# High-energy neutrino measurement at Super-Kamiokande

2024i-I-001
Allocated research fund: 100,000JPY
Used: 100,000JPY for travel expenses at ICRR


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ICRR Research result presentation meeting, Jan. 29, 2025

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FASERnu, arXiv:2412.03186, PRL133(2024)021802, Fedynitch et al.,EPJ Web of Conf. 99, 08001(2015)
IceCube, Nature551(2017)596, Science 380, 1338 (2023), JCAP02(2021)025, Murase, PRD97(2018)081301

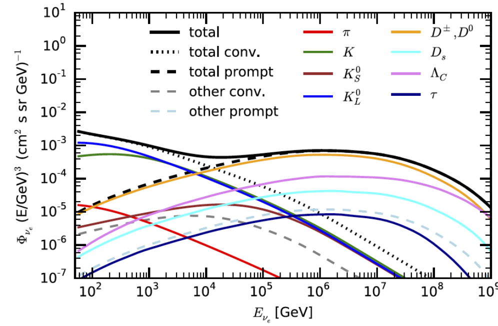
# TeV neutrino physics

## Rich neutrino physics around 1 TeV

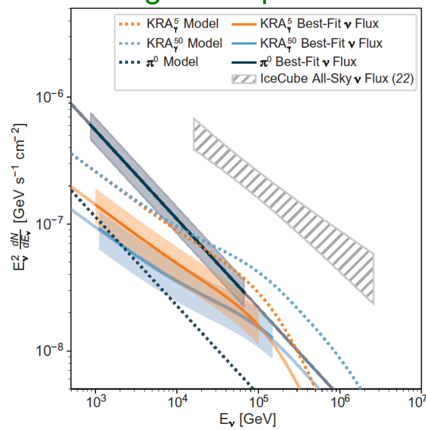
- New cross-section measurement
- Earth absorption measurement
- Galactic plane neutrino search
- Prompt atmospheric neutrino search
- Solar atmospheric neutrino search
- High-energy supernova neutrino search

