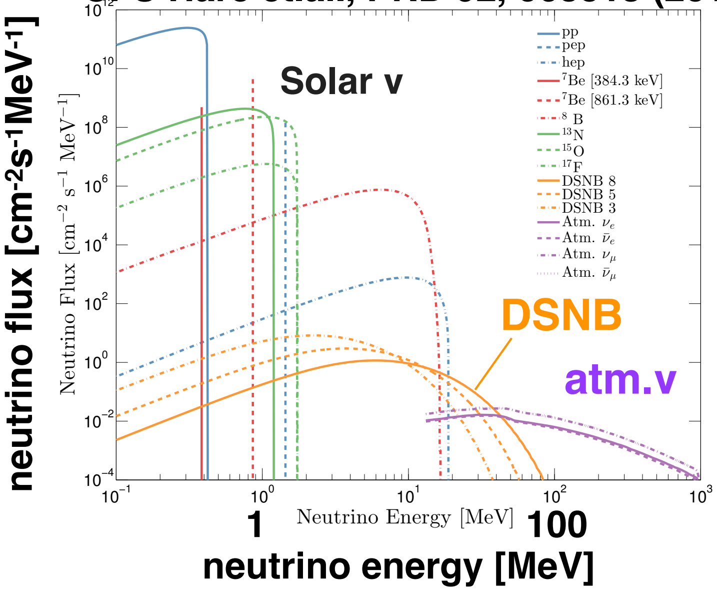
- Direct Dark Matter search
  - 40--100 MeV atm. ν can be ultimate BG = neutrino floor
- Diffuse Supernova BG (DSNB)
  - predicted in 20--40 MeV = excess on atm. ν BG
- Proton decay, Indirect DM search, etc...



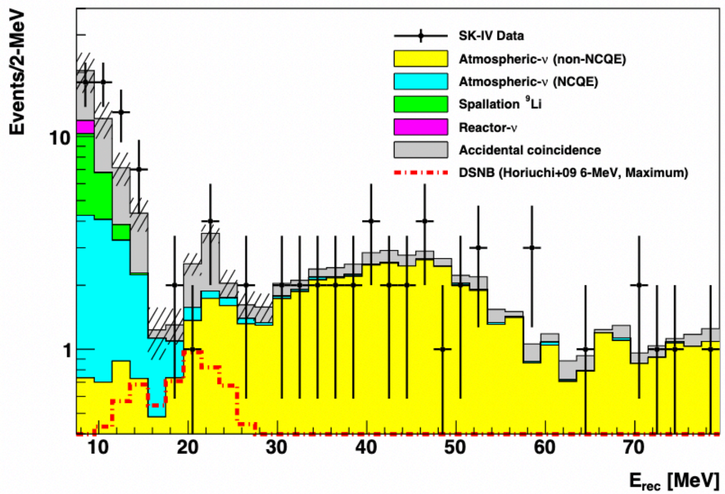
neutrino floor
C. O'Hare, PRL 127, 251802 (2021)



neutrino sources in 0.1--1000 MeV
C. O'Hare et.al., PRD 92, 063518 (2015)



DSNB search
SK group, Phys. Rev. D 104, 122002 (2021)



flux prediction

flux of $\nu_{\mu,e}$

$$\phi_{\nu_i} = \sum_A \phi_A \otimes R \otimes Y_{A \to \nu_i}$$

A : primary nuclei
- p : 75%
- He : 15%
- others : ~10%

flux of primary cosmic-ray

Transportation in geomagnetic field and atmosphere

Yields of ν through hadronic interactions

☞ use numerical calculation

- Monte Carlo technique
  - Honda
  - Bartol
- solve cascade equation
  - MCEq

3D simulation → **low E**

1D calculation → **high E**

flux prediction

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flux of primary cosmic-ray

Transportation in **geomagnetic field** and atmosphere

+ **transverse momentum of secondaries**

*** 1D-3D difference in low E**

- **for E_ν < O(1GeV)** horizon enhancement
- **for E_ν < O(10GeV)** East-West effect

Yields of ν through hadronic interactions

☞ use numerical calculation

- Monte Carlo technique
  - Honda
  - Bartol
- solve cascade equation
  - MCEq

3D simulation → **low E**

1D calculation → **high E**

source of uncertainty

flux of $\nu_{\mu,e}$

$$\phi_{\nu_i} = \sum_A \phi_A \otimes R \otimes Y_{A\rightarrow\nu_i}$$

uncertainty of hadron production

Yields of ν through hadronic interactions

Transportation in geomagnetic field and atmosphere

*** 1D-3D difference in low E**

flux of primary cosmic-ray

uncertainty of primary flux measurements

- dominant uncertainty arises from
  - **primary CR flux**
  - **hadron production cross-section**

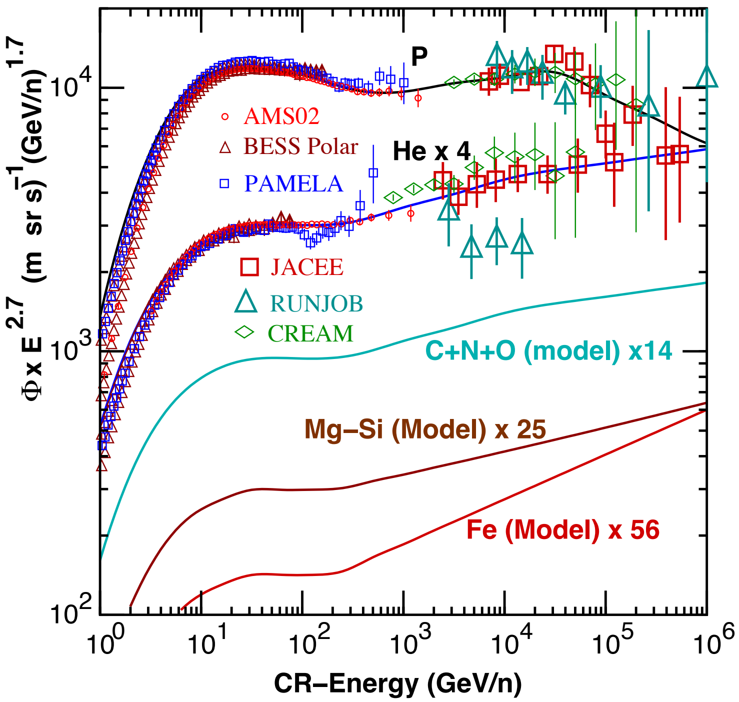
→ Reducing these uncertainties is a key for accurate prediction

primary cosmic-ray flux

- Provided by satellite-based & balloon experiments
  → Improvement in recent data reduces uncertainty

