Precision 3D Atmospheric Neutrino Flux Calculation Based on Honda Flux Model

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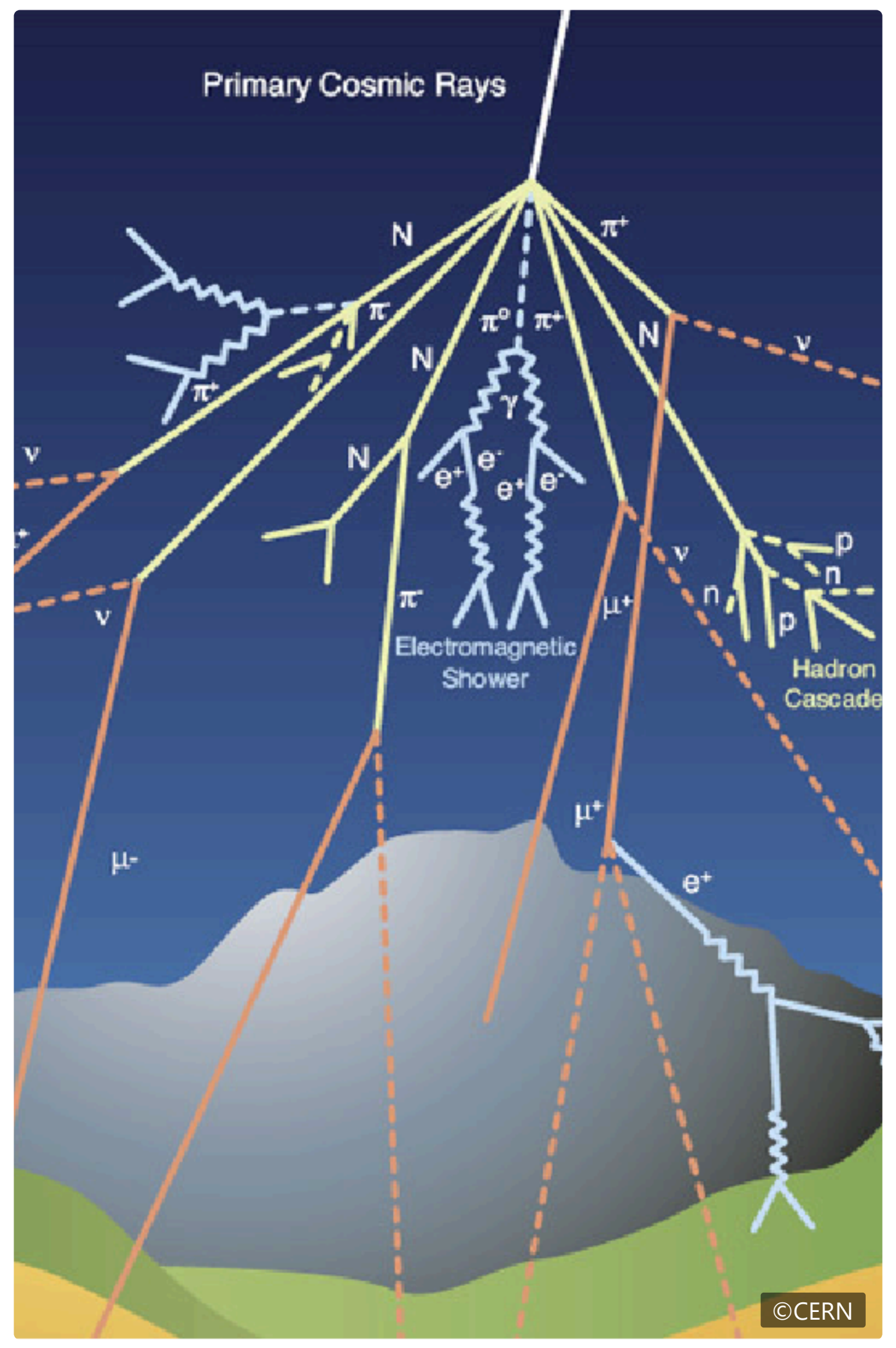
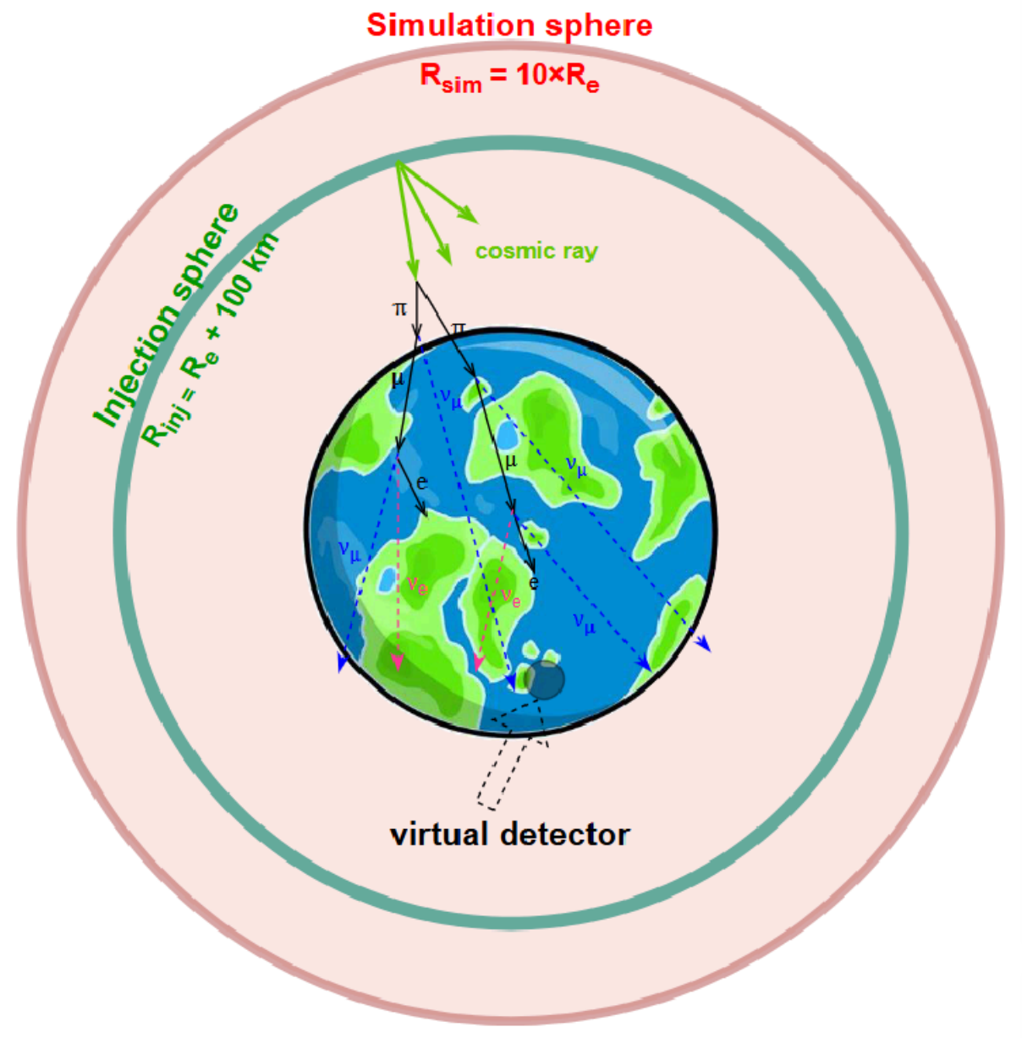
Atmospheric Neutrinos



