Atmospheric Neutrino Flux Calculation in Low Energies

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Atmospheric Neutrino

Atm-v sources:

- interactions of cosmic rays with nuclei in Earth's atmosphere, in the presence of geomagnetic field effect

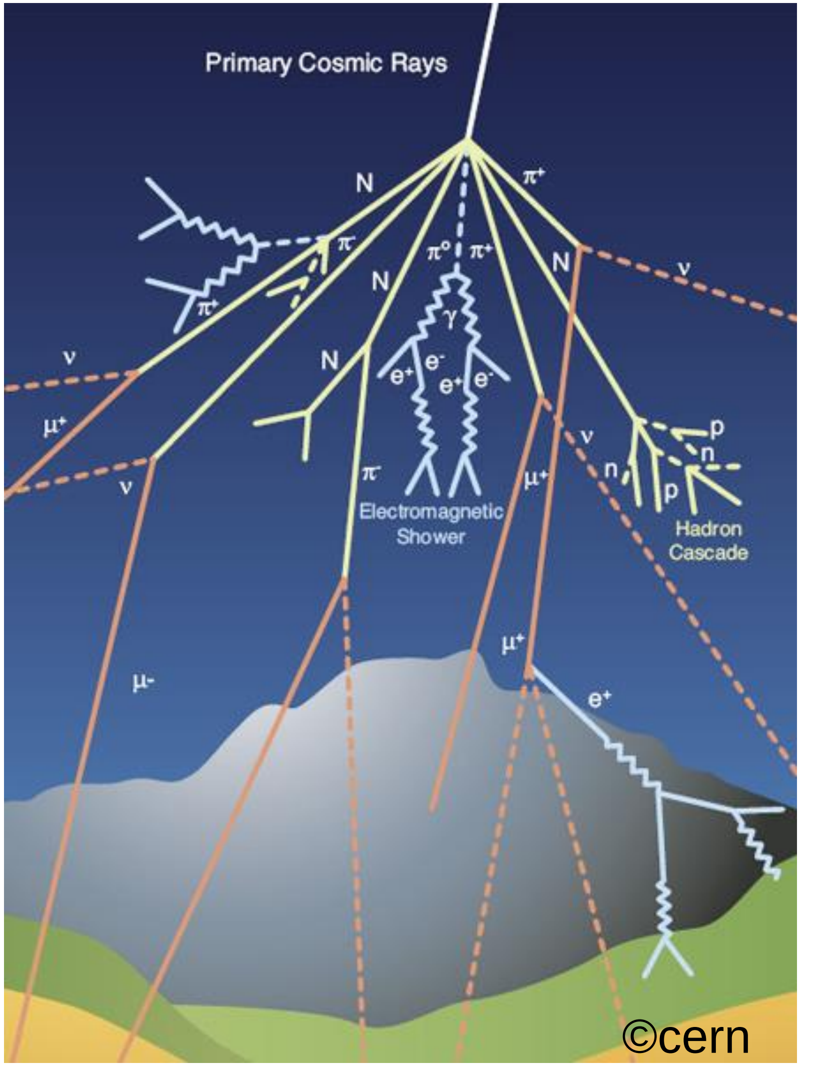
3D Atm-v calculation:

$$\Phi_{\nu} = \Phi_{primary} \otimes R_{cut} \otimes Y_{\nu}$$ (neutrino)

✓ $\boldsymbol{\Phi_{primary}}$: Primary cosmic ray flux

✓ $\boldsymbol{R_{cut}} = R_{cut}(R_{cr}, latitude, longitude, \theta, \varphi)$: depend on geomagnetic field and rigidity of cosmic ray particle $(R_{cr} \equiv \frac{P}{Ze})$

✓ $\boldsymbol{Y_{\nu}} = Yield_{\nu}(h, \theta)$: Hadronic Interaction Model, Air Profile, and meson-muon decay



A Full 3D Calculation

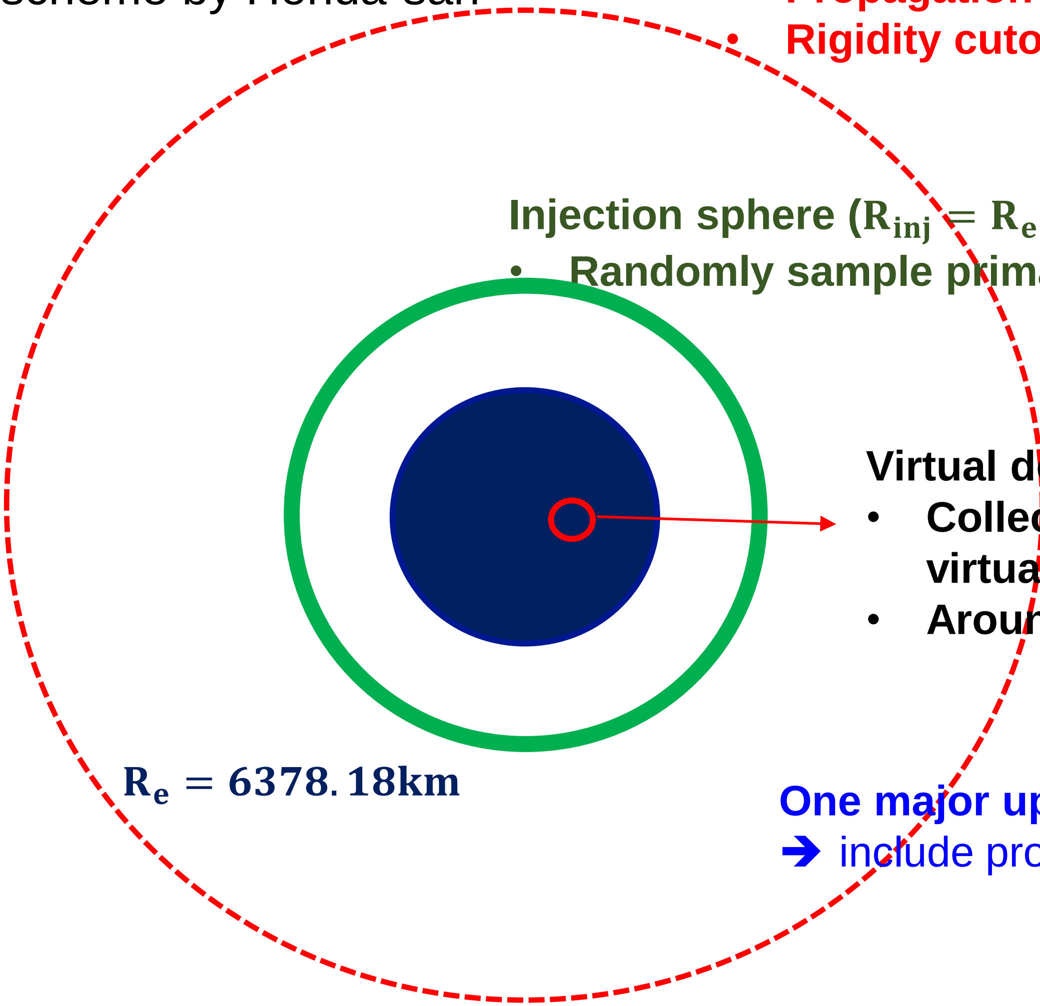
- Based on the calculation scheme by Honda-san

Simulation sphere($\mathbf{R_e < R_{sim} \le 10 \times R_e}$)

- **Propagation of cosmic rays**
- **Rigidity cutoff test**

Injection sphere ($\mathbf{R_{inj} = R_e + 100km}$)

- **Randomly sample primary cosmic ray**



Virtual detector

- **Collect neutrinos passing through the virtual detector**
- **Around true detector**