Primary CR flux

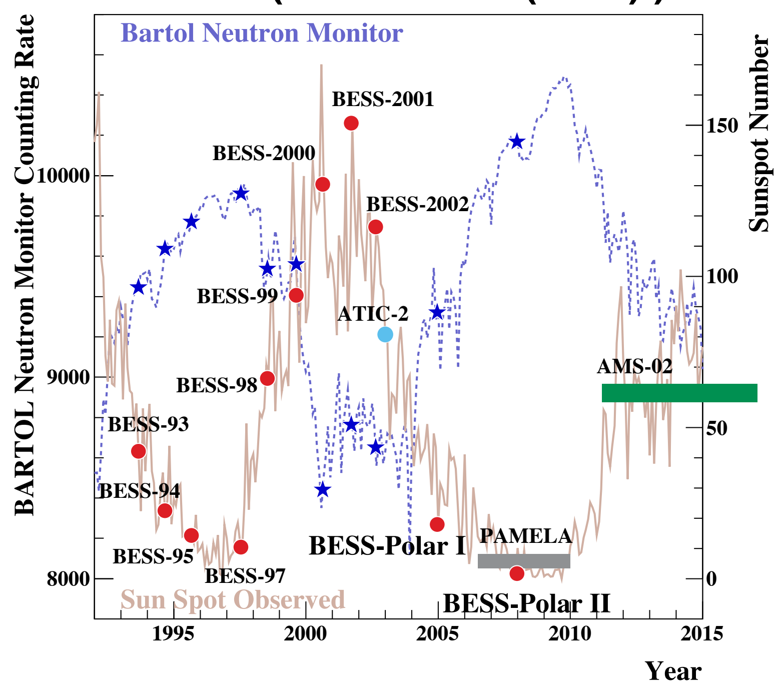
M. Honda et.al., PoS ICRC2017, 1022



← AMS-02 provides flux up to 1 TeV with < few% accuracy

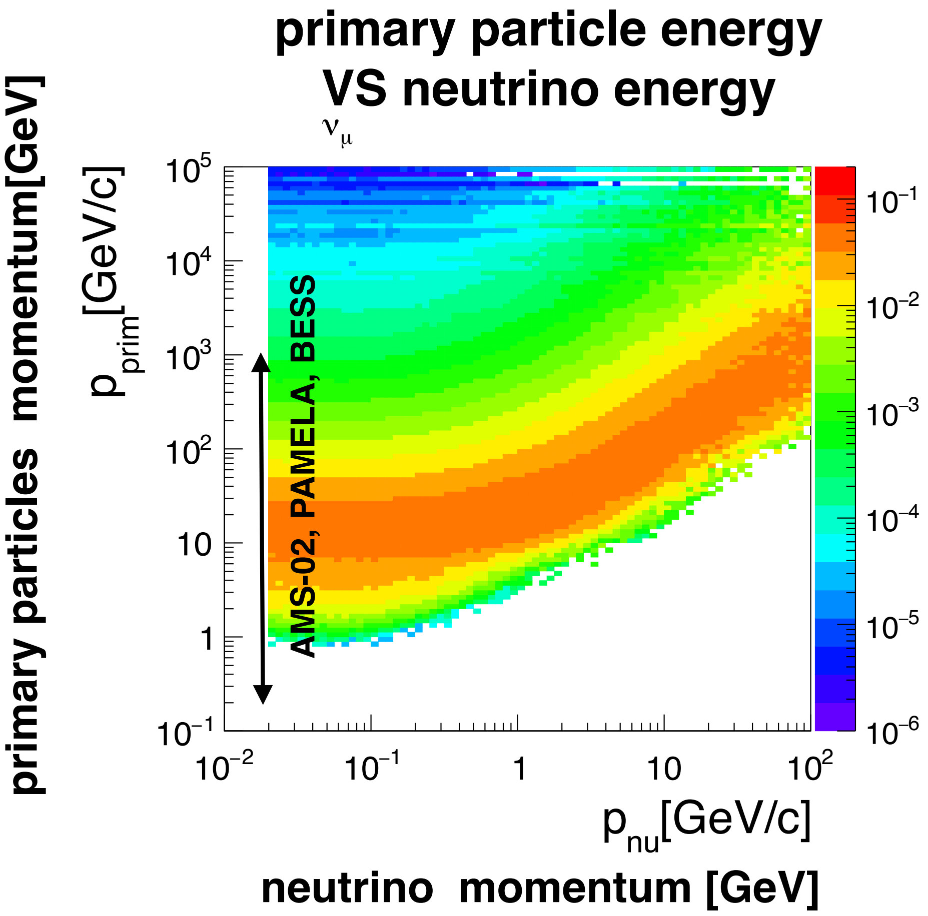
Data taking period and Solar activity

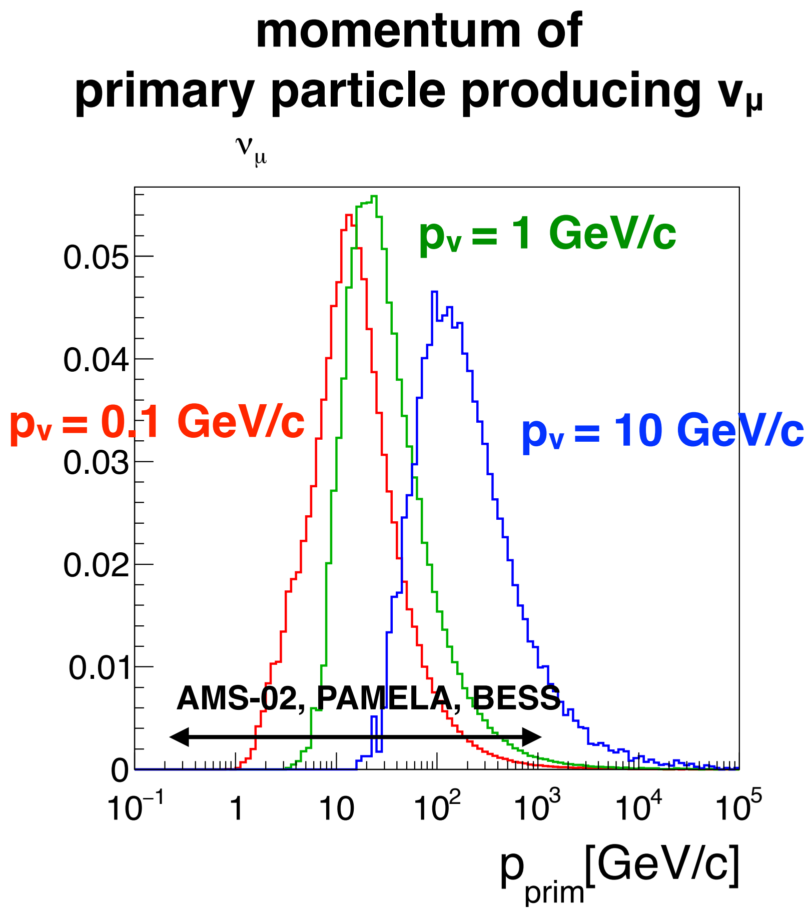
BESS (APJ 822 65 (2016))



data covers >20 years solar activity →

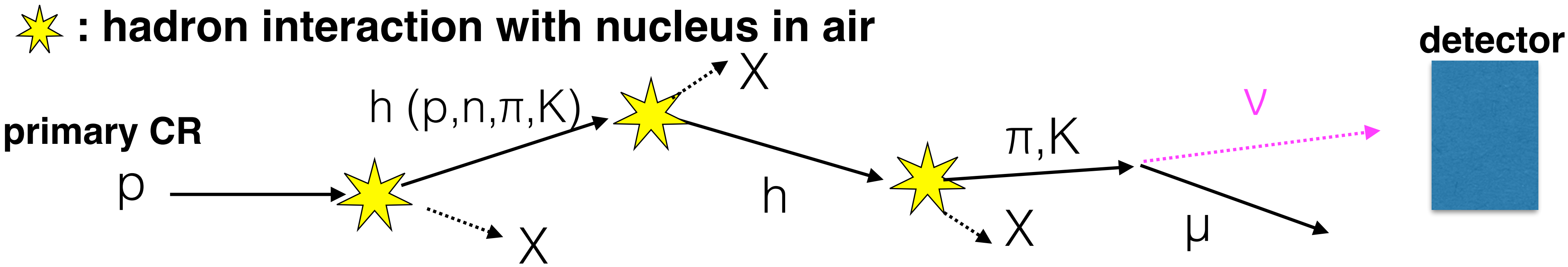
primary particle energy of interest





- Accurate measurement of primary flux up to 1TeV
  = improvement for E_ν < 10GeV ν flux accuracy