- **Atmospheric ν:** key signal for oscillations; background for **DSNB, DM, nucleon decay**
- Existing 3D models (HKKMS, Bartol, FLUKA) focus on **E_ν > 1 GeV**
- The **< 100 MeV** region — critical for DM searches — remains **unexplored**
- **3D Calculation Framework**

$\Phi_\nu = \Phi_{CR} \otimes R_{geo} \otimes Y_\nu$

Primary CR Flux
↓
Geomagnetic Cutoff
↓
Hadronic Interaction
↓
π/K/μ Decay



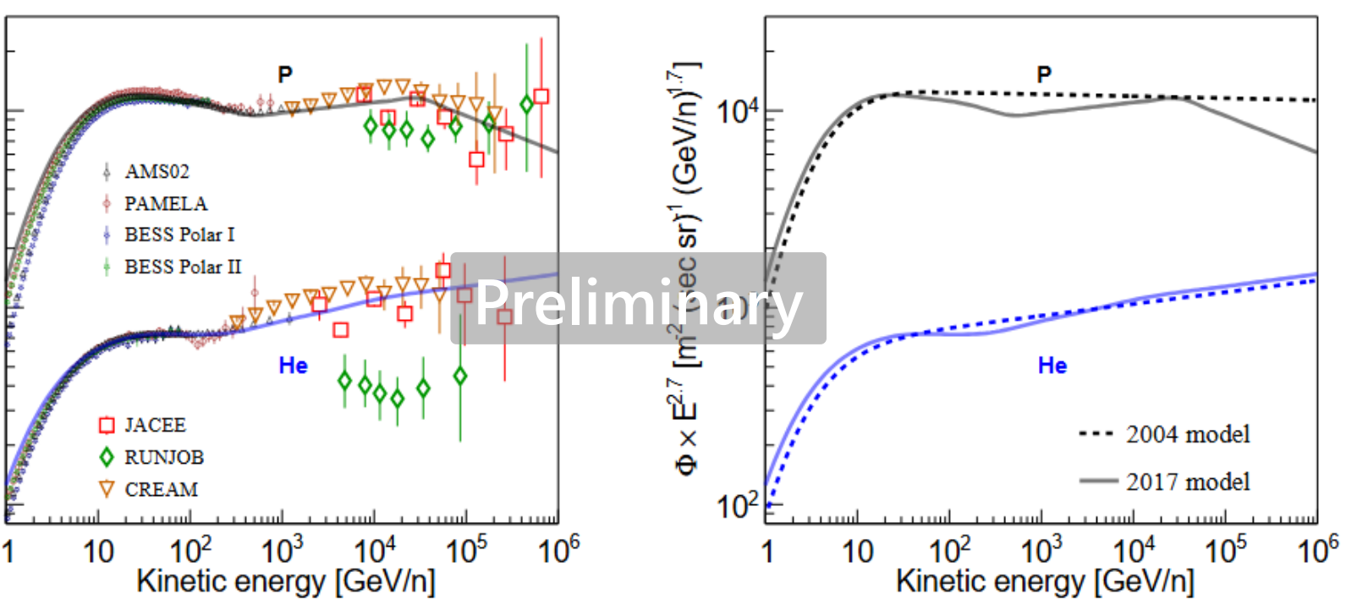
Based on the calculation scheme by Honda-san[1][2]

- **3D geometry:** Earth sphere (R_e) → Injection sphere (R_e+100 km) → Simulation sphere (10×R_e)
- **Virtual detector** with size correction for each site
- **Backward ray-tracing** for geomagnetic rigidity cutoff

