

TeV-scale ν_{μ} cross section measurements at Super-Kamiokande

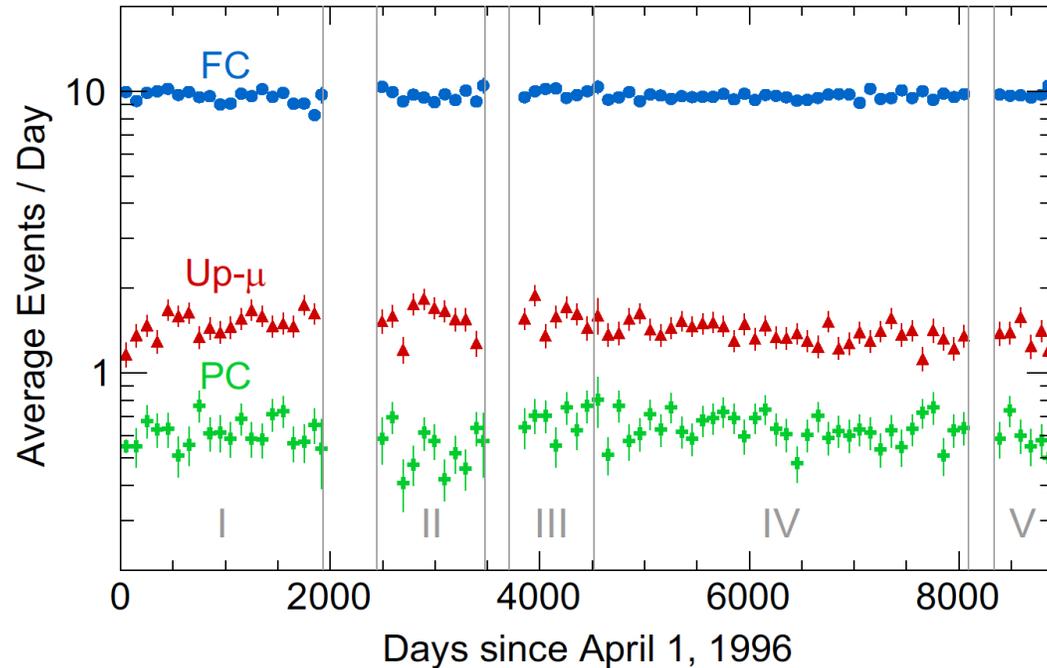
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