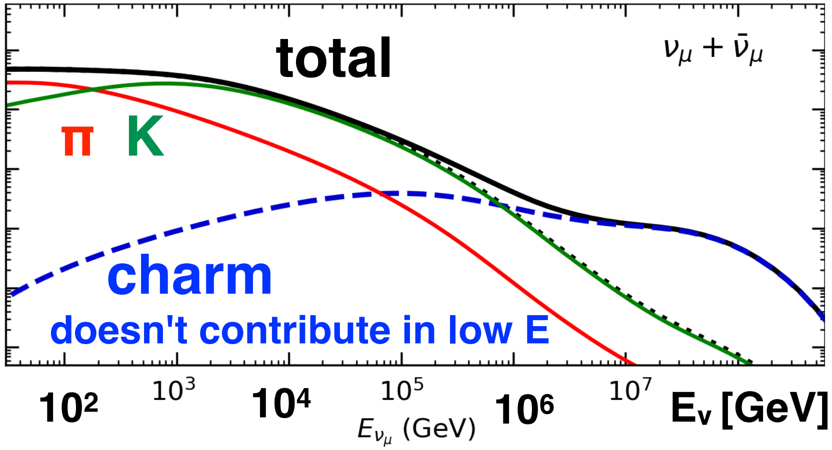
hadronic interactions



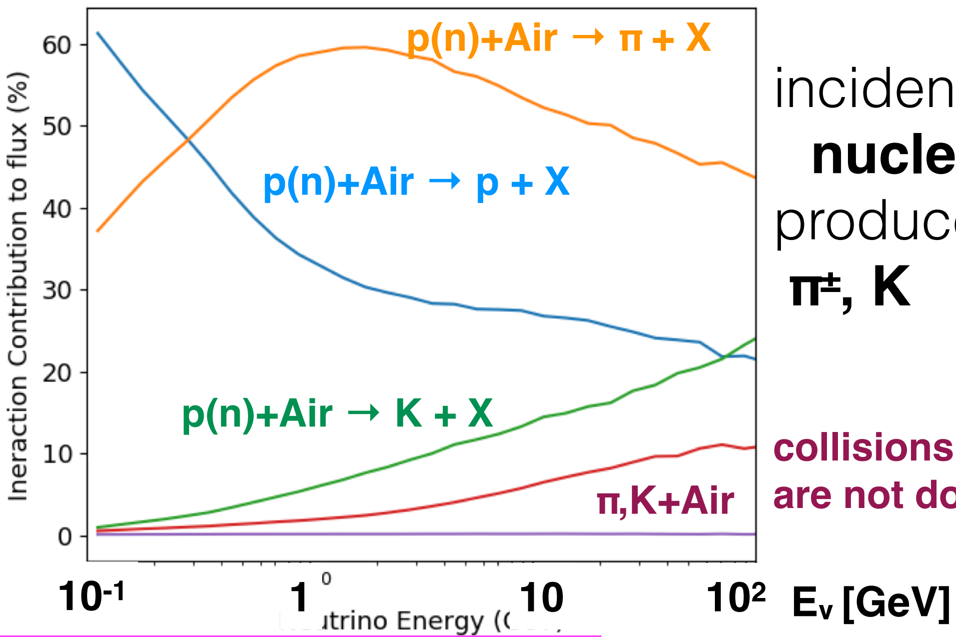
- chain of hadron interactions before producing ν

→ hadron production $d^3\sigma/dp^3$ on each vertex contributes to ν flux uncerainty

parent hadron of ν_μ
A. Fedynitch et.al. PRD100, 103018 (2019)



types of hadron interactions on the chain
(plot by L. Cook w/ Bartol flux simulation)



incident particle:
nucleon
produced meson:
π±, K

collisions of meson-Air are not dominant.

→ p + Air → π,K + X is important

accelerator-data-driven tuning

Hadronic interactions are calculated with event generator

Honda flux MC : JAM & dpmJet3 with tuning based on atm. μ

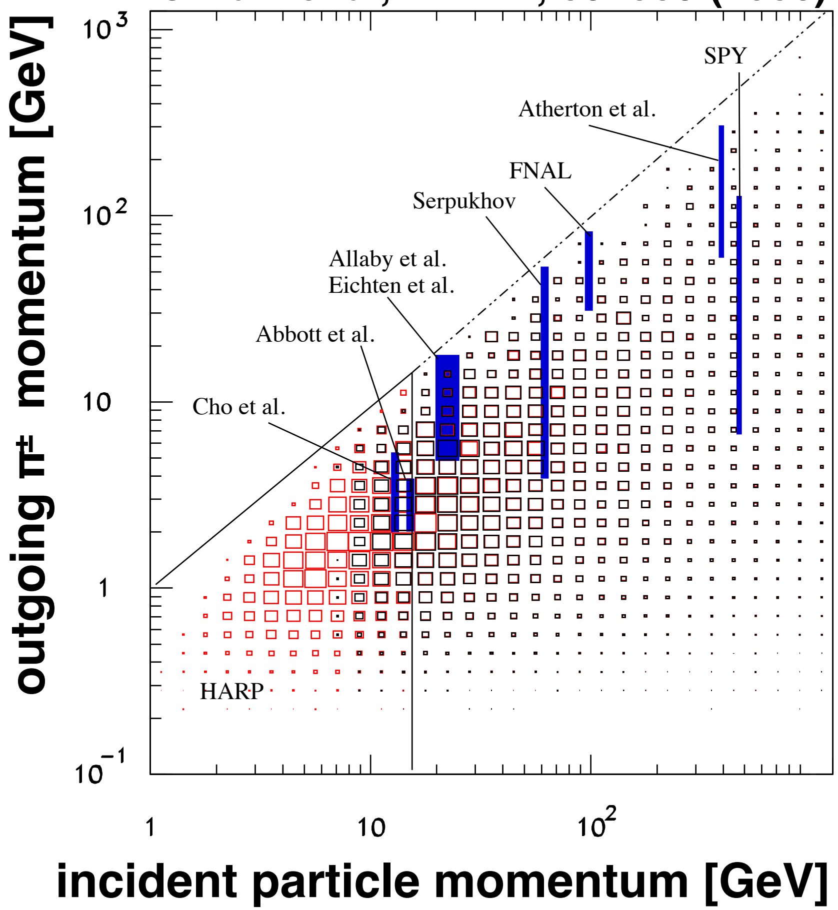
Bartol flux MC : Target 2.4

→ activity for **accelerator-data-driven tuning** has started.

Nagoya group : K. Sato, Y. Itow, H. Menjo (+ M. Honda)

Bartol group : L. Cook, G. Barr, M. Hartz (+T.K Gaisser, T. Stanev)

G.Barr et.al, PRD74, 094009 (2006)



- Tune the hadron interactions in MC based on **accelerator data**

Both group are working independently
→ **cross-check**

accelerator-data-driven tuning

Hadronic interactions are calculated with event generator

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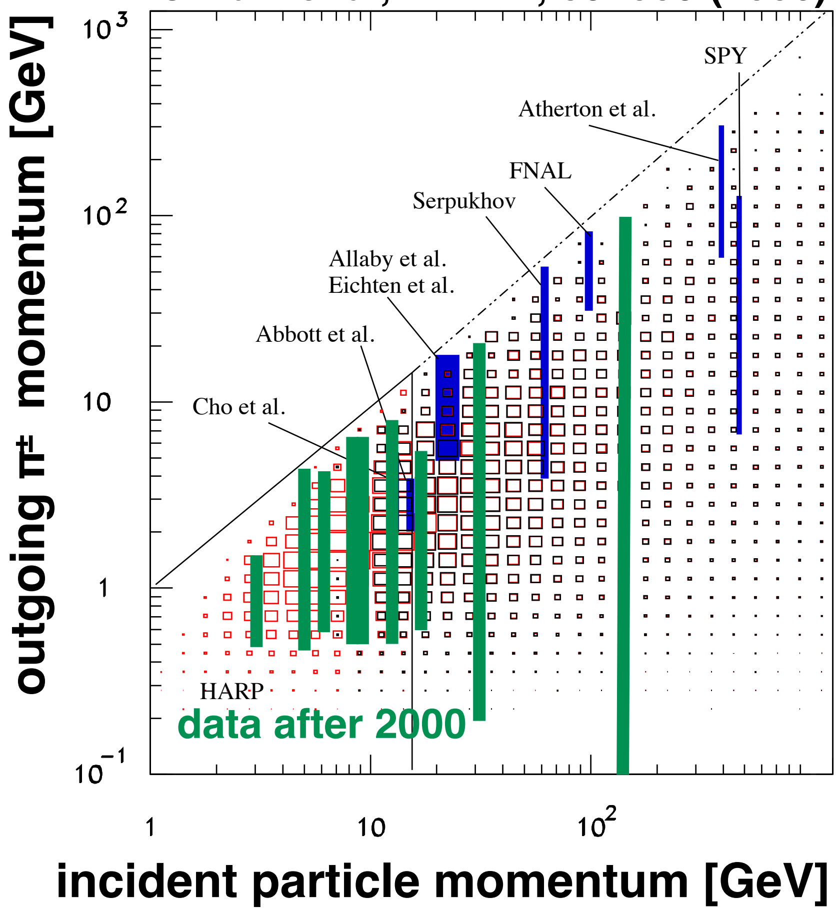


$\pi^{\pm}$ & $K^{\pm}$ production meas. in 2000s

- **NA61, NA49, HARP, E910,** ...