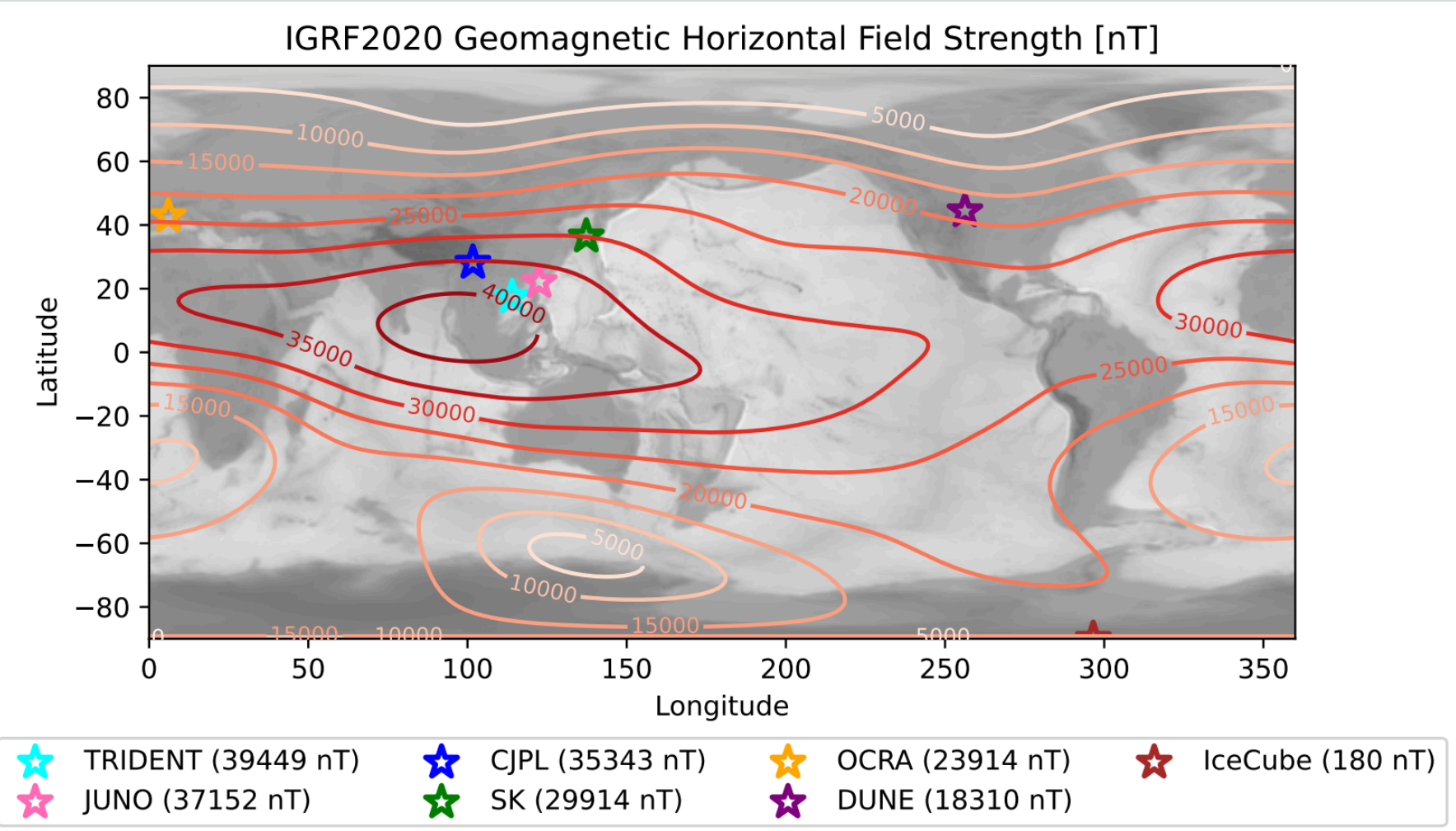
Model Updates

Component	HKKMS15	This Work
CR Model	2004	**2017 (AMS02)**
Geomagnetic	IGRF2010	**IGRF2020**
Atmosphere	NRLMSISE-00	**NRLMSISE-00**
Hadronic	JAM+DPMJET	**Recalibrated**
μ in Earth	✗	✓

Updated Primary Cosmic Ray Model

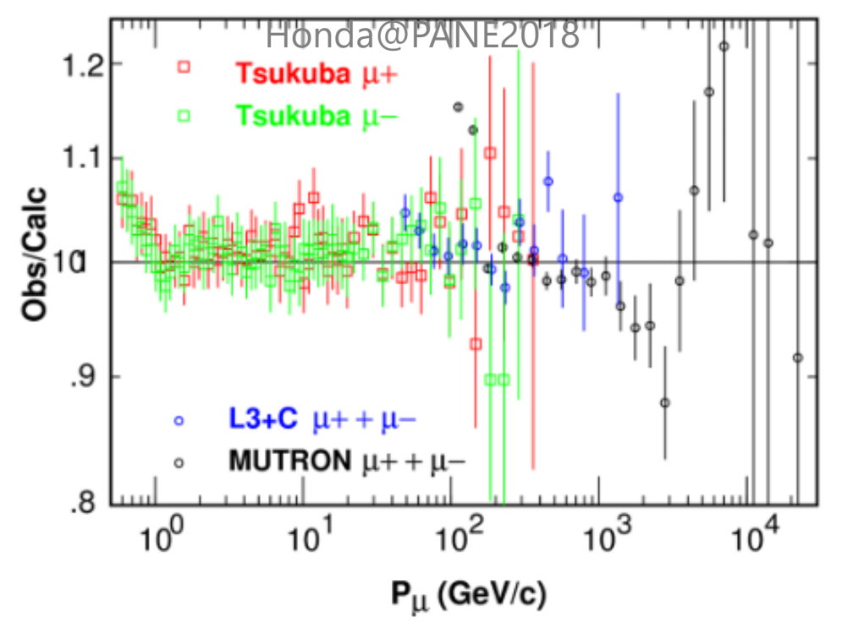


Geomagnetic Field (IGRF2020) & Sites



JUNO	~23°N
Super-K	~36°N
CJPL	~28°N
TRIDENT	~15°N
IceCube	~90°S
DUNE	~42°N
ORCA	~43°N