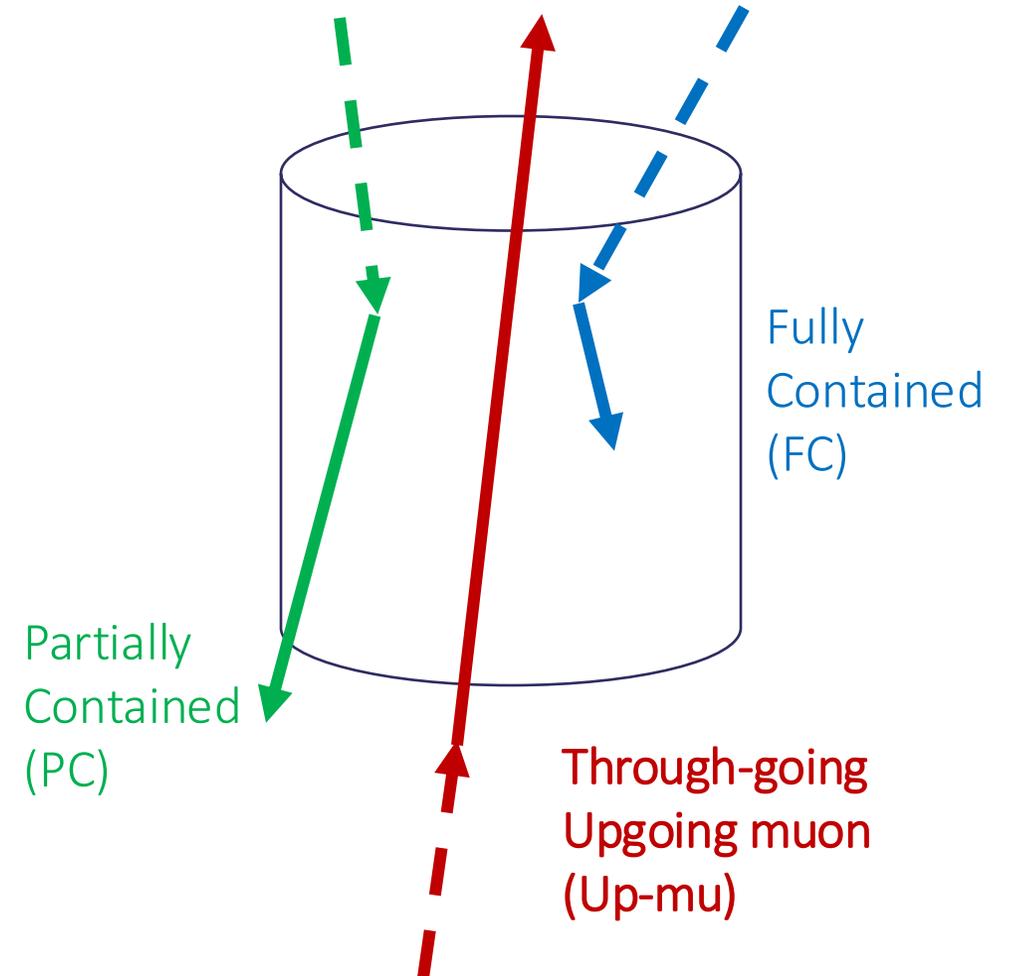
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High-energy atmospheric neutrinos in Super-K

