Search for Atmospheric Tau Neutrinos in Super-Kamiokande

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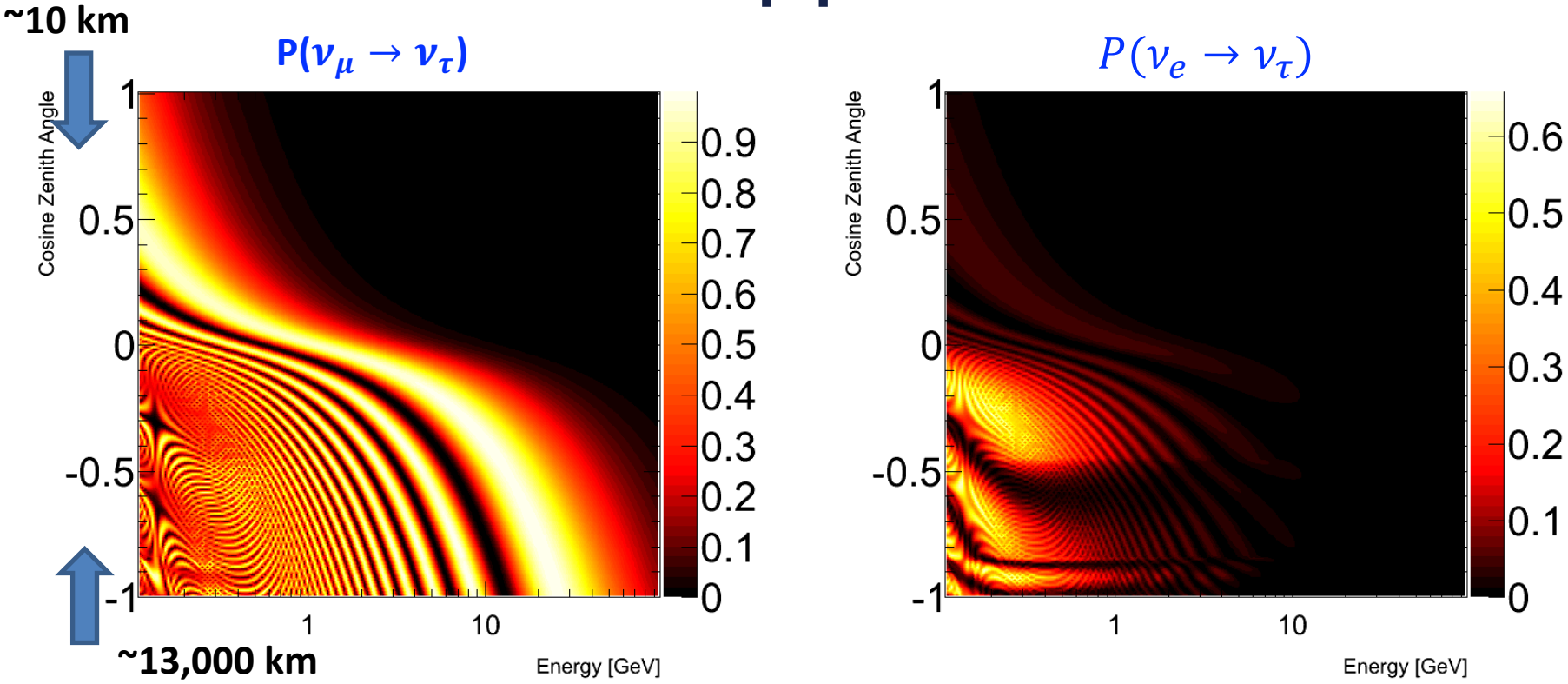
On behalf of the Super-Kamiokande collaboration
TMEX-2018

Content

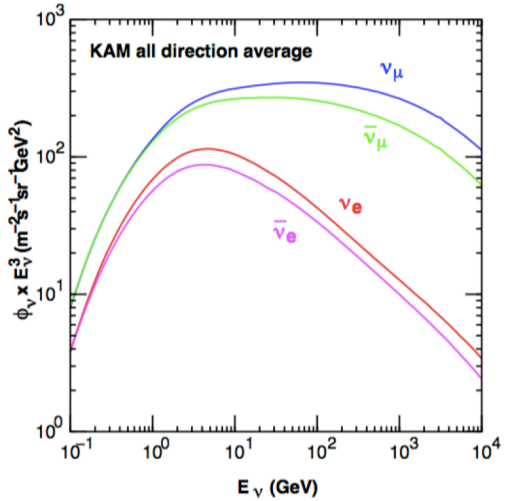
- Tau neutrino appearance in atmospheric neutrinos.
- Method of tau neutrino selection with neural network.
- Results.
- Future application of tau selection in three flavor oscillation analysis.

Tau Neutrino Appearance in SK

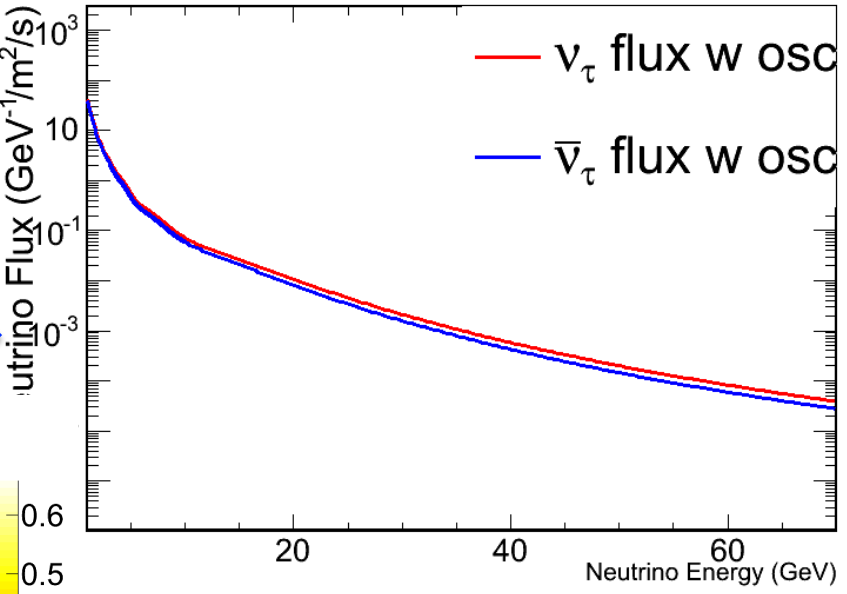


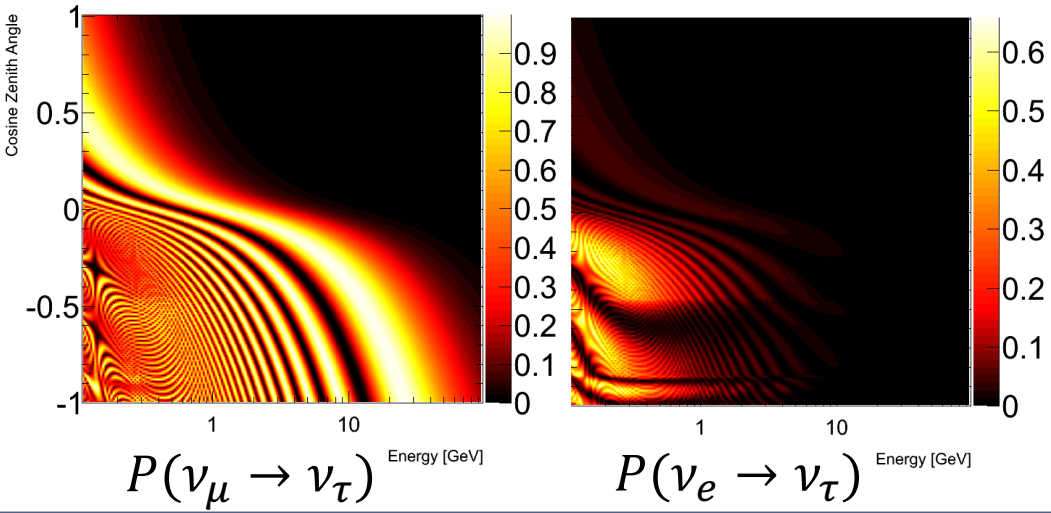
- Probabilities of ν_τ appearance are calculated as a function of direction and neutrino energy with assumption of ($sin^2 2\theta_{23} = 1, \Delta m^2_{32} = 2.1\times10^{-3} eV^2, sin^2 2\theta_{13} = 0.099$, NH).
- Most ν_τ appearance is from $\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$, has upward-going direction.

Tau Neutrino Appearance in SK



Neutrino fluxes at production

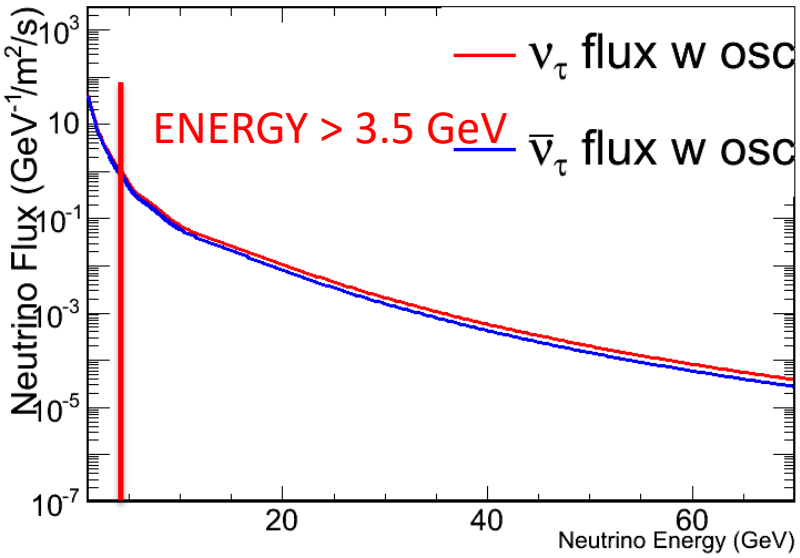


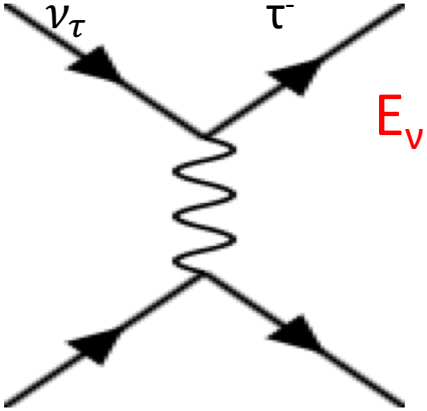


$P(\nu_\mu \rightarrow \nu_\tau)$ $P(\nu_e \rightarrow \nu_\tau)$

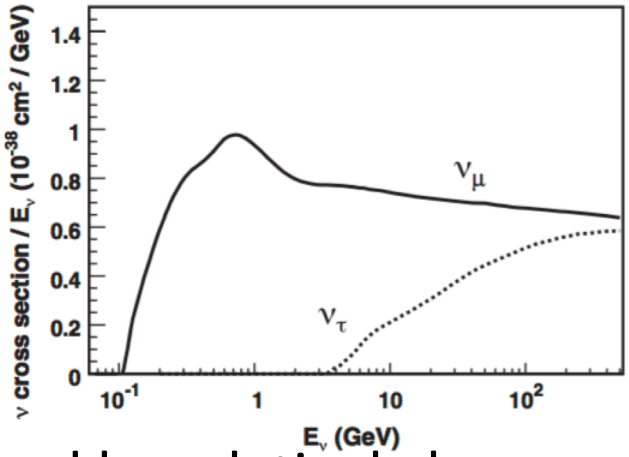
Fluxes of tau neutrinos from neutrino oscillations.