Hadronic model calibrated to muon observations



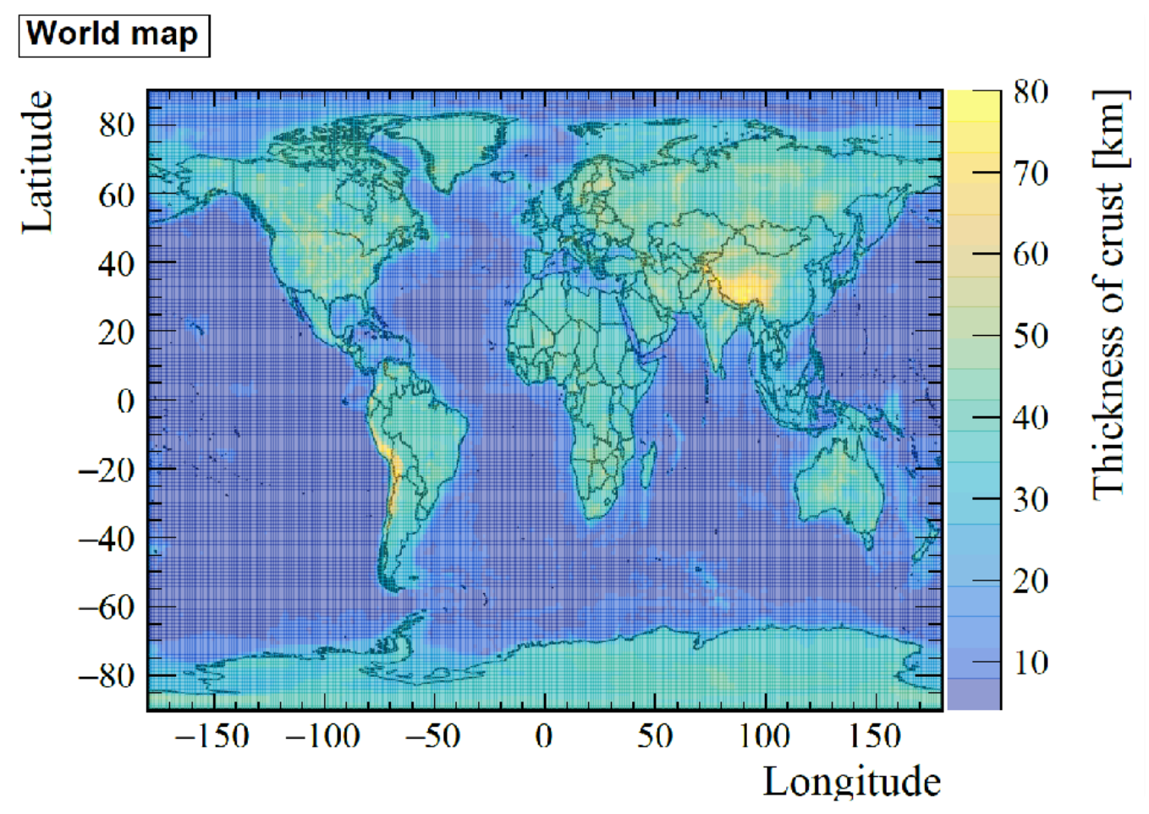
μ Propagation in Earth

Physical processes of muons inside the Earth — New contribution at E_ν < 100 MeV

- μ^+: stop and decay → $e^+ + \nu_e + \bar{\nu}_\mu$
- μ^-: stop and captured by atom
  - decay inside atom (→ $e^- + \nu_\mu + \bar{\nu}_e$)
  - nuclear capture ($\mu^- + p \to \nu_\mu + n$)

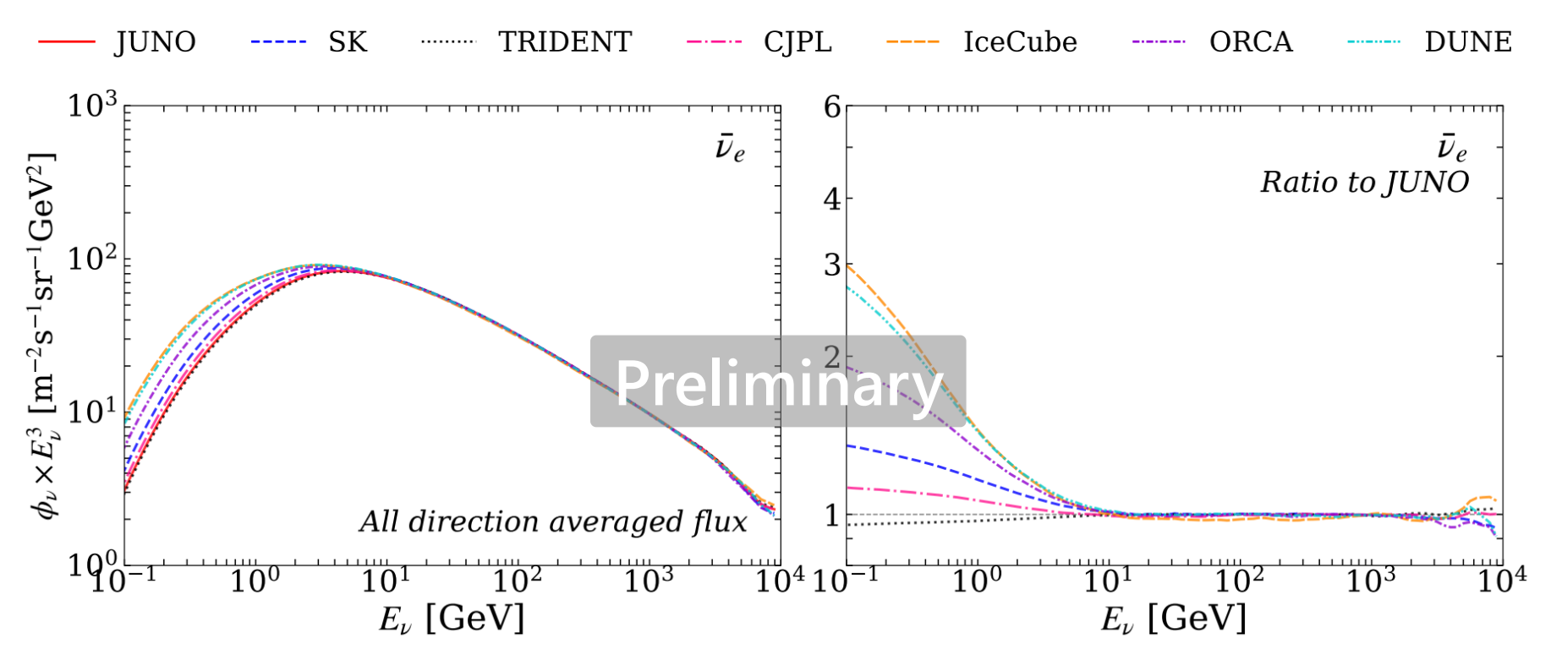
Atomic absorption probability and nuclear capture probability for μ^- considered