etc

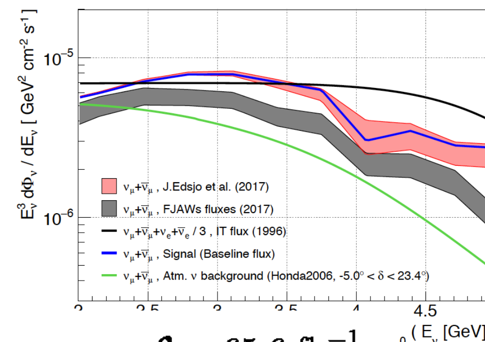
Prompt atmospheric neutrino




IceCube galactic plane neutrino

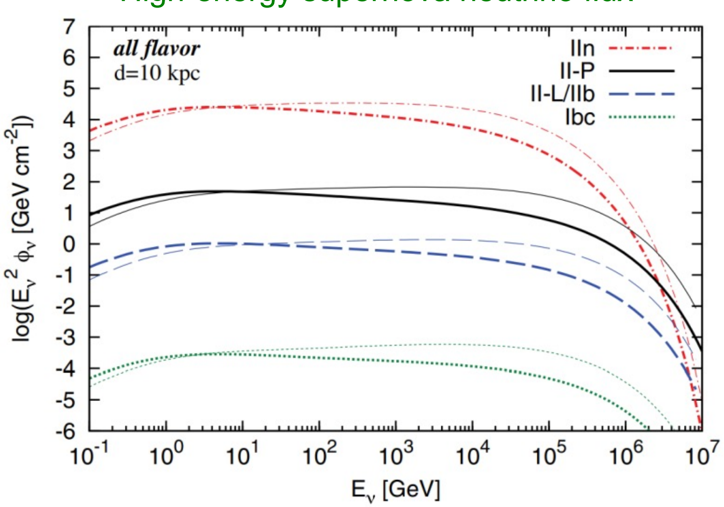


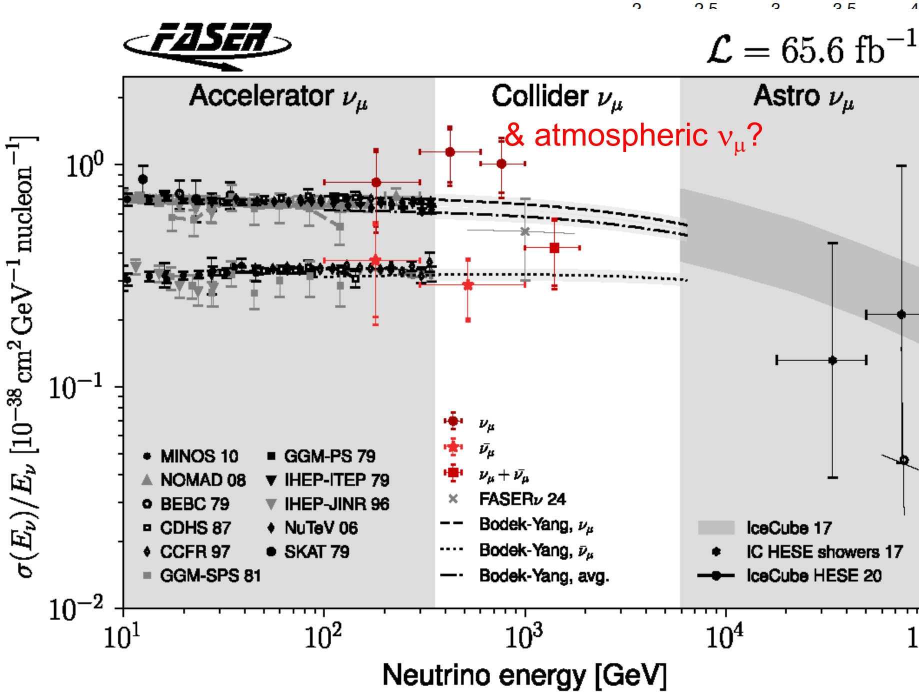

IceCube solar atmospheric neutrino limit




FASERnu neutrino cross-section

High-energy supernova neutrino flux