Super-K sees ~ 1.5 high-energy upgoing muons per day from neutrino interactions in rock



Throughgoing Up-mu ν_μ have correct energy to fill the gaps in TeV cross section measurements



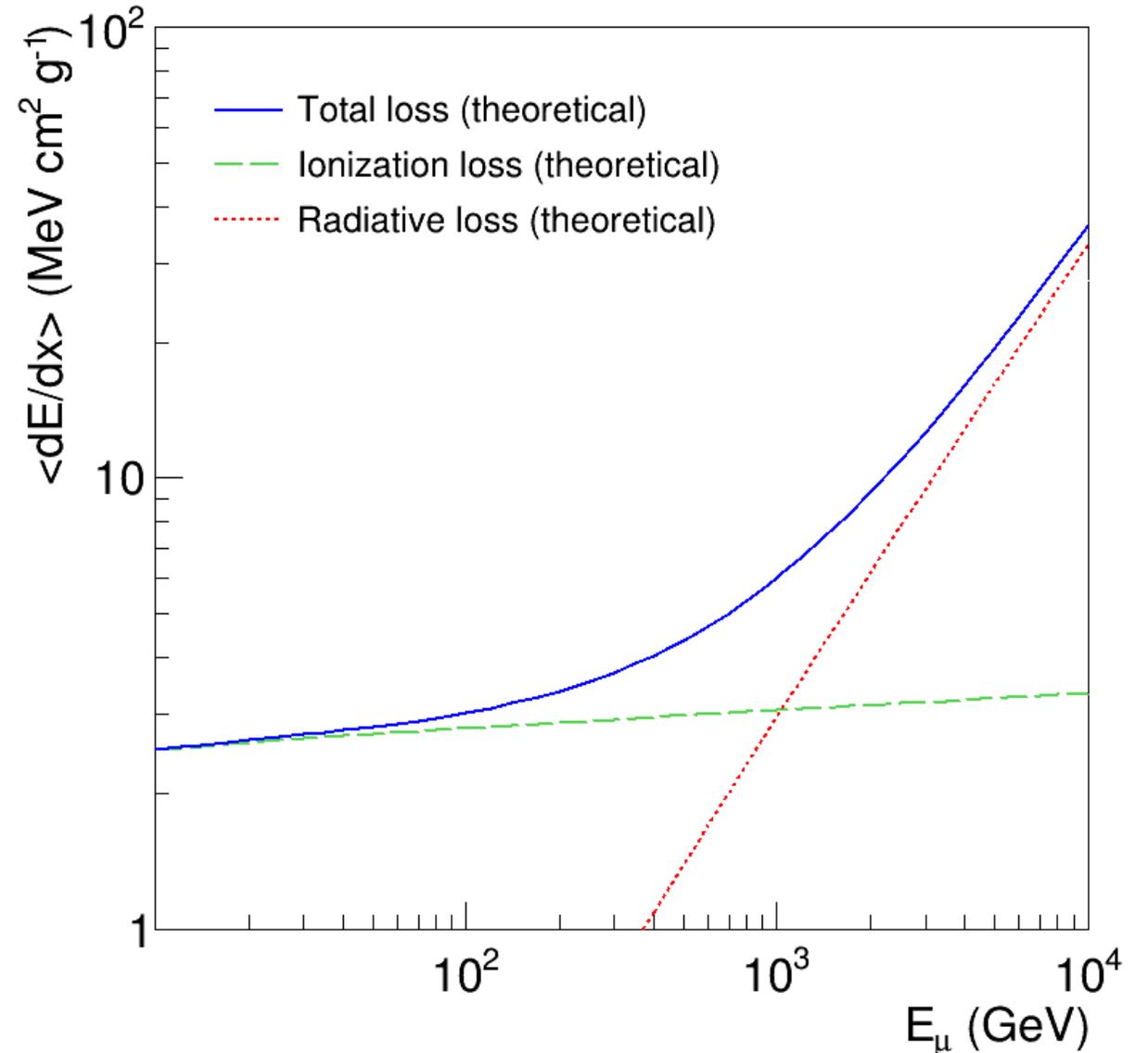
Radiative energy losses of muons

Muons mostly lose energy via radiative processes from a few hundreds of GeV

Energy deposition depends on muon energy, but with large variance along the track

Energy reconstruction is only possible statistically

We use **total charge deposit** and **track length** as an estimator for dE/dx , which serves as proxy with v_μ energy sensitivity



High-energy neutrino cross-section measurement

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

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

- $\Phi(E_\nu, \cos\theta_\nu)$: **atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux**
- $\sigma(E_\nu, \cos\theta_\nu; E, \cos\theta)$: **$\nu_\mu CC + \bar{\nu}_\mu CC$ cross-section**
- $\text{Att}(\vec{x}_{prod}, \vec{x}_{dtec})$: **attenuation in rock propagation**
- $\varepsilon(E, \cos\theta, \vec{x}_{enter})$: **detection efficiency**

Full detector simulation calculates Up-mu rate, MCMC framework fits cross section for data-MC agreement

