High-energy Neutrino Measurements at Super-Kamiokande and Hyper-Kamiokande

Outline

1. Introduction
2. Method
3. Results
4. Conclusions

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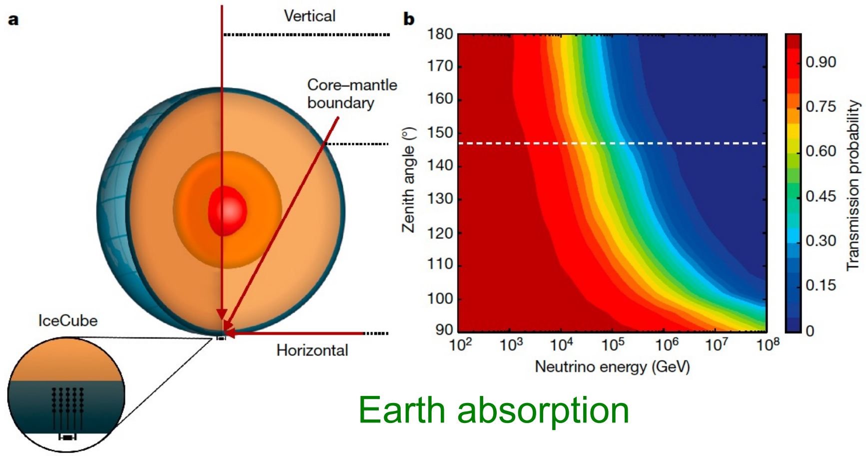
NAM25, Durham Univ., Durham, UK, July 8, 2025

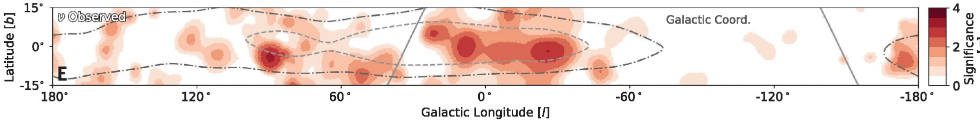
1. Diffuse TeV neutrino physics

Rich neutrino physics around 1 TeV

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

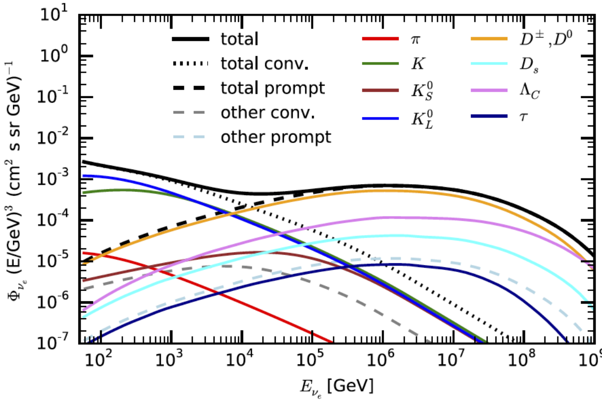


Earth absorption

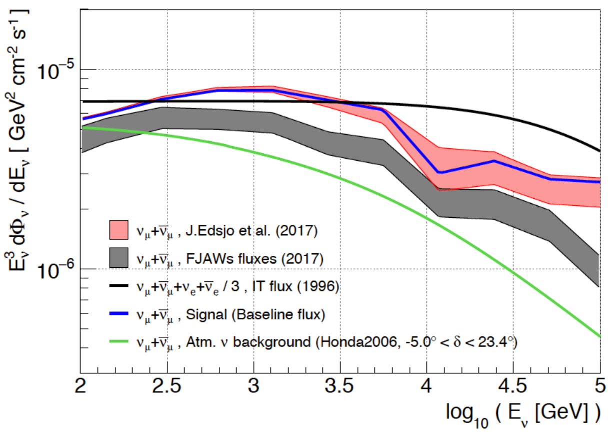


IceCube galactic plane neutrino

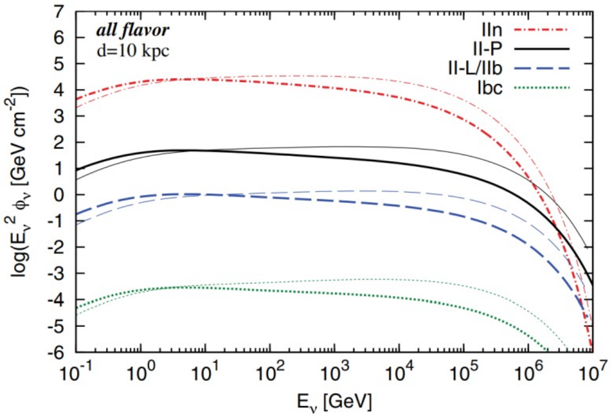
Prompt atmospheric neutrino



IceCube solar atmospheric neutrino limit



High-energy supernova neutrino flux



IceCube, Nature551(2017)596, Science 380, 1338 (2023), JCAP02(2021)025, Murase, PRD97(2018)081301, Fedynitch et al.,EPJ Web. Conf99, 08001(2015)
FASERnu, arXiv:2412.03186, PRL133(2024)021802,

1. Diffuse TeV neutrino physics

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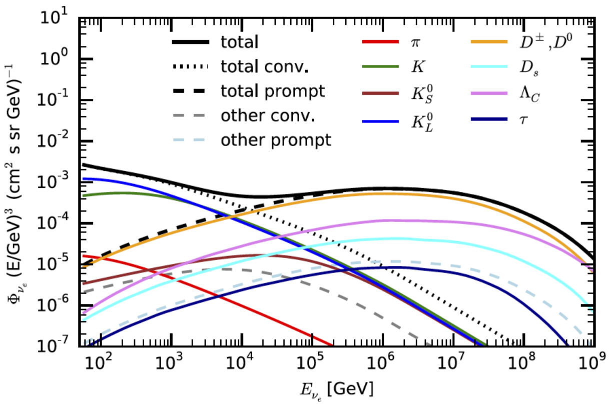
- Solar atmospheric neutrinos
- High-energy supernova neutrinos
- New cross-section measurement

E_ν < 360 GeV: Accelerator-based experiments
E_ν > 6 TeV: Neutrino telescopes (IceCube)