Tau Neutrino Appearance in SK



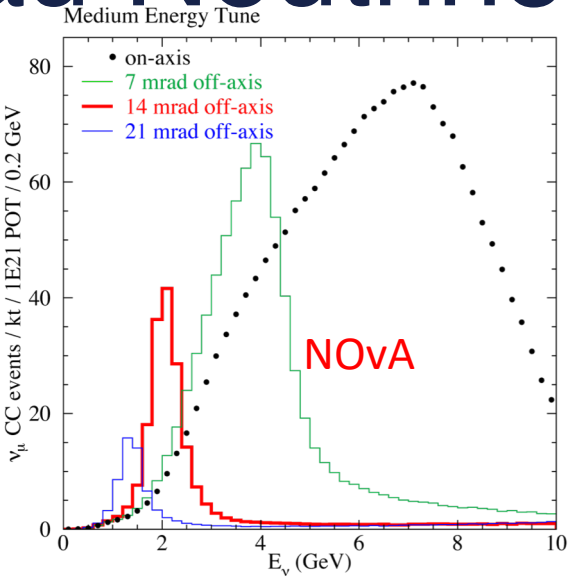


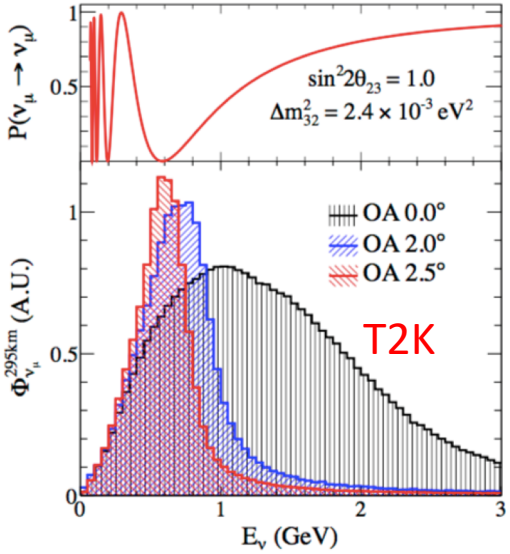
$E_\nu > 3.5$ GeV

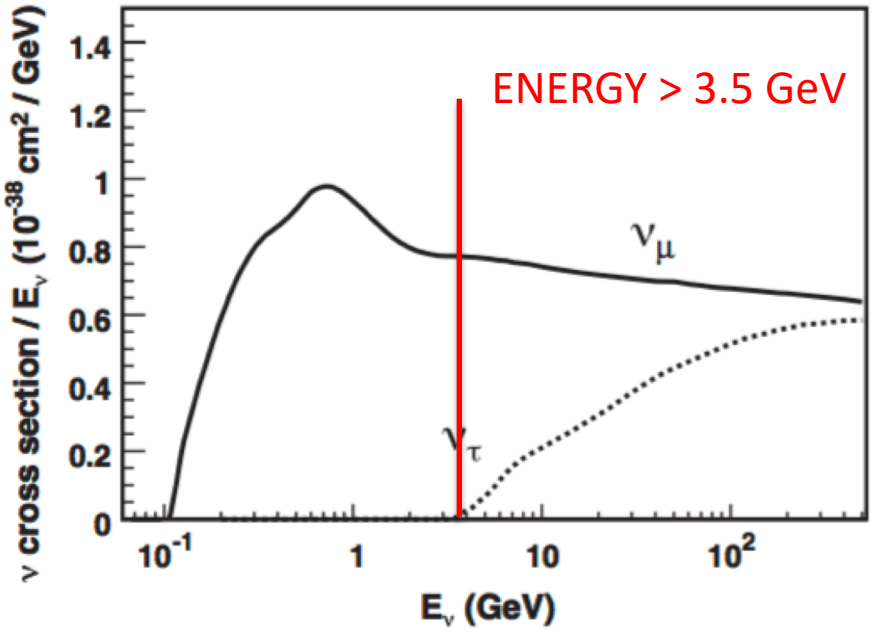


- CC ν_τ cross section suppressed by relatively large τ mass.
- Atmospheric tau neutrinos have wide energy range and a significant component of high energy neutrinos.

Tau Neutrino Appearance in SK

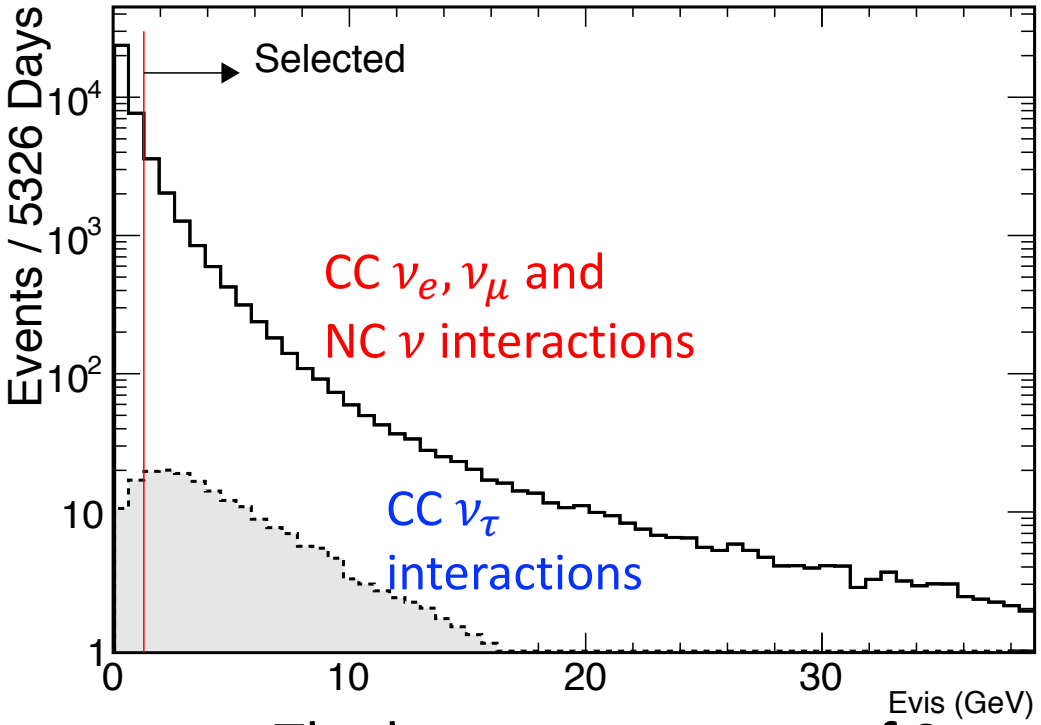






- Most accelerator-based neutrino experiments have bulk of neutrinos below the energy threshold for CC tau neutrino interactions.

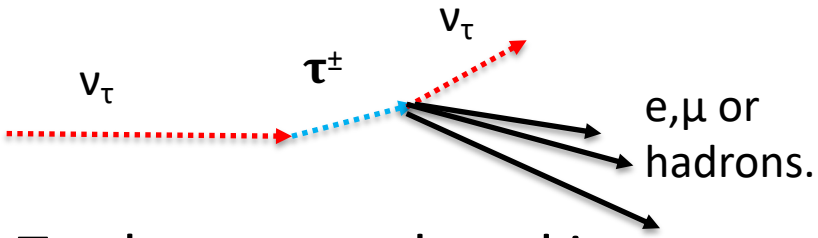
Tau Neutrino Appearance in SK



- Fully-contained.
- Vertex in fiducial volume (distance to wall > 200 cm).
- Multi-GeV (evis > 1330 MeV)

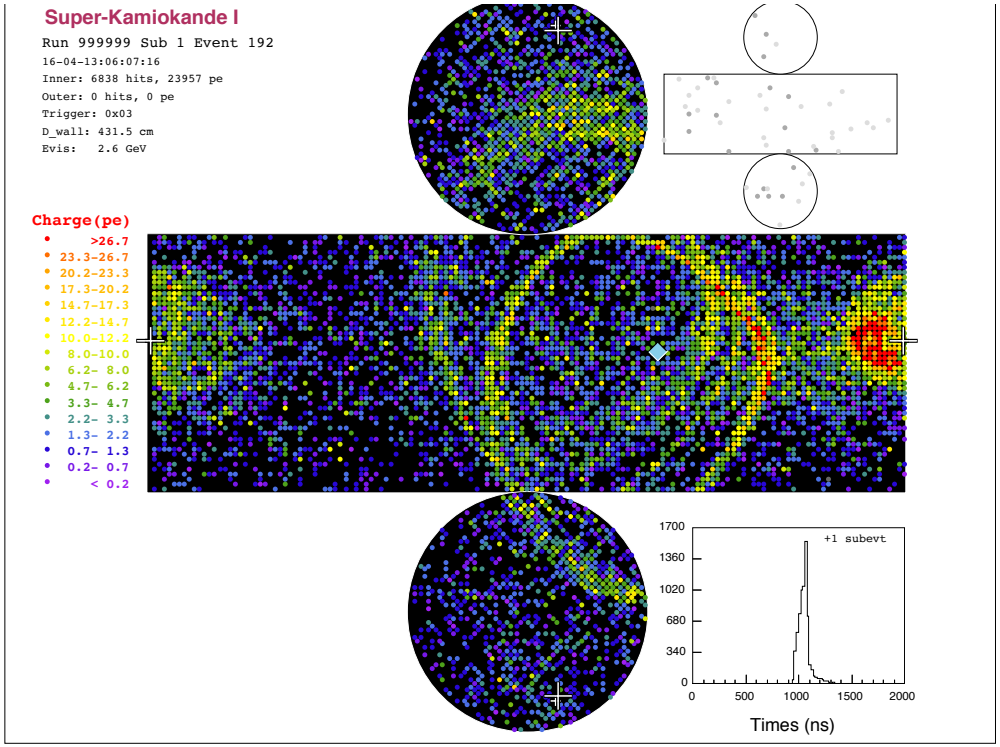
- The large target mass of Super-Kamiokande, coupling with the wide energy range of atmospheric neutrinos, makes it possible to detect CC tau interactions.
- About 20 events expected in SK every year, ~3000 atmospheric neutrino events detected every year!

Tau Neutrino Events in SK



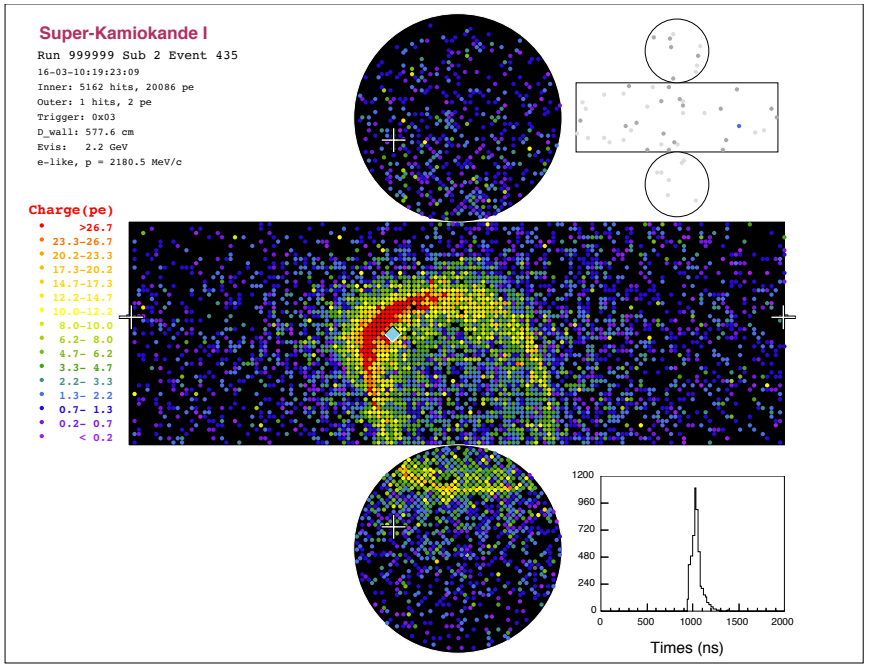
Tau lepton produced in CC-ν_τ interaction, but tau lepton decay in ~10^{-13} sec.