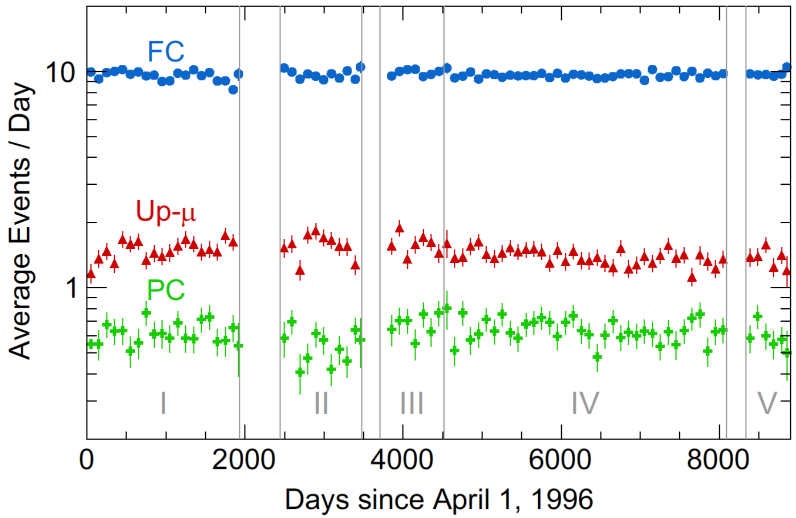


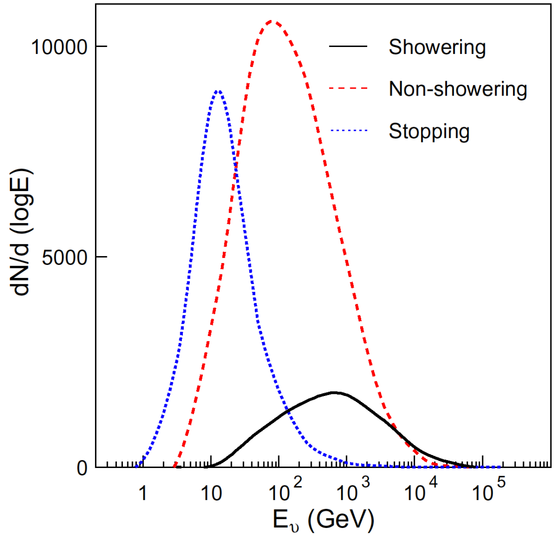



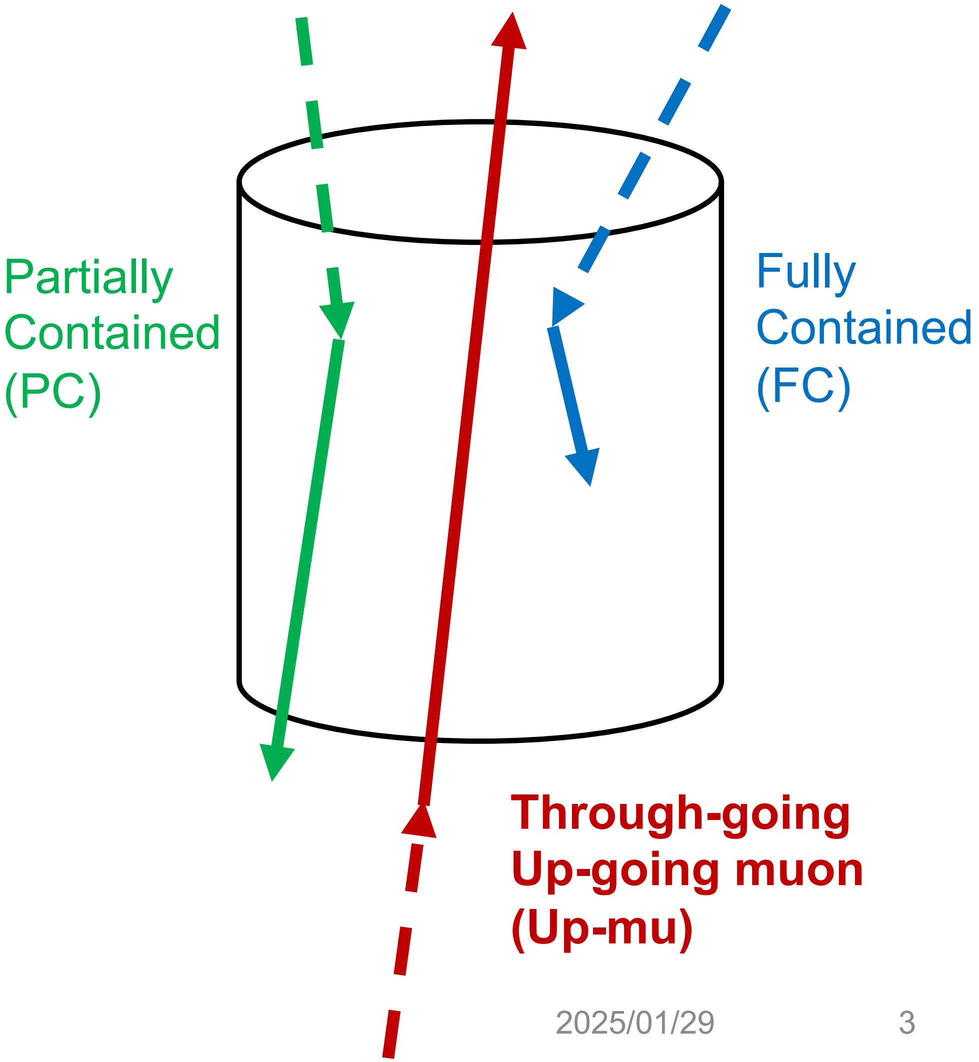
SuperK, PRD109(2024)072014, Astroparticle Physics 29 (2008) 42

# Neutrino measurement from through going up-going muons

SuperK sees ~1.5/day high-energy muons originated from neutrino interactions in rock.