→ tune the differential cross-section for hadron production in MC

weight for tuning:

$$w = \frac{\left(\frac{d\sigma}{dpd\Omega}\right)_{data}}{\left(\frac{d\sigma}{dpd\Omega}\right)_{MC}}$$

based on measurements

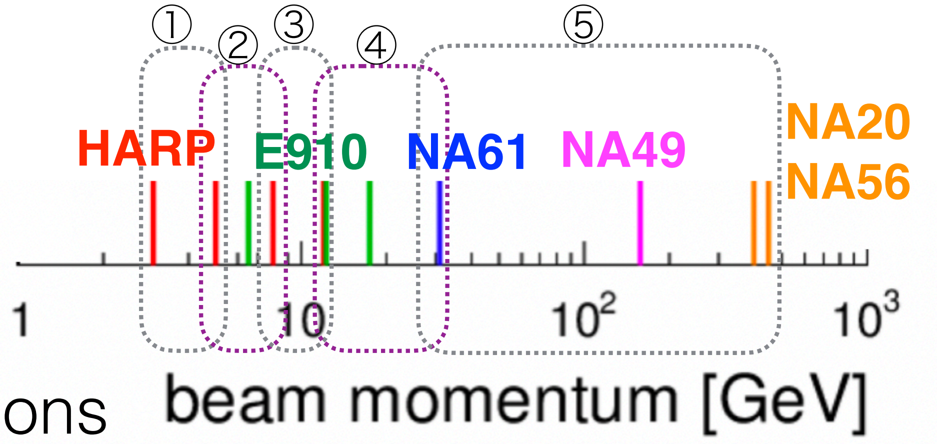
used in MC

Nagoya group data fit

Interpolation between discrete beam E is a challenge.

- Feynman scaling is not applicable.

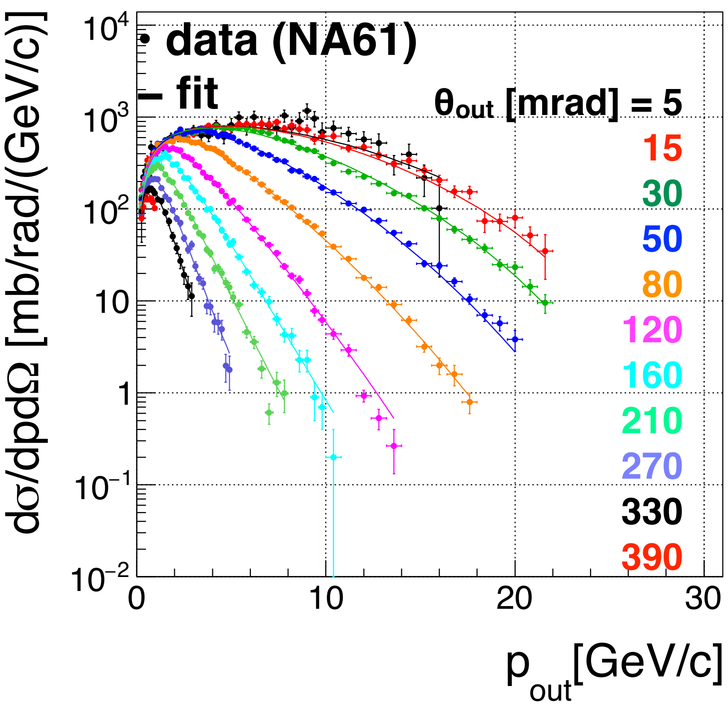
→ grouped beam data into small sections

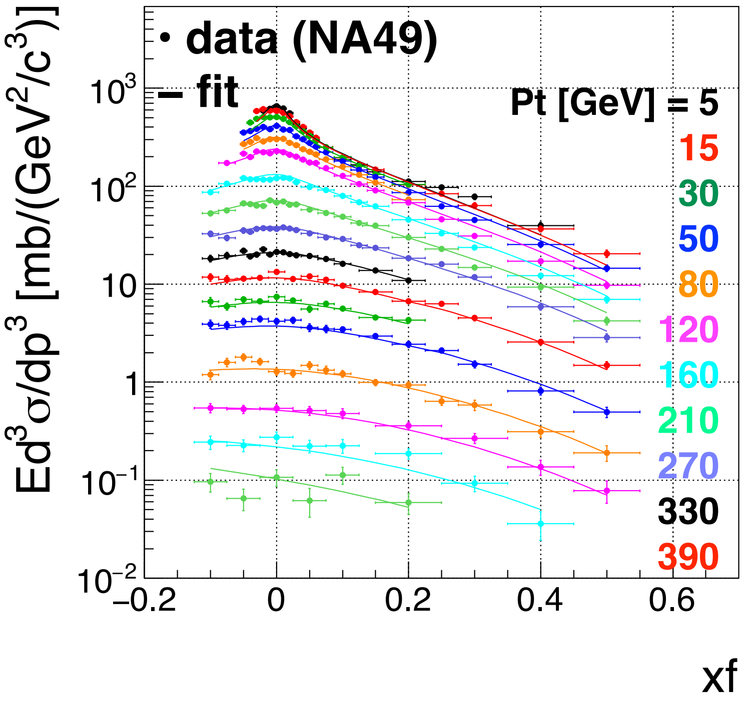


$$f_{fit} = f_{pp} \times f_{pA_0/pp} \times f_{A/A_0} \times \left(1 + C_1 \log_{10} \frac{p_{beam}}{C_2}\right)$$ **beam E dependence**

result of simultaneous fit for π+ data in group ⑤ (NA61, NA49, NA56)