World map for muon hit point on the Earth



Flux with E_ν > 100 MeV

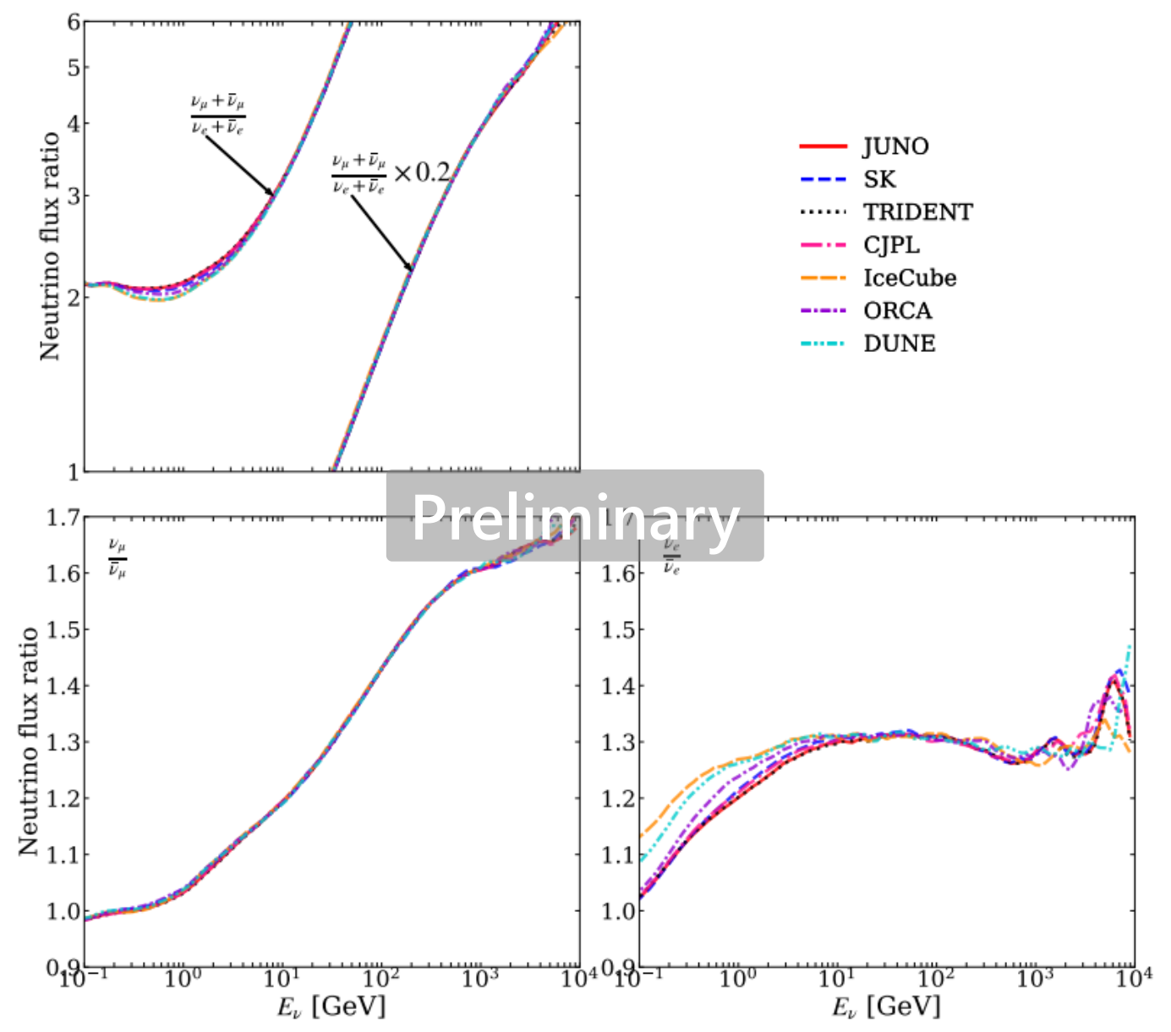
All-Direction Fluxes



($\bar{\nu}_e$ shown as example; patterns similar for other flavors)

- **E_ν > 10 GeV:** all sites converge → location-independent
- **E_ν < 1 GeV:** site-dependent deviations up to **3×**
- IceCube & DUNE show **~3× higher flux** vs JUNO at low E