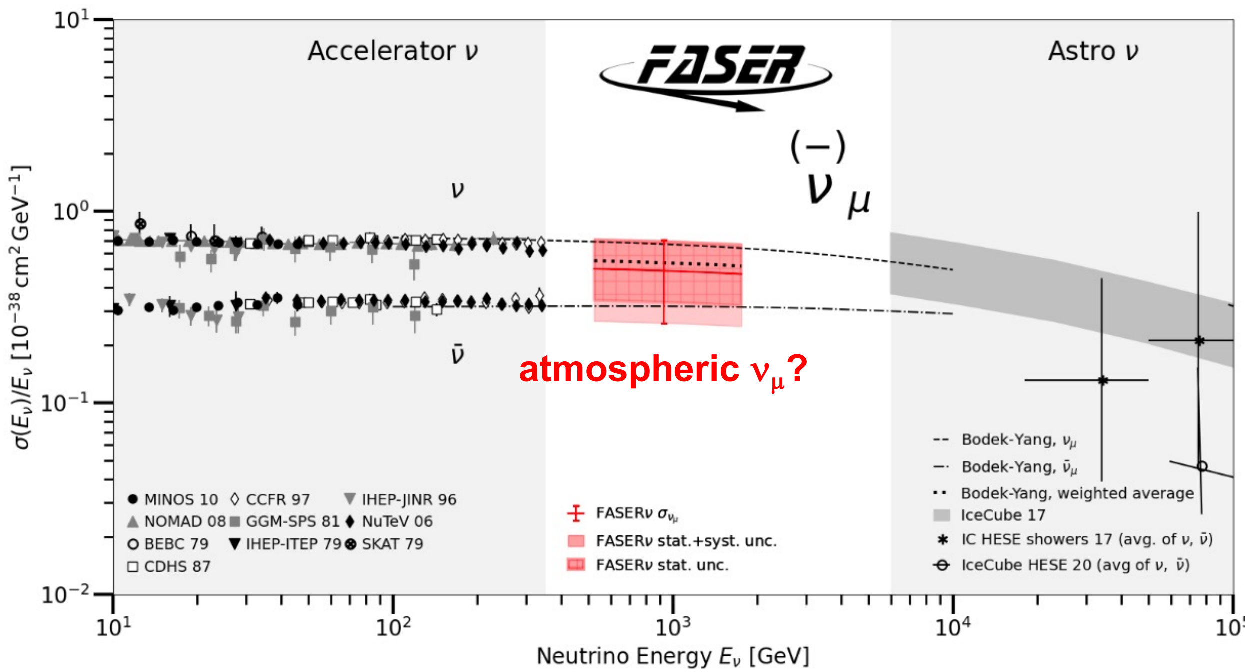
360 GeV < E_ν < 6 TeV
New region measured by FASERν

Super-K can measure this using atmospheric data!

Prompt atmospheric neutrino



FASERnu neutrino cross-section measurements



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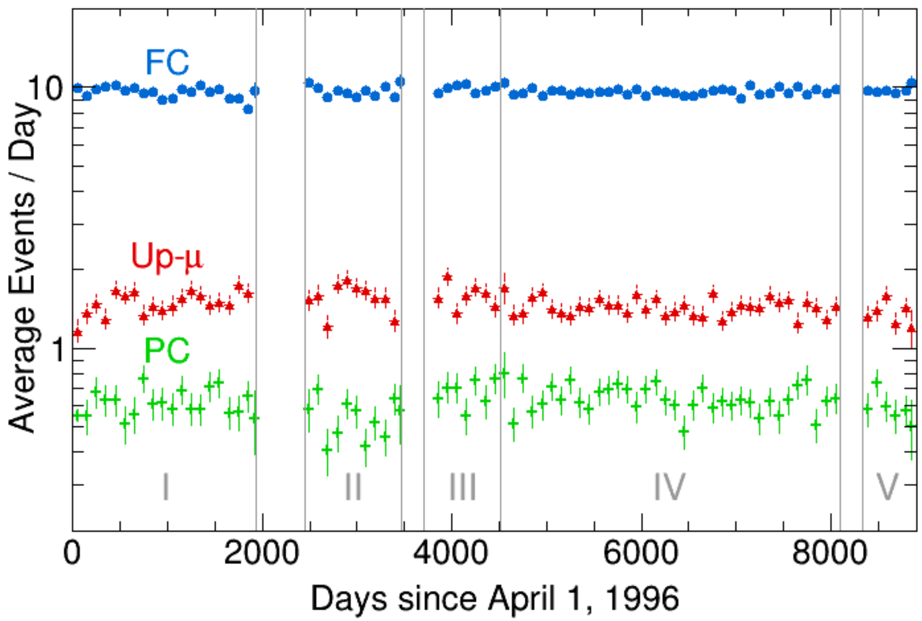
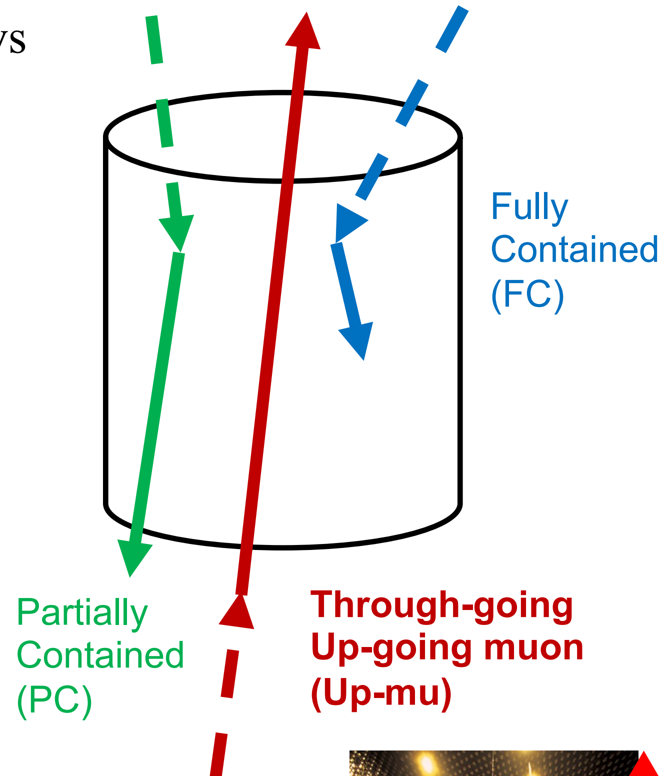
SuperK, PRD109(2024)072014