χ² /NDF = 1227 / 692



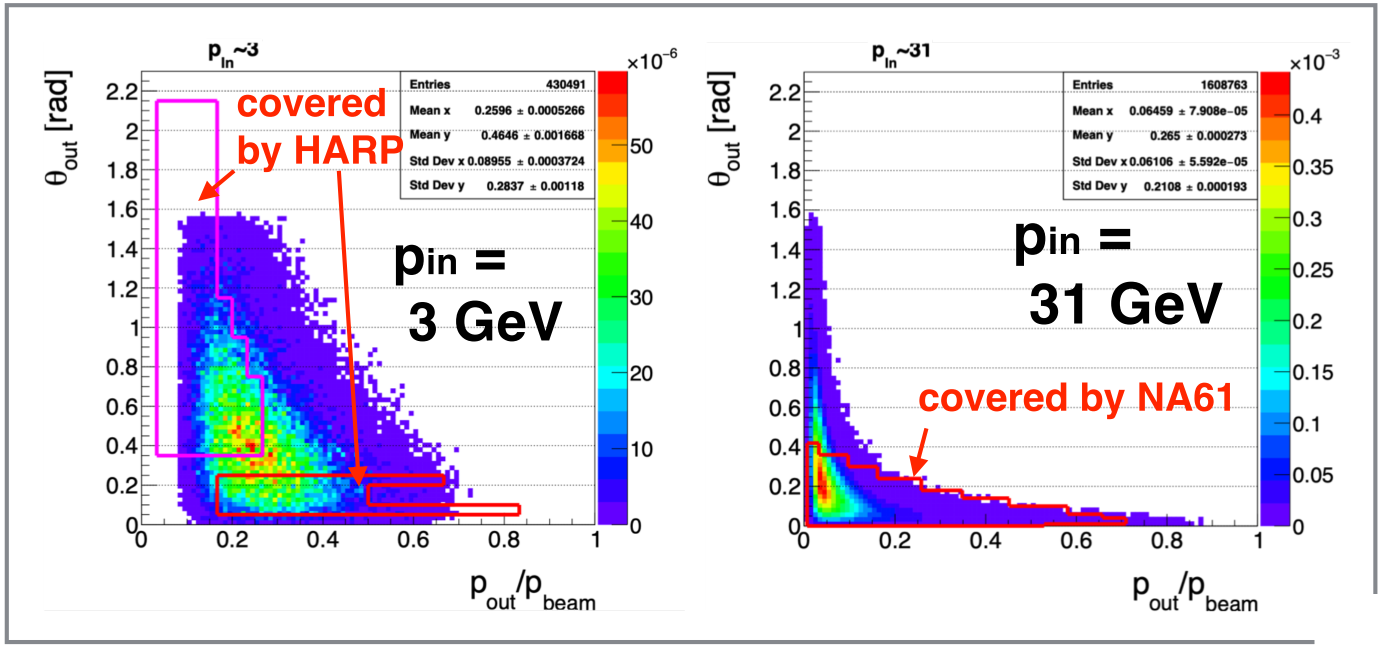


→ reduced χ² < ~2 in all energy range

Nagoya group

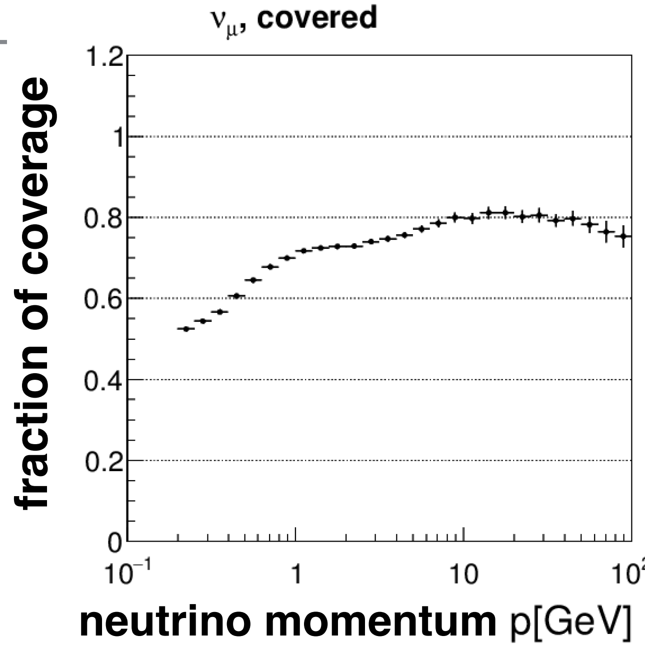
phase space coverage

ex) phase space of π^+ production for 0.3 GeV ν_μ



← hadron production phase space (PS) as a function of p_{in}, p_{out}, θ_{out}

phase space coverage for ν_μ

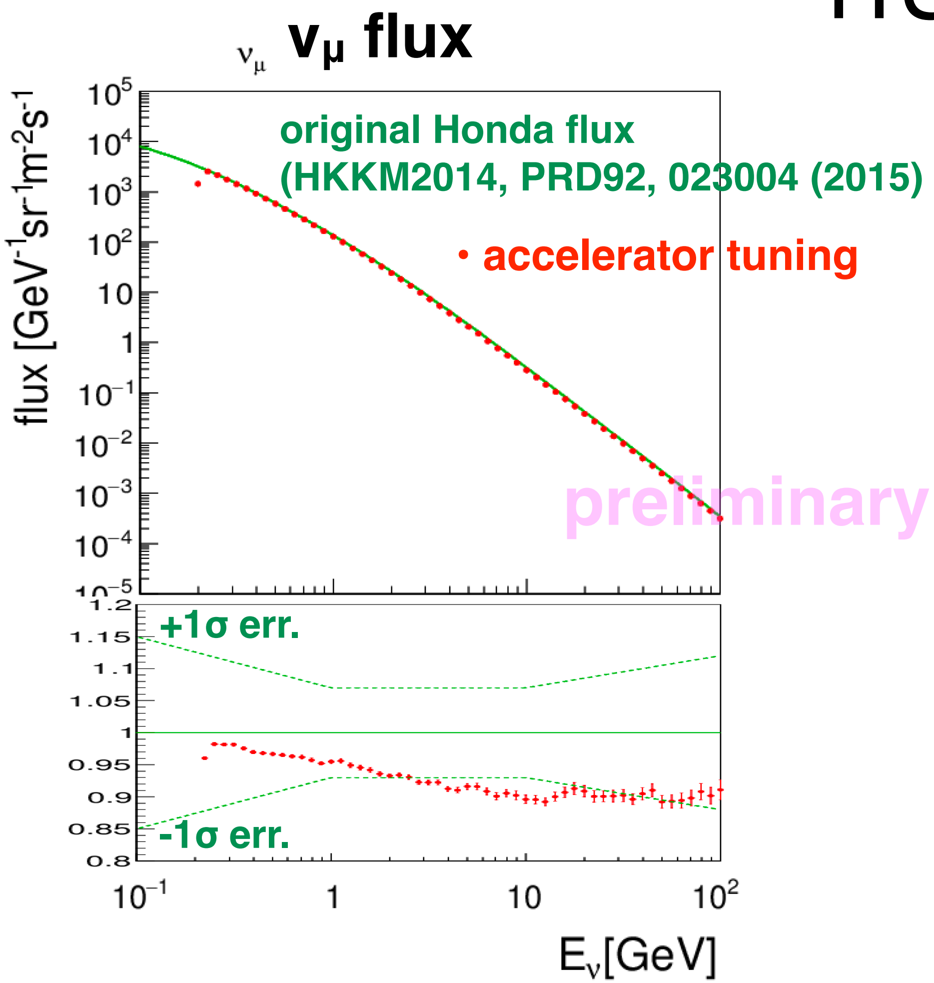


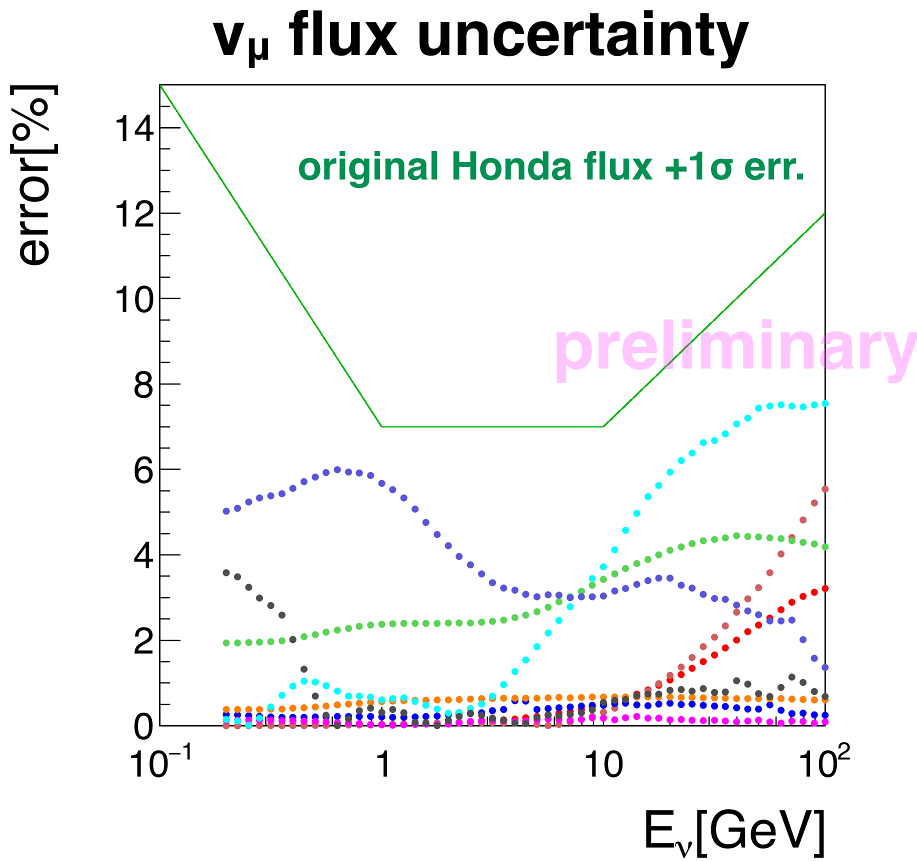
- good (~80%) PS coverage for ~10 GeV ν
  - due to wide PS of NA61 & NA49
- lower coverage in E_ν < 1 GeV
  - due to lack of E_{beam} < 3GeV beam data

→ shortage of phase space is considered as systematic uncertainty of ν flux.