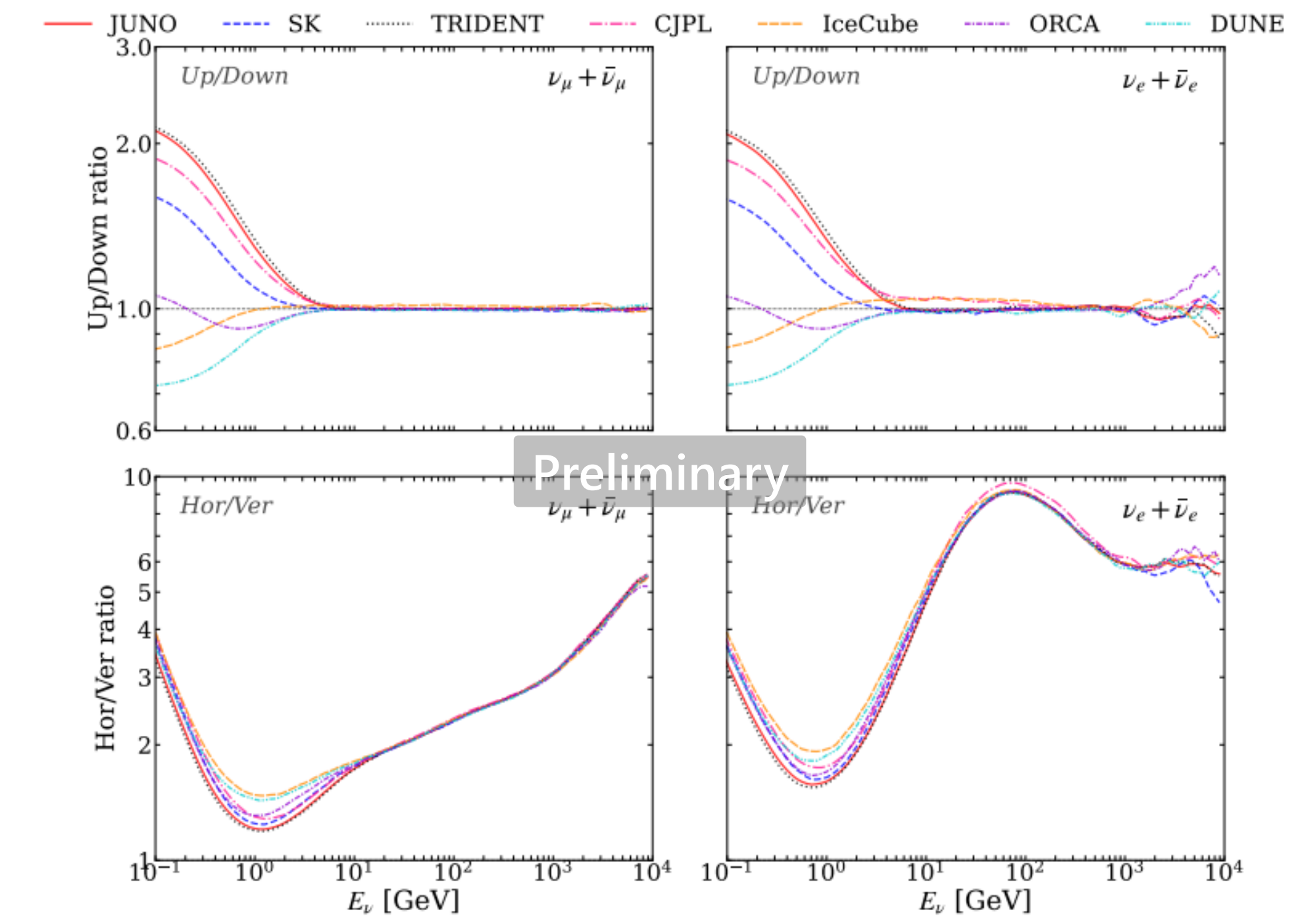
Neutrino flavor ratios



$\nu_e/\bar{\nu}_e$ reflects **μ^+/μ^- production asymmetry**

Zenith-Angle Dependence

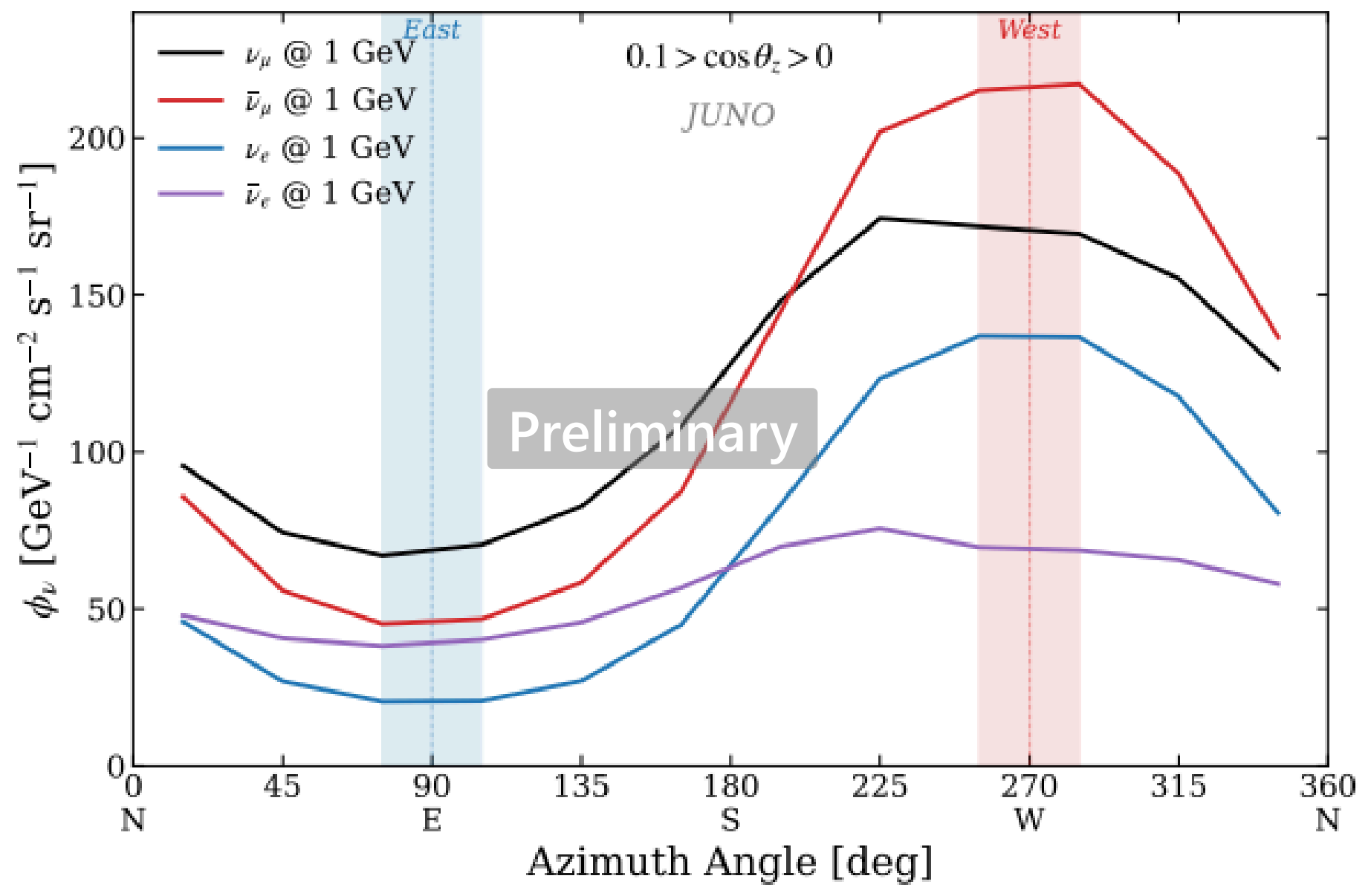
Hor: 0.1 > $\cos\theta_z$ > 0 | Ver (down): 1 > $\cos\theta_z$ > 0.9 | Average all azimuth angles



- **Downward:** compact production region above detector
- **Horizontal:** max enhancement at 1–100 GeV (μ decay length effect)
- **Upward:** broad antipodal production, dilution
- **Up/Down ratio** spans ~0.7 (DUNE) to ~2.2 (TRIDENT) at 0.1 GeV

At 5–100 GeV, downward fluxes at **IceCube** (cold → low air density) and **CJPL** (1580 m → smaller production area) are lower than at other sites.