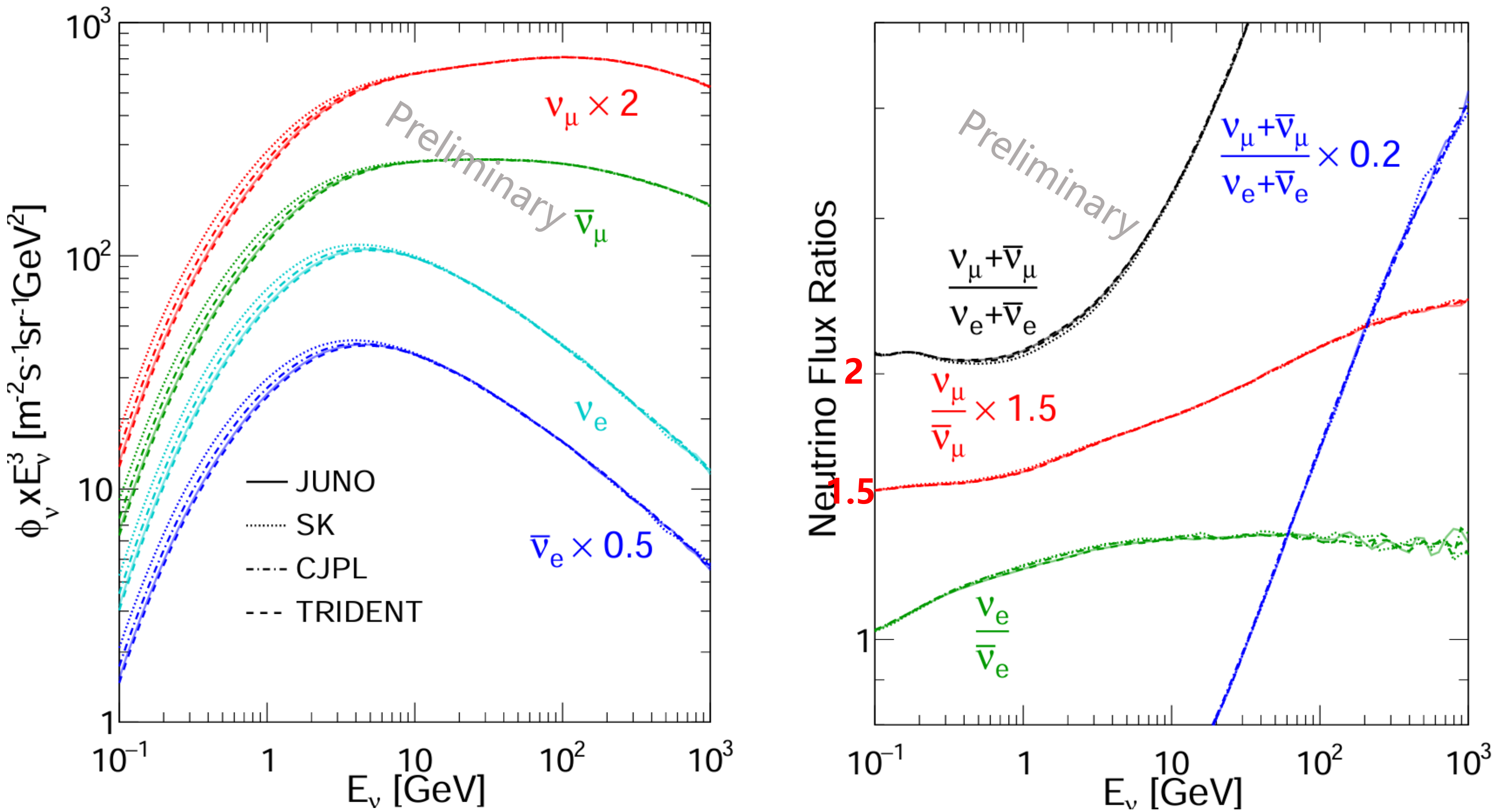
$\mathbf{R_e = 6378.18km}$

One major update on E_ν<100 MeV:

➔ include propagation of muons inside earth

Phys. Rev. D 83, 123001 (2011)
Phys. Rev. D 92, 023004 (2015)

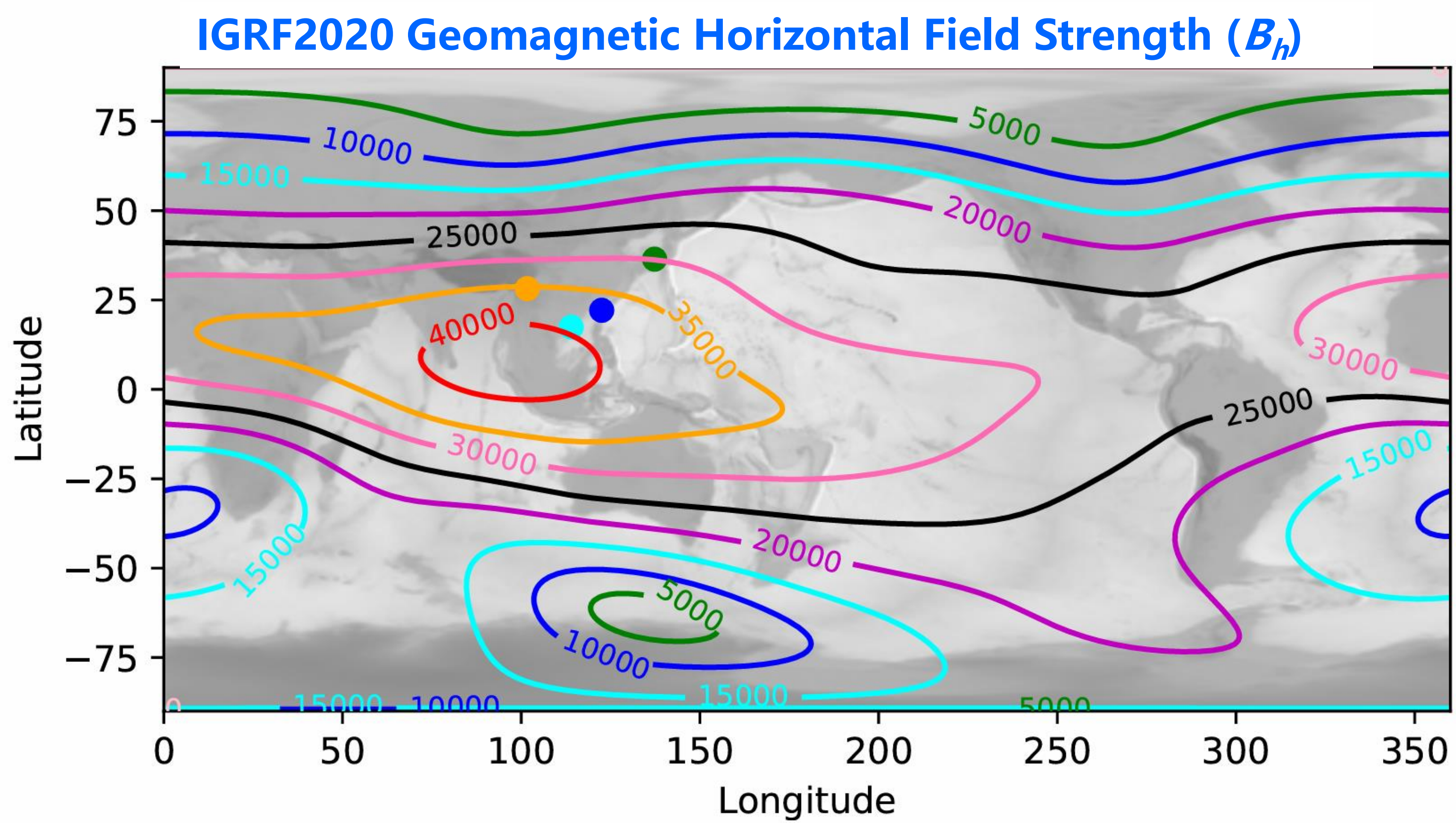
Latest Atmospheric Neutrino Flux (>100 MeV)



- All direction averaged flux
- The differences in < 10 GeV for 4 site: related to different local **geomagnetic** field strength
- Assuming all mesons and muons decay: $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$ $\frac{\nu_e}{\bar{\nu}_e} \sim 1$ $\frac{\nu_\mu}{\bar{\nu}_\mu} \sim 1$