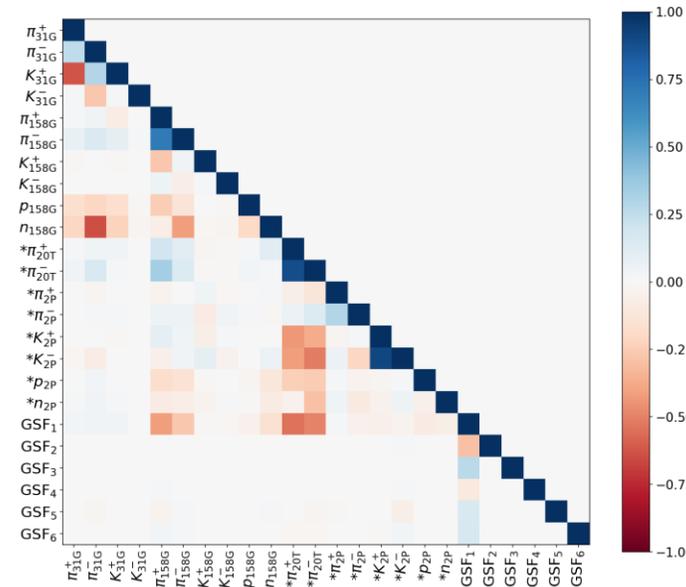
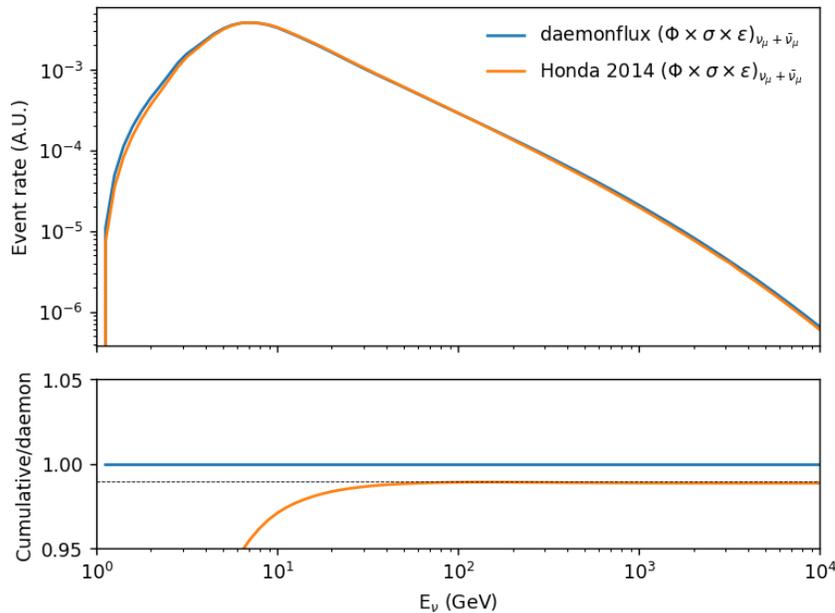
- 1st bin [1.6 GeV - 500 GeV]
- 2nd bin [500 GeV - 5 TeV]
- 3rd bin [5 TeV - 90 TeV], overflow bin

Fake data studies returns the right value

Uncertainty evaluations

Flux uncertainty

- Using daemonflux (1-D MCEq based model):
<https://github.com/mceq-project/daemonflux>
- Tuned to hadron production data
- Differs from Honda 2014 flux by ~1%
- Expected flux uncertainty: 5–20%

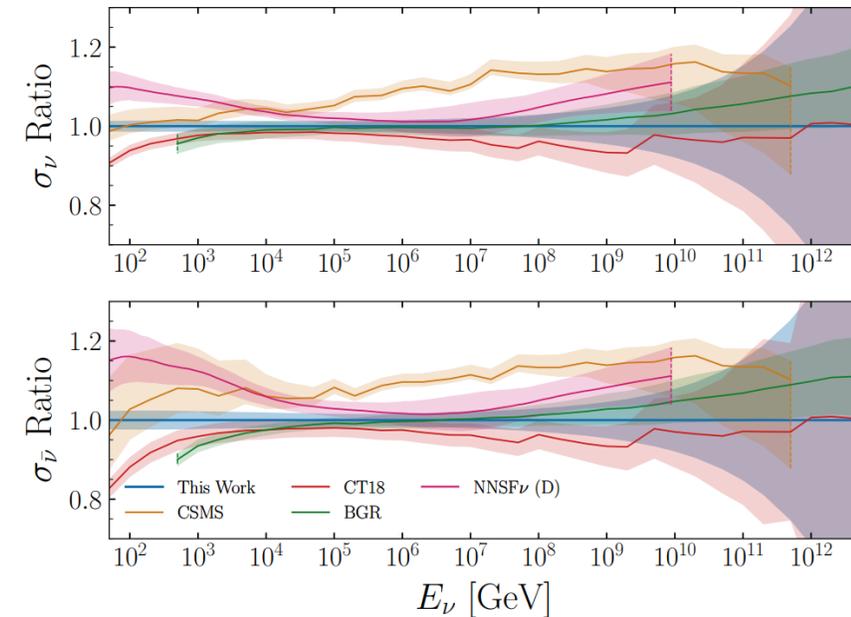


Kinematics uncertainty

- Using evaluations published in 2025
- Used to recalculate the acceptance/observed events