Nagoya group

flux & uncertainty





- measurement error of beam data in each bin
- normalization of beam data
- parameterization
- Feynman scaling (x_F-p_T shape)
- Feynman scaling (nomalization)
- coverage of phase space
- • • • atomic mass dependence

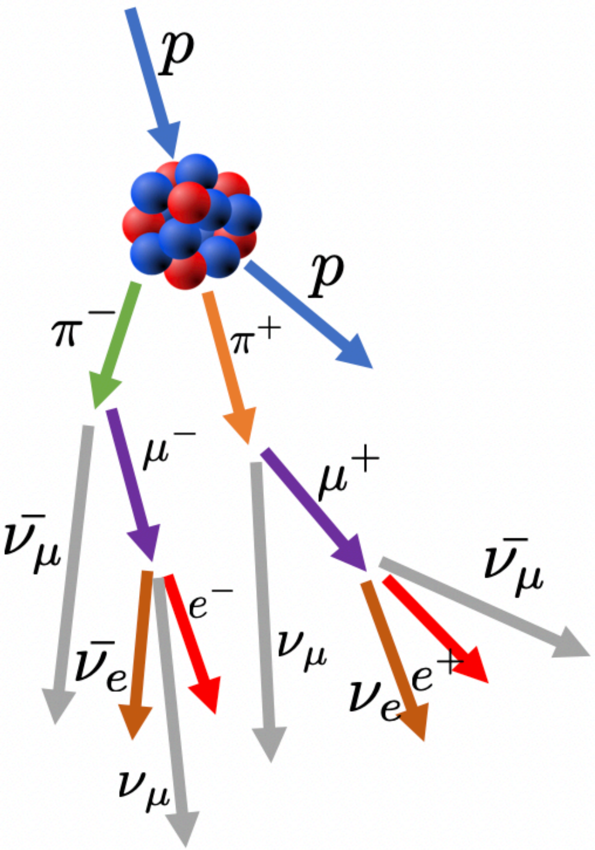
- Honda flux uncertainty was originally evaluated using atm. μ data

(M. Honda et.al., PRD75, 043005 (2007))

→ large Error in < 1GeV & > 10GeV

→ will be able to reduce uncertainty of Honda flux (preliminary) slide from L. Cook

Tuning of the Bartol Atmospheric Neutrino Flux



- Tuning the Bartol Neutrino Flux to Pion and Kaon production datasets from fixed target experiments
- Reweighting neutrino flux based on ratio of meson multiplicity in data to multiplicity in Monte Carlo

$$W = \frac{dn_{\mathrm{data}}(\pi^+)}{dx_F dP_T} \Big/ \frac{dn_{\mathrm{MC}}(\pi^+)}{dx_F dP_T}$$

- Consider interactions as described in terms of inclusive production cross sections e.g.

$$\sigma(pN \to \pi^+ + X)$$

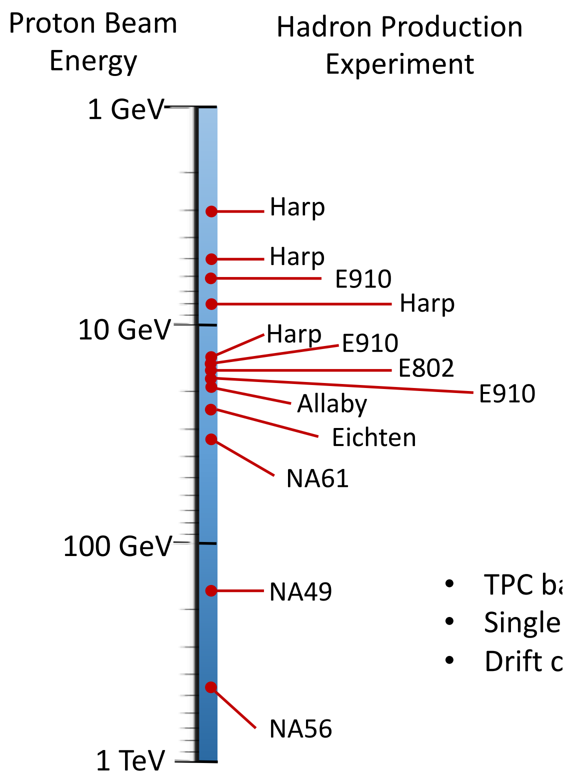
data-driven tuning in Bartol flux

$$\frac{d^2\sigma(A)}{dx_F dP_T} = \frac{A^{\alpha(x_F,P_T)}}{2} \frac{d^2\sigma_{\mathrm{BMPT}}}{dx_F dP_T}$$

A-scaling (target atom dependence)

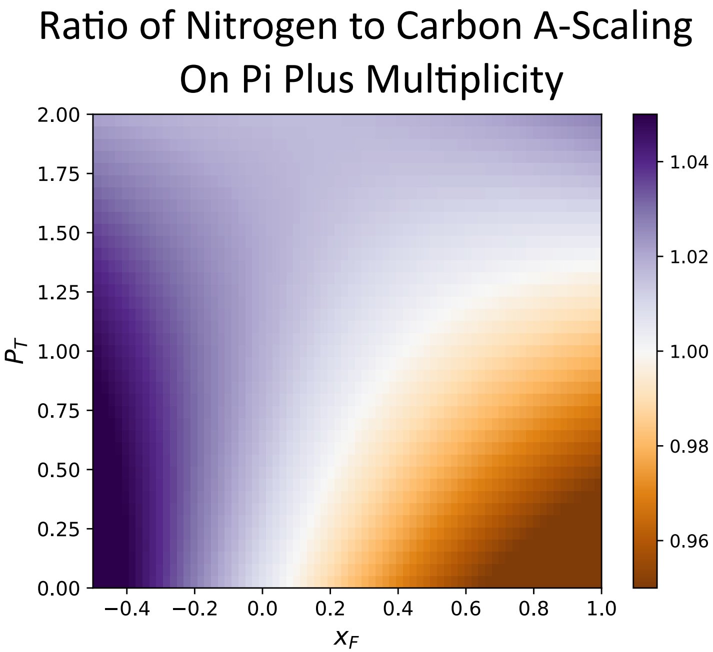
BMPT parameterization
Eur.Phys.J.C20,13 (2001)

data set



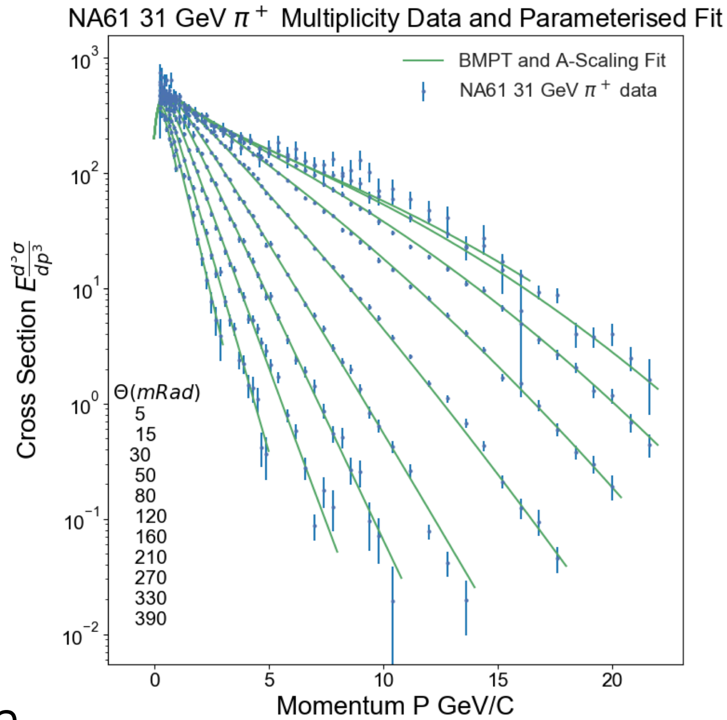
→ grouped into 7 regions

groups	• 12, 12.3, 14.6 GeV
• 3 GeV	• 17.5, 19.2, 24 GeV
• 5, 6.4 GeV	• 31 GeV
• 8GeV	• 158 GeV