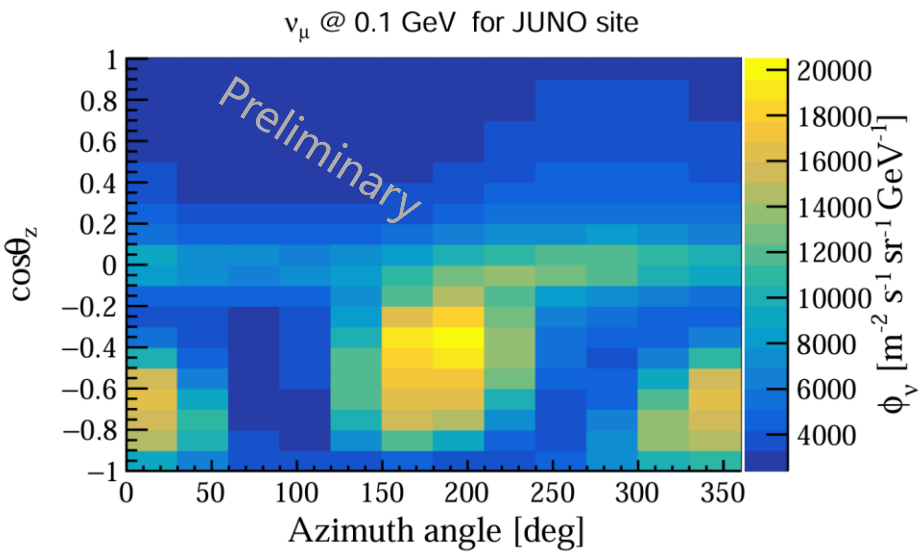
Geomagnetic Effects

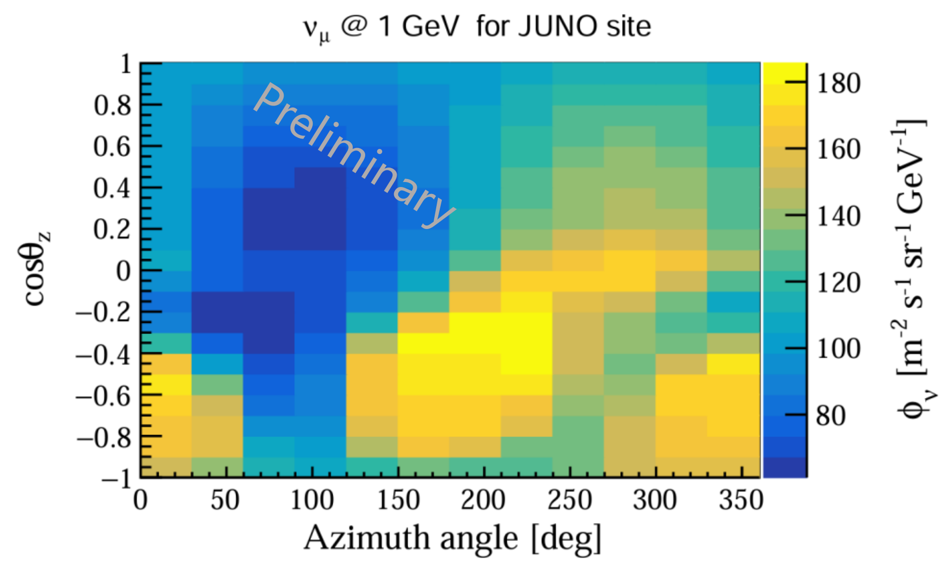
- Geomagnetic field model: International Geomagnetic Reference Field (IGRF)
- IGRF2020 (latest version) is used in current calculation

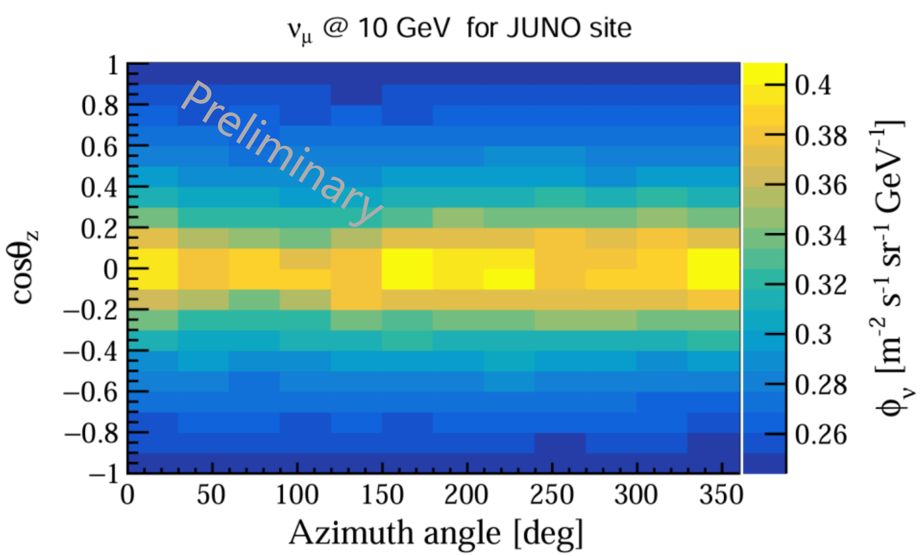


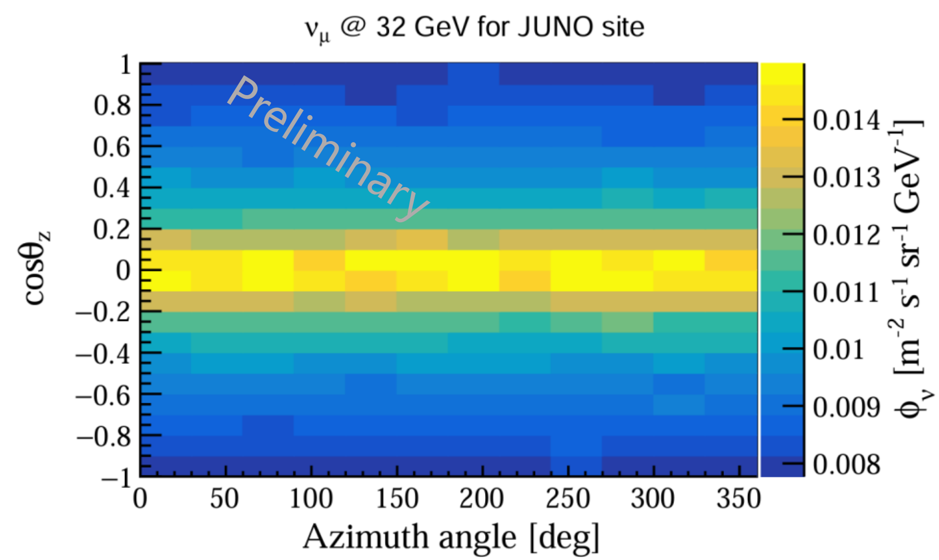
B_h(SK) < B_h(CJPL) < B_h(JUNO) < B_h(TRIDENT)