Stochastic uncertainty

- From the variance in muon energy loss



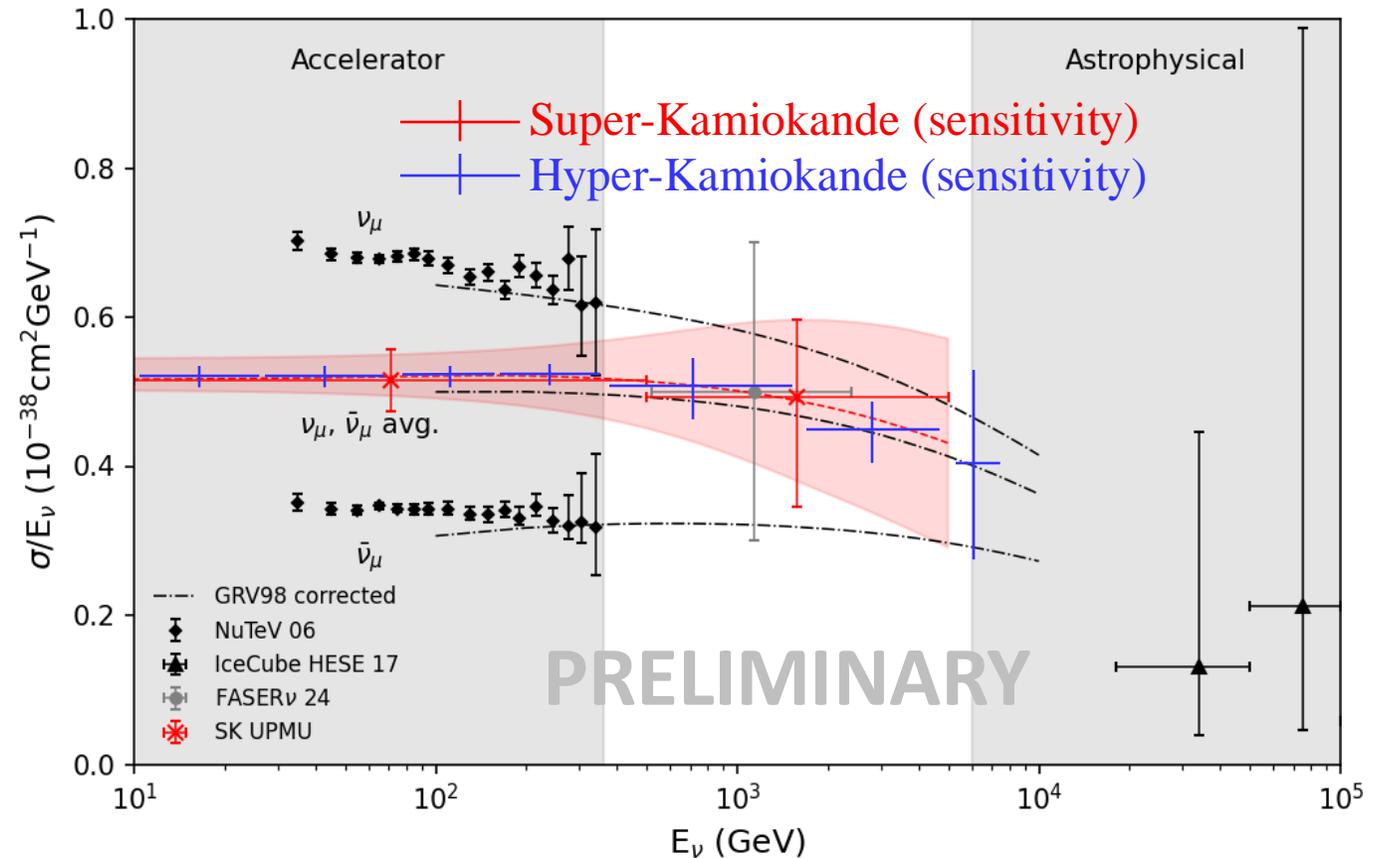
$\nu_\mu + \bar{\nu}_\mu$ CC total cross-section

Preliminary fake data study is promising as shown – now finalising result!

Dominant error from stochastic statistics of muon energy loss

This result will fill gaps in neutrino data, complimenting the recent collider-based efforts by FASER ν

Hyper-K can further refine these measurements with its improved statistics



Thank you for your attention and look forward to the result!