- derive A-scaling from Be, C, & Al target data

NA61 π+ fit result

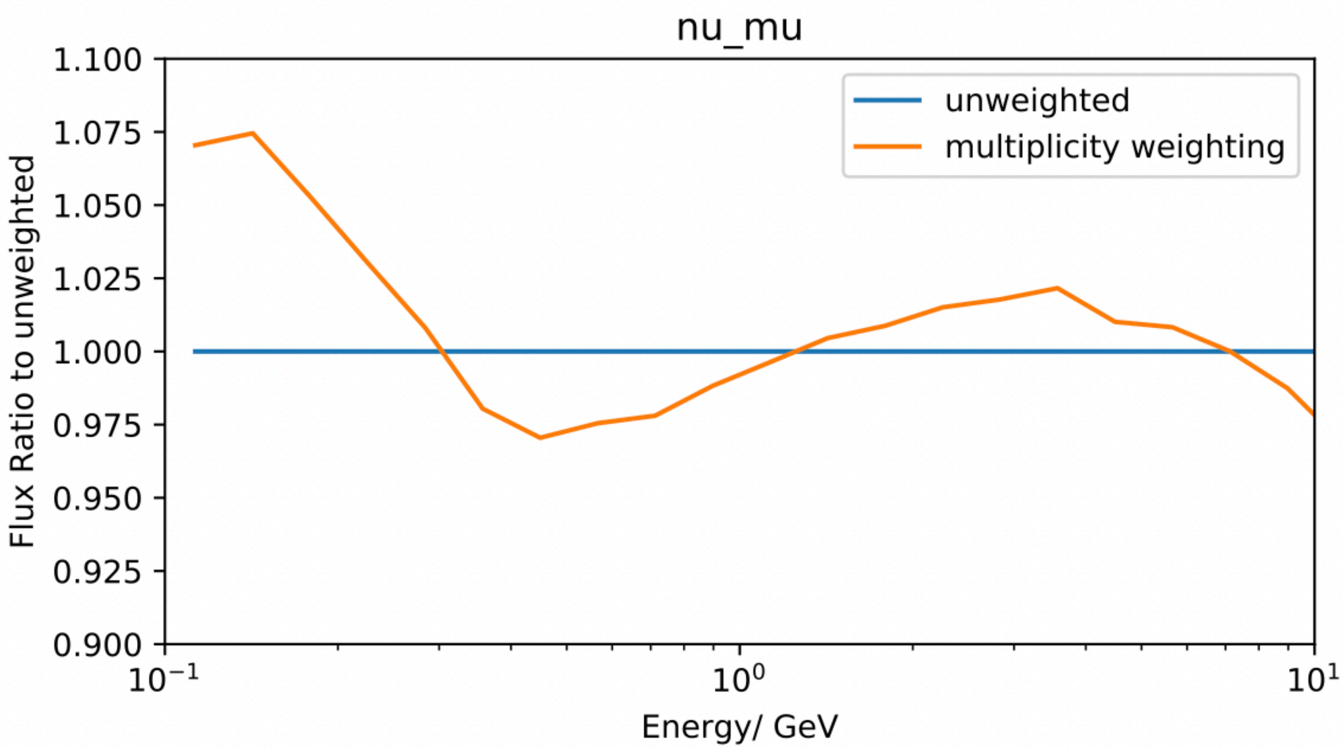


- fit function well describes the data

slide from L. Cook

Tuned neutrino flux results

- Within the previous 10% uncertainty
- Low energy increase from high angle dataset tuning
- Systematic Uncertainty on the tuned fluxes to be released shortly



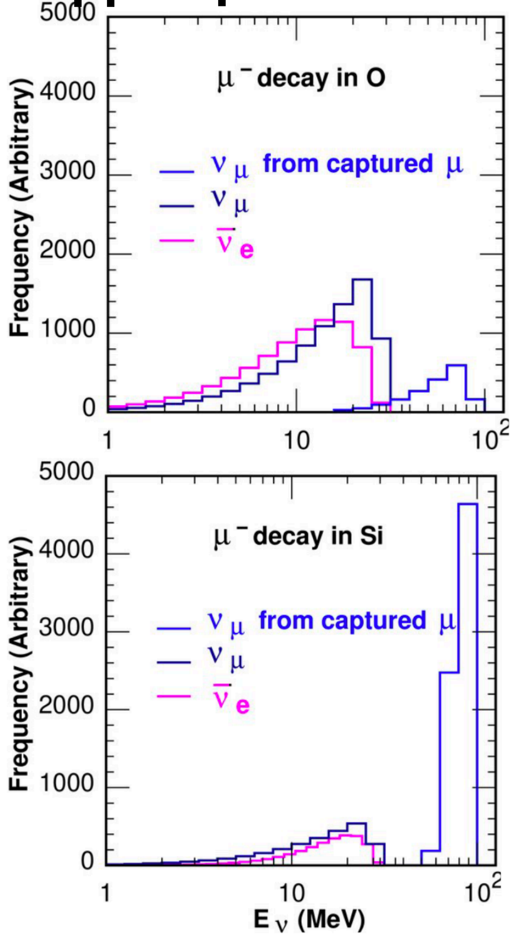
Works in both groups are in progress
→ consistency checks between **Honda flux** and **Bartol flux** will be started soon.

flux in < 100 MeV/c

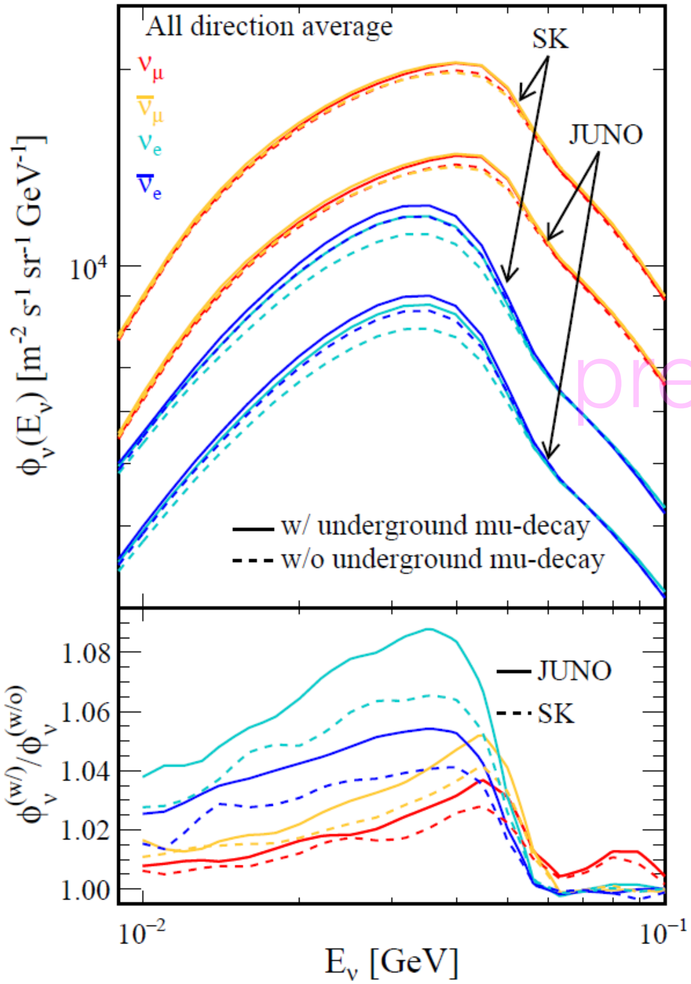
ref) Wan-Lei Guo, PRD99, 073007 (2019)
M. Honda's poster in Neutrino2020

- **plot provided by Yu-Feng Li (JUNO collaboration)**

neutrino energy from stopped μ



- need to consider decays of atm. μ stopped in rock or water



- ν from μ at rest → enhancement in <50 MeV flux

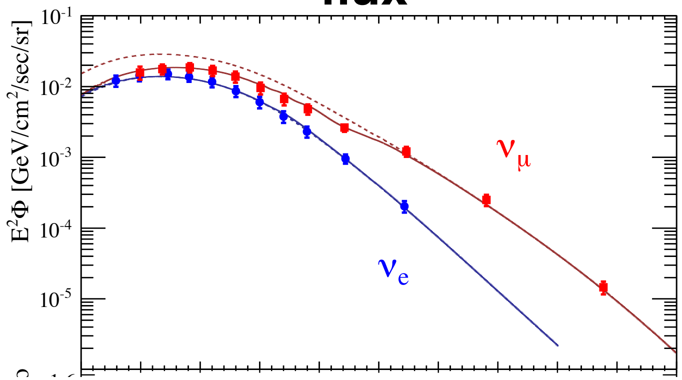
- depends on geographical features of observation site