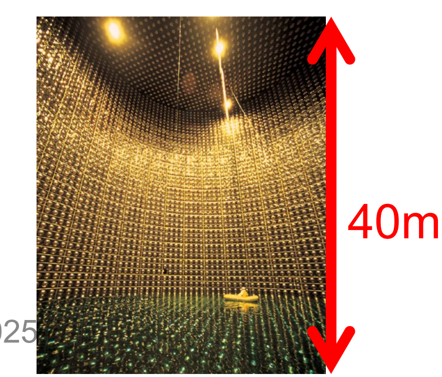
1. Neutrino measurement from through going up-going muons

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

- 3989 up-going through-going muon events in 4269 days







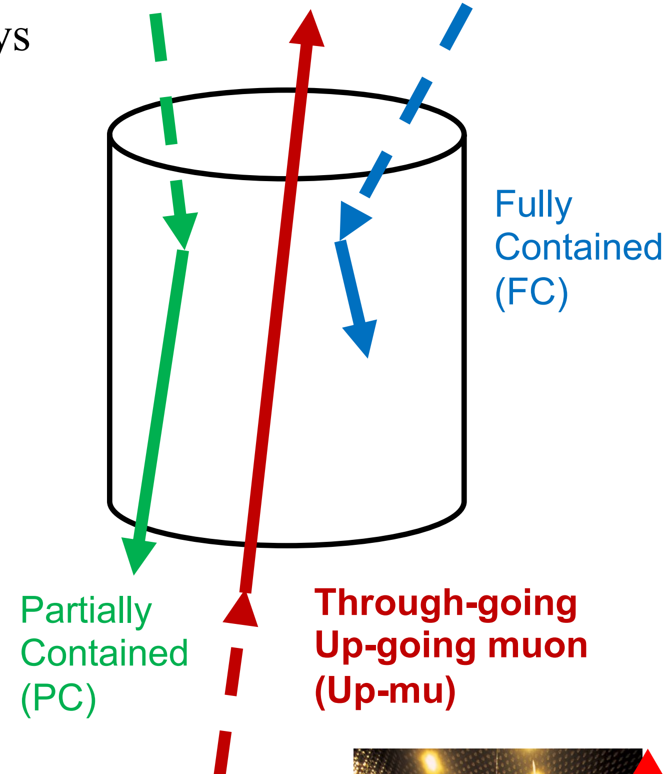
1. Neutrino measurement from through going up-going muons

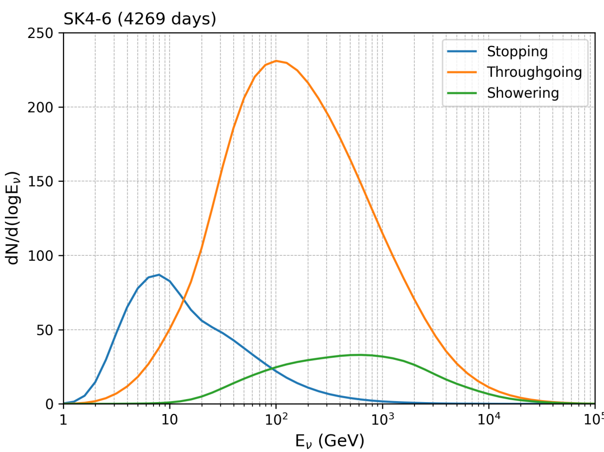
SuperK sees ~1.5/day high-energy muons originated from neutrino interactions in rock.

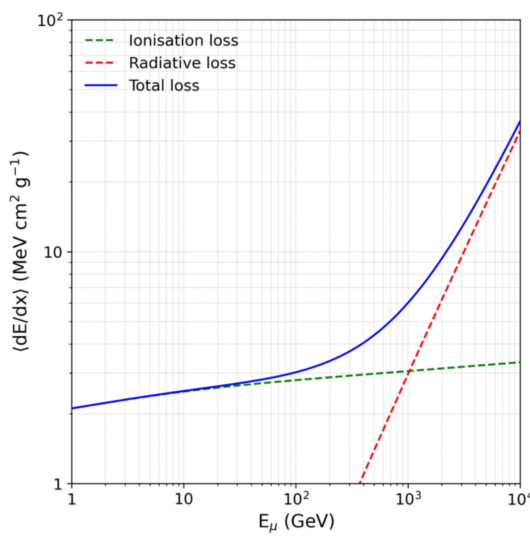
- 3989 up-going through-going muon events in 4269 days

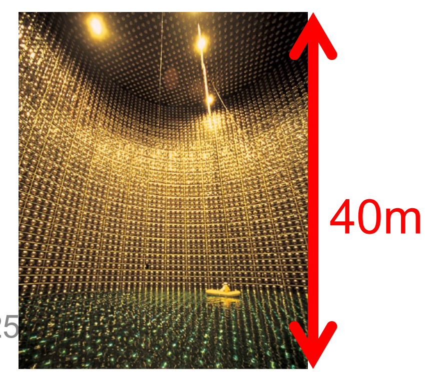
~15% of through-going muons lose energy by showers

