Atmospheric Neutrino Results from Super-Kamiokande

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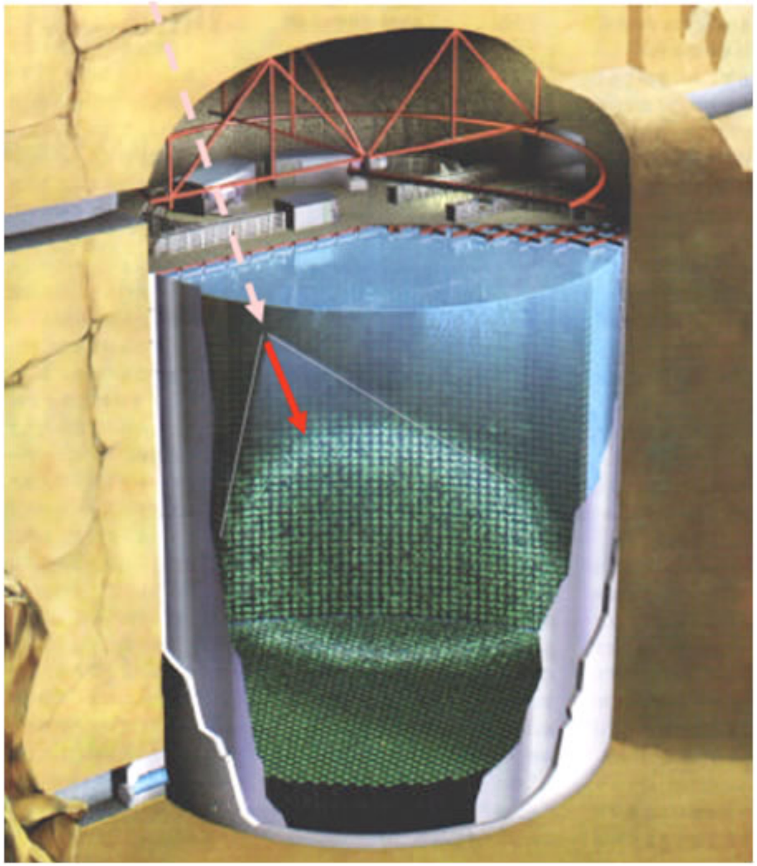
For The Super-Kamiokande Collaboration

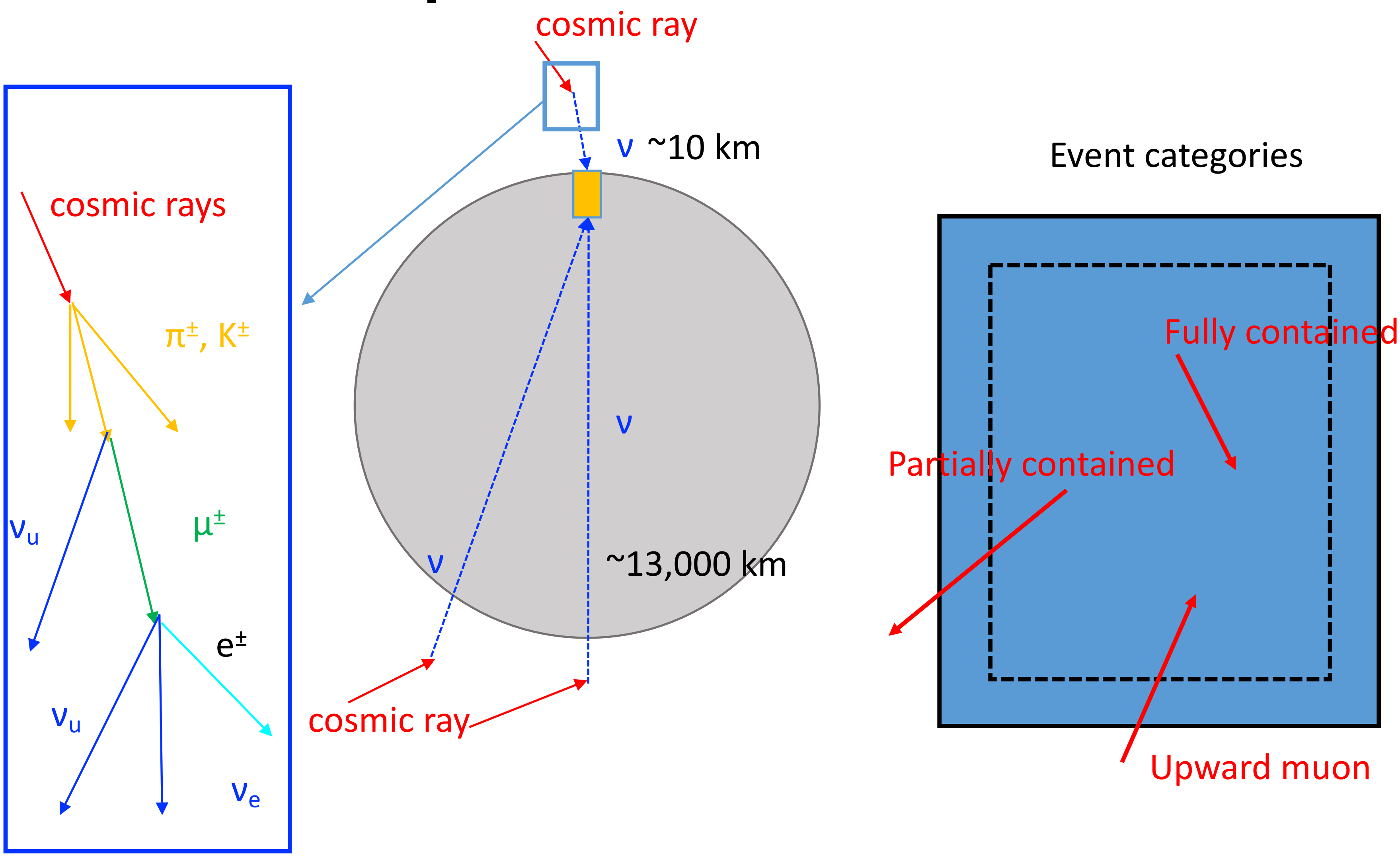
Super-Kamiokande



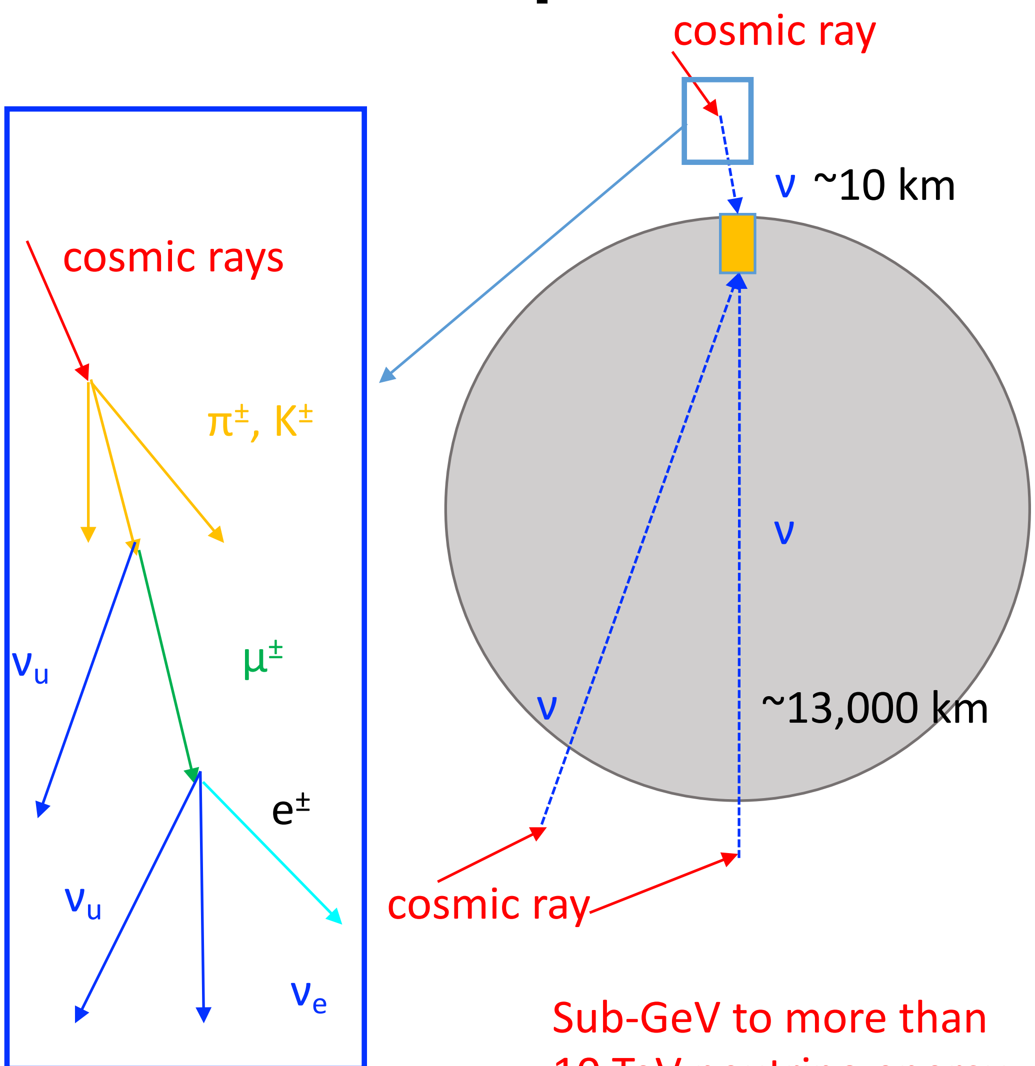
Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III(2005-2008) SK-IV(2008-Present)

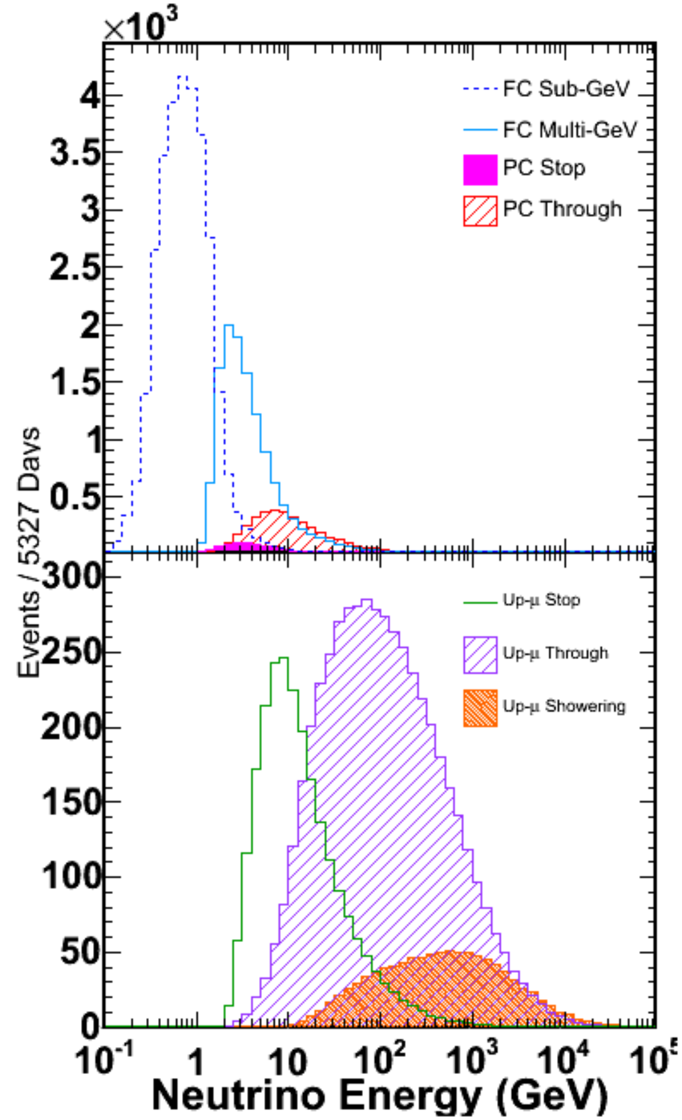
- Super-K is a 50 kton water Cherenkov detector with 22.5 kton of fiducial volume at 2,700 m.w.e underground.
- The detector is optically separated into ID and OD.
- Excellent in detection of atmospheric neutrinos.
- 20 years since the start of data taking in 1996, >47,000 atmospheric neutrino events.
- A Nobel prize winning experiment!