Decay mode	Branching ratio (%)
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.41 ± 0.04
$e^-\bar{\nu}_e\nu_\tau$	17.83 ± 0.04
$\pi^-\nu_\tau$	10.83 ± 0.06
$\pi^-\pi^0\nu_\tau$	25.52 ± 0.09
$\pi^-2\pi^0\nu_\tau$	9.3 ± 0.11
$\pi^-3\pi^0\nu_\tau$	1.05 ± 0.07
$\pi^-\pi^+\pi^-\nu_\tau$	8.99 ± 0.06
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$	8.99 ± 0.06
$h^-\omega\nu_\tau$	2.00 ± 0.08

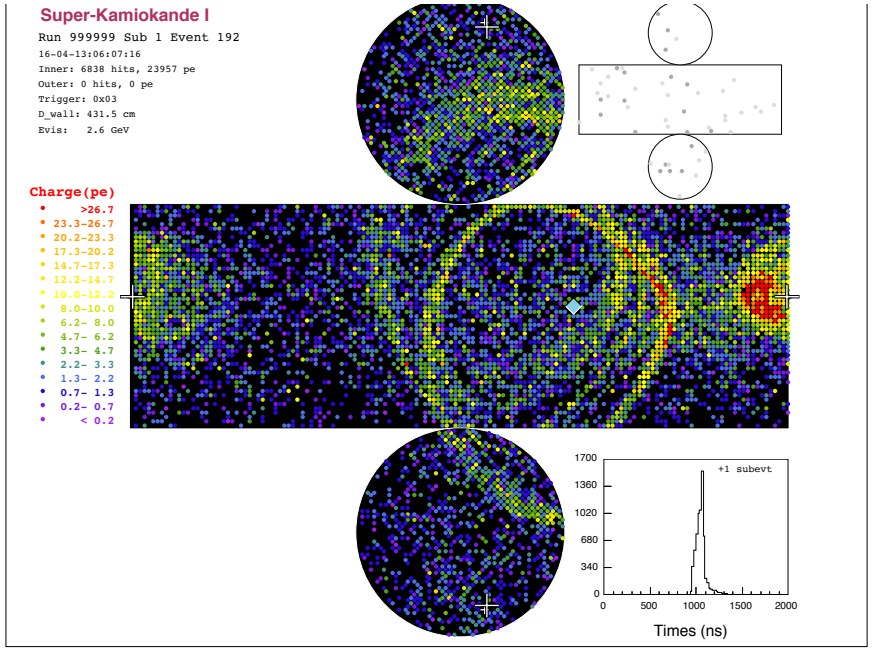


- Tau lepton is not directly detectable in Super-K.
- Multiple light-producing particles from hadronic tau decay.

Selection of CC Tau Events



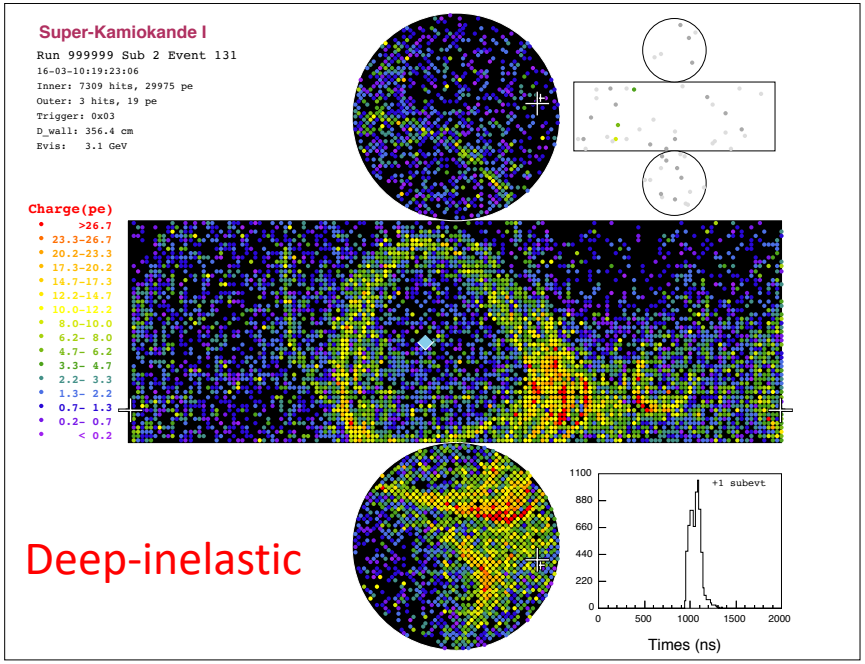
Example of Background Simulation



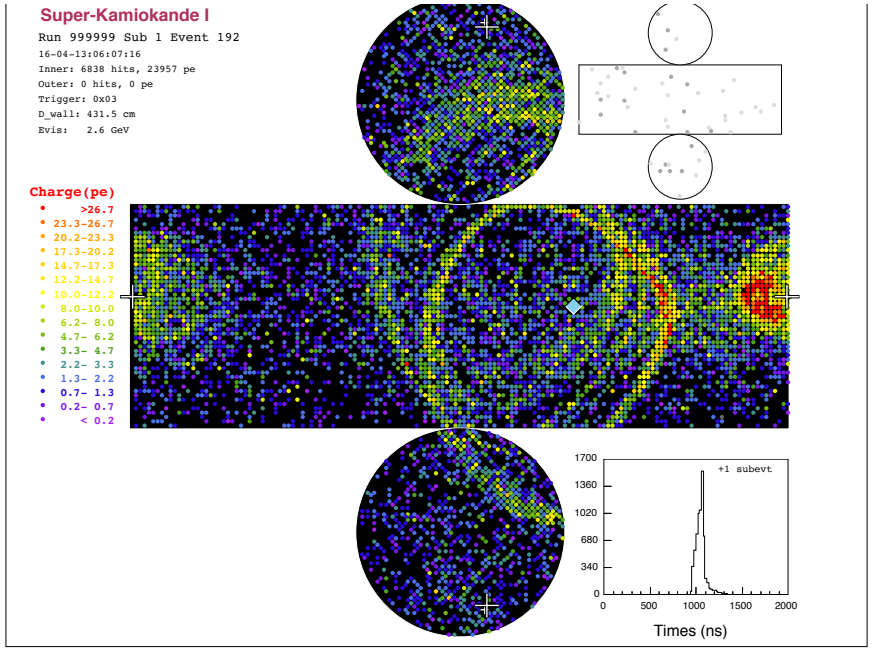
Example of Tau Signal Simulation

- Signal events have signatures of tau decay.
- Tau signal events are typically classified as e-like event in standard reconstruction.

Selection of CC Tau Events



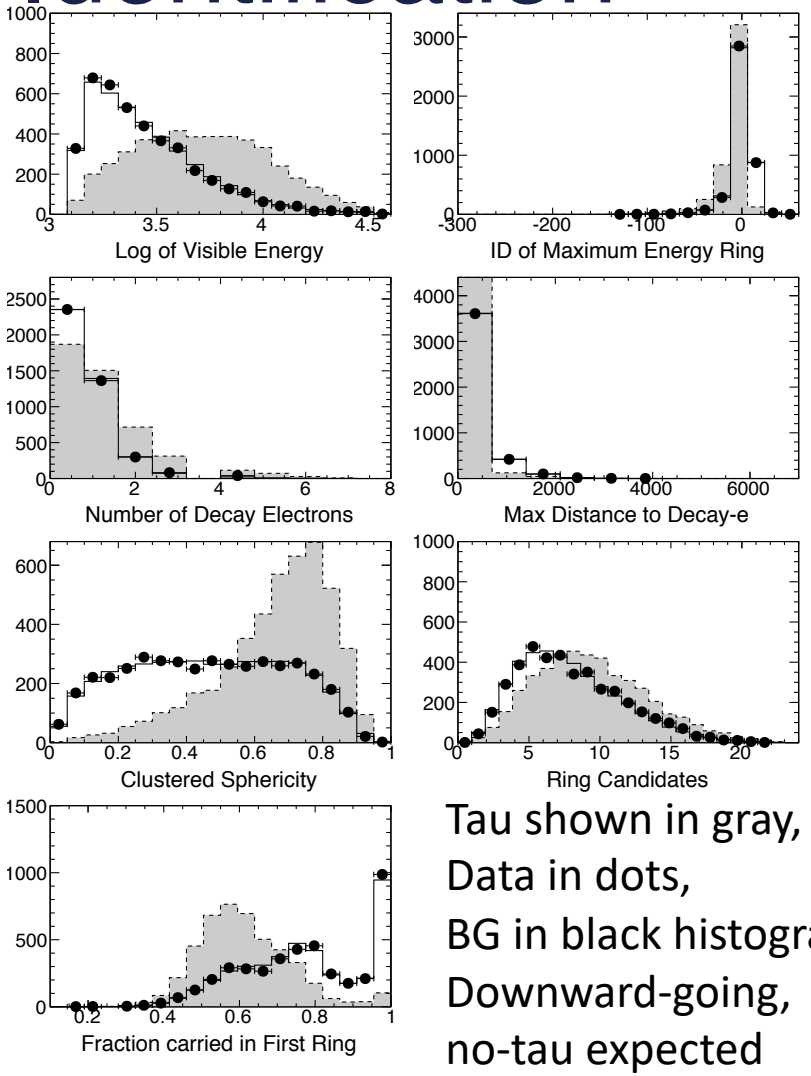
Example of Background Simulation



Example of Tau Signal Simulation

- Signal events have signatures of tau decay.
- Tau signal events are typically classified as e-like event in standard reconstruction.
- Not able to select with a single variable.