Atmospheric Neutrino Flux at Different Directions



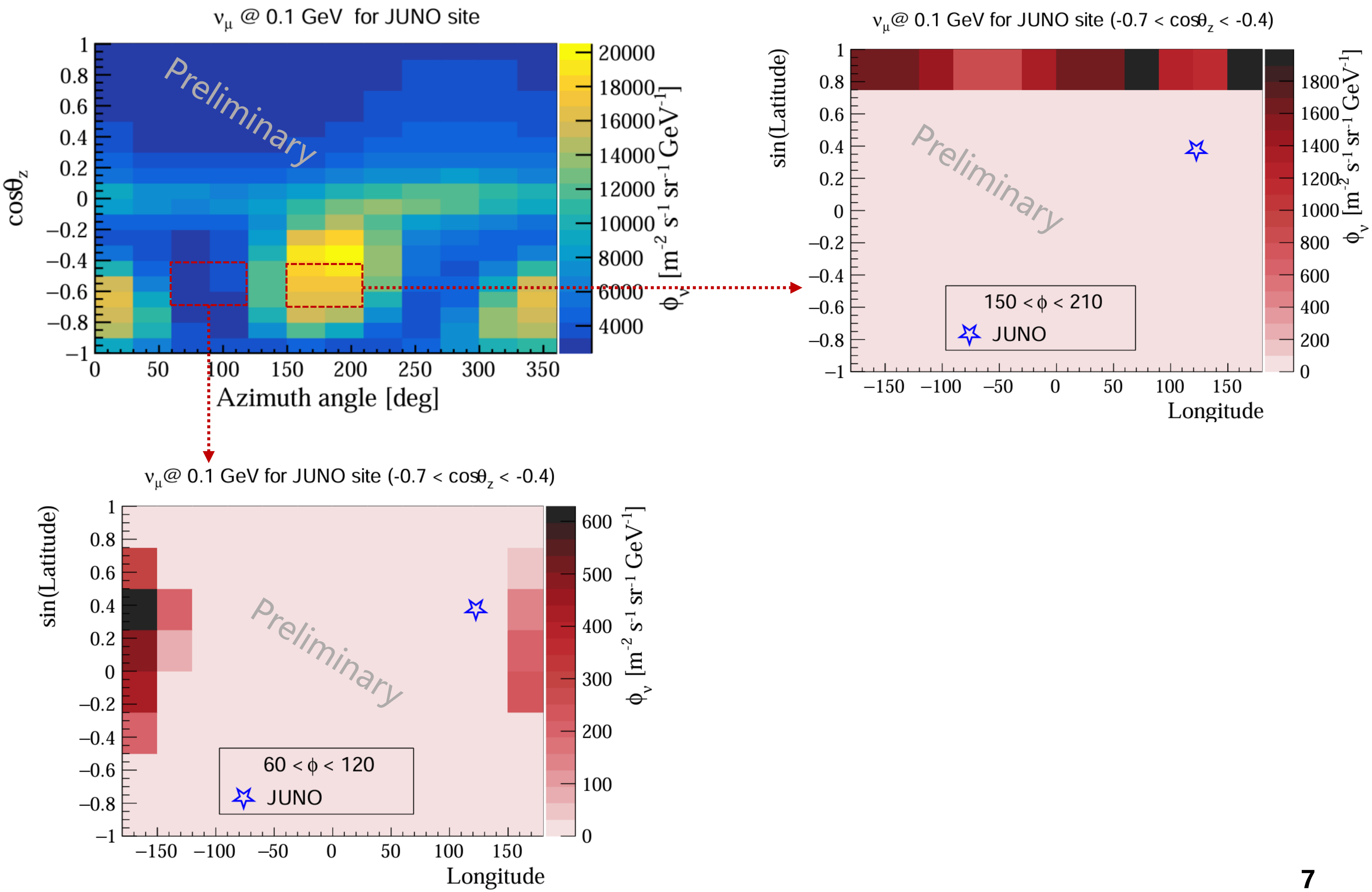




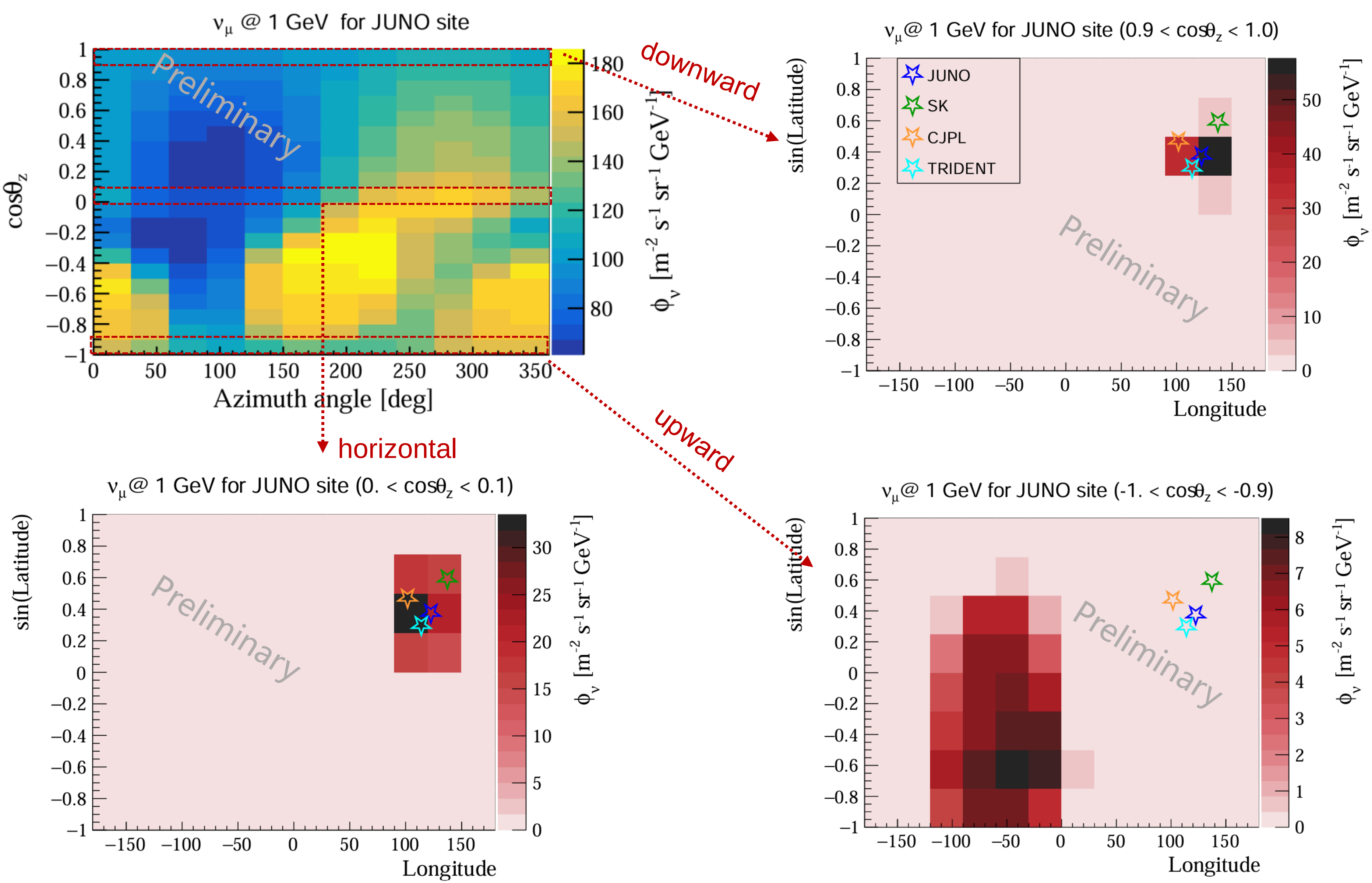


- In neutrino energy range (< 10 GeV), 3D structures are obvious

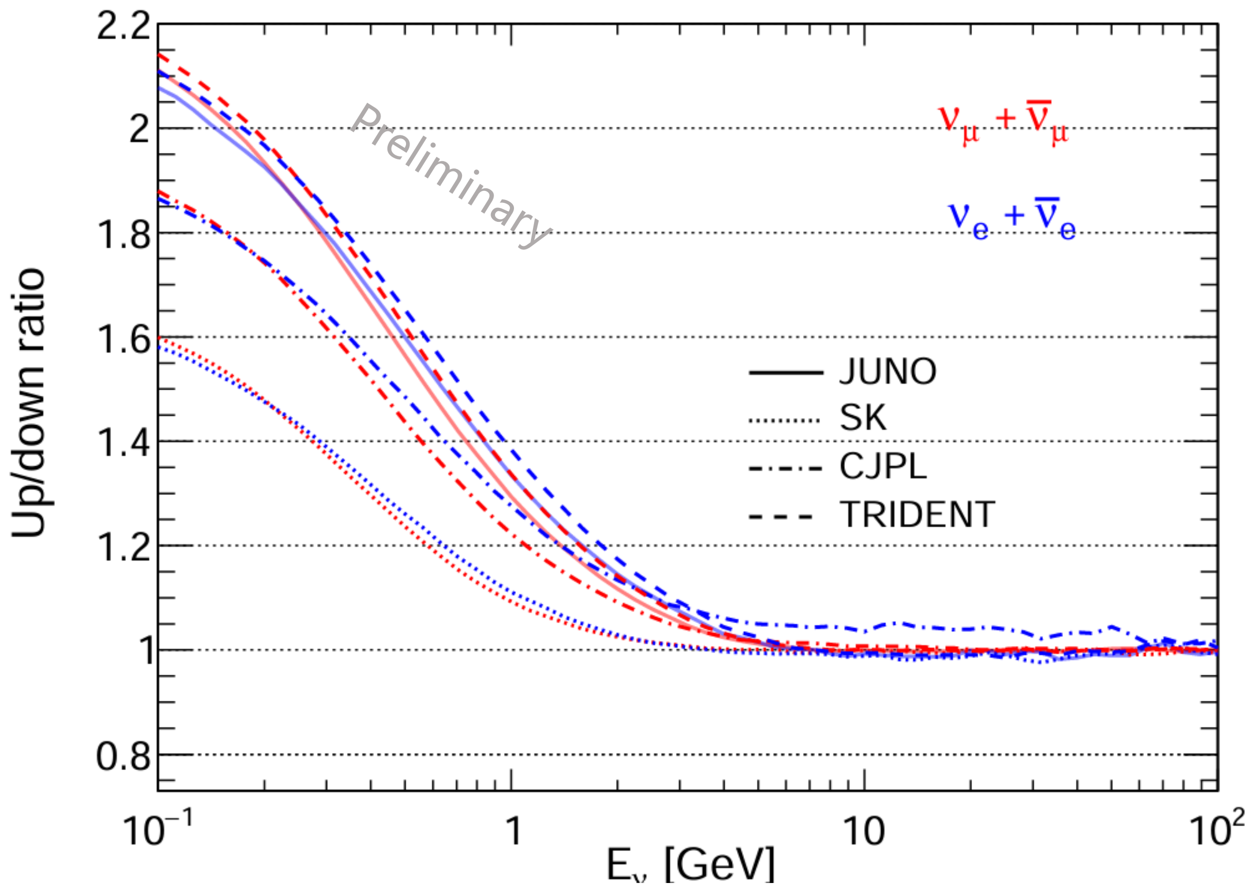
Neutrino Produced Position Zone



Neutrino Produced Position Zone

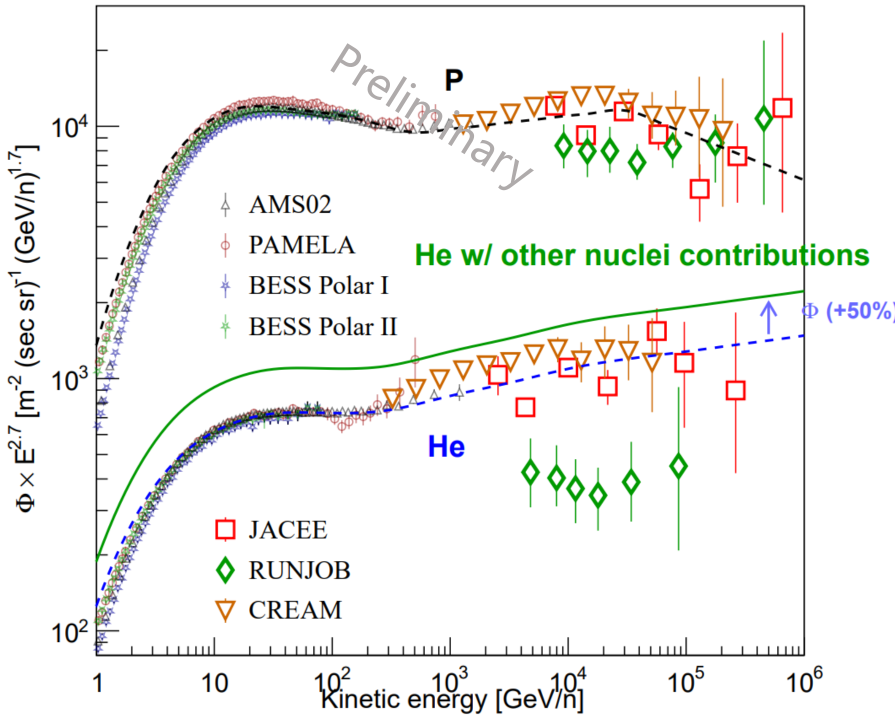


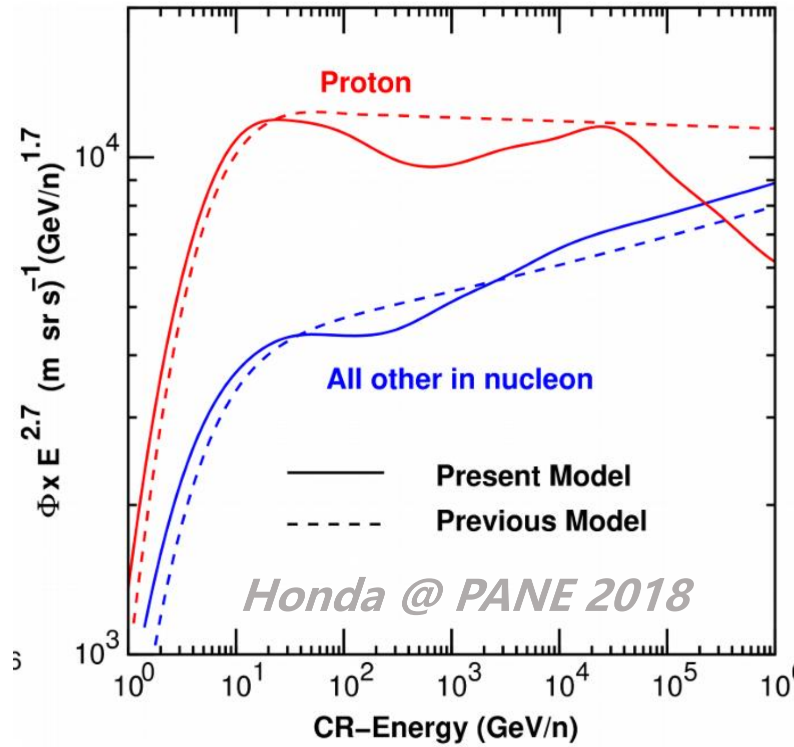