Atmospheric neutrinos in SK



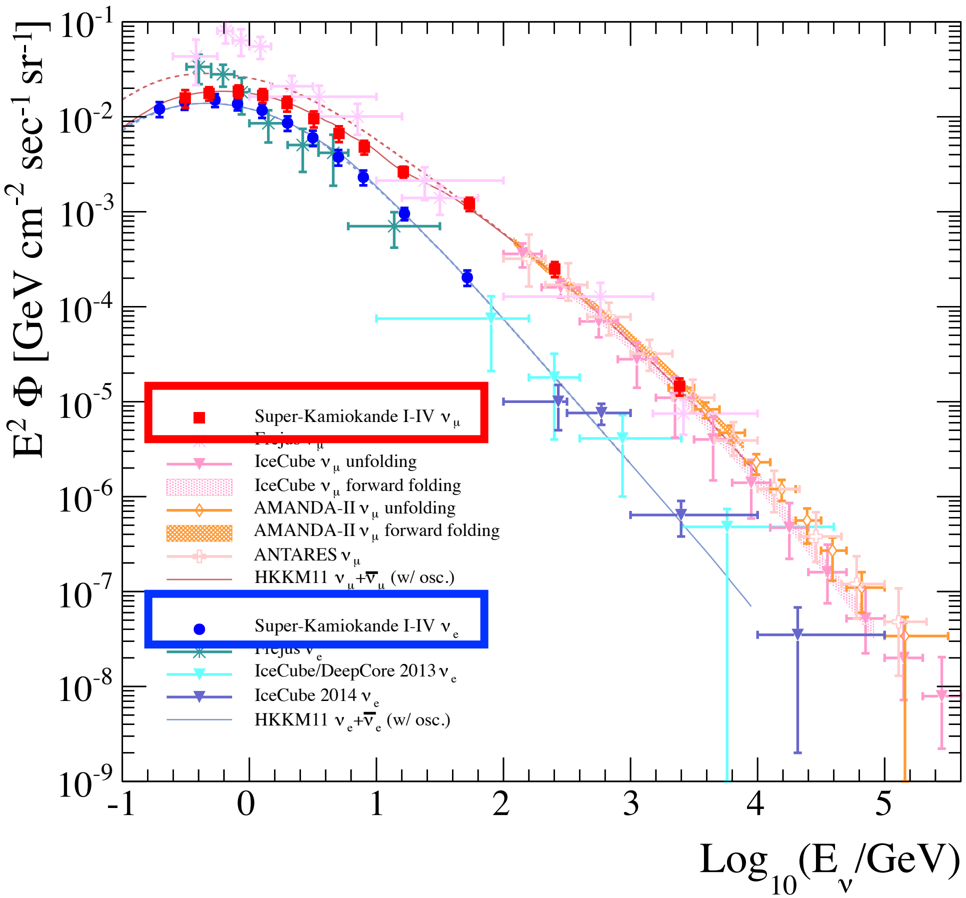
Atmospheric neutrinos in SK

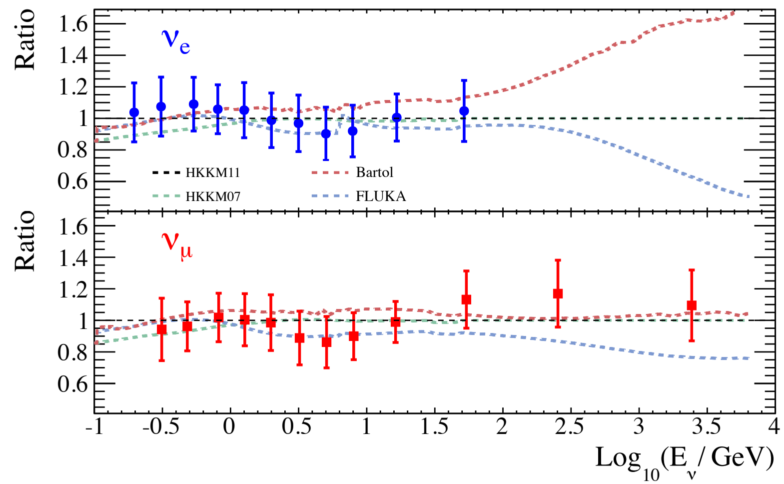




Sub-GeV to more than 10 TeV neutrino energy.

Atmospheric neutrinos measurement in SK





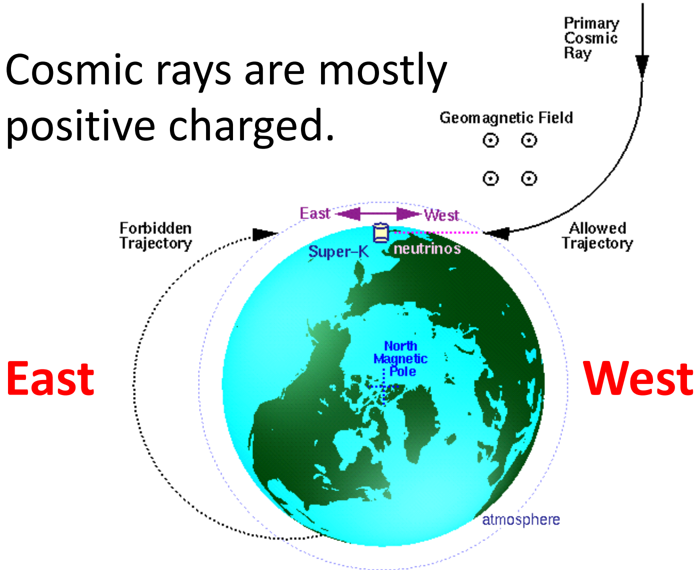
SK measures the flux of atmospheric neutrino with energy of sub-GeV to ~10 TeV. The measurement is consistent with model prediction.

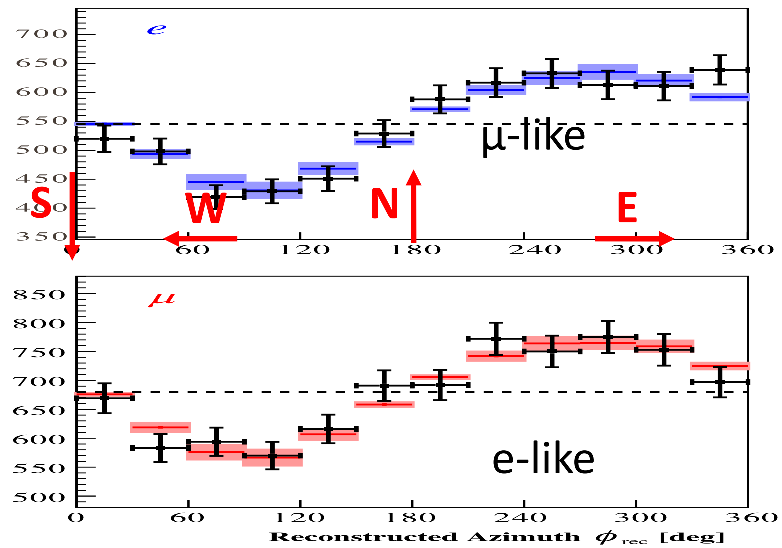
With the large sample, SK can test the effects on atmospheric neutrino flux of geo-magnetic field, solar activity, etc.

arXiv:1510.08127

Atmospheric neutrinos measurement in SK

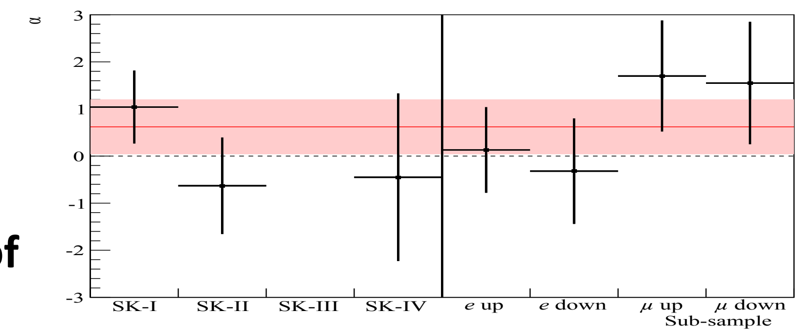
Cosmic rays are mostly positive charged.





Azimuthal asymmetries of SK neutrino events

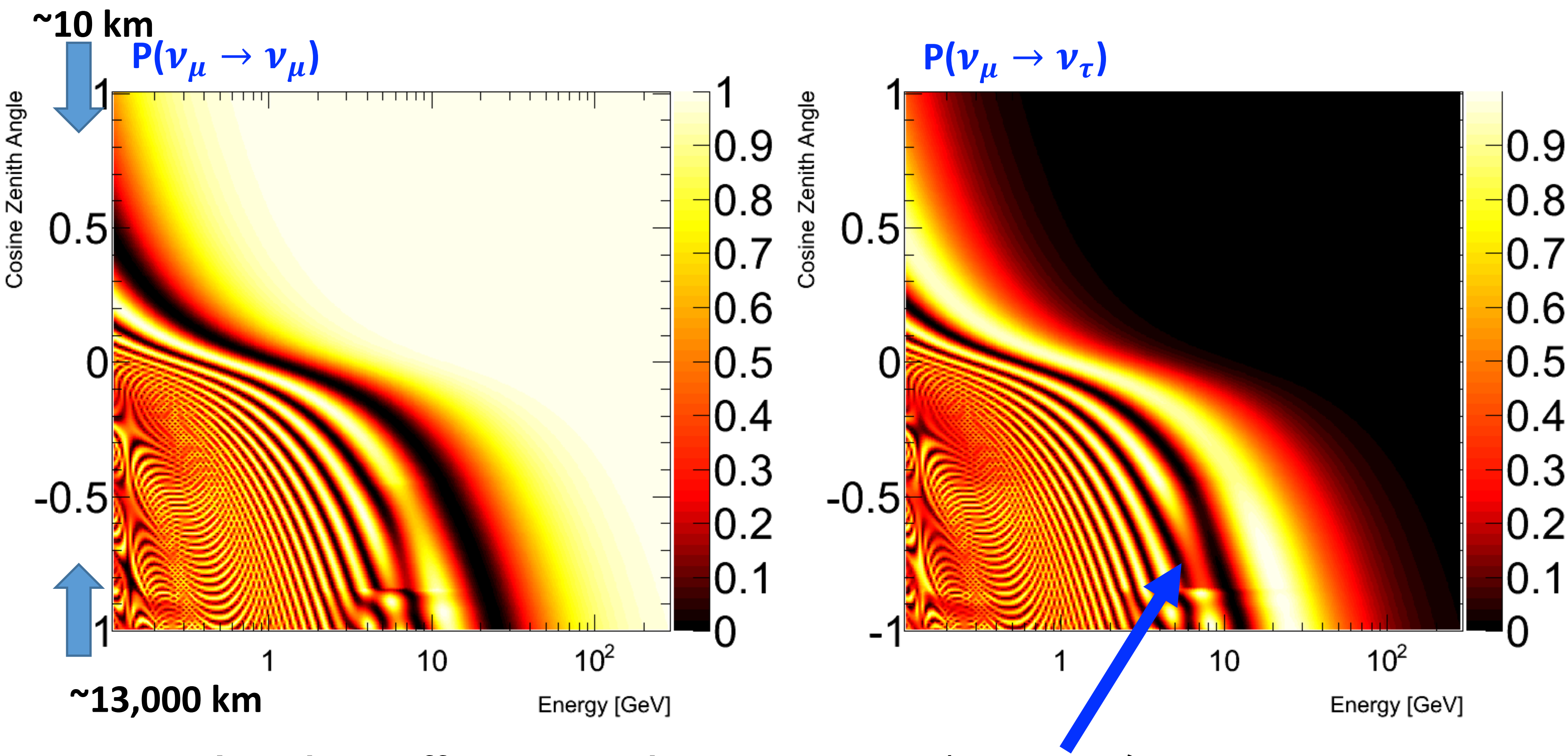
SK observes clear azimuthal dependence for both μ-like(6.0σ) and e-like(8.0σ) samples due to the effect of geo-magnetic field, and no significant solar modulation of atmospheric neutrino flux.