→ High-energy neutrino information







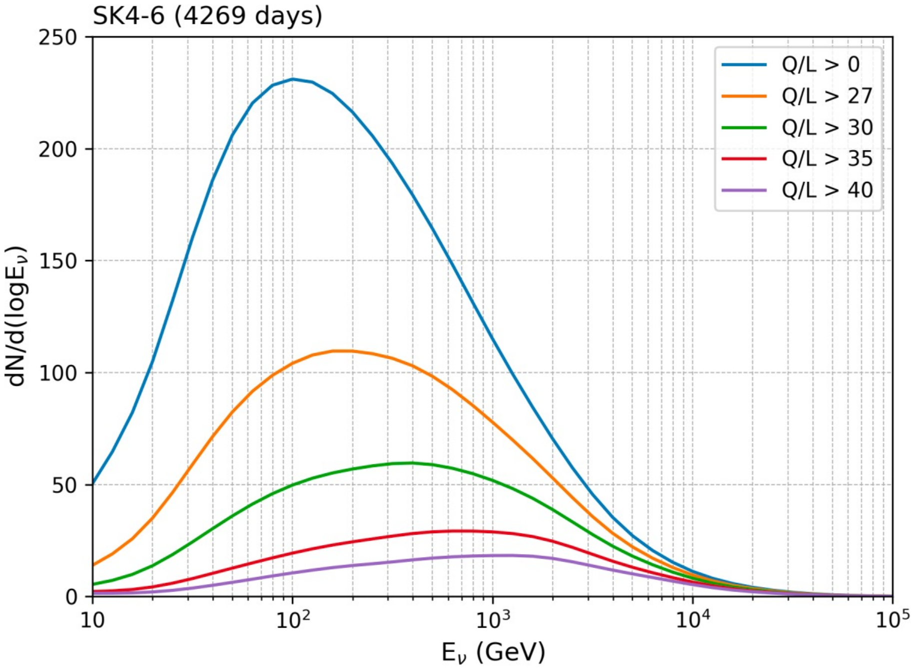


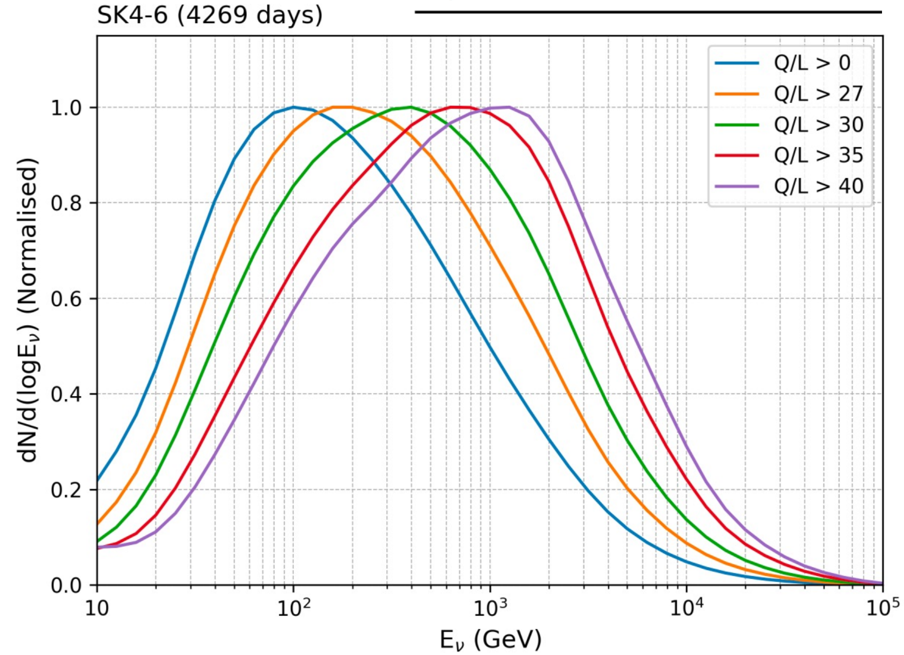
1. Radiative energy loss of charged particles

This energy dependent energy deposit allows to estimate the energy of through going muons
- Statistical energy reconstruction

Cut	Data	MC (Pre-fit)
QL > 0	3989	3367
QL > 27	2010	1673
QL > 30	1130	931
QL > 35	533	460
QL > 40	316	288

Total charge / fit track length (Q/L) is used as an estimator of dE/dx
- Q/L cut to shift energy spectrum





2. High-energy neutrino cross-section measurement

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

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

$\Phi(E_\nu, cos\theta_\nu)$: Atmospheric ν_μ and $\bar{\nu}_\mu$ flux

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

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

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

Full detector simulation calculates the event rate $N(E, cos\theta)$, and a 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)

Analysis is statistically limited

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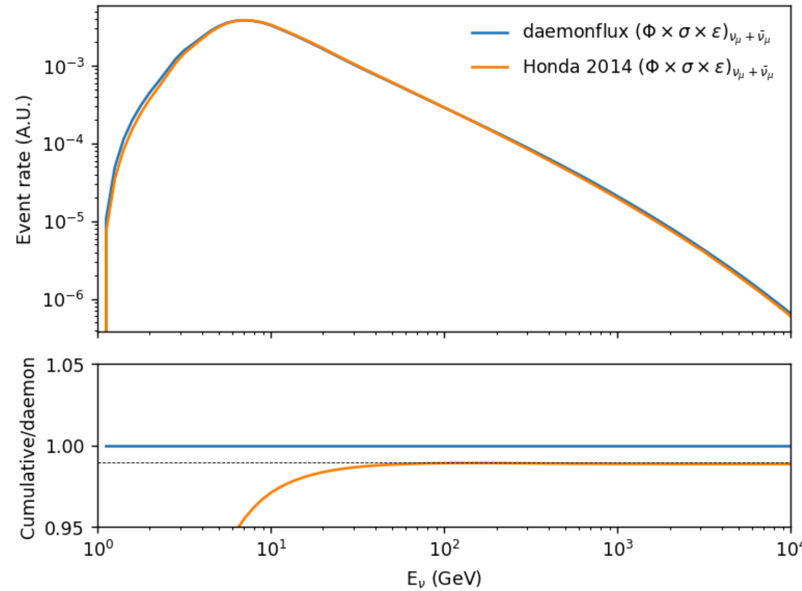
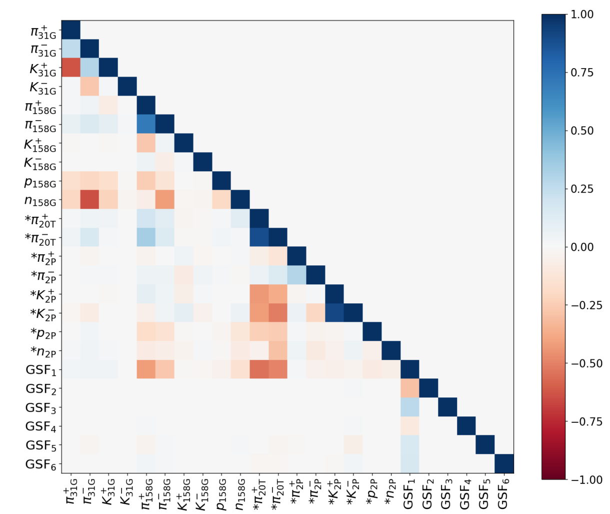
2. Atmospheric neutrino flux systematic error

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 https://github.com/mceq-project/daemonflux

DAEMON flux
- MCEq based flux prediction
- Tuned with atmospheric muon and hadron production data
- Full covariance matrix is available
- Difference with Honda flux 2014 is ~1%
- Flux systematic error
  - 1-500 GeV: 4%
  - 500-5000 GeV: 9%
  - 5000-10000 GeV: 19%