A Neural Network Algorithm for Tau Identification

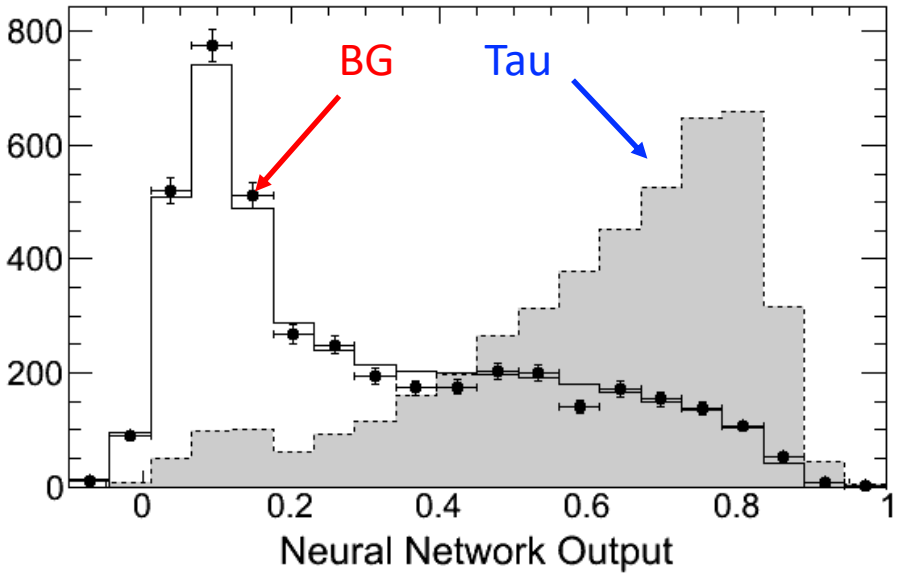


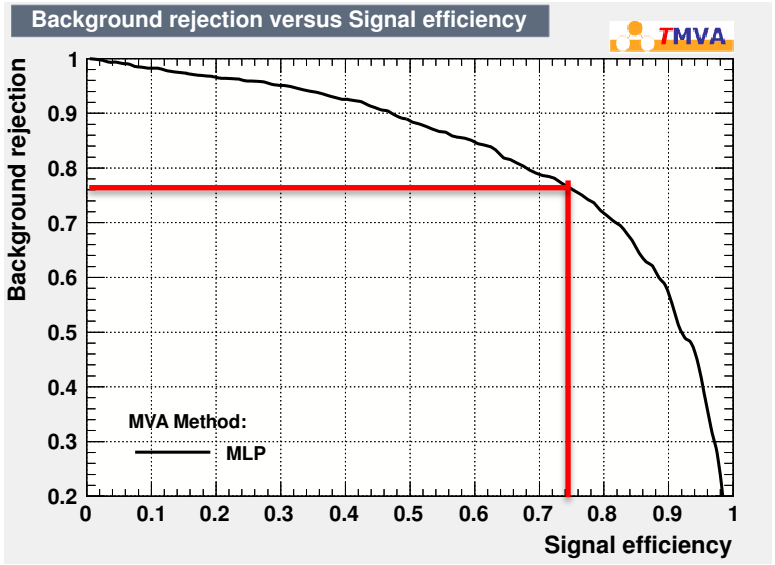
Tau shown in gray,
Data in dots,
BG in black histogram.
Downward-going,
no-tau expected

- Log evis.
- PID max energy ring.
- # of decay electron.
- Max distance to decay-e.
- Sphericity.
- # of ring candidates.
- Fraction of energy in the first ring.

A Neural Network Algorithm for Tau Identification

Downward sample
No-tau expected in this sample

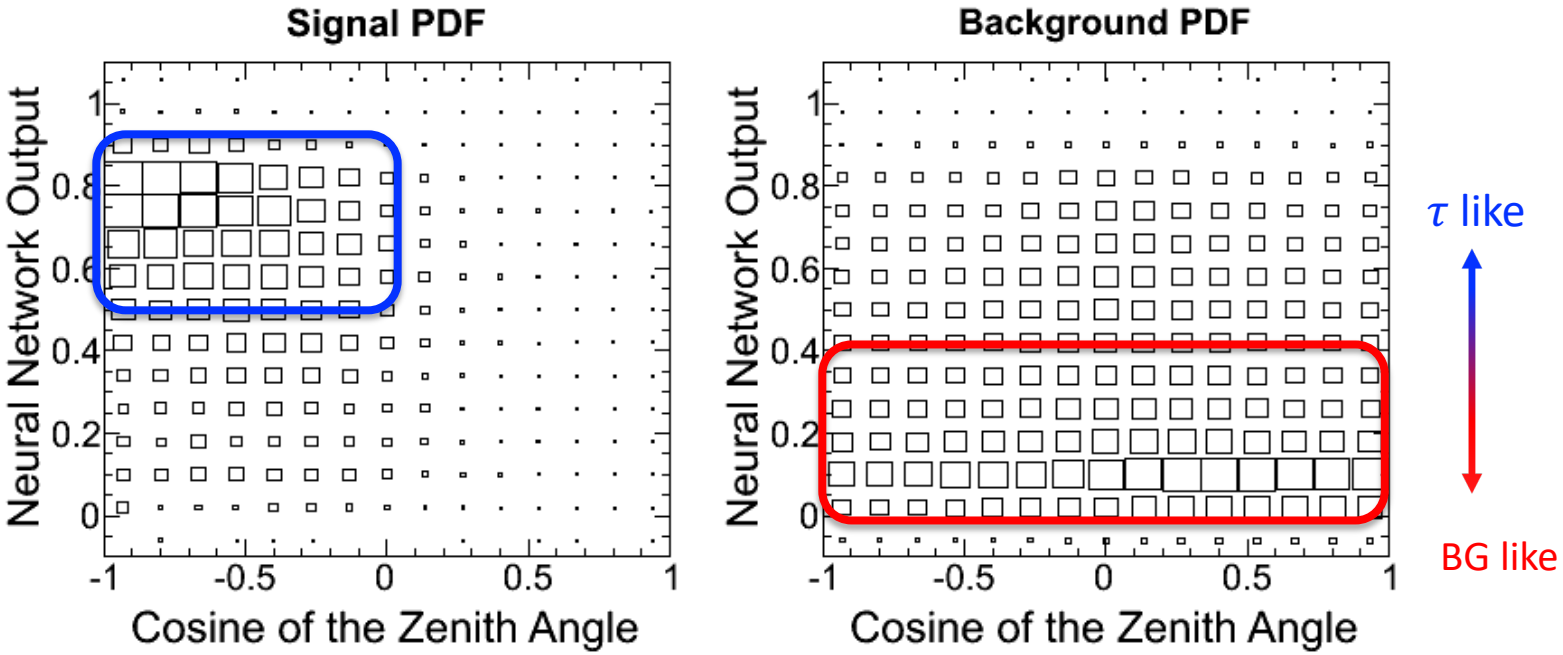




Good BG/signal separation
Good data/MC agreement

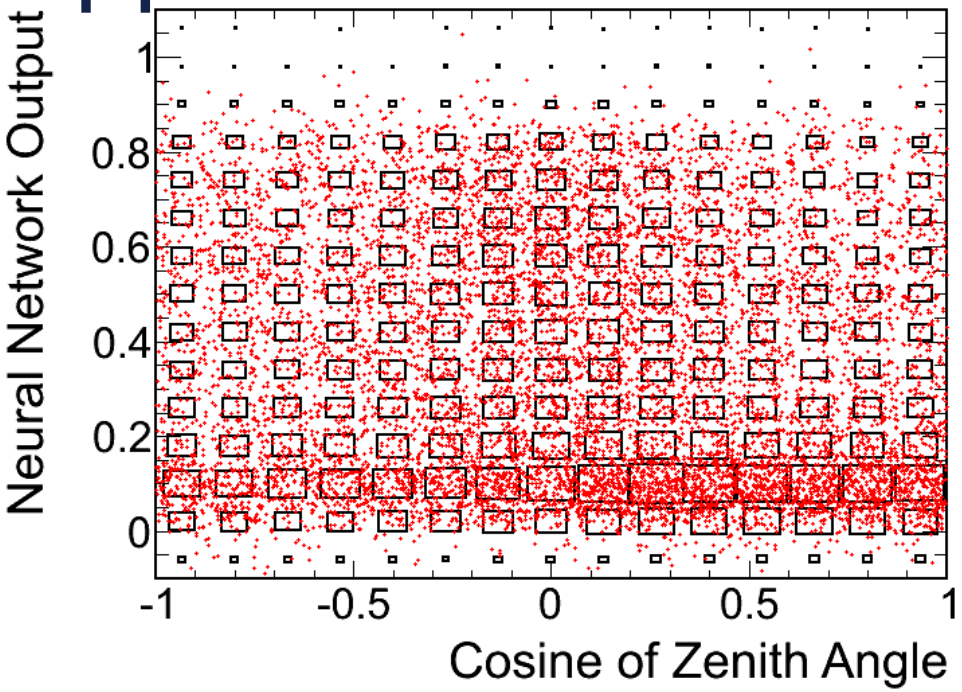
If cut events at NN>0.5, 76% signal are selected, 28% background pass the cut.

Search for Tau Neutrino Appearance



- Two-dimensional likelihood built with event direction and neural network output for signal and background.
- Signal has high neural network output, and are mostly upward-going.

Search for Tau Neutrino Appearance



- Unbinned likelihood of data against PDFs.
- 5,326 days of SK atmospheric neutrino data used from SK-I to SK-IV.

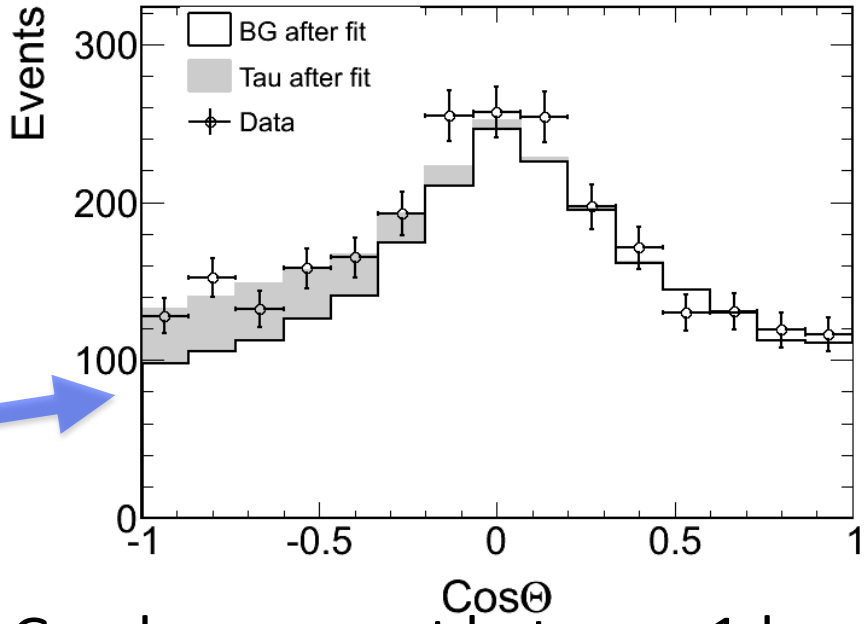
$$\mathbf{Data = PDF_{bg} + \alpha \times PDF_{tau} + \sum \varepsilon_i \times (tauPDF_i + bgPDF_i)}$$

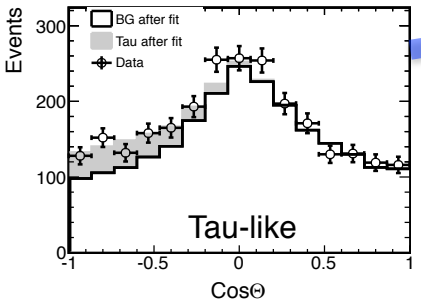
α is the normalization of tau events.
$(tau, bg)PDF_i$ is the PDF of i'th systematic error of shifting it by 1σ, ε_i is the magnitude of the systematic error.