Fitted α as degree of solar modulation,
α=0: no correlation, 1:expected

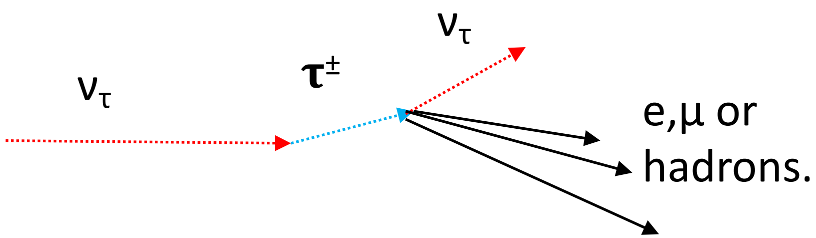
arXiv:1510.08127

Neutrino oscillations at Super-K



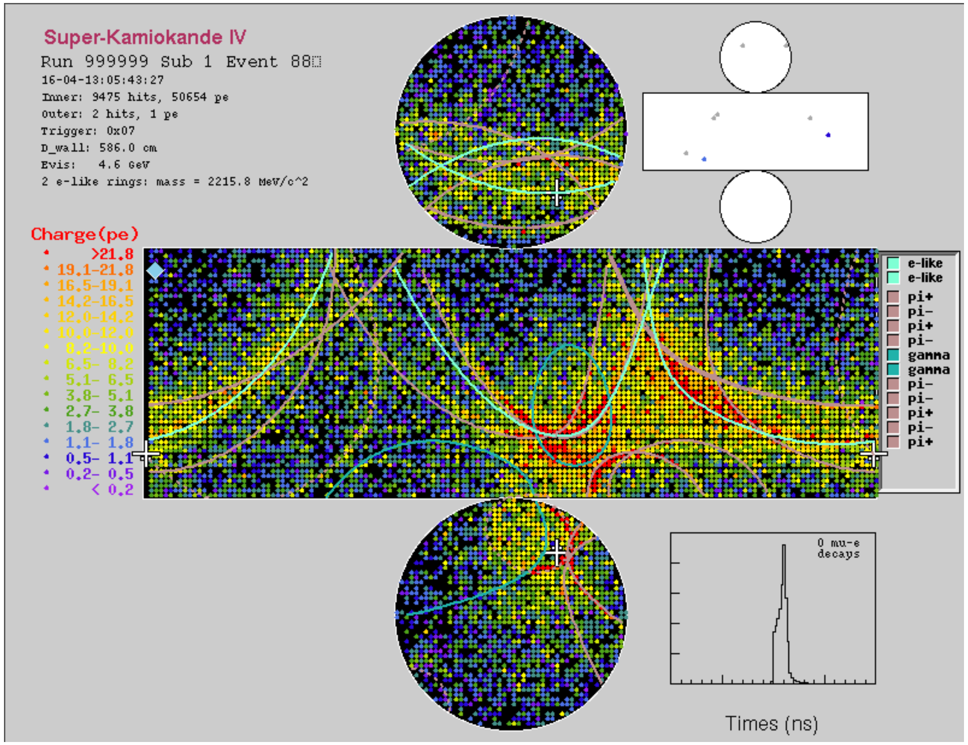
Leading effect is ν_μ disappearance($\nu_\mu \rightarrow \nu_\tau$).
ν_τ appearance from neutrino oscillations could be detected by charged current ν_τ interaction in SK.

Tau neutrino appearance in SK

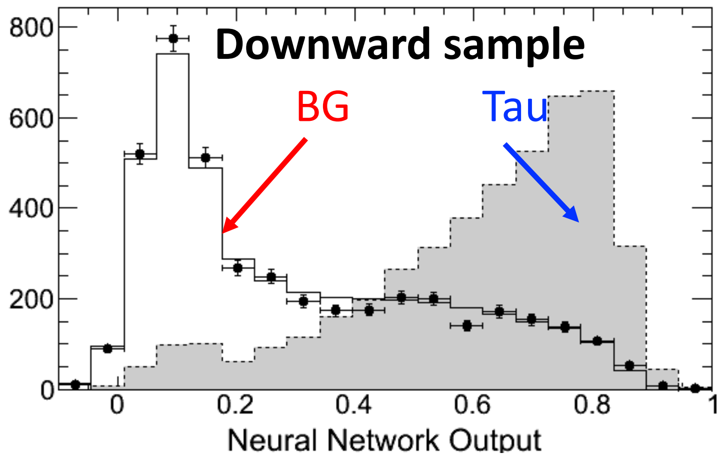


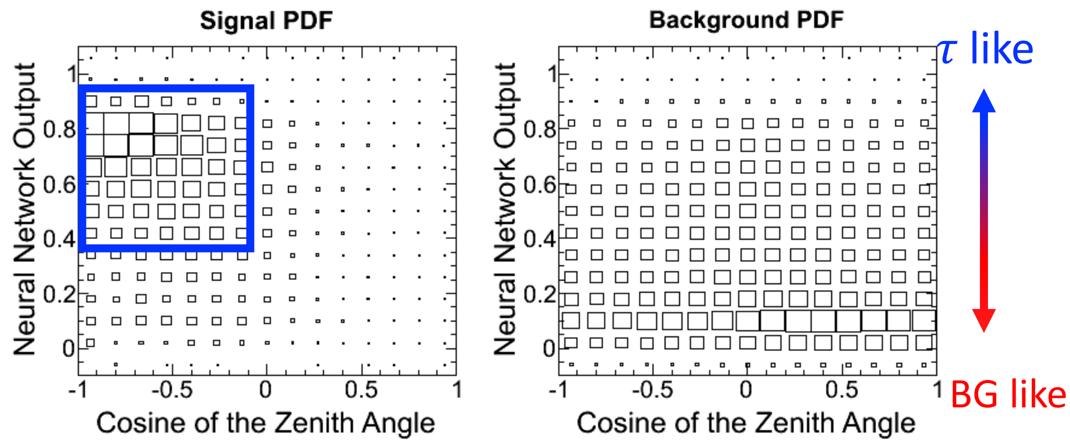
Tau lepton decays in ~10^{-13}s, tau lepton track is undetectable in SK detector.

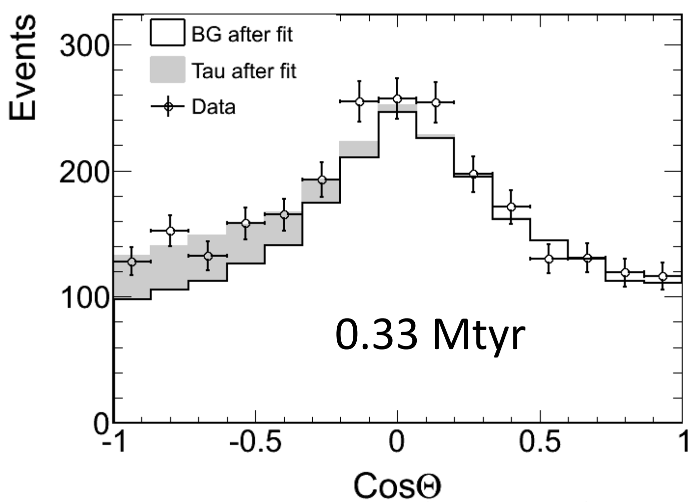
- Tau lepton production is rare in SK due to 3.5GeV energy threshold of charged-current ν_τ interaction.
- Multiple light-producing particles from tau decay.
- Neural network(input variables in backup) to select hadronic tau decay events.



Tau neutrino appearance in SK







tau-like events after the fit

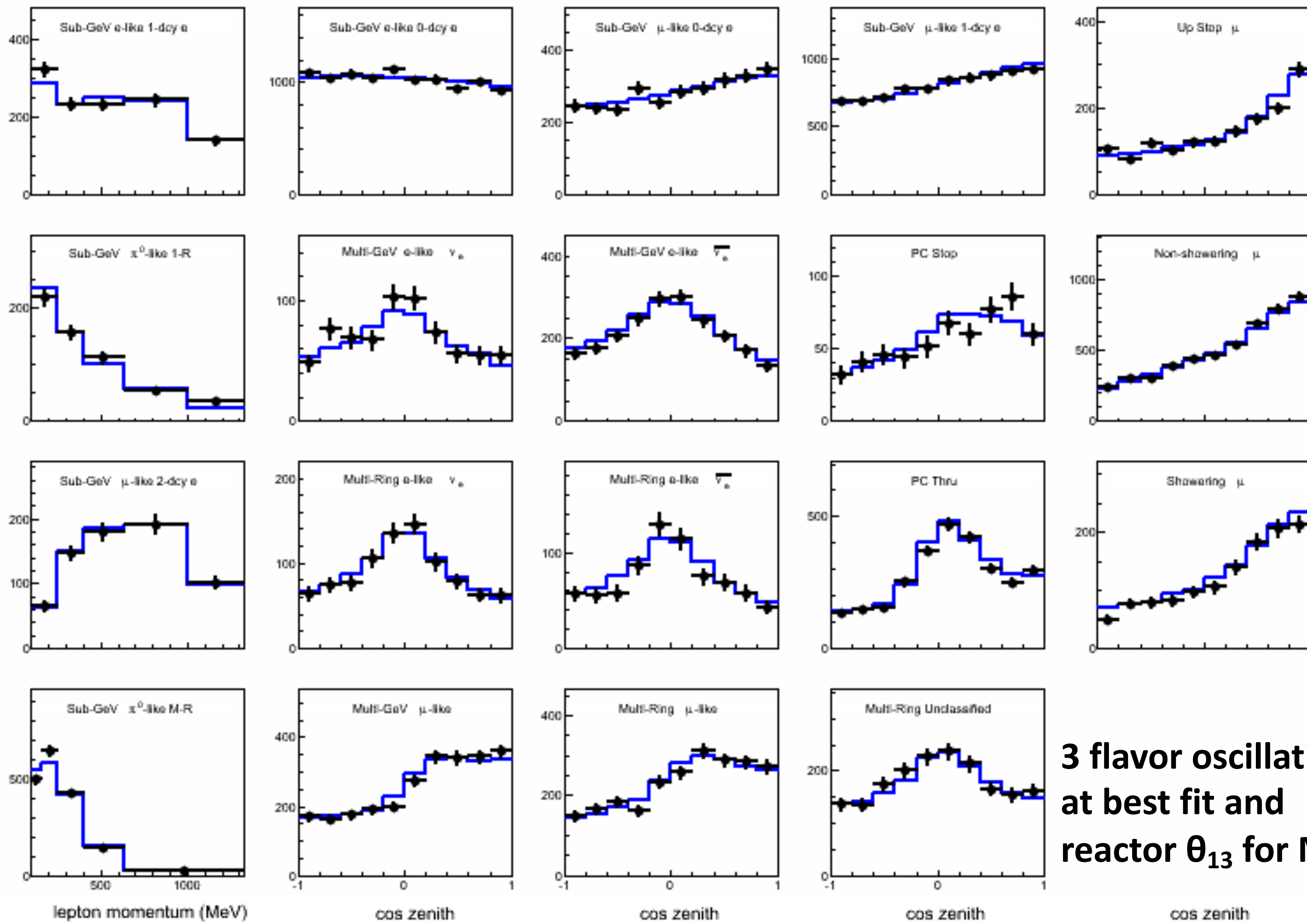
$$\mathbf{Data = PDF_{bg} + \alpha\times PDF_{tau} + \sum \varepsilon_i\times(tauPDF_i + bgPDF_i)}$$

α is the normalization of tau events.