Asymmetry in Up-to-Down Ratio



- Average all azimuth angles
- **Downward direction flux: dependent on local geomagnetic field**
- **Upward direction flux: quite similar for these 4 sites**

Primary Cosmic Ray Model





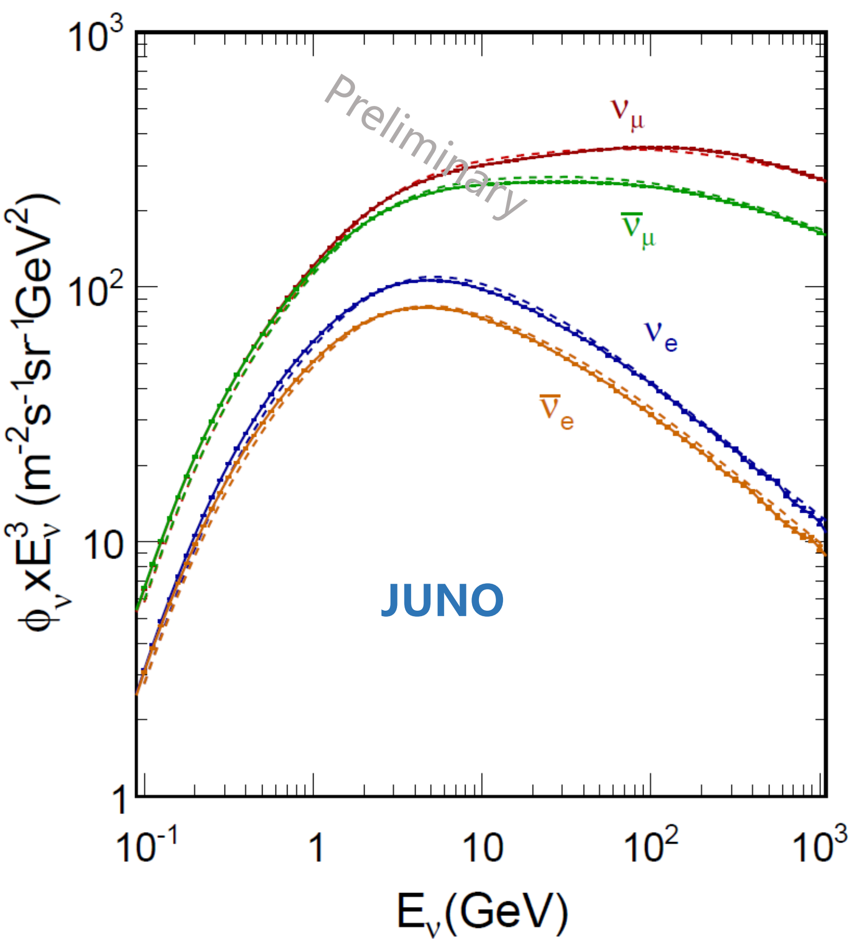
➔ Left plot: present cosmic ray model

- Based on AMS02 and other measurements, looking forward to more future measurements

