Systematics for Atmospheric Neutrinos in Super-Kamiokande and Hyper-Kamiokande

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Introduction

- Some Introductory Material
  - Atmospheric Neutrinos, Super-K and Hyper-K

- Systematic Uncertainties
  - …that hamper mass hierarchy measurements
  - …that hamper δ_{cp} measurements

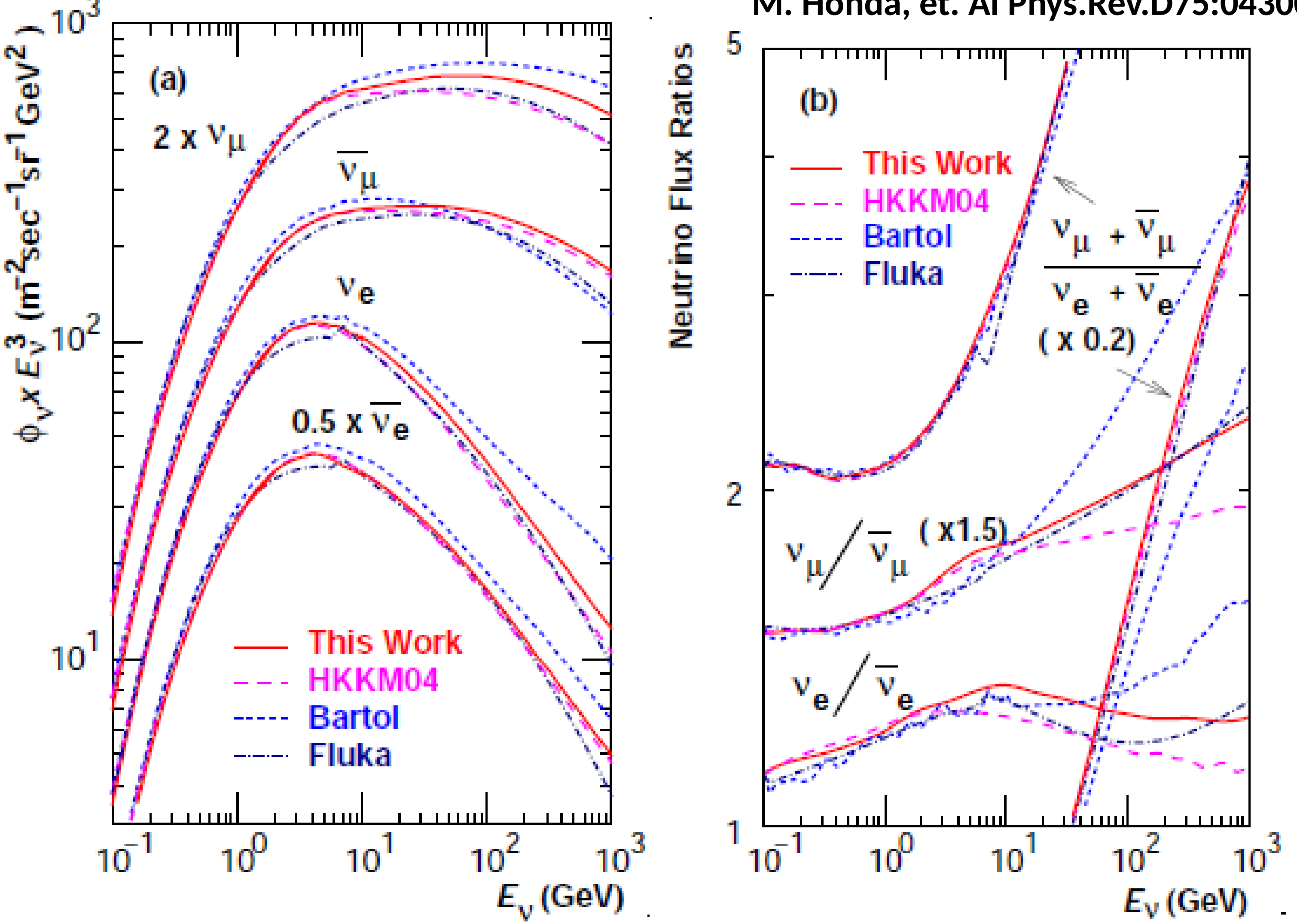
- Generally speaking most of the content of this talk is relevant to any detector with capability to distinguish atmospheric νe and $\nu\mu$
  - Most of the relevant systematic errors are from the flux and cross section models and nothing too specific to water Cherenkov