$(tau, BG)PDF_i$ is the PDF of ith systematic error of shifting it by 1σ, ε_i is the magnitude of the systematic error.

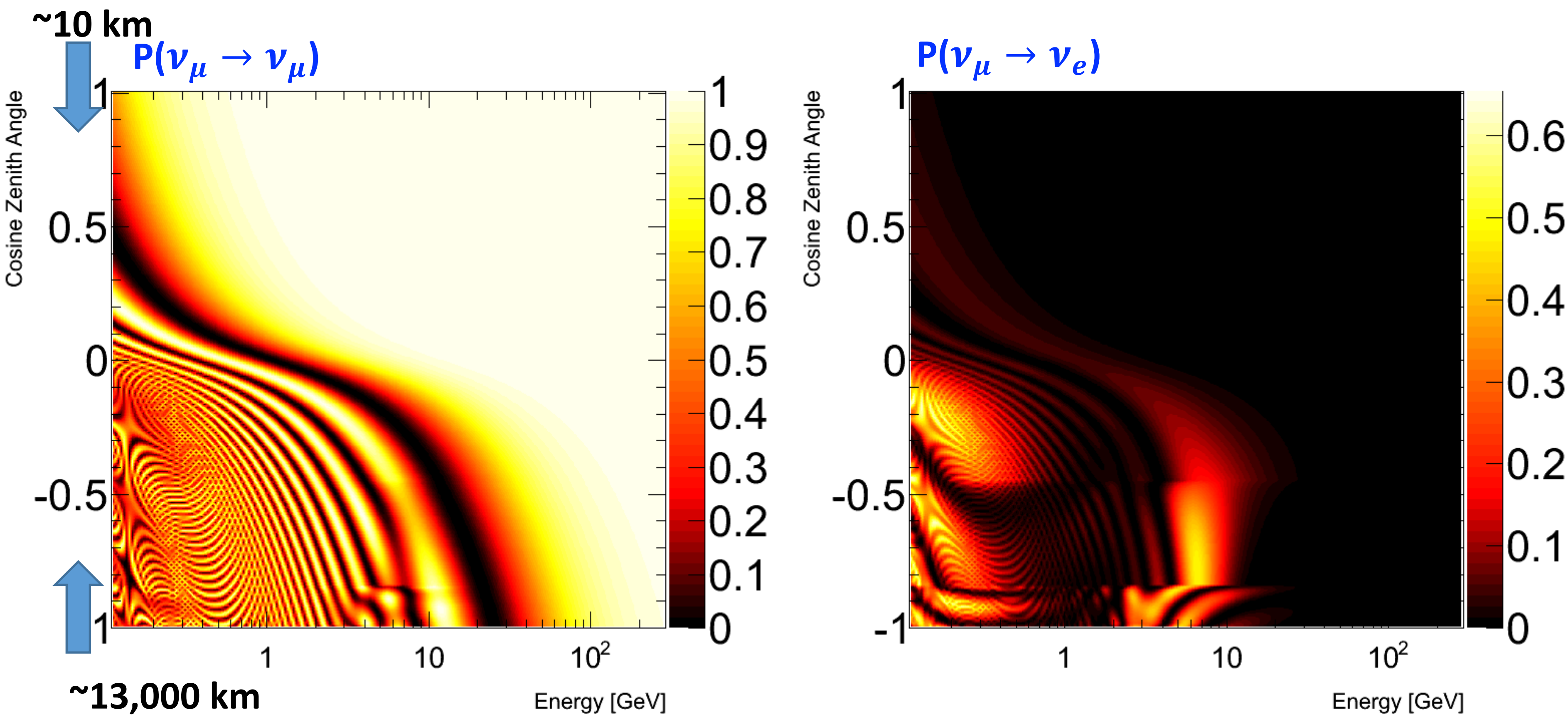
α=1.47±0.32 preliminary
compared to simulation
(4.6σ from 0)assuming NH
Sensitivity at α=1: 3.3σ

SK1-4 0.33 Mtyr data and MC



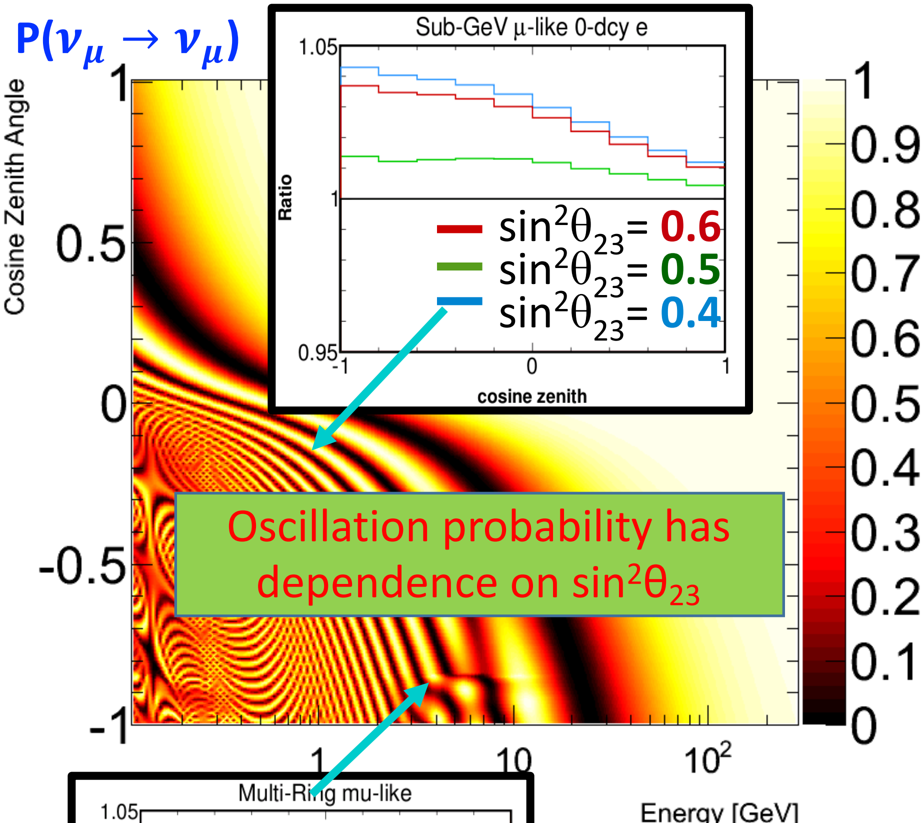
3 flavor oscillation at best fit and reactor θ_{13} for MC.

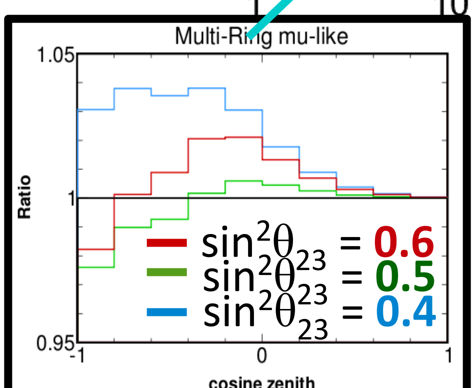
Neutrino oscillations at Super-K

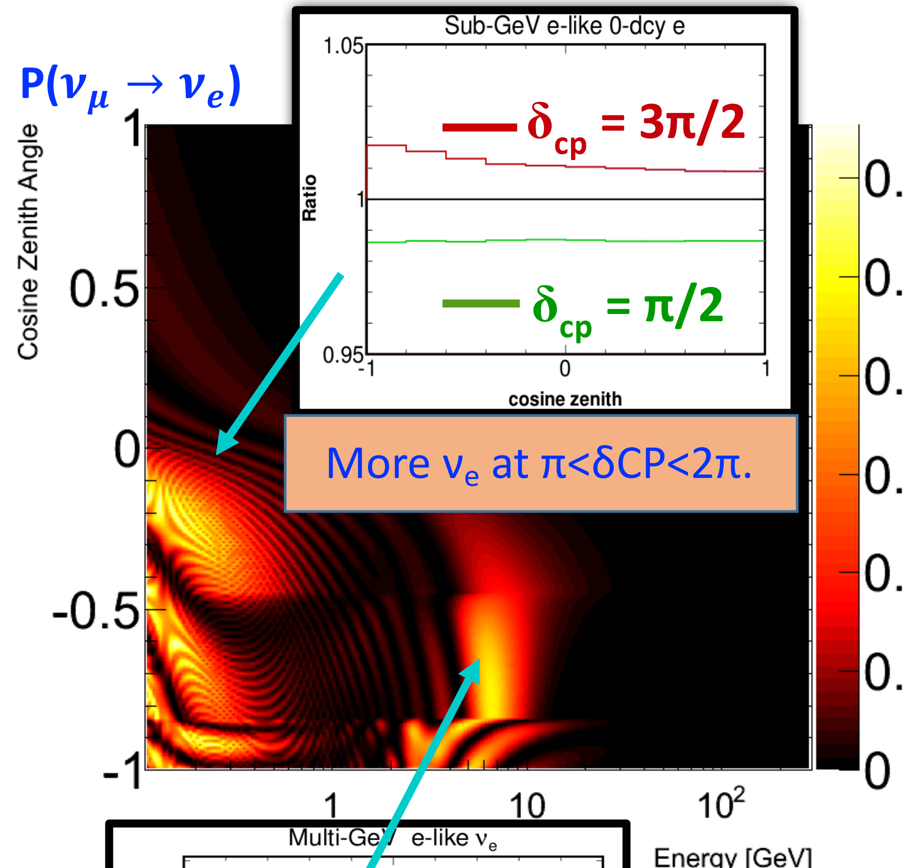


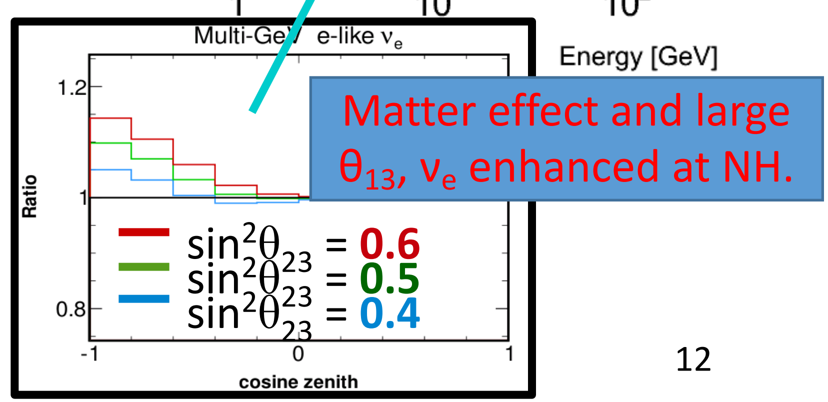
Leading effect is ν_μ disappearance.
Sub-leading effects help to resolve θ_{23} octant, δ_{CP} and mass hierarchy.