➔ Right plot: present model vs. previous model

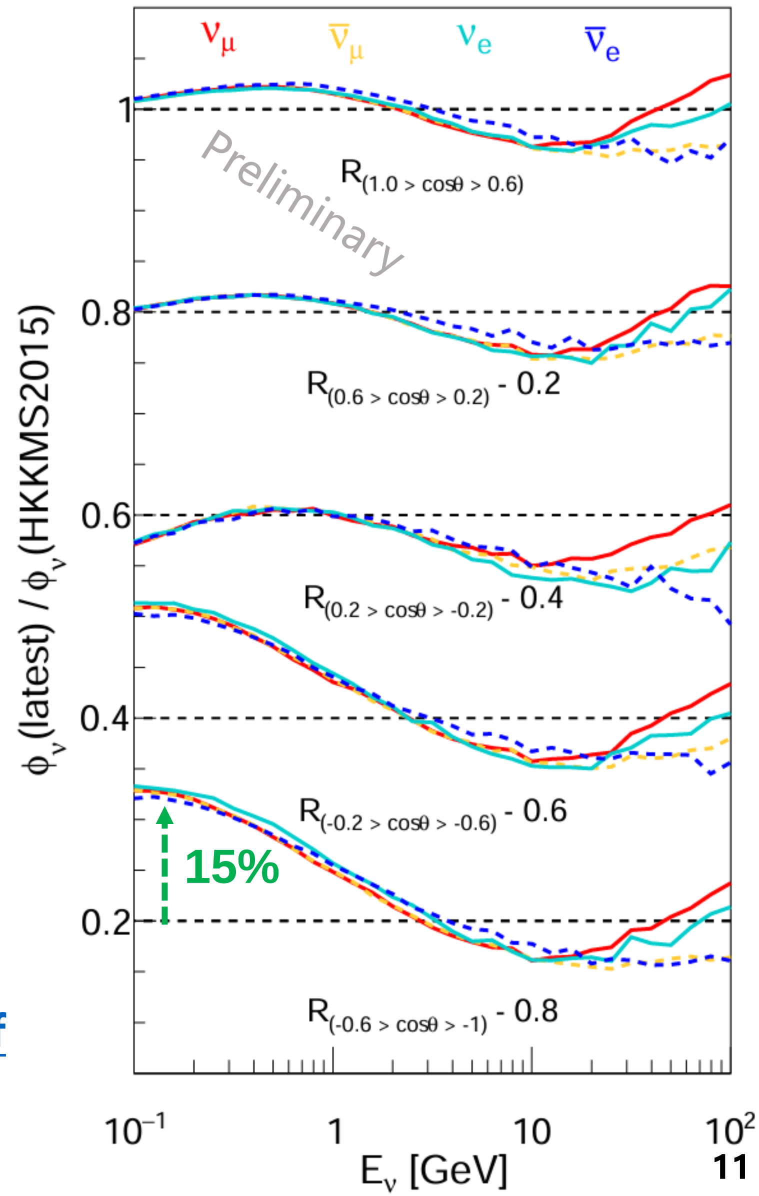
- **Previous model used in HKKMS15**

Comparison between Current Calculation and HKKMS15

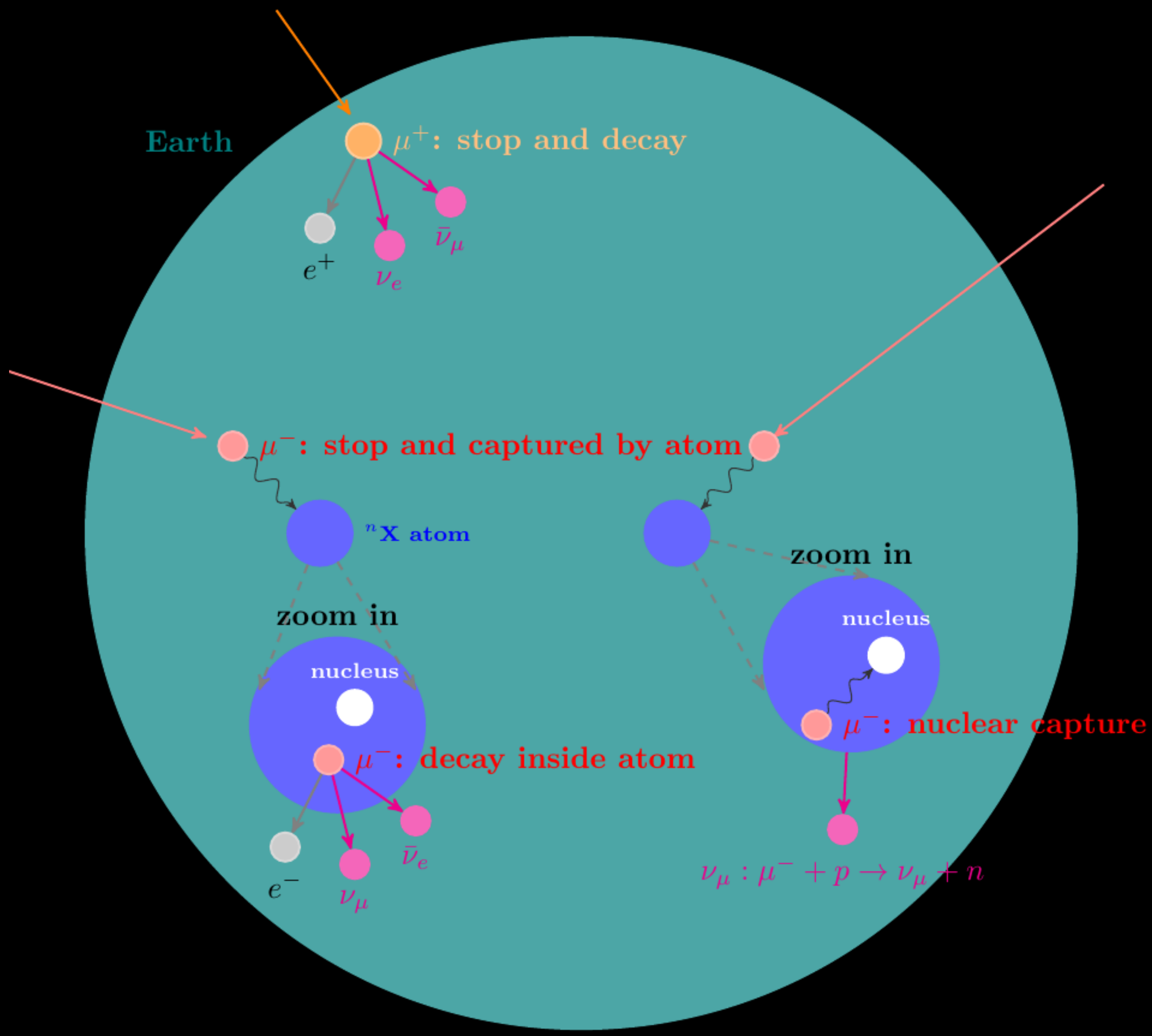


Dash line: flux provided by Honda (http://www.icrr.utokyo.ac.jp/~mhonda/nflx2014/index.html)