ν flux measurement

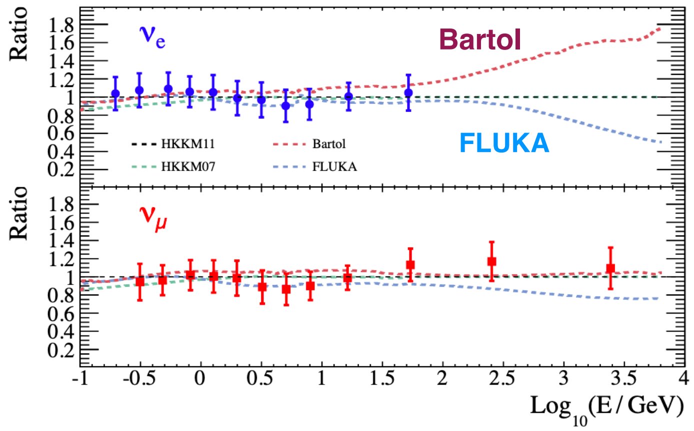
ν flux measurement in SK (ν_e : >158 MeV, ν_μ: >400 MeV)

ref) E. Richard et.al. (SK collaboration) , PRD 94, 052001 (2016)

flux



ratio to Honda flux



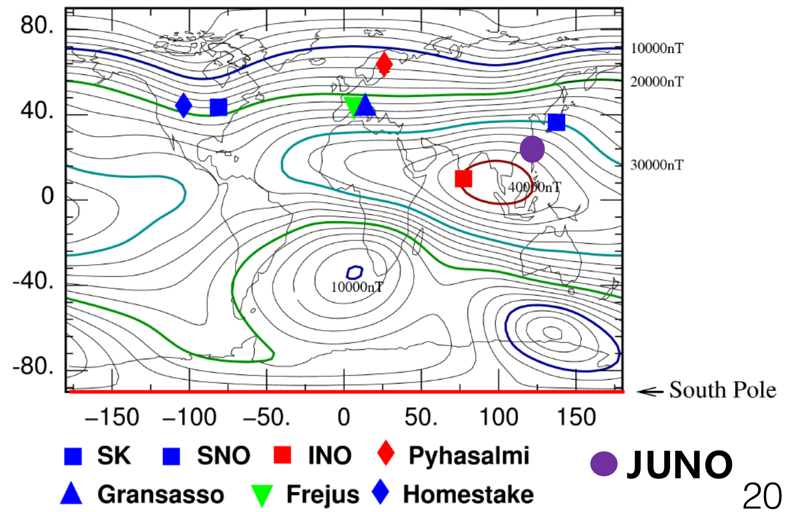
i	$\log_{10}(E/\text{GeV})$	$\log_{10}(\bar{E}_i/\text{GeV})$	$\bar{E}_i^2\Phi_i^\nu$ [GeV/cm^2/sec/sr]	$\Delta\Phi_i^\nu/\Phi_i^\nu$ [%]
ν_e				
1	-0.8 – -0.6	-0.71	1.21×10^{-2}	±18
2	-0.6 – -0.4	-0.51	1.46×10^{-2}	±17
3	-0.4 – -0.2	-0.27	1.50×10^{-2}	±16
4	-0.2 – 0.0	-0.09	1.37×10^{-2}	±15
5	0.0 – 0.2	0.10	1.16×10^{-2}	±17
6	0.2 – 0.4	0.30	8.55×10^{-3}	±17
7	0.4 – 0.6	0.50	6.09×10^{-3}	±18
8	0.6 – 0.8	0.70	3.73×10^{-3}	±19
9	0.8 – 1.0	0.90	2.32×10^{-3}	±18
10	1.0 – 1.5	1.22	9.42×10^{-4}	±15
11	1.5 – 2.0	1.72	2.03×10^{-4}	±18

measurement error : 16~20%

dominantly ν interaction cross section

- important to constrain the prediction

Geomagnetic field model



- Measurement in different places

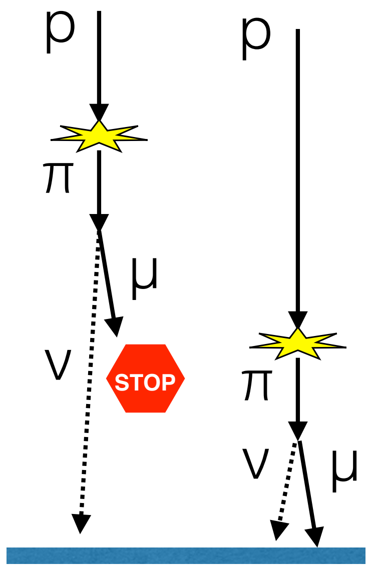
e.g.) JUNO, EPJ. C, 81 10 (2021) 887

will be interesting to varify the prediction

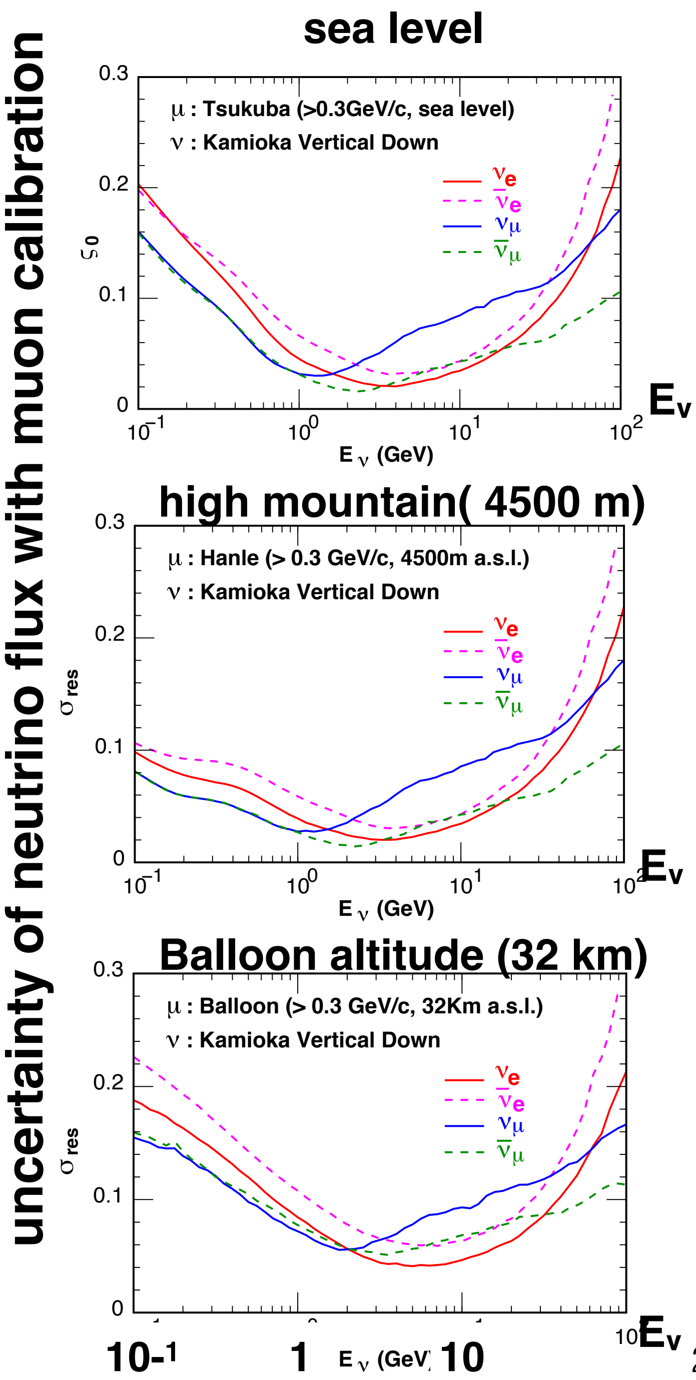
muon flux measurement

- atm. μ is useful for calibration/uncertainty evaluation of ν flux
- Honda flux is calibrated based on atm.μ

  M. Honda et.al., PRD75, 043005 (2007)



- Both ν and μ carry information of π production
- Phase space covered by μ data depends on detector altitude



Systematic study by Honda et.al.

M. Honda et.al., PRD 100, 123022 (2019)

→ measurement in high mountain is effective

Summary

- atm. ν in low E region (0.1--100GeV)
  - important as both physics target and background
    → accurate prediction is key point
- uncertainties of ν flux prediction
  - flux of primary particle
    - good improvement from recent measurements
  - hadron production
    - accelerator-data-driven tuning is ongoing for both Honda flux & Bartol flux
- Measurements of atm. ν and μ will be useful to calibrate prediction