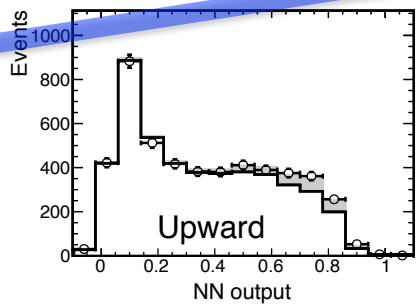
Search for Tau Neutrino Appearance

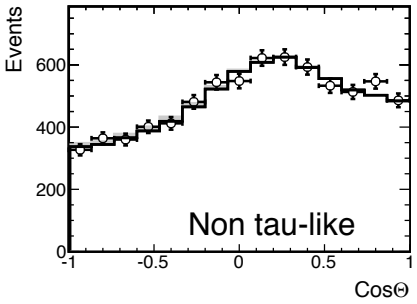
Phys. Rev. D **98**, 052006

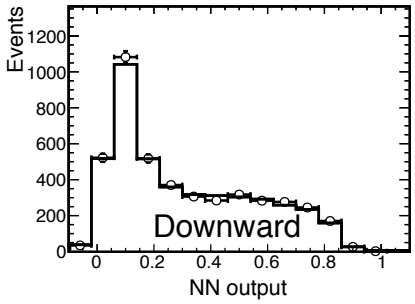
$\alpha = 1.47 \pm 0.32$
compared to simulation
(4.6σ from 0) assuming NH











Good agreement between 1d projection of rescaled MC and data after fit.

338.1±72.7 fully-contained CC tau events measured in Super-K fiducial volume.

Results of Search for Tau Neutrino Appearance

- A neural network algorithm is used to tag CC ν_τ interactions.
- SK measures the normalization of tau events to be 1.47±0.32, excluding the no-tau-appearance hypothesis by 4.6σ.
- 338.1±72.7 fully-contained CC ν_τ interactions measured.

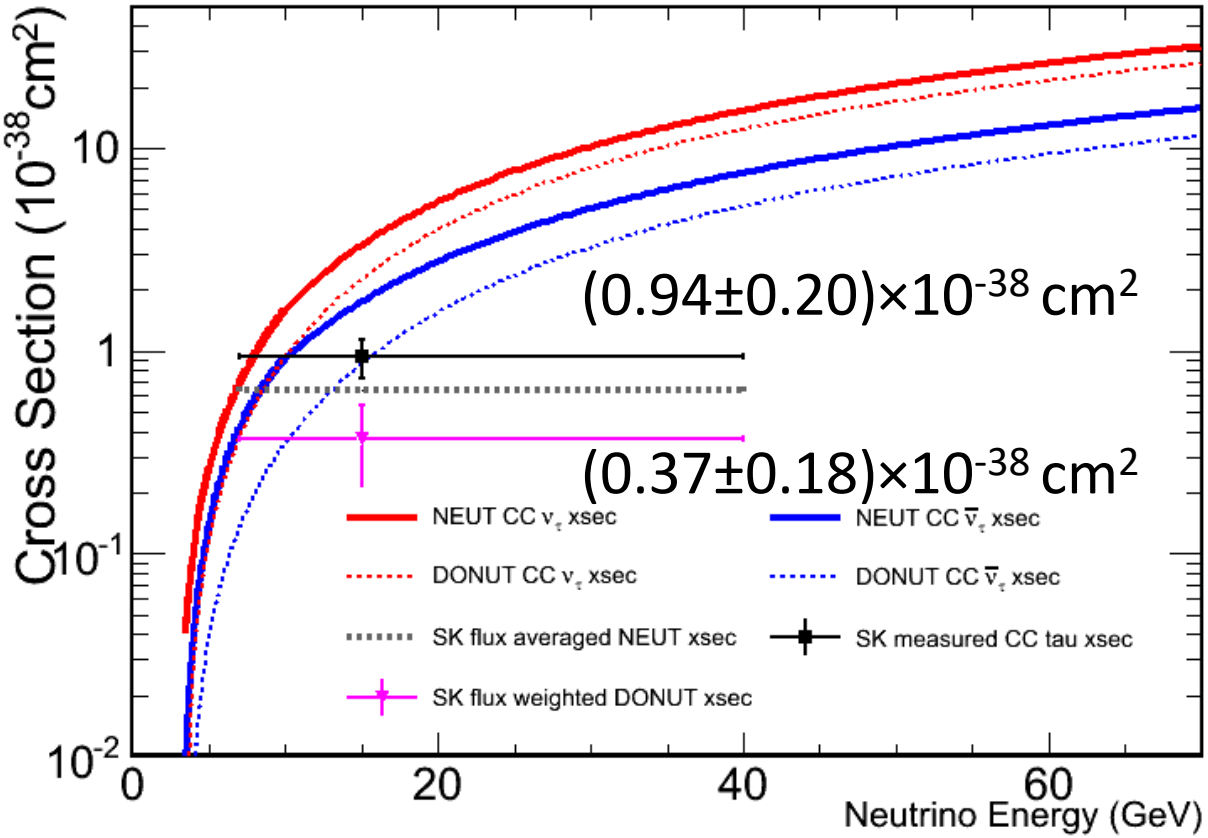
Measurement of CC Tau Neutrino Cross in Super-K

$$Measured\,Normalization \times \langle \sigma_{theory} \rangle$$

- we need to calculate flux averaged cc tau cross section in the MC.

$$\langle \sigma_{theory} \rangle = \frac{\sum_{\nu_\tau, \bar{\nu}_\tau} \int \frac{d\Phi(E_\nu)}{dE_\nu} \sigma_{theory} E_\nu dE_\nu}{\sum_{\nu_\tau, \bar{\nu}_\tau} \int \frac{d\Phi(E_\nu)}{dE_\nu} dE_\nu}$$

Comparisons of the Result with DONUT Measurement



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DONUT results converted to differential cross section and weighted by SK flux.

DONUT measured almost pure CC deep-inelastic at high neutrino energies. The extrapolation of DONUT measurement to low energy does not work well.

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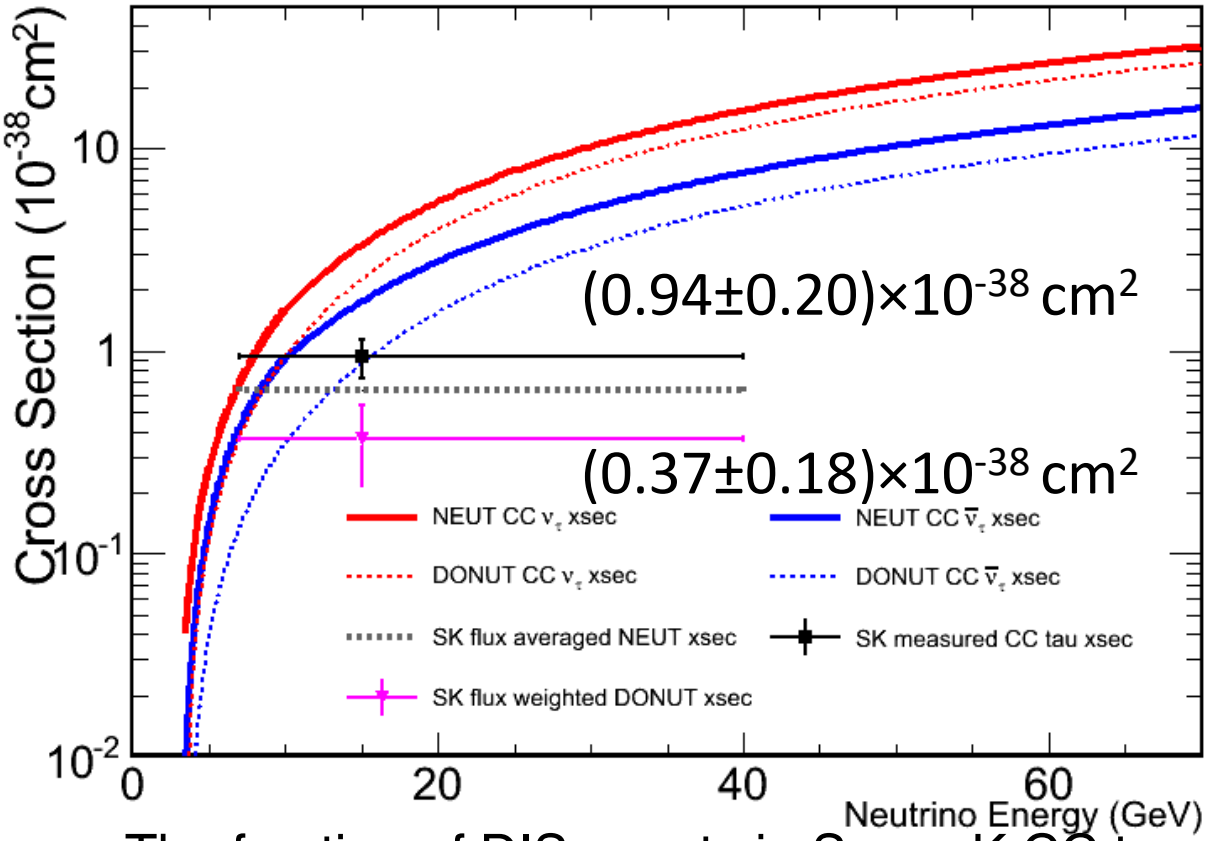

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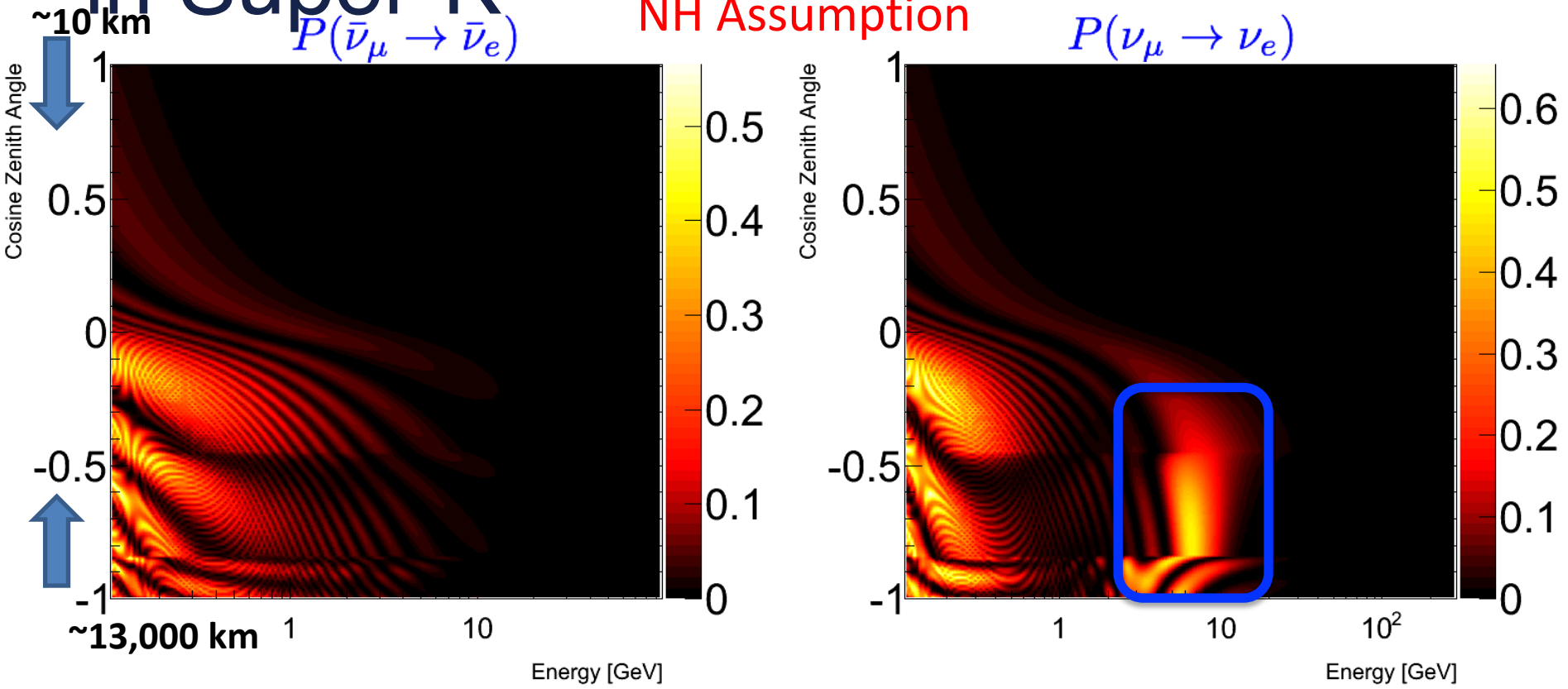
The tau neutrino flux at Super-K has a large component of neutrinos below 10 GeV, where CCQE and resonant pion production makes a significant contribution.