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2. Astrophysical neutrino flux systematic error

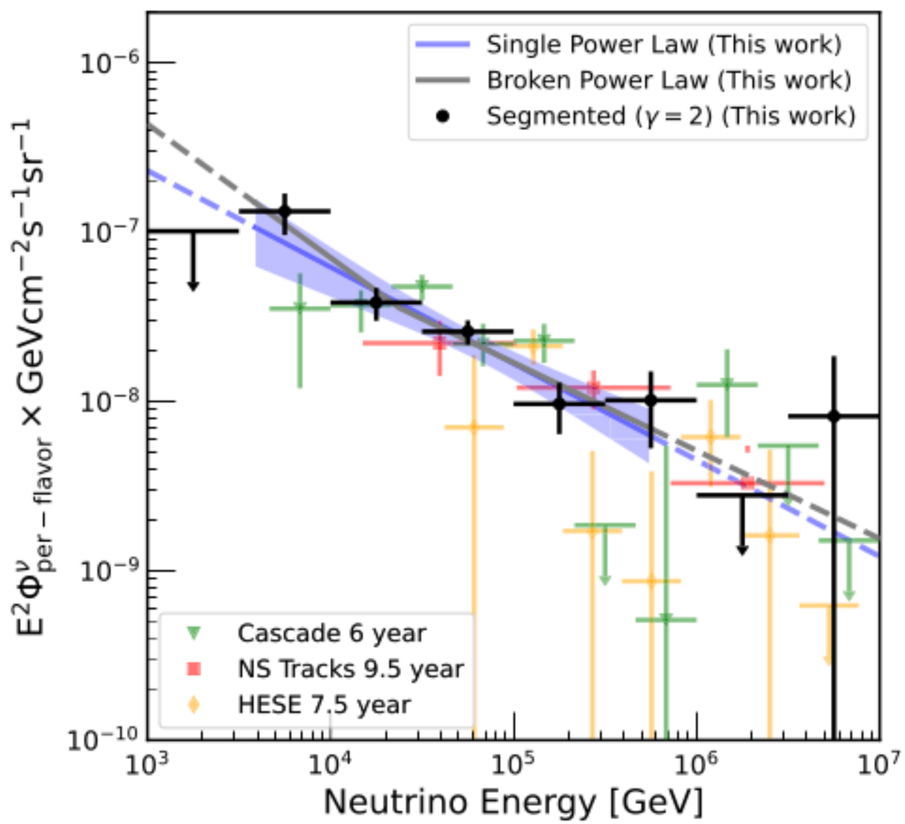
Astrophysical neutrino components are treated as background

Both single and broken power laws give negligible contribution (<2%)

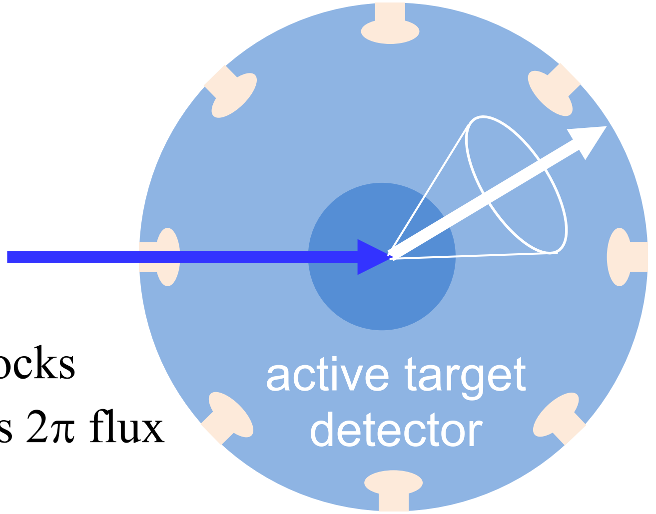
Single power law spectrum index

$$\Phi \sim \phi_{astro} \cdot E^{-\gamma_{astro}}$$

ϕ_{astro}: 12%
γ_{astro}: 20%



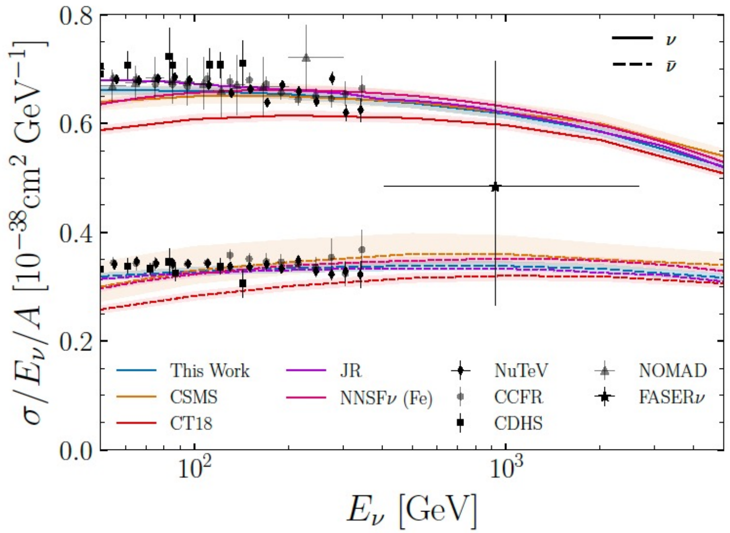
2. Kinematic systematic error

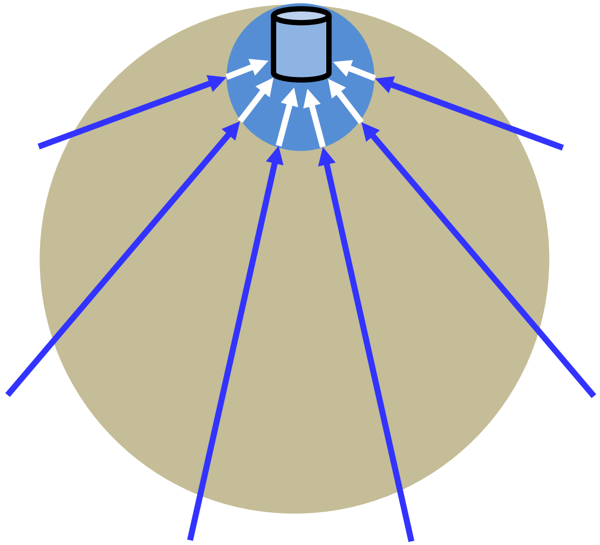


Total cross-section measurement needs 4π detector
→ the detector accepts events with any kinematics