Neutrino oscillations at Super-K



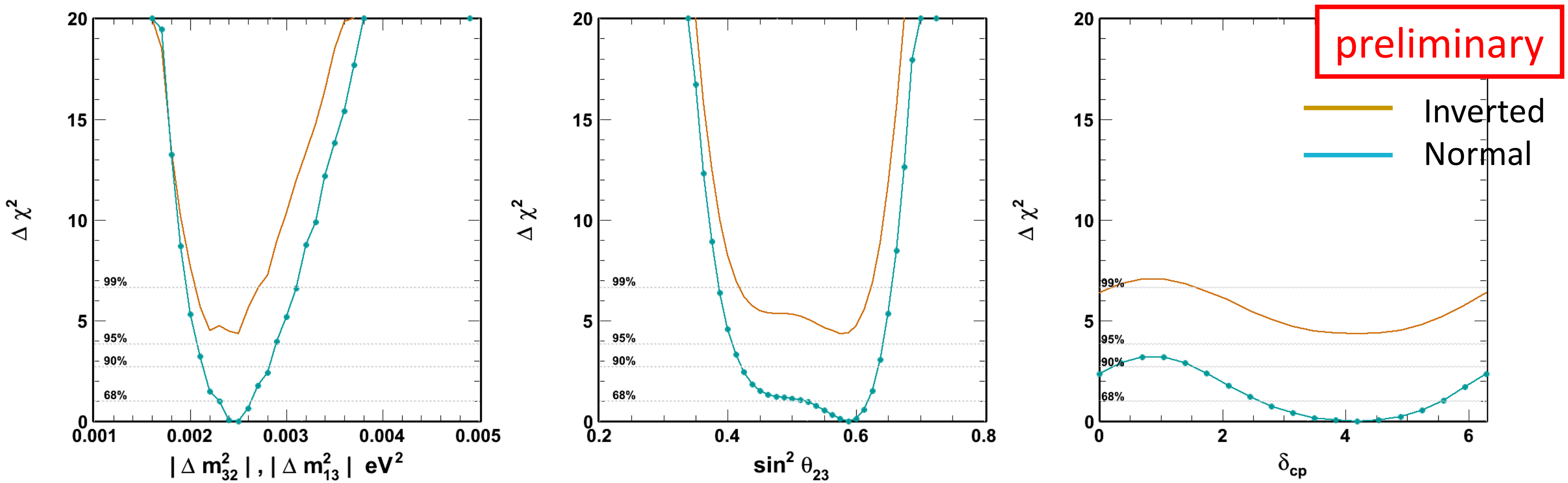






Ratio to two-flavor oscillations shown. Multiple samples used in the analysis.

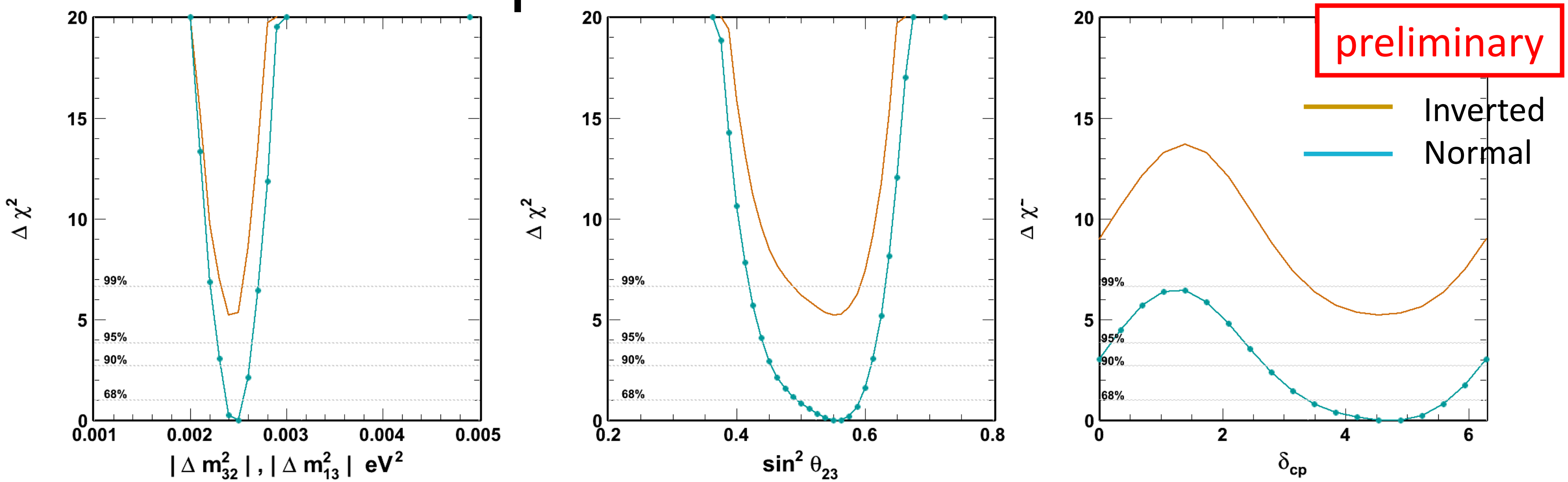
SK oscillation analysis-θ_{13} constrained



Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$eV^2
SK (IH)	576.0	0.0219	4.2	0.58	2.5x10^{-3}
SK (NH)	571.7	0.0219	4.2	0.59	2.5x10^{-3}

- θ_{13} is constrained at PDG average, uncertainty is included as a systematic error.
- $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -4.3$ (-3.1 of sensitivity)
- The p-value of obtaining $\Delta\chi^2$ of -4.3 or less is 0.031 ($\sin^2\theta_{23}$=0.6) and 0.007 ($\sin^2\theta_{23}$=0.4) in IH hypothesis. Under NH hypothesis, the p-value is 0.45 ($\sin^2\theta_{23}$=0.6).

Oscillation analysis with constraint from published T2K data



Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ eV^2
SK (IH)	644.8	0.0219	4.5	0.55	2.5×10^{-3}
SK (NH)	639.6	0.0219	4.9	0.55	2.4×10^{-3}

- $\Delta\chi^2$ = -5.2 (-3.8 of sensitivity for SK best, -3.1 for combined best)
- The p-value of obtaining $\Delta\chi^2$ of -5.2 is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4). Under NH hypothesis, the p-value is 0.43 ($\sin^2\theta_{23}$=0.6).

Summary

- Measurement of atmospheric neutrino flux of energies from sub-GeV to 10 TeV.
- Tau neutrino appearance with significance of 4.6σ.
- Normal hierarchy preferred by $\Delta\chi^2$ = -5.2 , p-value is between 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4) in IH hypothesis.
- Weak preference of second octant and δ_{CP} near 3/2π.
- More analyses in SK, indirect WIMP search in poster session.

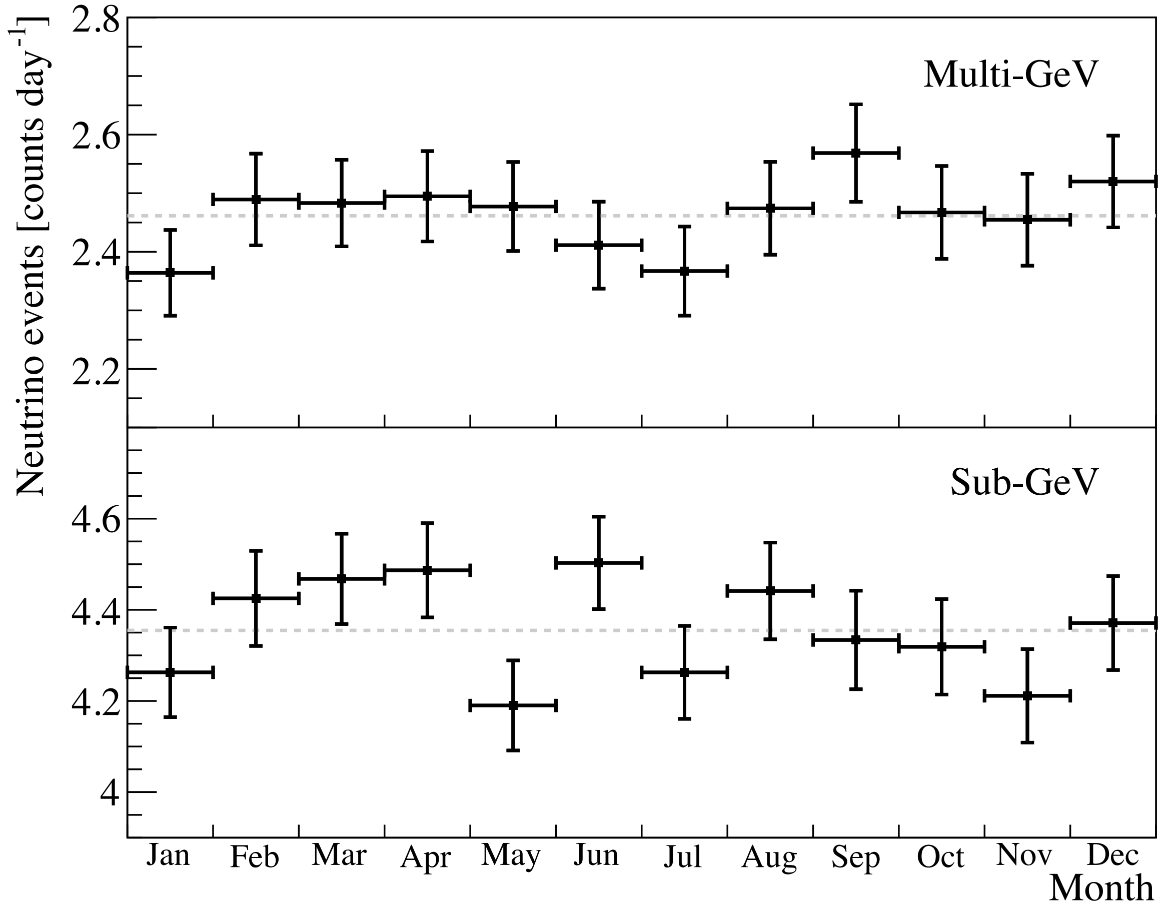
Super-Kamiokande Collaboration

1 Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
2 RCCN, ICRResearch, Univ. of Tokyo, Japan
3 University Autonoma Madrid, Spain
4 University of British Columbia, Canada
5 Boston University, USA
6 Brookhaven National Laboratory, USA
7 University of California, Irvine, USA
8 California State University, USA
9 Chonnam National University, Korea
10 Duke University, USA
11 Fukuoka Institute of Technology, Japan
12 Gifu University, Japan
13 GIST College, Korea
14 University of Hawaii, USA
15 Imperial College London, UK
16 KEK, Japan
17 Kobe University, Japan
18 Kyoto University, Japan
19 University of Liverpool, UK
20 Miyagi University of Education, Japan
21 National Centre For Nuclear Research, Polar
22 Okayama University, Japan
23 Osaka University, Japan
24 University of Oxford, UK
25 Queen Mary University of London, UK
26 University of Regina, Canada
27 Seoul National University, Korea
28 University of Sheffield, UK
29 Shizuoka University of Welfare, Japan
30 STE, Nagoya University, Japan
31 Sungkyunkwan University, Korea
32 SUNY, Stony Brook, USA
33 Tokai University, Japan
34 University of Tokyo, Japan
35 Kavli IPMU (WPI), University of Tokyo, Japan
36 Dep. of Phys., University of Toronto, Canada
37 TRIUMF, Canada
38 Tsinghua University, China
39 University of Washington, USA