# Radiative energy loss of charged particles

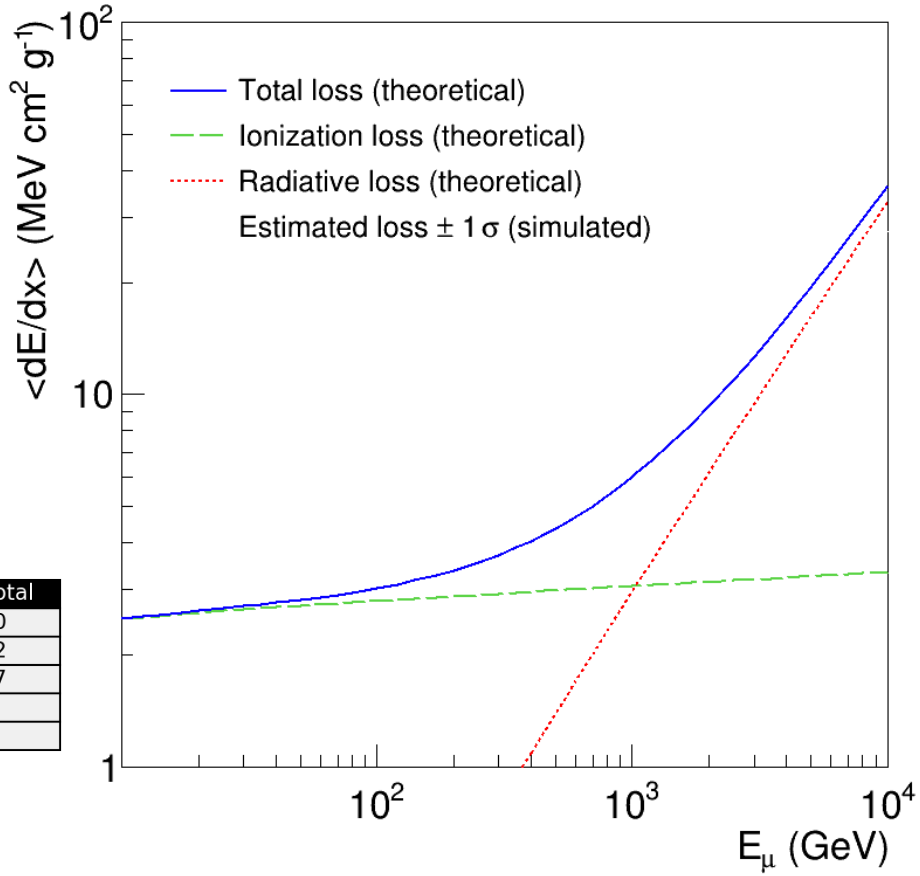
Muons start to lose energy by radiation process around from 100s GeV

This energy dependent energy deposit allows to measure the energy of through going muons with large variance

Energy reconstruction is only possible in statistical way

Total charge / fit track length (Q/L) is used as an estimator of dE/dx

| Cut | MC Total | <0.5 TeV | 0.5~5 TeV | >5 TeV | Data Total |
|---|---|---|---|---|---|
| Q/L>0 | 3049 | 2267 (74.4%) | 711 (23.3%) | 70 (2.3%) | 3550 |
| Q/L>27 | 1531 | 985 (64.3%) | 485 (31.7%) | 60 (3.9%) | 1862 |
| Q/L>30 | 858 | 478 (55.7%) | 329 (38.3%) | 50 (5.8%) | 1037 |
| Q/L>35 | 424 | 194 (45.8%) | 190 (44.8%) | 39 (9.2%) | 519 |
| Q/L>40 | 265 | 108 (40.8%) | 124 (46.8%) | 32 (12.1%) | 309 |

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# High-energy neutrino cross-section measurement

Measured muon spectrum $N(E, cos\theta)$ is

$$N(E, cos\theta) = \int \boxed{\Phi(E_\nu, cos\theta_\nu)} \otimes \boxed{\sigma(E_\nu, cos\theta_\nu : E, cos\theta)} \otimes \boxed{Att(E, \vec{x}_{prod}, \vec{x}_{enter})} \otimes \boxed{\varepsilon(E, cos\theta, \vec{x}_{enter})}$$

$\Phi(E_\nu, cos\theta_\nu)$: Incoming atmospheric muon neutrino and anti-neutrino flux

$\sigma(E_\nu, cos\theta_\nu : E, cos\theta)$: $\nu_\mu CC + \bar{\nu}_\mu CC$ DIS cross-section

$Att(\vec{x}_{prod}, \vec{x}_{dtec})$: Attenuation of muons in the rock

$\varepsilon(E, cos\theta, \vec{x}_{enter})$: detection efficiency

We use our simulation to calculate the upmu event rate, and compare with data

Use MCMC framework to extrapolate the total cross section of muon neutrinos in 1.6 GeV – 5 TeV