Through going muons are generated by interactions with rocks
Atmospheric neutrino total cross-section measurement uses 2π flux
→ Geometric (kinematic) effect mostly cancel

Error is guided by recent DIS differential cross-section model
$d\sigma/dy$: 5%



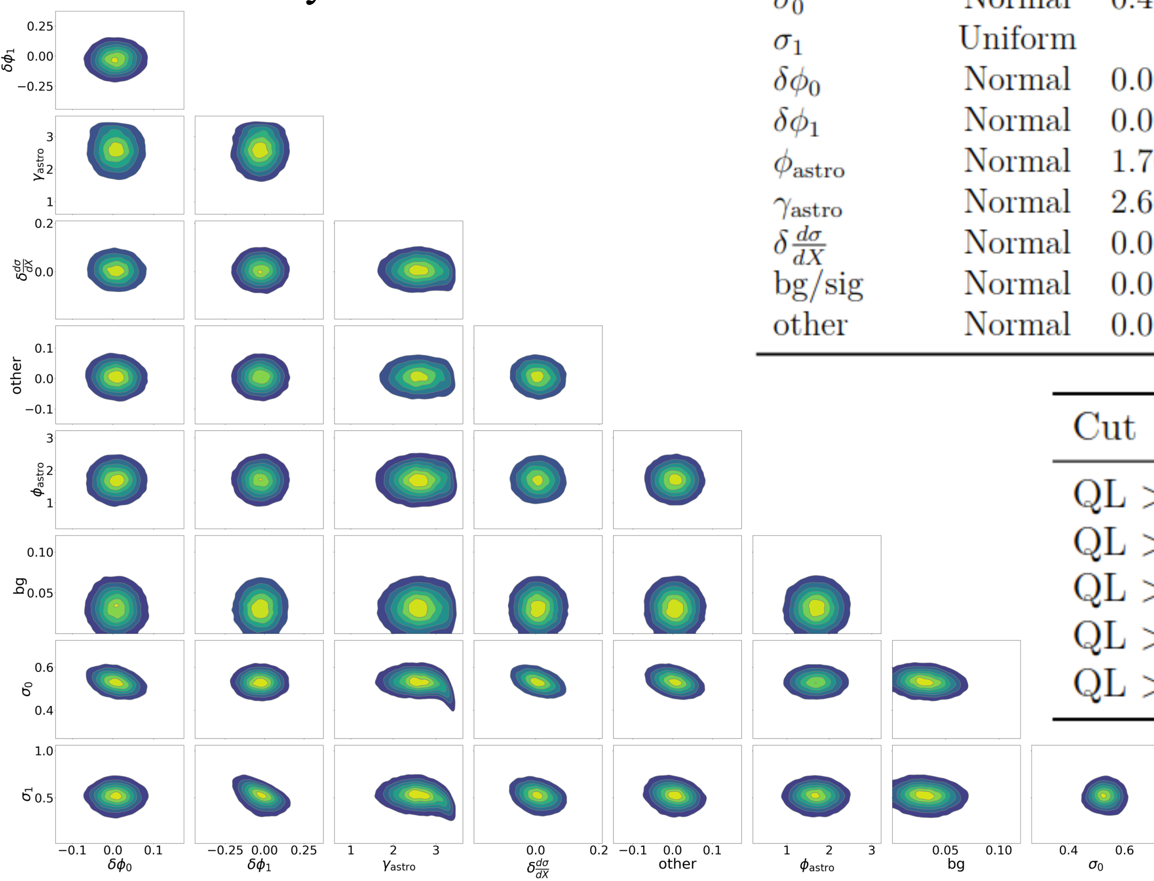


2. Systematic errors - Summary

Weak correlations of all systematics

- Flux models (conventional atmospheric, astrophysical)
- Backgrounds (mis-reconstructed down-going muons)
- Kinematics
- Detector systematics

Parameter	Prior	Constraint	Best-fit	Description
σ_0	Normal	0.48 ± 0.08	0.53 ± 0.04	σ below 0.5 TeV
σ_1	Uniform	...	0.51 ± 0.11	σ between 0.5 to 5 TeV
$\delta\phi_0$	Normal	0.00 ± 0.04	$0.01^{+0.04}_{-0.03}$	$\delta\phi$ below 0.5 TeV
$\delta\phi_1$	Normal	0.00 ± 0.09	-0.01 ± 0.04	$\delta\phi$ between 0.5 to 5 TeV
$\phi_{\rm astro}$	Normal	1.70 ± 0.20	1.69 ± 0.20	Astro. normalisation
$\gamma_{\rm astro}$	Normal	2.60 ± 0.50	$2.56^{+0.57}_{-0.40}$	Astro. spectral index
$\delta\frac{d\sigma}{dX}$	Normal	0.00 ± 0.05	0.01 ± 0.05	Kinematics modelling
bg/sig	Normal	0.03 ± 0.03	0.03 ± 0.02	Background-signal ratio
other	Normal	0.00 ± 0.05	$0.00^{+0.04}_{-0.03}$	Detector systematics