~150 collaborators
39 institutions
8 countries

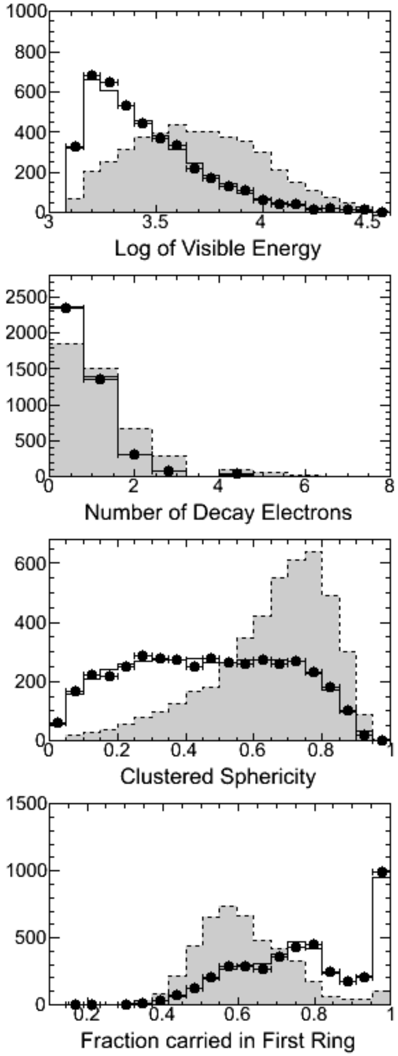
Backups

Seasonal variation

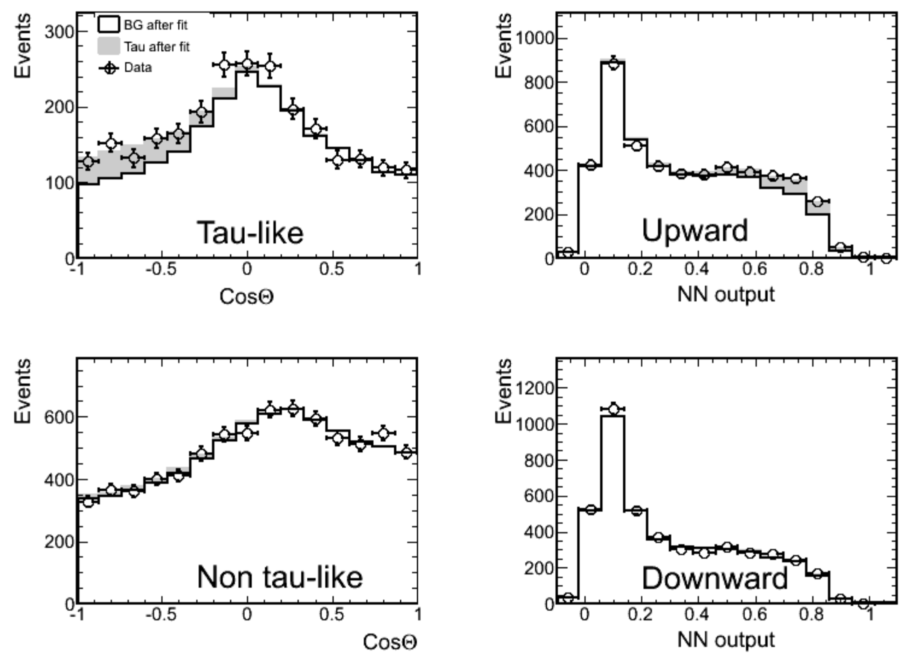


No seasonable variation is seen as expected.

Tau analysis

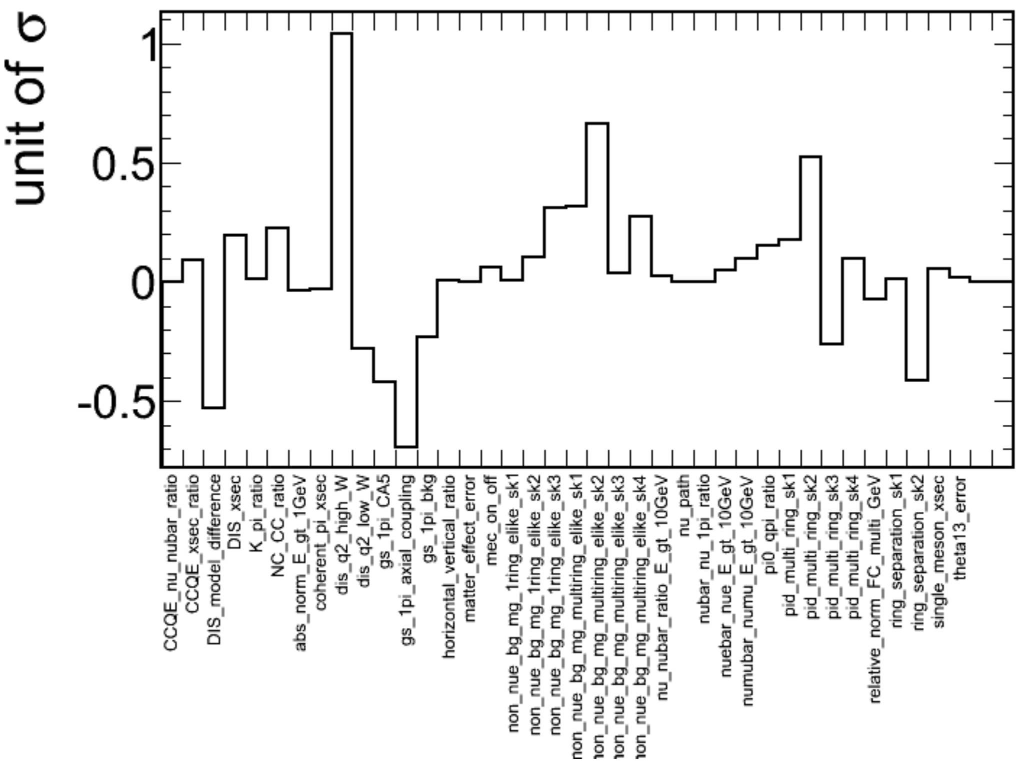


Seven input variables to neural network.

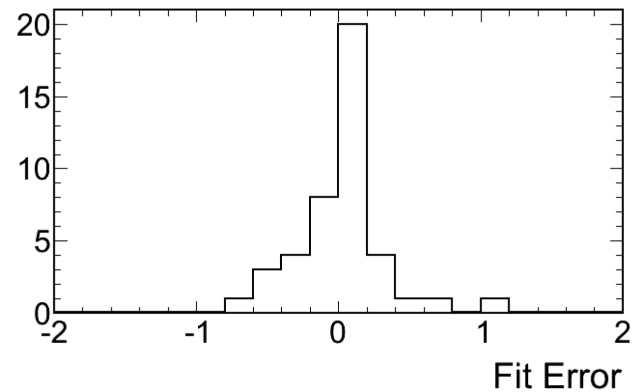


Fit result for different samples, signal/BG MC scaled by fit result.

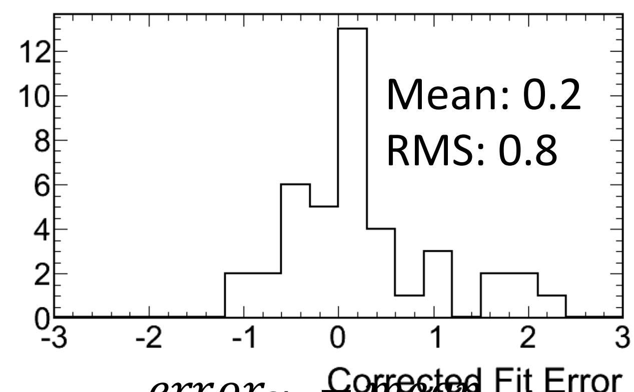
Fitted systematic errors in tau analysis



Fitted value of systematic terms, distributed around 0.

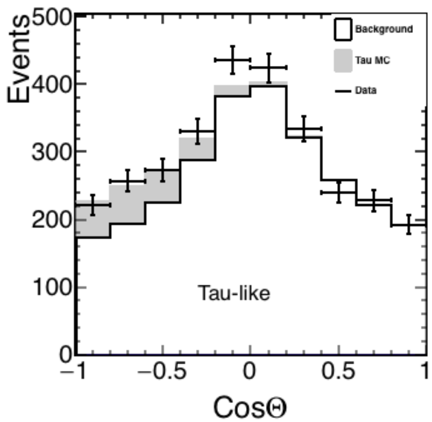


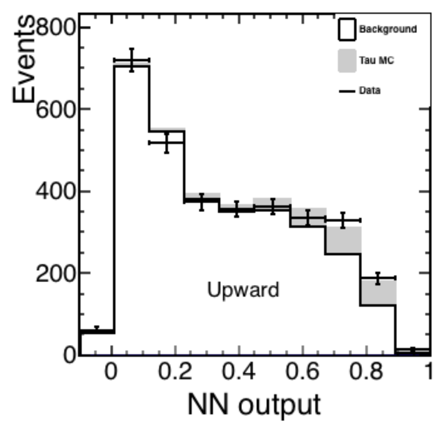
Fitted deviation in unit of σ of systematic errors

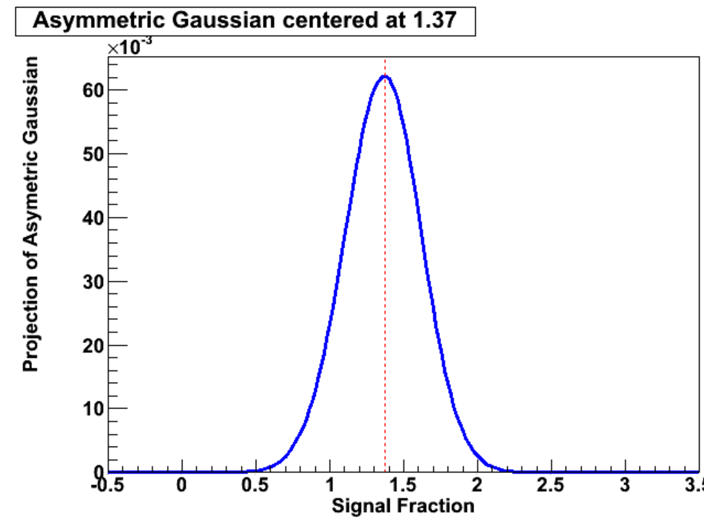


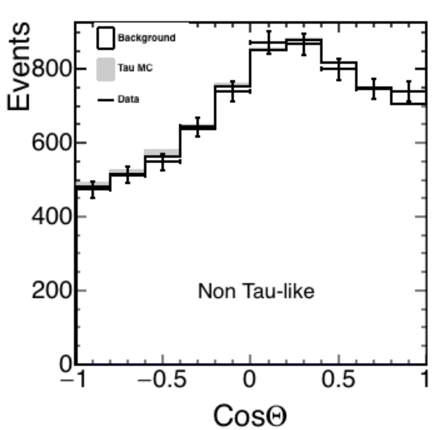
$$\frac{error_{fit} - mean}{sigma_{input} - sigma_{fit}}$$