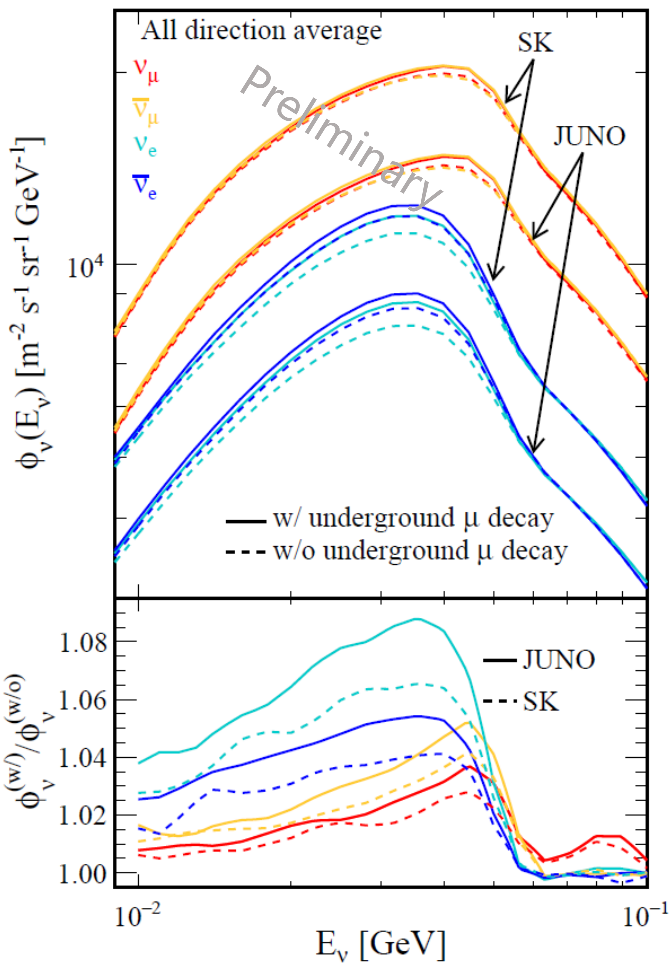
Solid line: Current calculation

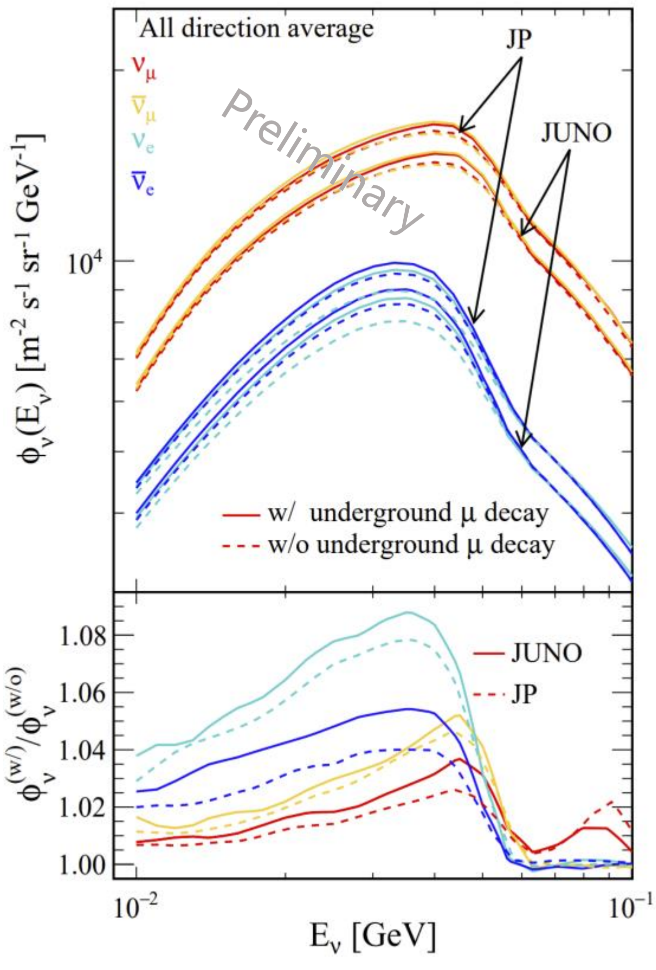


The possible physical processes of muons inside the Earth



Flux Calculation below 100 MeV

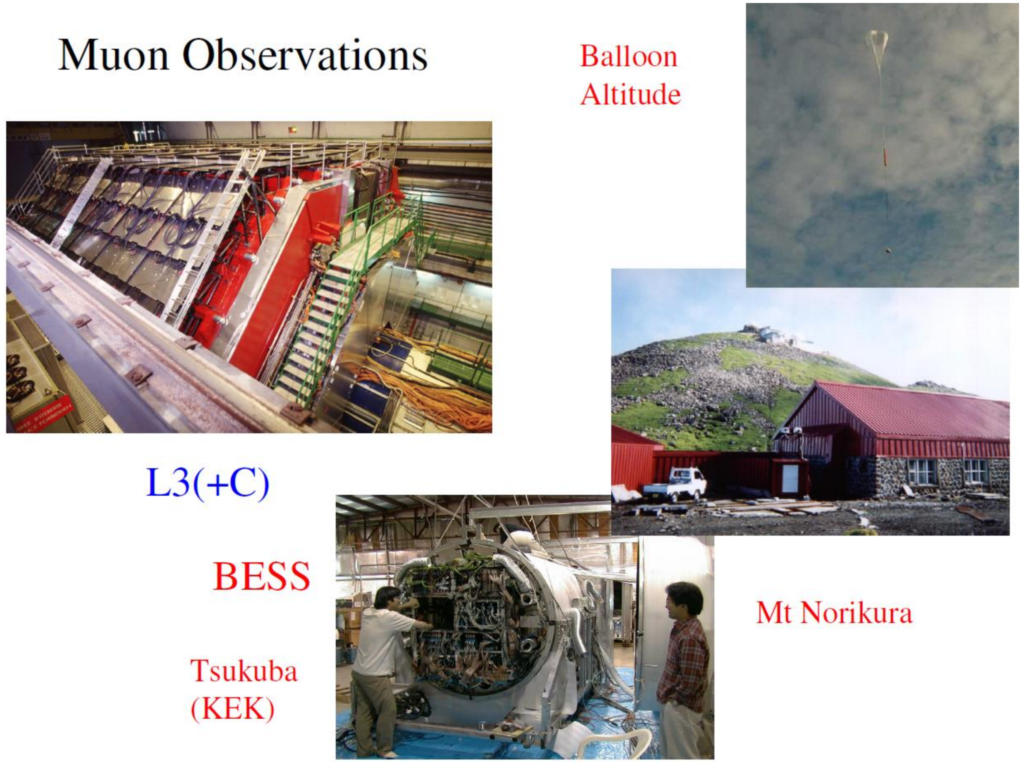


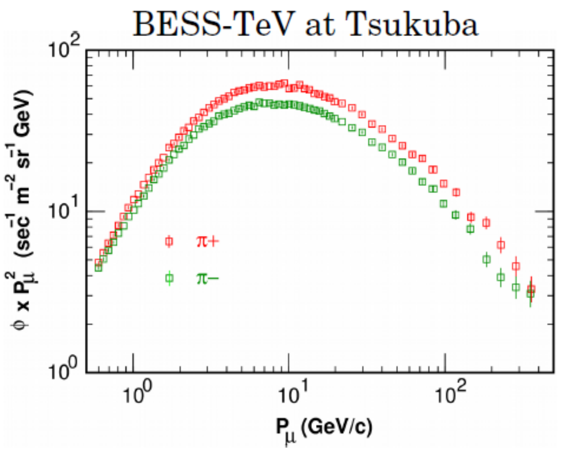


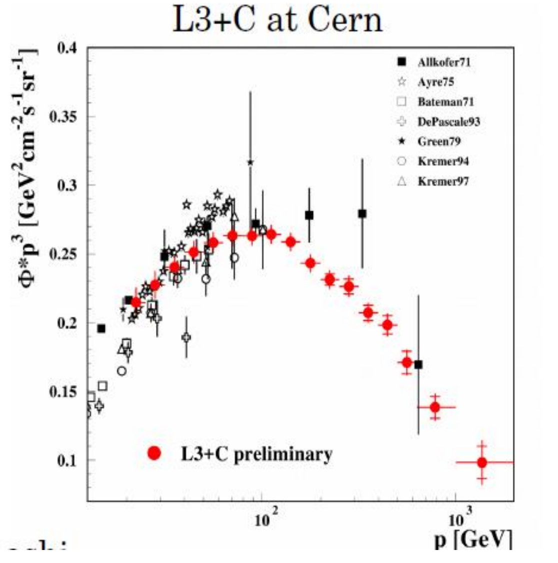
- **Because of lower geomagnetic intensity in SK, more low energies cosmic rays can pass the cutoff rigidity**
- **The magnetic field effect can be verified by comparing the different sites**

Hadronic Interaction Model

- Models of hadron production: based on accelerator data
  - < 32 GeV: JAM model
  - > 32 GeV: modified DPMJET-III
- Muon observations have been used to calibrate the hadronic models and constraint the associated uncertainty