East-West Effect



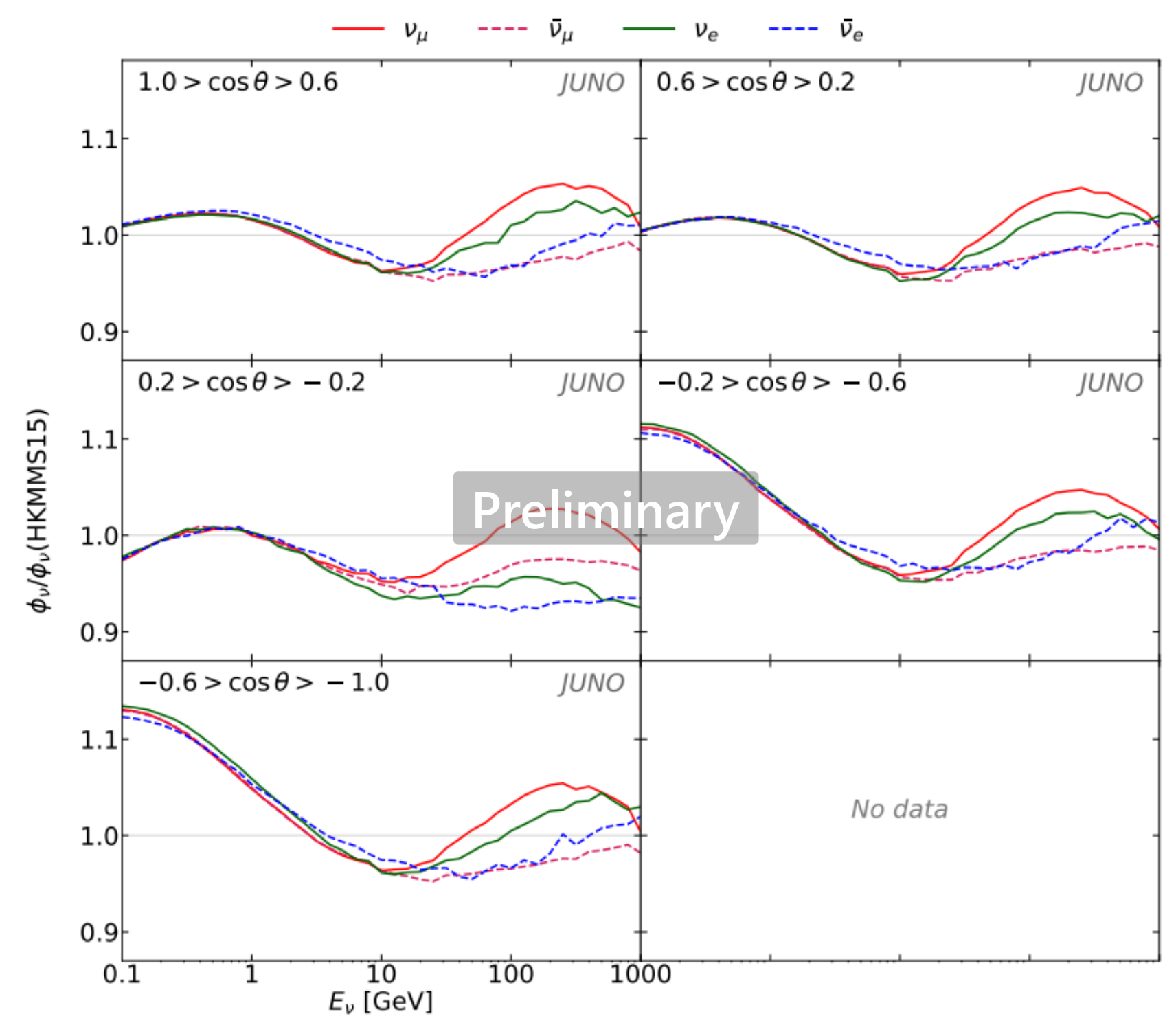
- **JUNO at 1 GeV (horizontal):** flux peaks at **West (~270°)**, minimum at **East (~90°)**
- Earth's magnetic field acts as a **rigidity filter**: CR from **East need higher rigidity** to penetrate
- **Proton-dominated CR spectrum → excess from West**, **deficit from East**

- **Flavor-dependent:** μ^+/μ^- geomagnetic bending introduces **$\nu/\bar{\nu}$ asymmetry** (ν_μ vs $\bar{\nu}_\mu$ differ slightly)

References

[1] HKKMS11: Phys. Rev. D 83, 123001 (2011)
[2] HKKMS15: Phys. Rev. D 92, 023004 (2015)
[3] Honda et al. (μ constraint): Phys. Rev. D 100 (2019) no.12, 123022
[4] HKKMS06: Phys. Rev. D 75 (2007), 043006

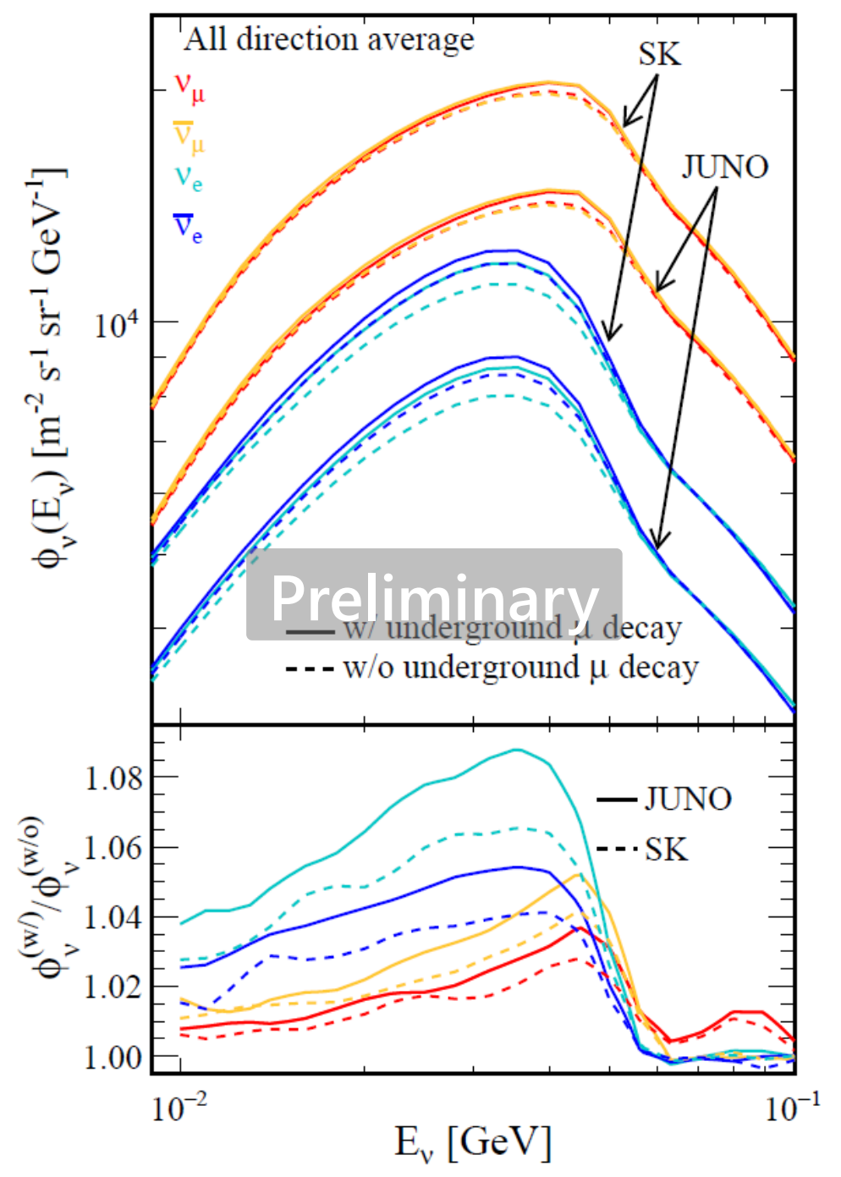
Comparison with HKKMS15



Illustrated with JUNO site results; comparison between this work and HKKMS15:

- **E_ν < 10 GeV:** upward ν **enhanced** (2017 CR model → more low-E CR through opposite-side low-cutoff regions)
- **E_ν > 10 GeV:** ratios ~1, **$\nu/\bar{\nu}$ split 1–3%** (CR charge asymmetry + hadronic recalibration)
- All within **HKKMS uncertainties** (~10% for E_ν > 1 GeV, ~15–25% for < 1 GeV)

Flux with E_ν < 100 MeV

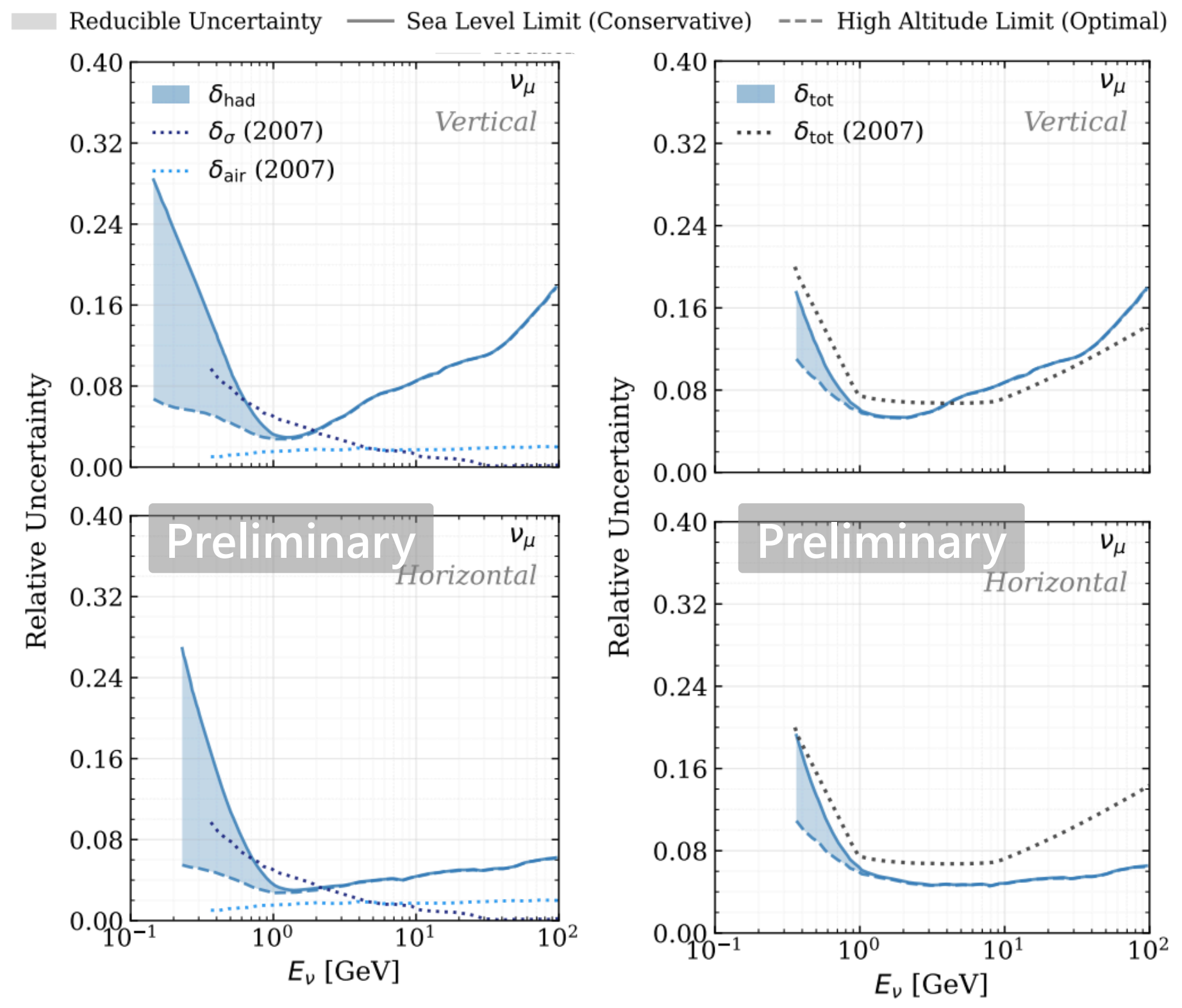


Results computed for all 7 sites; JUNO & SK shown as examples.

- **μ propagation in Earth** adds ν flux **below ~100 MeV**
- **JUNO vs SK:** absolute enhancement **~site-independent**; relative enhancement **larger at JUNO** (lower baseline flux from higher geomagnetic cutoff)
- **Flavor hierarchy of μ propagation enhancement: $\nu_e \approx \bar{\nu}_\mu > \nu_\mu > \bar{\nu}_e$** ($\mu^+$ decay dominates; μ^- captured by nuclei)
- Previously **ignored** by HKKMS, Bartol & FLUKA — **critical for DSNB & low-mass DM searches**

Flux Model Uncertainty Estimation

(ν_μ shown as example; results for all flavors computed)



- **Method:** hadronic uncertainty (**δ_{had}**) constrained by atmospheric μ data (**Honda et al.[3]**)
- Shaded bands: **reducible uncertainty range**
- **Upper solid:** conservative constraint from **sea-level μ observations** (Fig. 9 of Ref. [3])
- **Lower dashed:** optimal constraint from **high-altitude observations at Hanle**, 4500 m a.s.l. (Fig. 12 of Ref. [3])

- **Production cross-section (δ_σ)** and **atmospheric density (δ_{air})**, inherited from **HKKMS06[4]**
- **δ_{tot}:** total relative uncertainty of atmospheric ν flux
- Shaded bands: updated total uncertainty combining μ-constrained **δ_{had}** with **δ_σ** and **δ_{air}**
- Band width: **conservative (sea-level)** vs **optimal (high-altitude)** scenarios
- Dotted black lines: historical **δ_{tot}(2007)** from **HKKMS06[4]**