- 3 bin total cross-section normalization parameter fit

$$N_i = A \cdot k_i \cdot \sigma_i$$

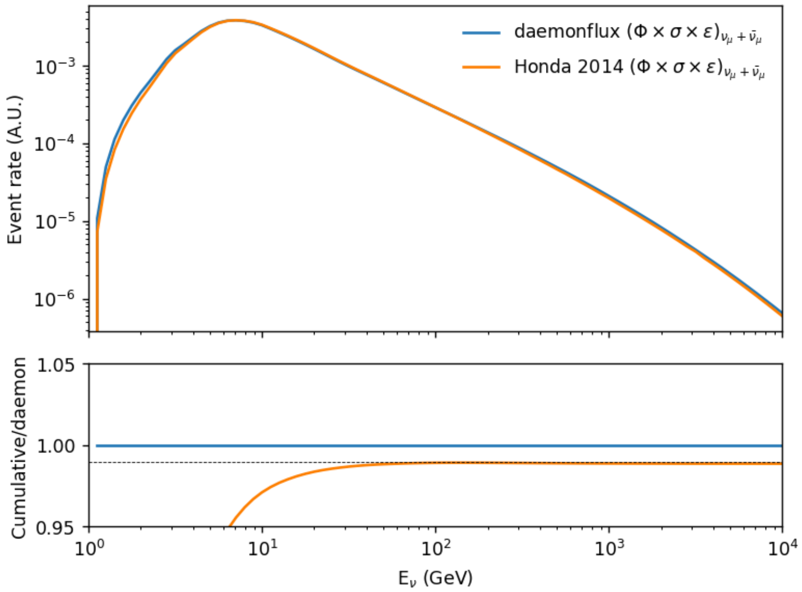
- 1st bin [1.6 GeV - 500 GeV], $k_1$= Gaussian prior (20%)
- 2nd bin [500 GeV - 5 TeV], $k_2$= Gaussian prior (50%)
- 3rd bin [5 TeV - 10 TeV], $k_3$=Lognormal prior (50%)

Fake data study returns the right value

| Cut | MC Total | <0.5 TeV | 0.5~5 TeV | >5 TeV | Data Total |
|---|---|---|---|---|---|
| Q/L>0 | 3049 | $2267\times k_1$ | $711\times k_2$ | $70\times k_3$ | 3550 |
| Q/L>27 | 1531 | $985\times k_1$ | $485\times k_2$ | $60\times k_3$ | 1862 |
| Q/L>30 | 858 | $478\times k_1$ | $329\times k_2$ | $50\times k_3$ | 1037 |
| Q/L>35 | 424 | $194\times k_1$ | $190\times k_2$ | $39\times k_3$ | 519 |
| Q/L>40 | 265 | $108\times k_1$ | $124\times k_2$ | $32\times k_3$ | 309 |

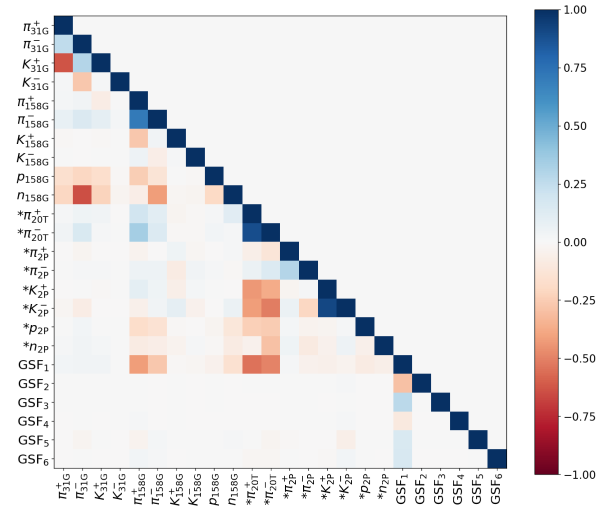
# Atmospheric neutrino flux systematic error

Flux prediction > 10 GeV is relatively simpler
- Weak dependence on the earth magnetic field
- No need of 3d cascade equation
- More abundant hadron production library