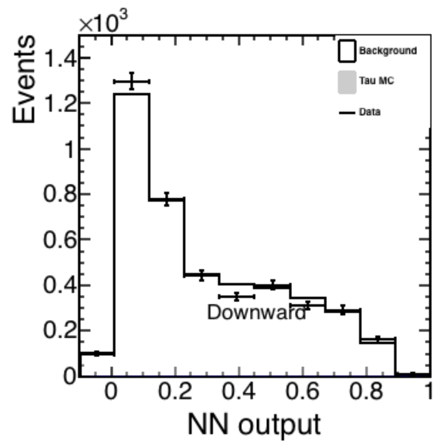
Paper fit update of tau analysis





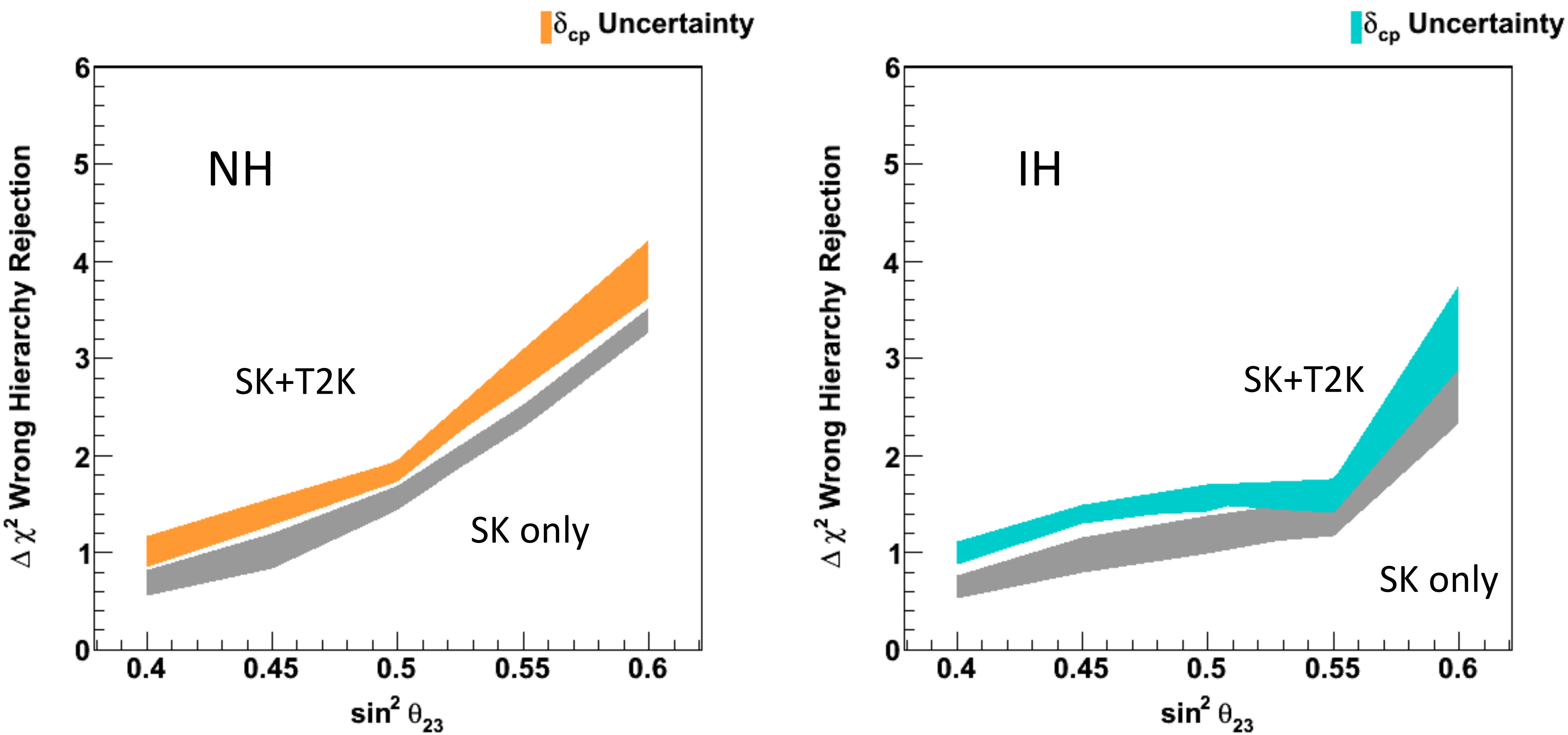




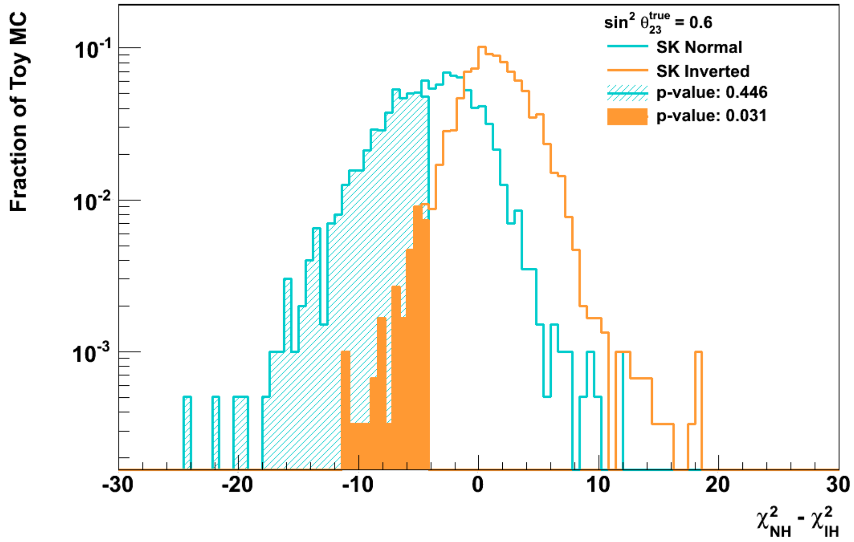


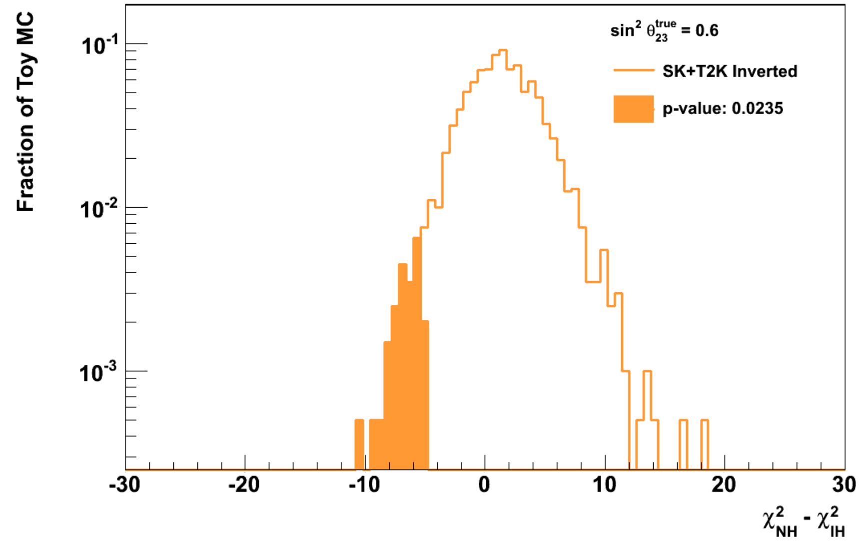
Tau fraction: $1.37\pm0.23^{+0.13}_{-0.11}$, the significance is 5.1σ.

Improved MH sensitivity with T2K constraint

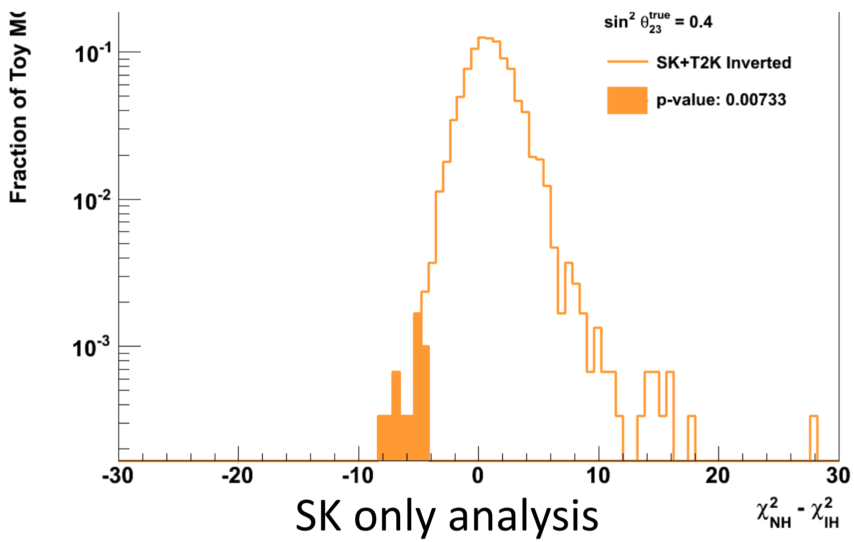


p-value for MH preference



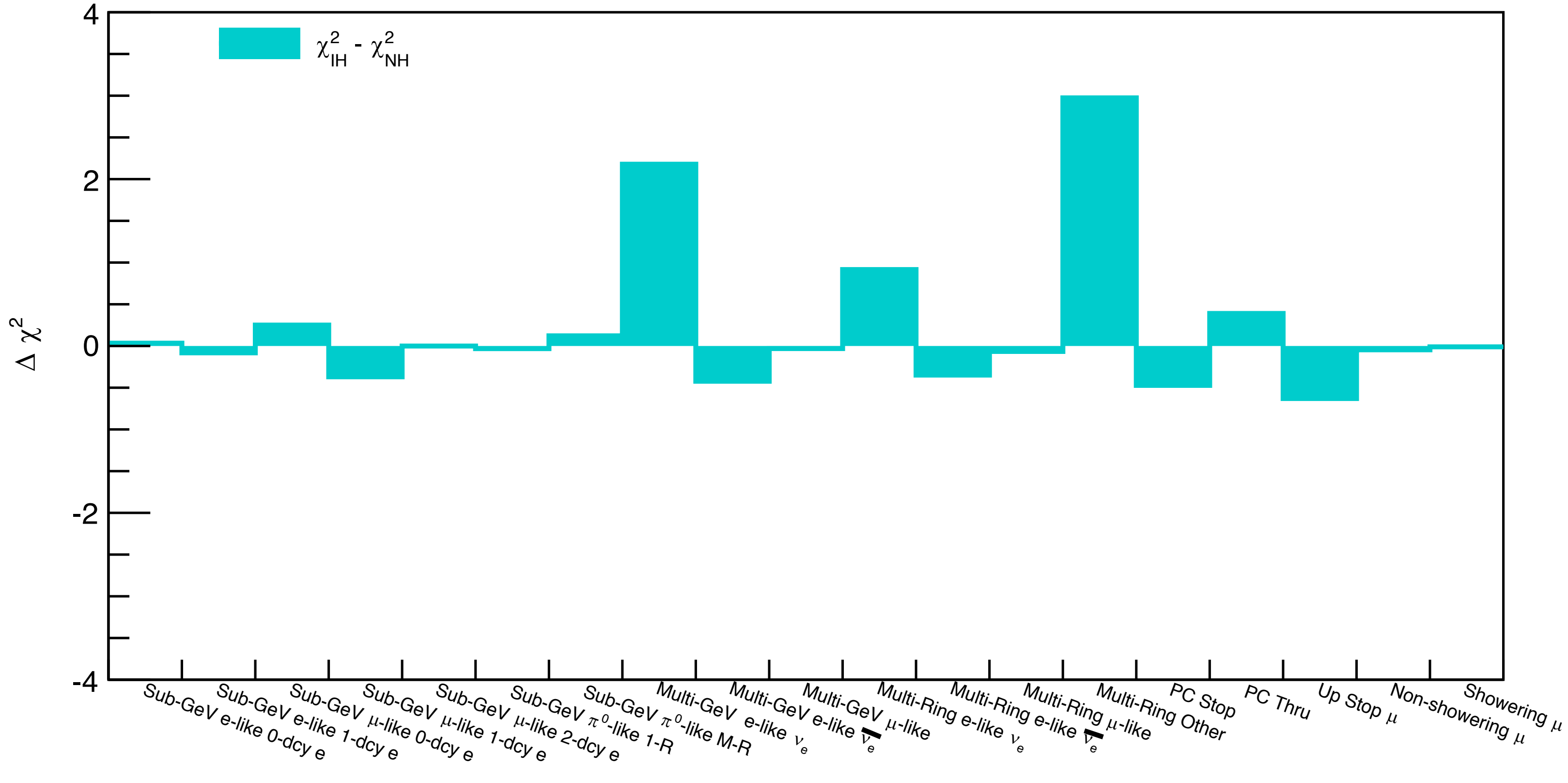


SK analysis with T2K constraint.