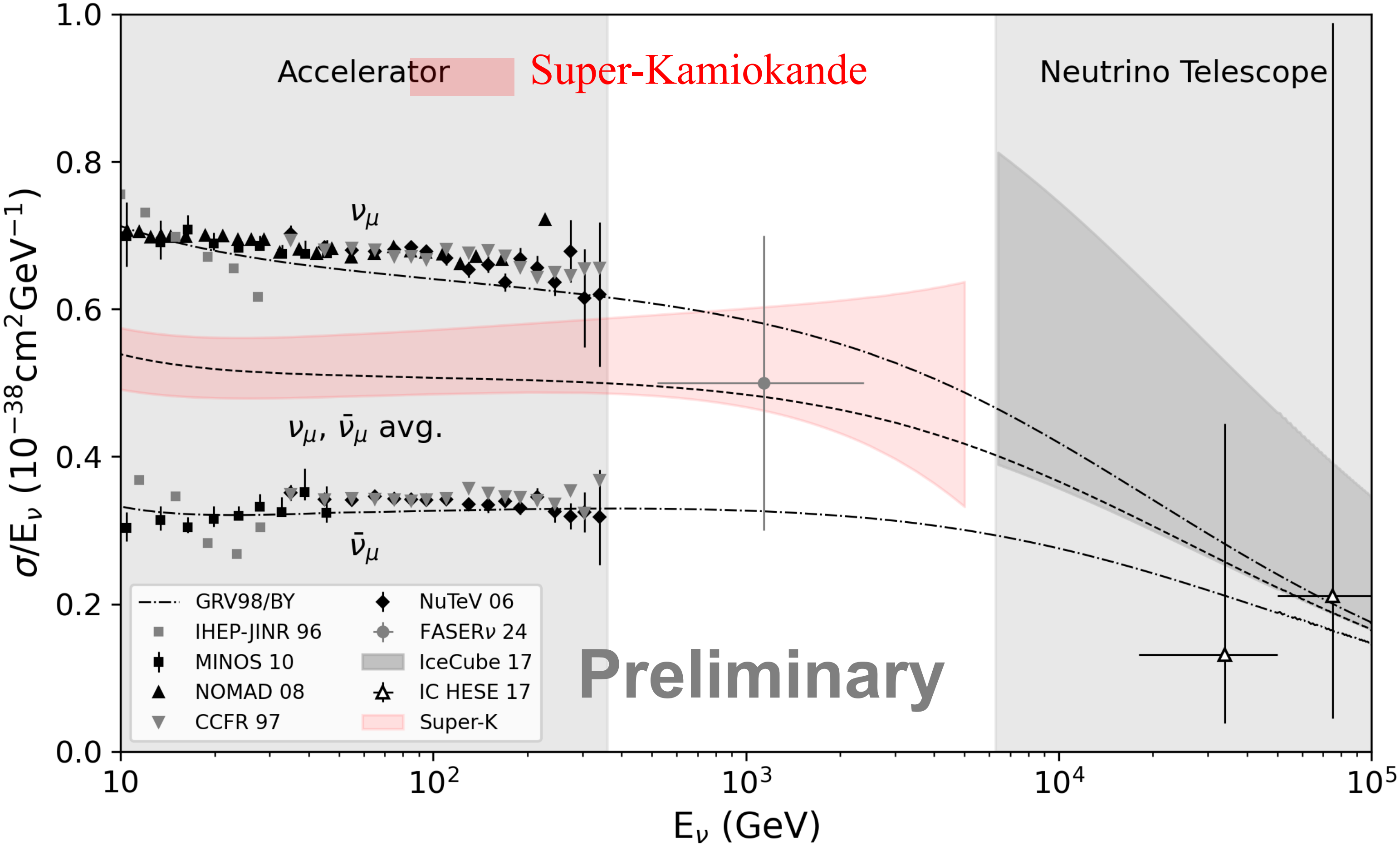


Cut	Data	MC (Pre-fit)	MC (Post-fit)
QL > 0	3989	3367	3938^{+462}_{-488}
QL > 27	2010	1673	1962^{+254}_{-285}
QL > 30	1130	931	1092^{+153}_{-183}
QL > 35	533	460	538^{+81}_{-107}
QL > 40	316	288	336^{+52}_{-75}

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

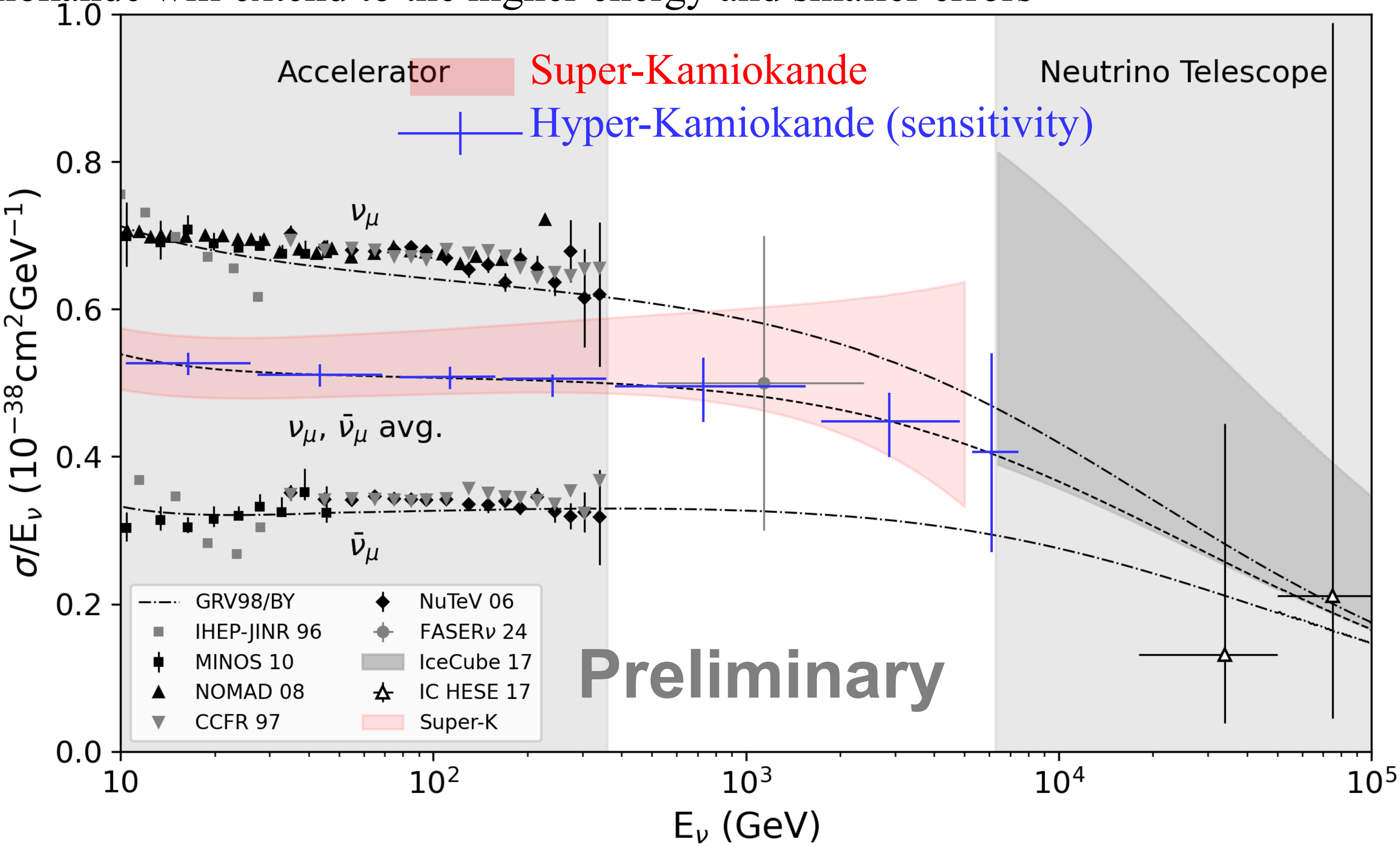
Statistical error dominated result, will be improved in future