MCEq https://github.com/mceq-project/MCEq
- 1-d cascade equation
- Open software

DAEMON flux https://github.com/mceq-project/daemonflux
- MCEq based flux prediction
- Tuned with atmospheric muon and hadron production data
- Full covariance matrix is available
- Difference with Honda flux 2014 is ~1%
- Expected flux error, 5-20%

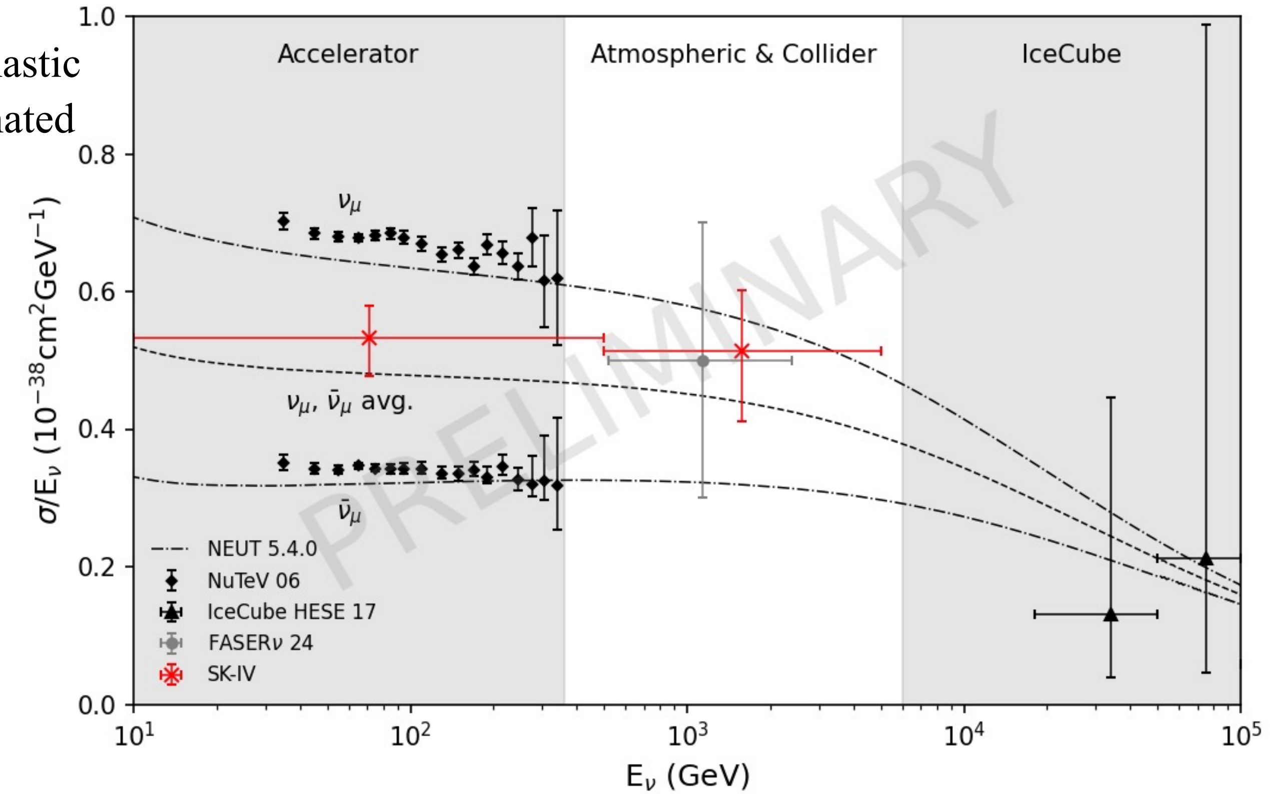


# $\nu_\mu CC + \bar{\nu}_\mu CC$ DIS cross-section total cross-section

Finalizing systematic error evaluations, but the preliminary result is promising.

The dominant error is the stochastic statistics, as the energy is estimated from the radiation loss.

The result is competitive to the latest TeV cross-section measurement by FASERν.




**FY2025 plan**

- Publish the paper
- Start Hyper-Kamiokande sensitivity study;

1. Smaller error
2. More bin
3. Higher-energy

# Thank you for your attention

# Backup