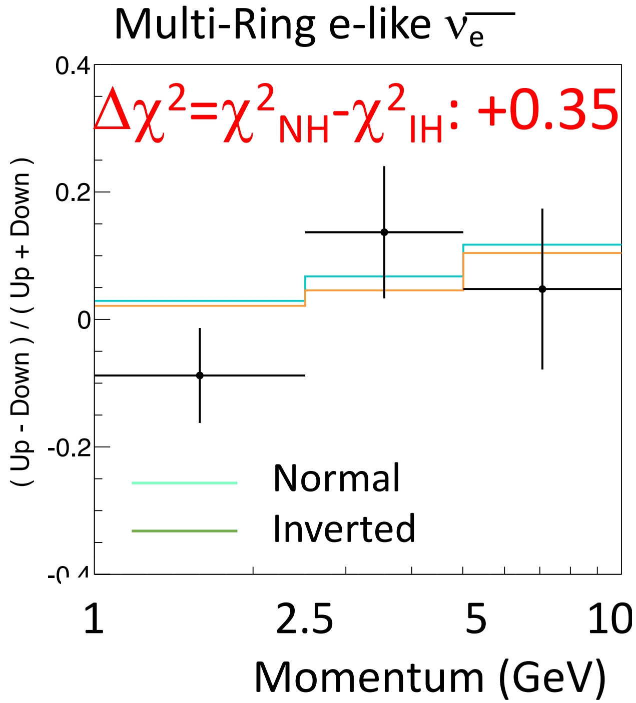


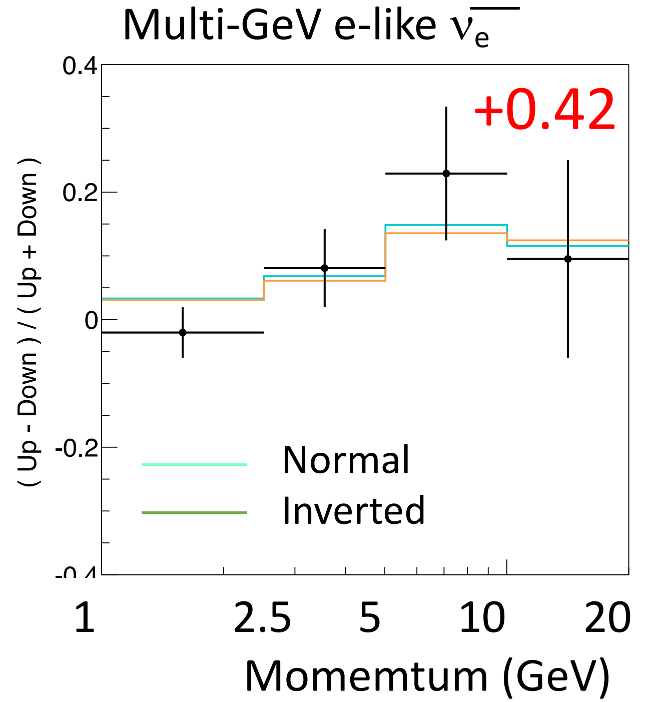
SK only analysis

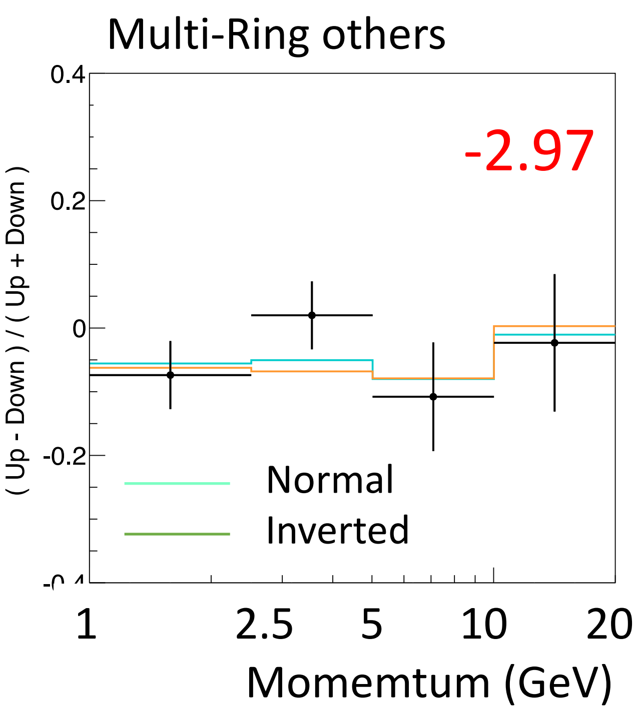
MH preference in sub-samples

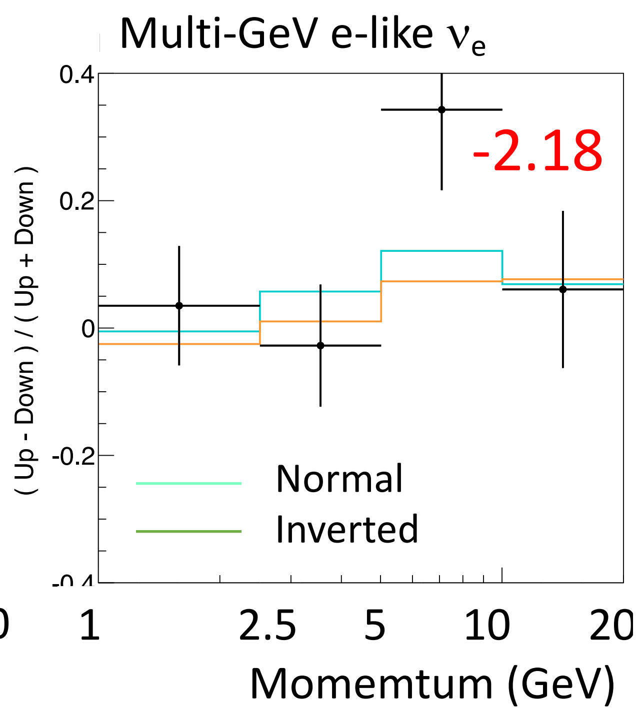


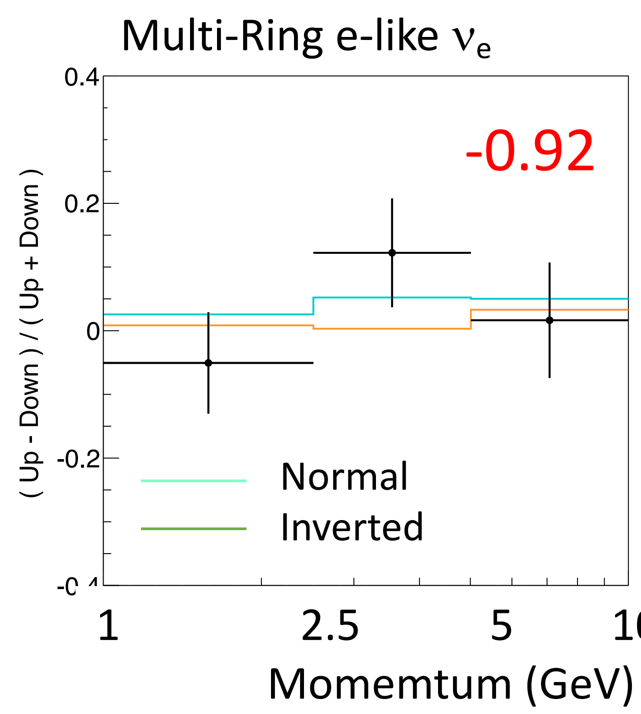
Hierarchy preference in sub-samples



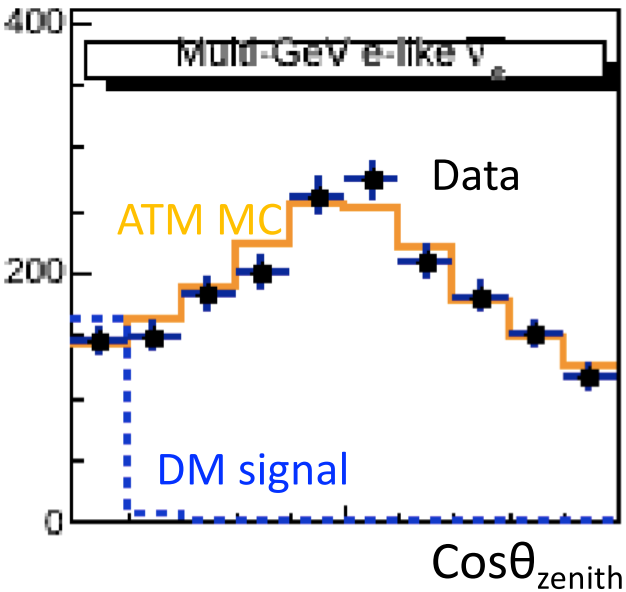








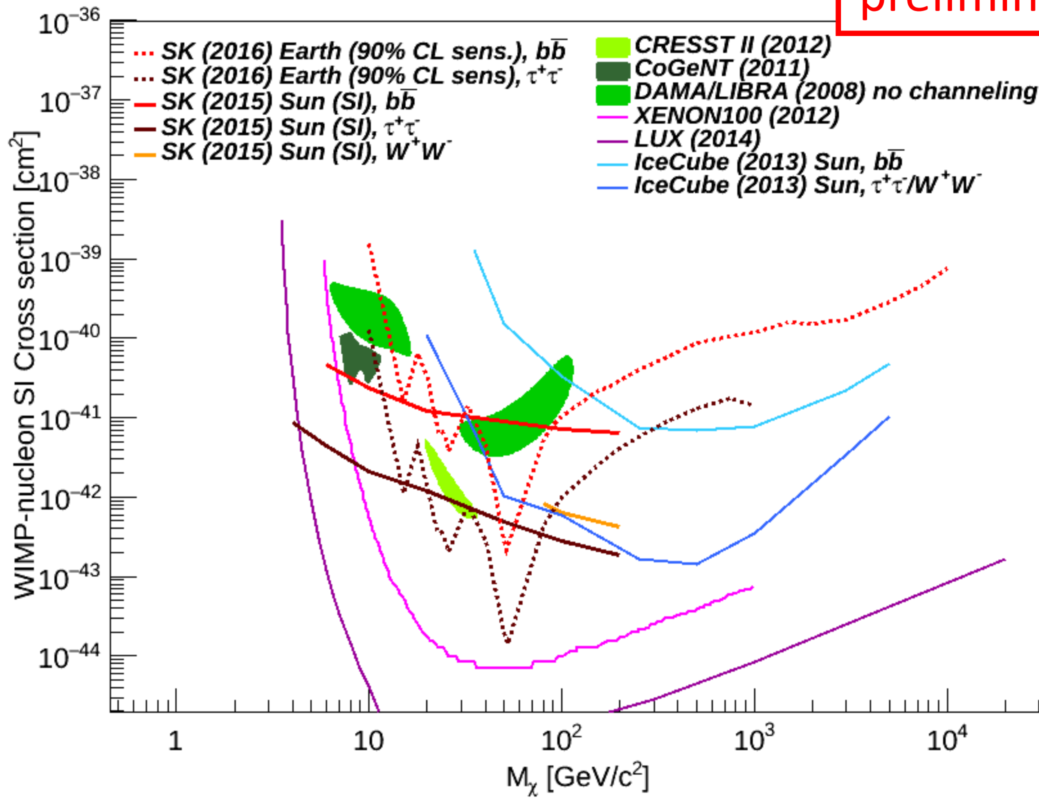
Indirect WIMP search



Search for an excess of neutrinos from galaxy, sun or earth(shown in the plot).

Indirect Dark Matter Searched with Super-Kamiokande Poster by K. Frankiewicz

preliminary



Preliminary sensitivity result of 90% CL limits for background only scenario for WIMP decay in earth core.