The fraction of DIS events in Super-K CC tau neutrino sample is estimated to be 41%.

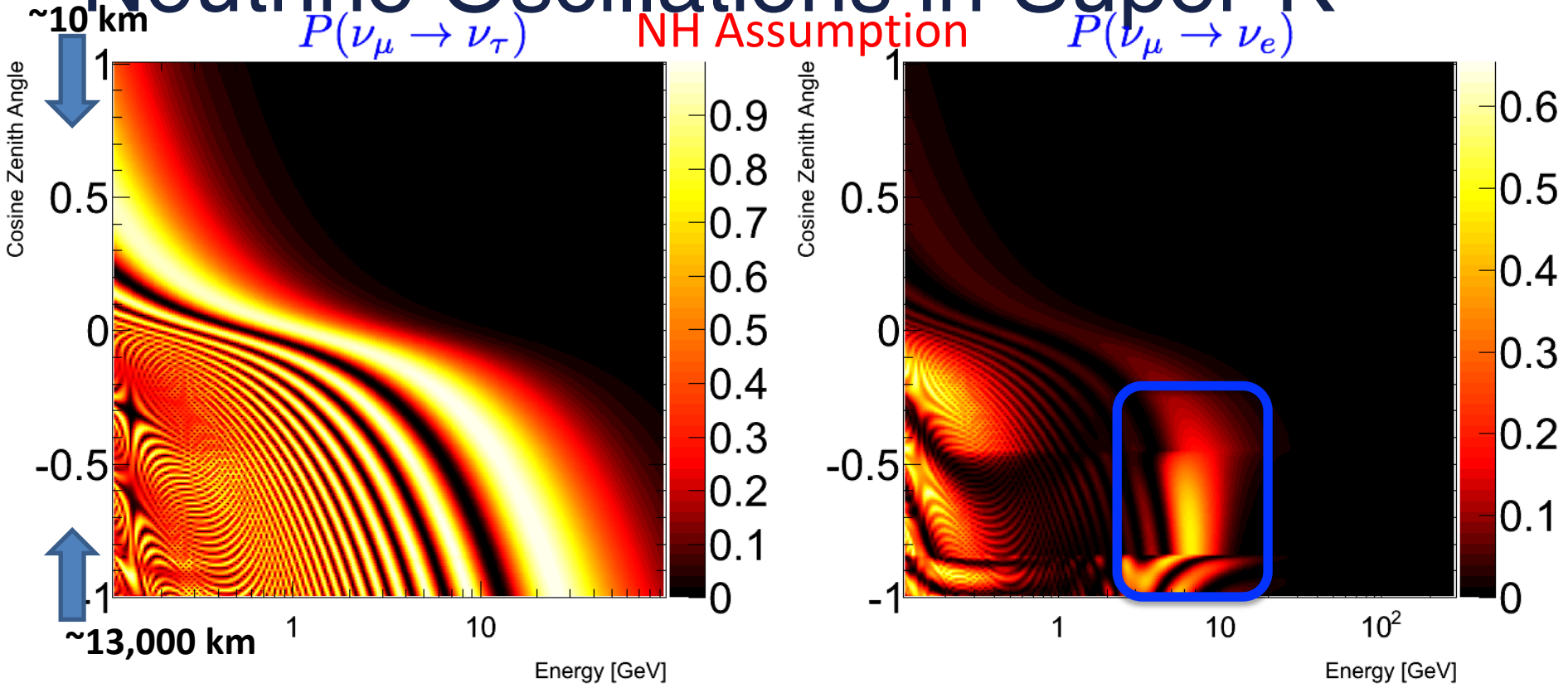
The DIS-only cross section is found to be $(0.40\pm0.08)\times10^{-38}$ cm^2, consistent with DONUT result.

Three-flavor Neutrino Oscillations in Super-K



- θ_{13}-induced electron neutrino appearance.
- A resonance depending on MH due to the matter effect.
- A measurement of the resonance helps to determine the MH.

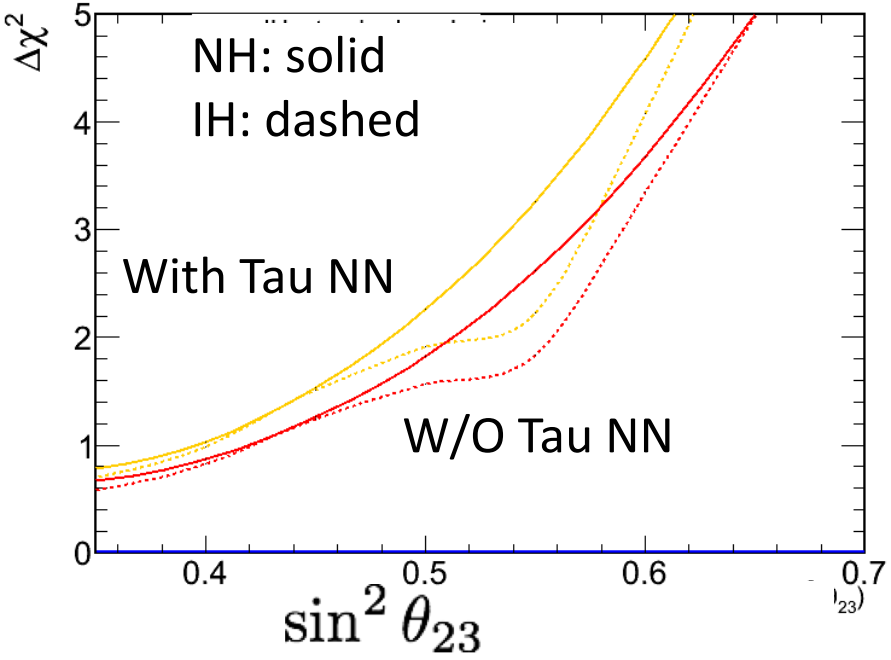
Tau as Background in Three-flavor Neutrino Oscillations in Super-K



- CC tau events also shows up in upward-going multi-GeV region.
- Tau events are generally identified as showering e-like events.

Sensitivity to Mass Hierarchy with Tau Identification

- Event by event separation using the tau identification tools.
- SK performs a binned likelihood fit.



- A larger $\Delta\chi^2$ indicates better separation of two MH cases.
- Sensitivity study shows ~10% improvement in the sensitivity to MH.

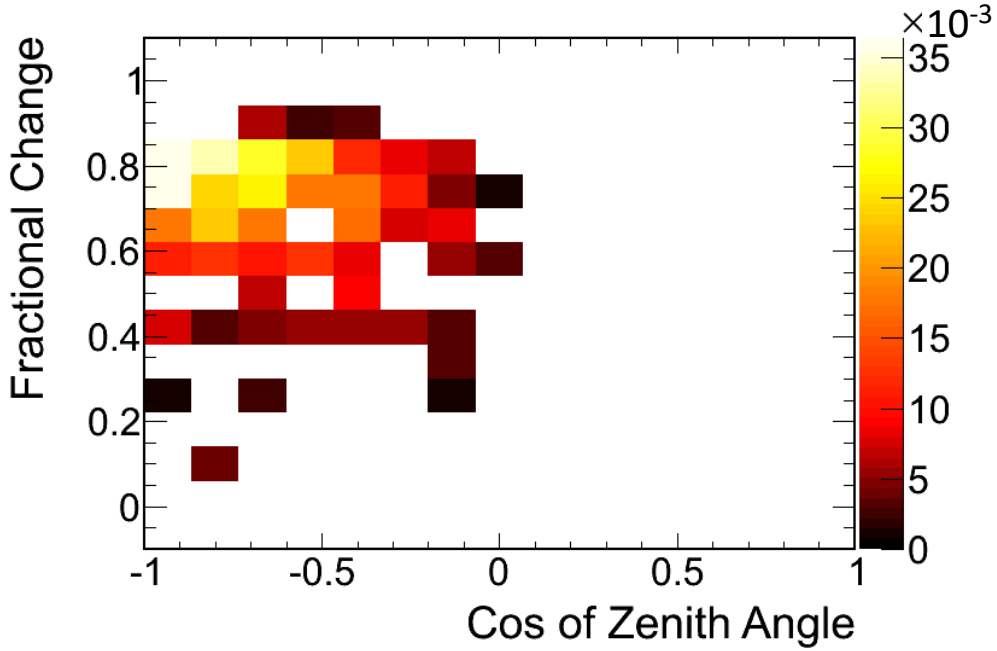
Summary

- Tau normalization is measured to be 1.47±0.32 in Super-K, excluding the no-tau-appearance hypothesis at a 4.6σ significance.
- A flux-averaged charged-current tau neutrino cross section is measured to be $(0.94\pm0.20)\times10^{-38}$ cm^2.
- Tau identification tools are implemented in the three-flavor oscillation analysis, improving the sensitivity to MH by ~10%.

Backups

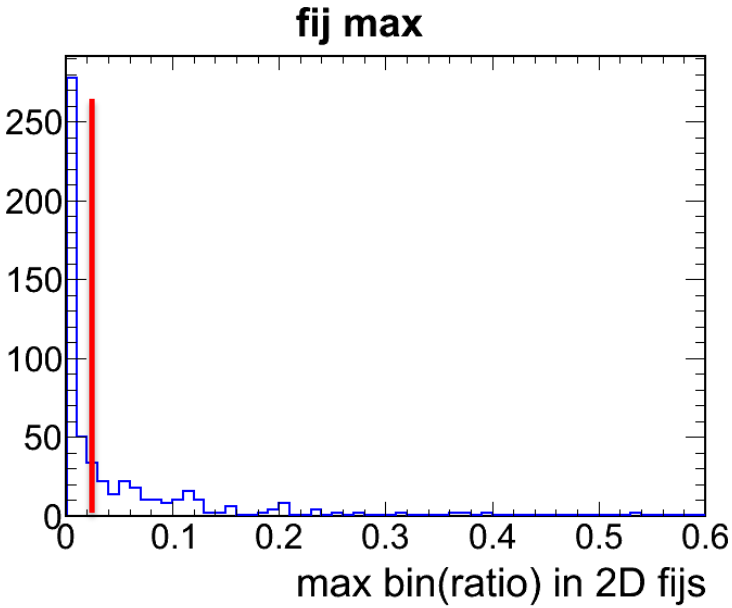
Systematic Errors

- The systematic errors in the oscillation analyses are used.
- The PDFs are built as change of event distribution for 1-σ change of systematic error.