- Competitive with FASERnu result



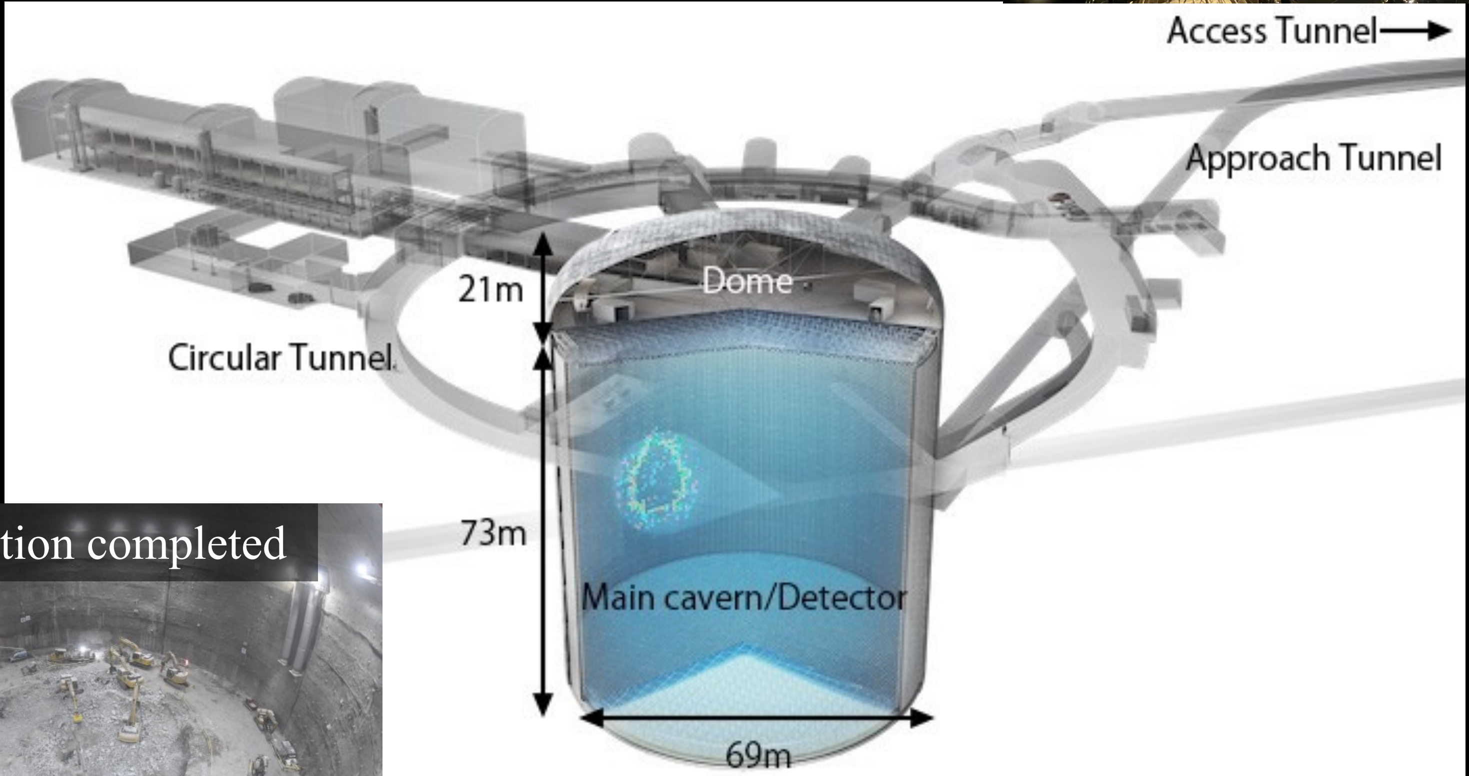
3. $\nu_\mu CC + \bar{\nu}_\mu CC$ DIS total cross-section

Statistical error dominated result, will be improved in future
- Competitive with FASERnu result
- Hyper-Kamiokande will extend to the higher energy and smaller errors



Hyper-Kamiokande

3rd generation of Kamioka water Cherenkov detector
- Kamiokande (1983 starts), Nobel Prize 2002
- Super-Kamiokande (1996 starts), Nobel Prize 2015
- Hyper-Kamiokande (2028 starts), Nobel Prize ???
- Detector volume ~250 kton
- x8.4 fiducial volume of Super-K

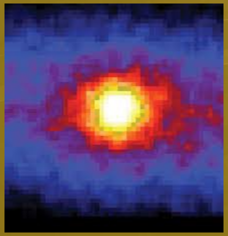


The largest man-made cavern in the world

Hyper-Kamiokande Science

Supernova neutrinos

Solar neutrinos



Reactor neutrinos

Astrophysics

- Cosmic ray physics
- Multi-messenger astronomy

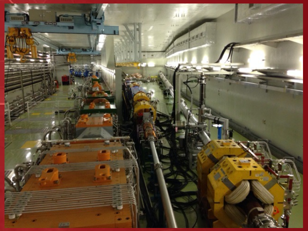
Particle Physics

- Leptonic CP violation
- Neutrino parameters

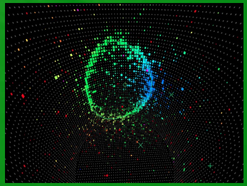
New physics

- Proton decay
- Dark sector particles
- Indirect DM search
- Unexpected!

Accelerator neutrinos



Atmospheric neutrinos



High-energy astrophysical neutrinos

4. Conclusions

TeV neutrinos have rich physics

Super-Kamiokande has high-statistics TeV neutrino data from atmospheric neutrinos

Using the up-going through going muon samples, we measured the TeV muon and anti-muon neutrino total cross-section between 500 GeV and 5 TeV. The measurement is statistically limited.

These results will be improved in the Hyper-Kamiokande

Thank you for your attention!

Backup