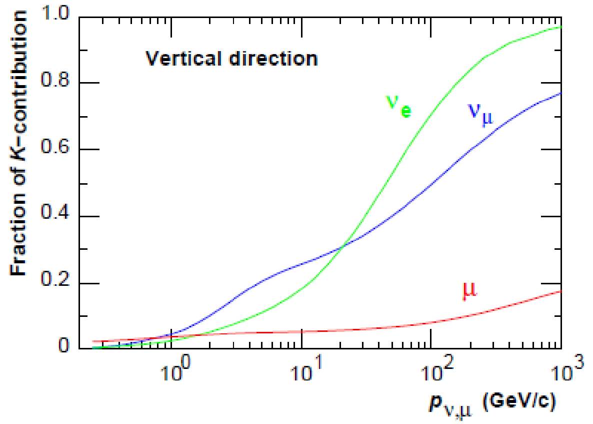


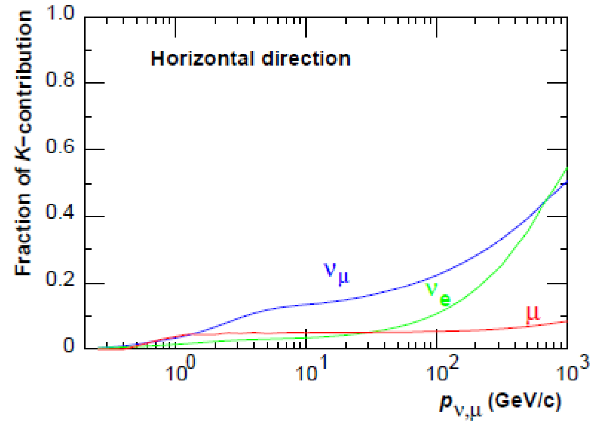


Honda @ PANE 2018

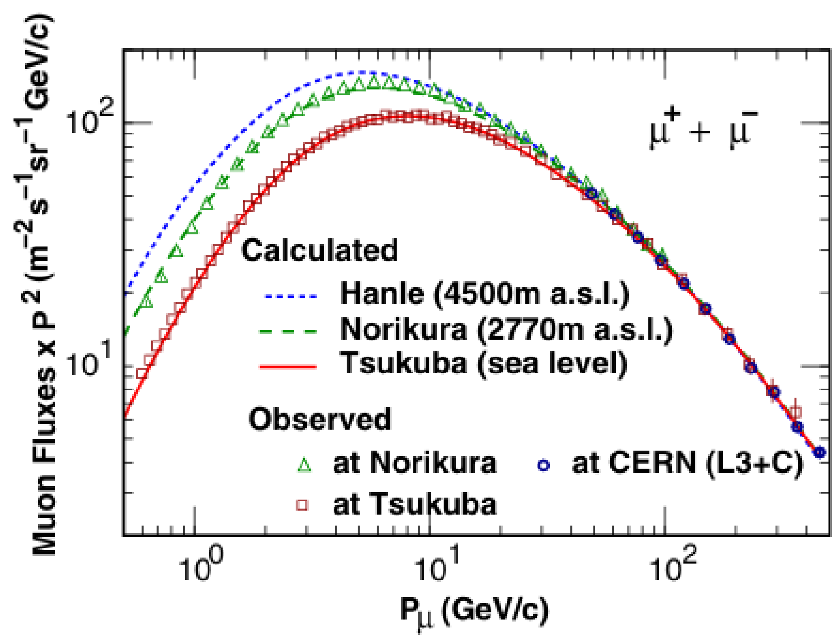
Observation / Calculation Ratio

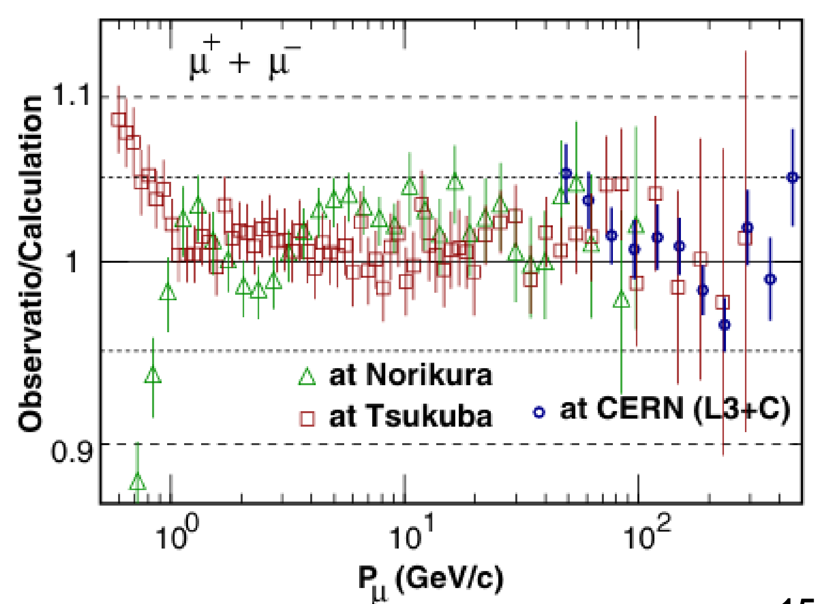
Honda et al., PRD100,123022(2019)
PRD 75 (2007) 043005



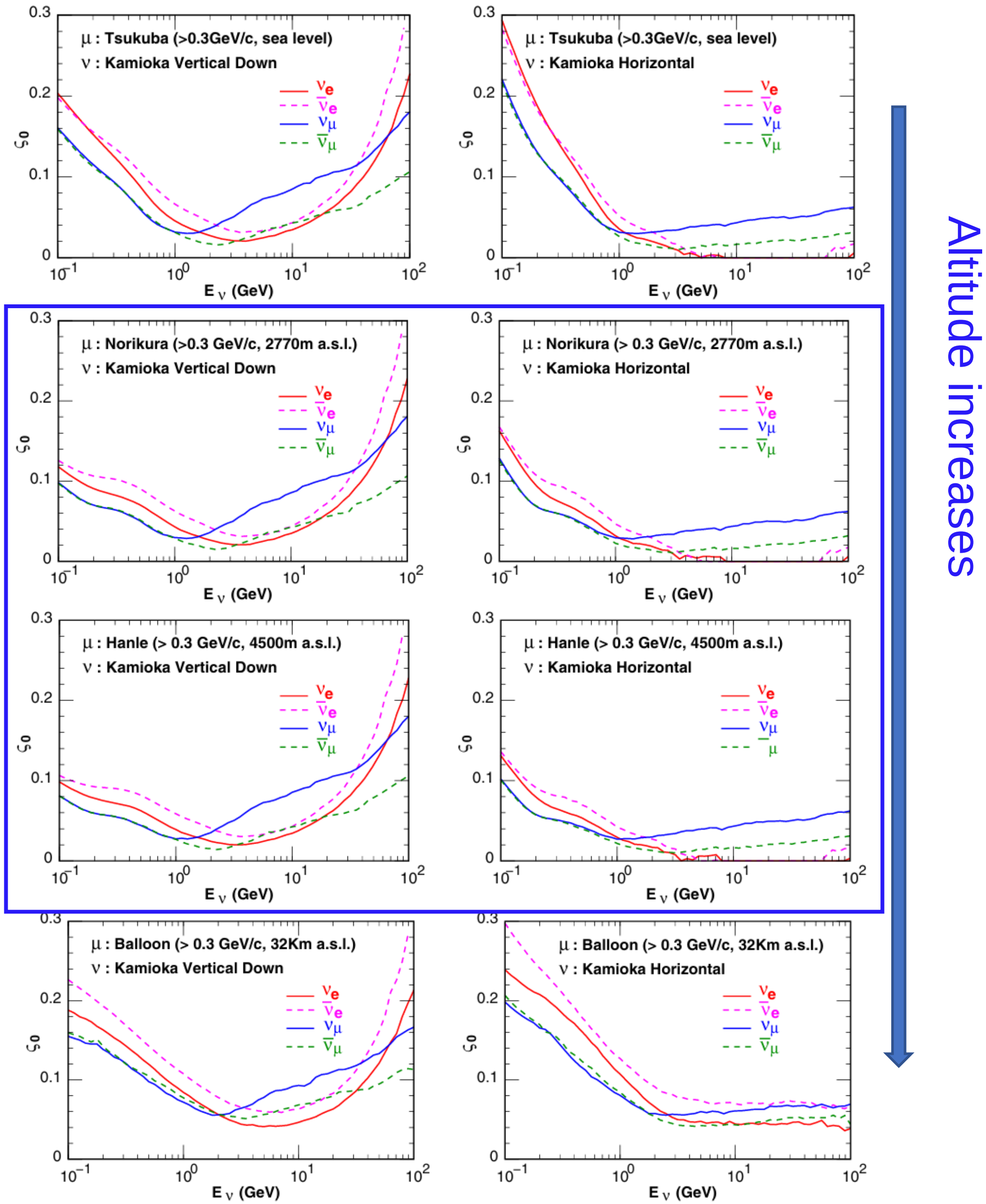


- Cosmic ray muons are mainly produced by pion decay ➔ the measurement data of cosmic ray muons can be used to calibrate $\boldsymbol{\delta_\pi}$ (**the uncertainty of pion production in the hadronic interactions**)





Survey of Calibration Power at Muon Observation Site



Honda et al., PRD100,123022(2019)
PRD 75 (2007) 043005

- Try to divide the neutrino flux uncertainty into 2 parts: related to atmospheric muon flux or not
- ς_0: the atmospheric muon independent variation component of neutrino flux
- For muon observation, the mountain site (3000 ~ 5000 m a.s.l.) works most efficiently
- The other way used to reduce the uncertainty of neutrino flux: studied with accelerator data
  - Nagoya group works on this topic

Summary

a) Latest (preliminary) atmospheric neutrino flux for JUNO, SK, CJPL, TRIDENT are presented

b) Deeply understand the geomagnetic effects on neutrino flux

c) Compared to HKKMS15, major changes are because the updated primary cosmic ray models (closer to measurements)

d) Muon propagation inside the Earth are included in the calculation, contributing more neutrinos below 100 MeV

e) To improve the precision of atmospheric neutrino flux calculation, the most challenge part is how to constraint the uncertainty from the hadronic interaction model

- Atmospheric muon flux measurement still works at low energy range, more measurements at high mountain are required
- Using acceleration data and build a good cooperation with accelerator study

Thanks

Backup