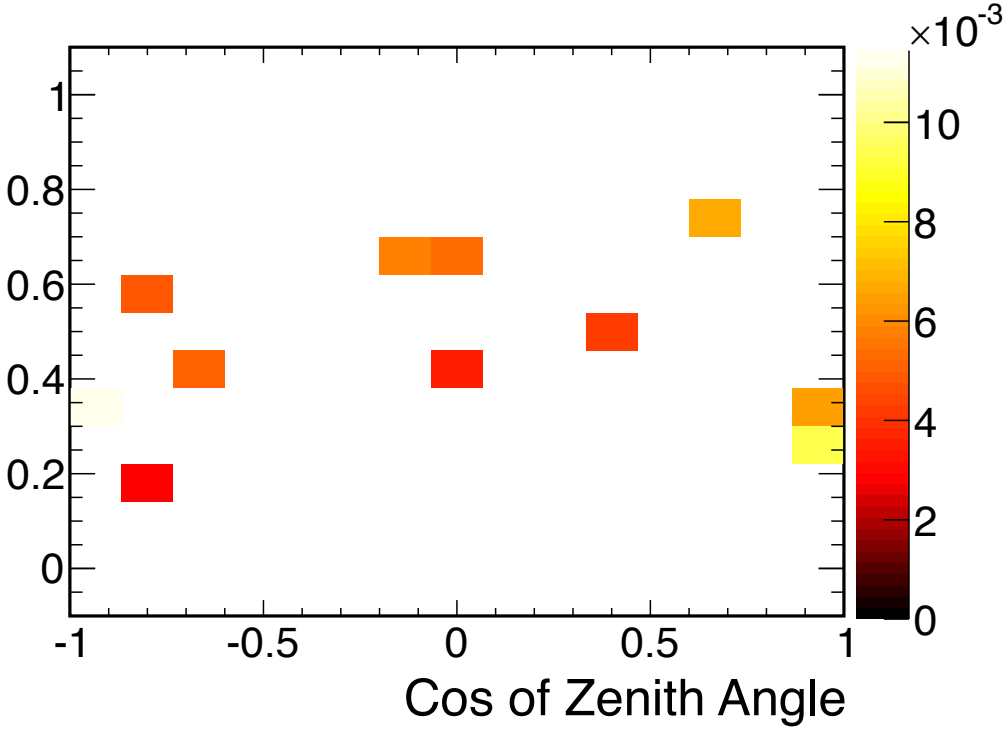


An example of systematic PDF.

Rejected Systematic Errors

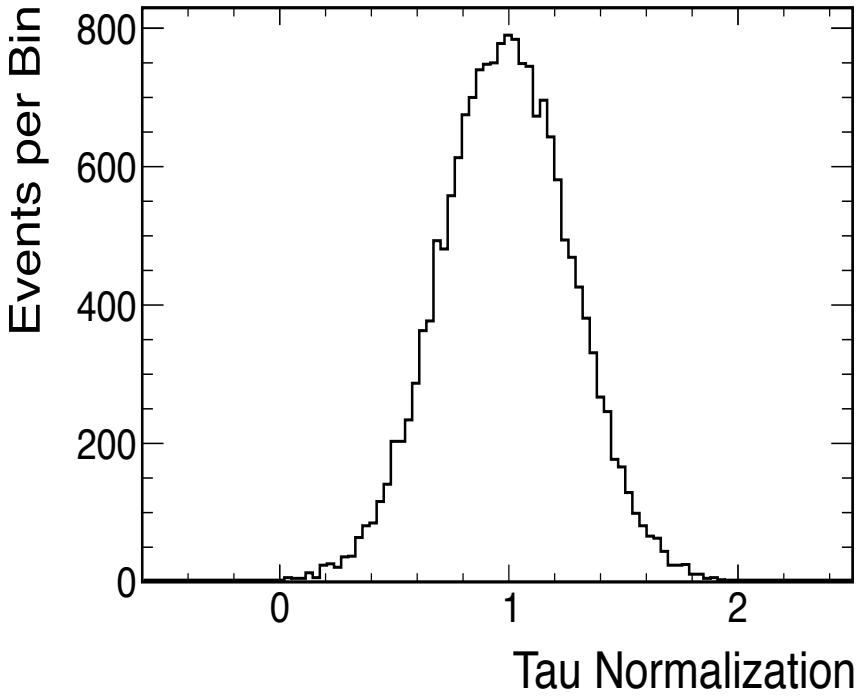


Select the systematic errors at a value (2.5%) where sensitivity does not change.



Nu/nubar ratio < 1 GeV.

Sensitivity Study with Toy MC

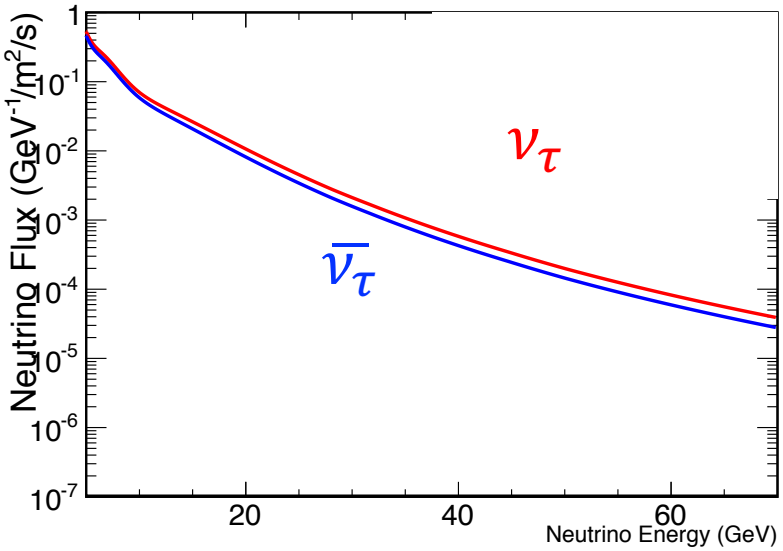


- Toy MC generated from signal and BG PDFs.
- Fit the tau normalization in the toy MC.
- The p-value, fraction of toy MC with negative tau normalization, is calculated to be 4.4×10^{-4}.
- The expected significance is estimated to be 3.3σ.

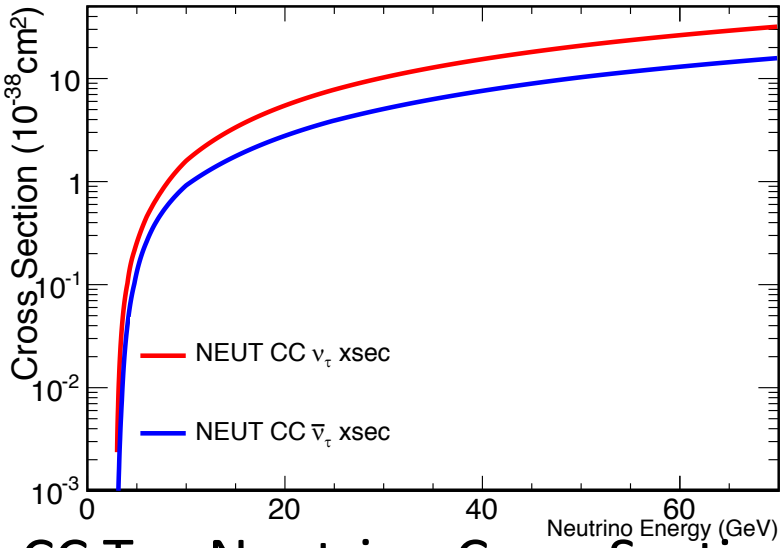
Flux averaged CC tau cross section

$$Measured\,Normalization \times \langle \sigma_{theory} \rangle$$

- we need to calculate flux averaged cc tau cross section in the MC.

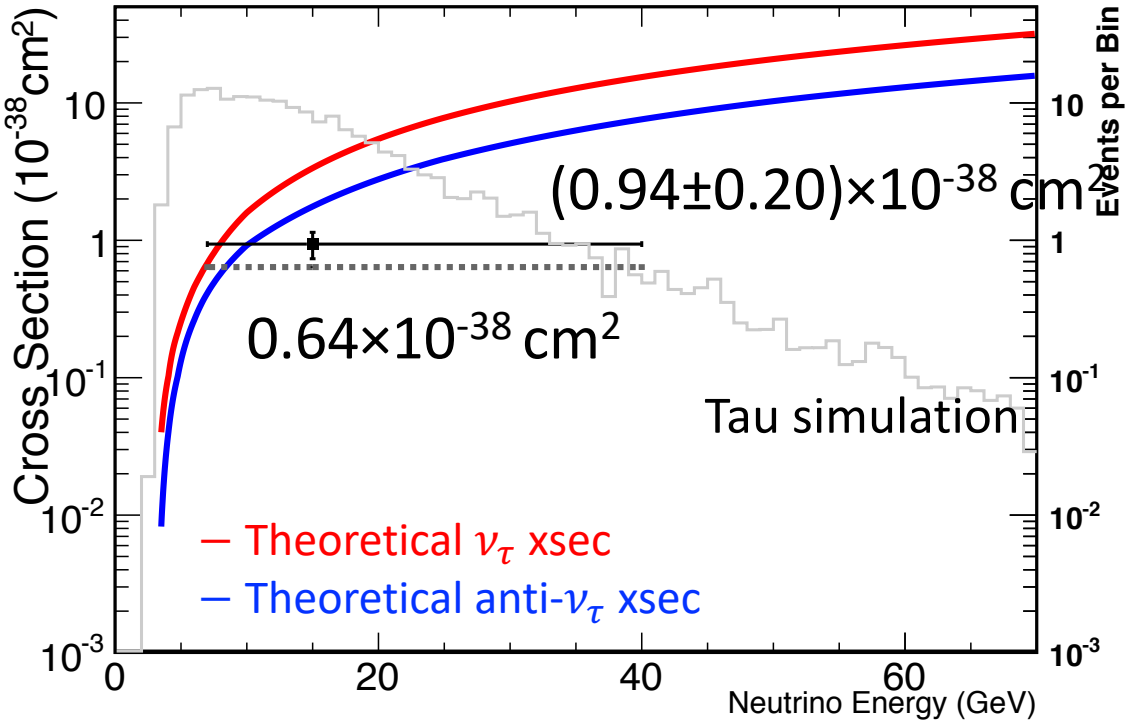


Tau Neutrino Flux



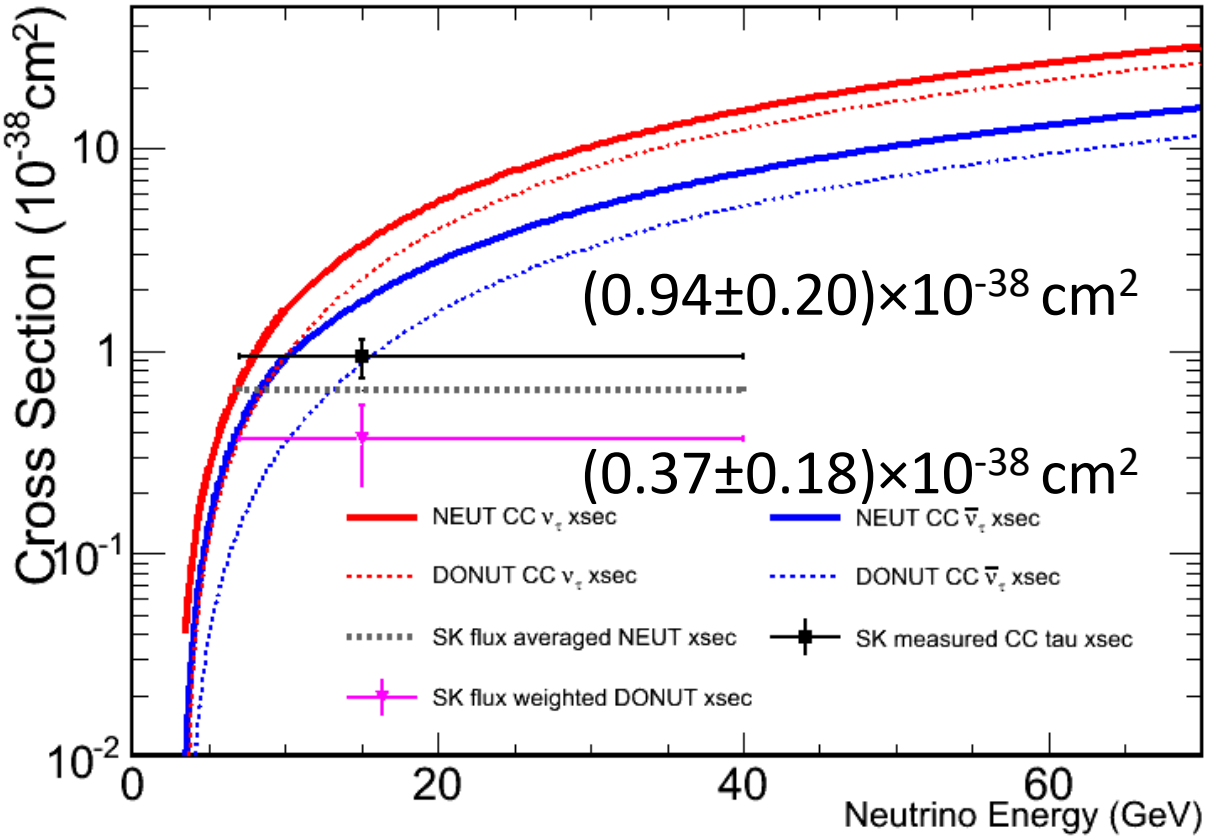
CC Tau Neutrino Cross Sections

Measurement of CC tau cross section in Super-K



The flux-weighted theoretical cross section (**gray dashed**) is scaled to calculate the measured cross section (**black cross**).

Comparisons of the Result with DONUT Measurement



DONUT results converted to differential cross section and weighted by SK flux.

DONUT measured almost pure CC deep-inelastic at high neutrino energies. The extrapolation of DONUT measurement to low energy does not work well.

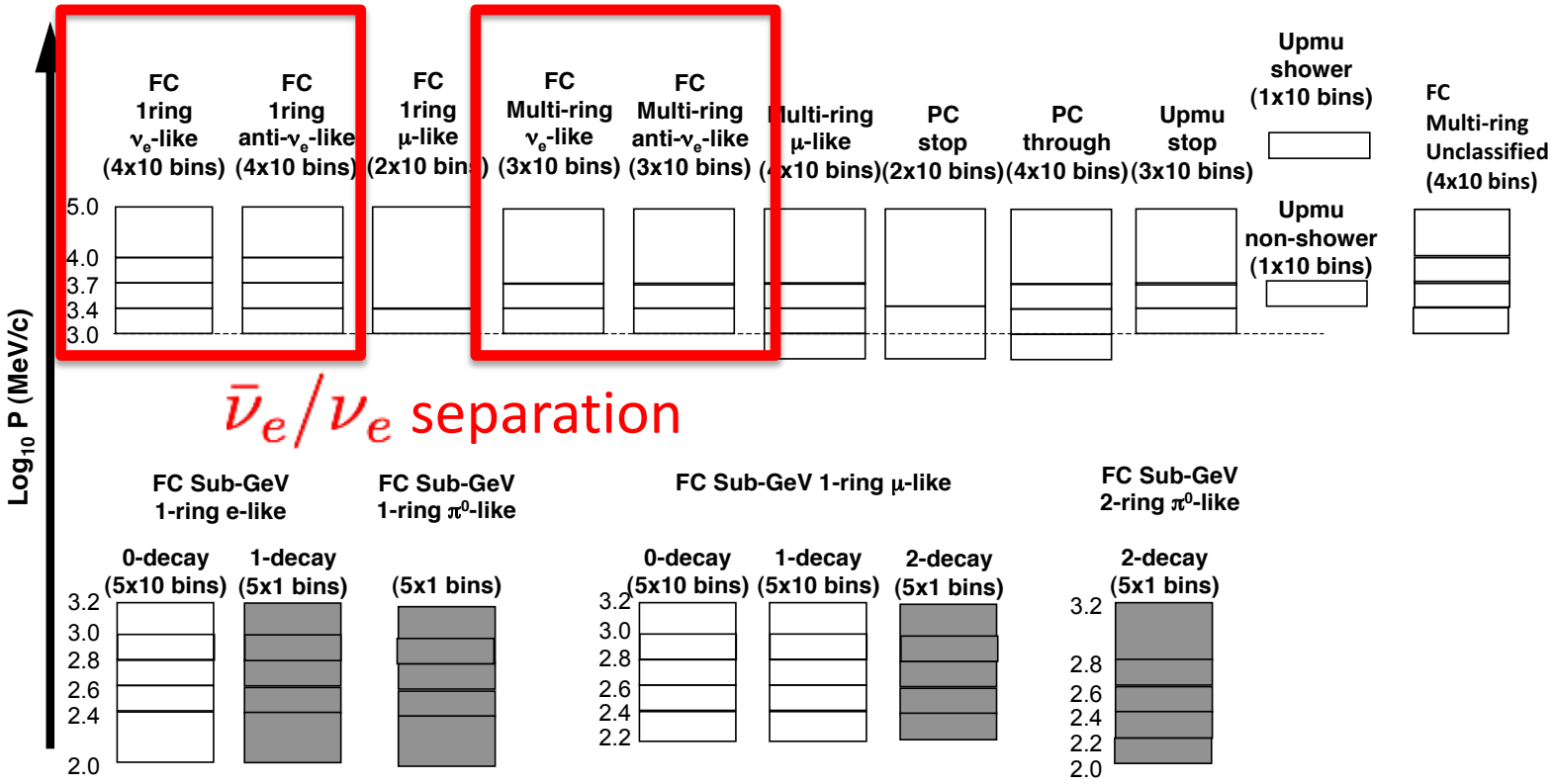
Comparison of σ/E Measurement at 70 GeV

arXiv:1711.09436

$10^{-38}cm^2/GeV$	SK Simulation	SK	DONUT
neutrino	0.46	0.67	0.52
Anti-neutrino	0.23	0.33	0.26
Average	0.35	0.51±0.11	0.27±0.13

- Neutrino/anti-neutrino ratio in SK – 1.16 .
- At high neutrino energy, the agreement is better.

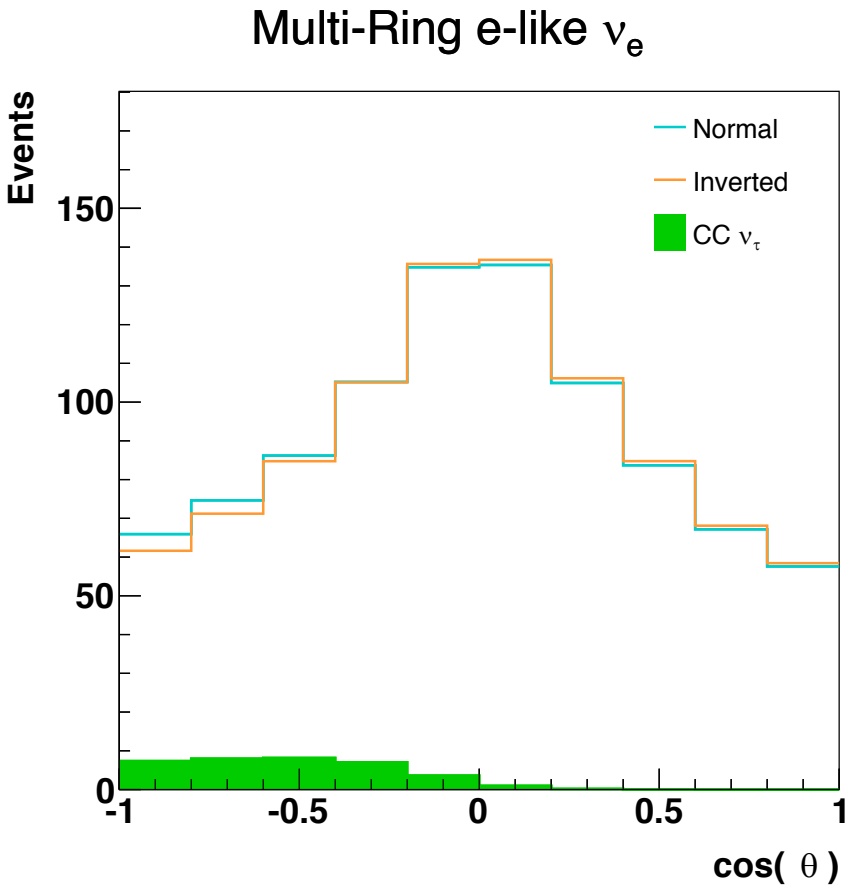
Three-flavor Oscillation Analysis

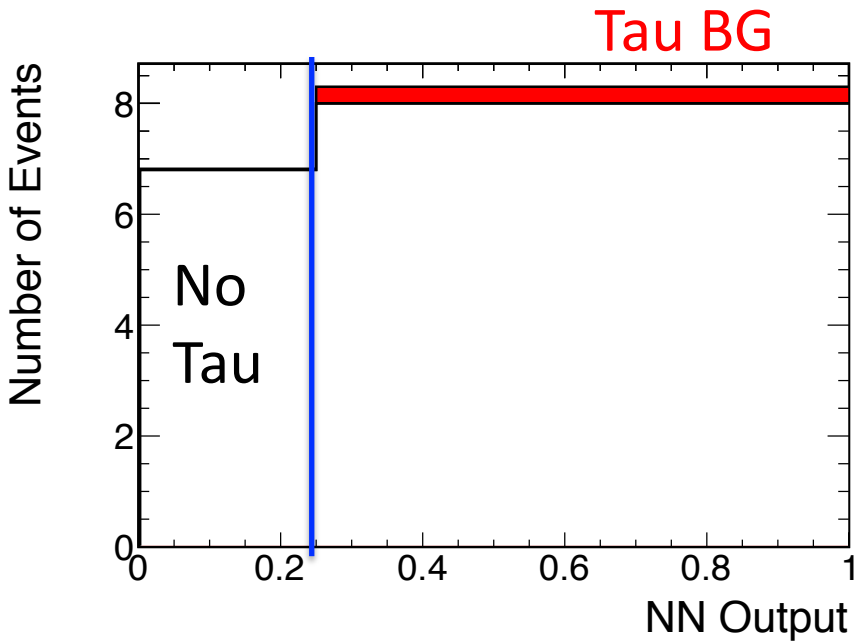


SK performs a binned likelihood fit in the three-flavor analysis:

$$\chi^2 = 2\sum_{i=1}^{n}[(N_i^{exp}(1+\sum_j f_{ij}\epsilon_j) - N_i^{obs}) + N_i^{obs}\ln\frac{N_i^{obs}}{N_i^{exp}(1+\sum_j f_{ij}\epsilon_j)}] + \sum_j(\frac{\epsilon_j}{\sigma_j})^2.$$

Use the Tau Identification in Three-flavor Oscillation Analysis





Each multi-GeV e-like bin is further divided into two bins: one with almost no tau BG, one with tau BG, in the binned fit.