- Some comments about other experiments

- Conclusion

Atmospheric Neutrino Fluxes

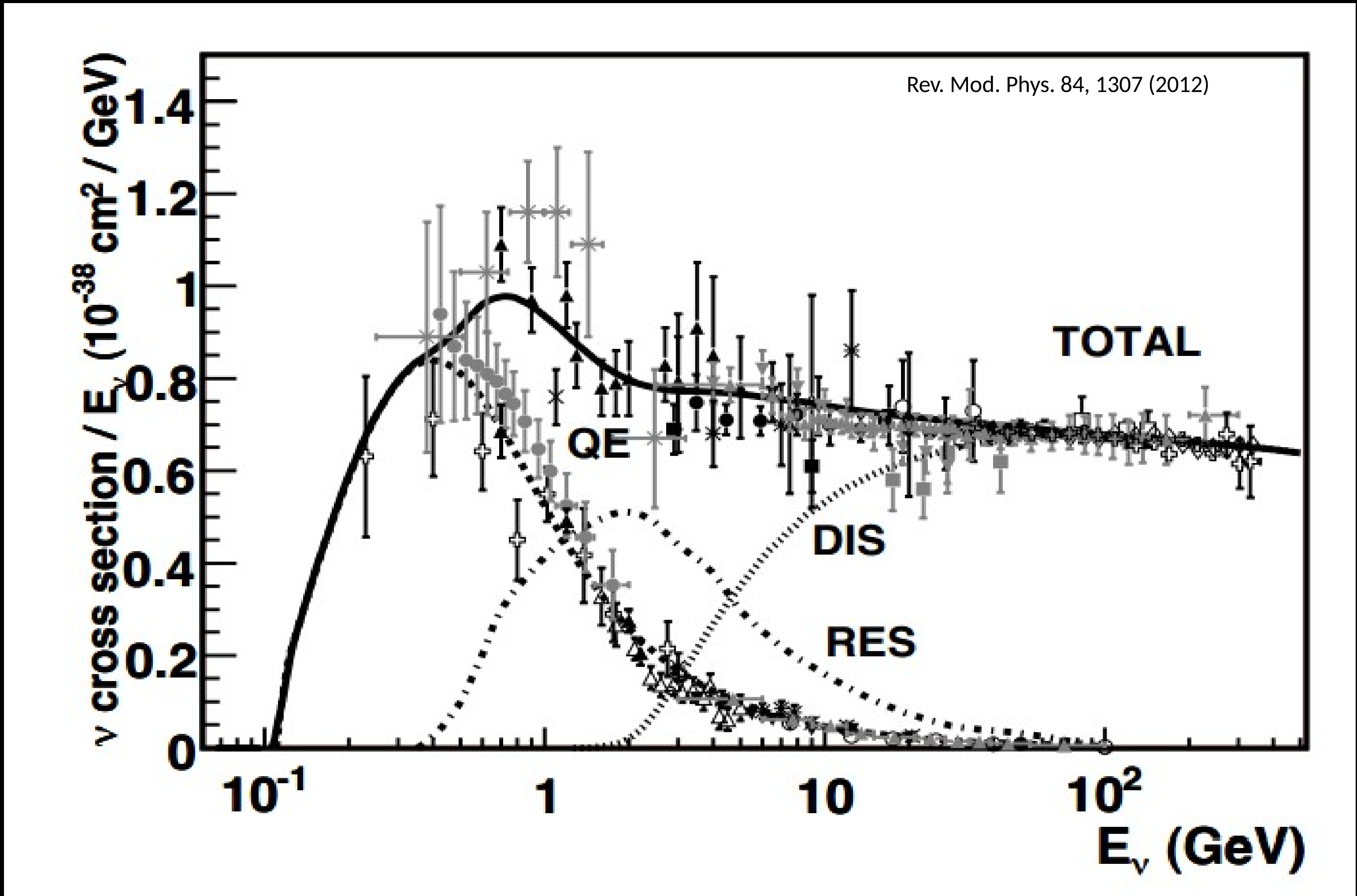
M. Honda, et. Al Phys.Rev.D75:043006,2007



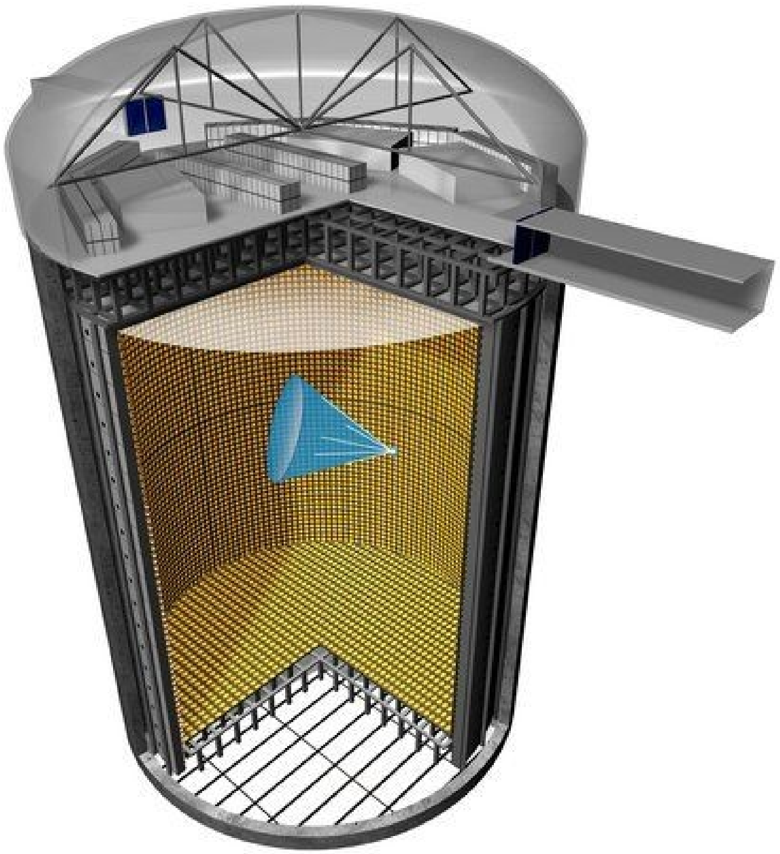
$$p + A \rightarrow N + \pi + \; + x$$

$$\Rightarrow \mu^{+} + \nu_{\mu} \;\; \rightarrow \;\; e^{+} + \nu_{e} + \nu_{\mu}$$

Neutrino Interactions Relevant for Atmospheric Neutrinos



Super-Kamiokande: Introduction

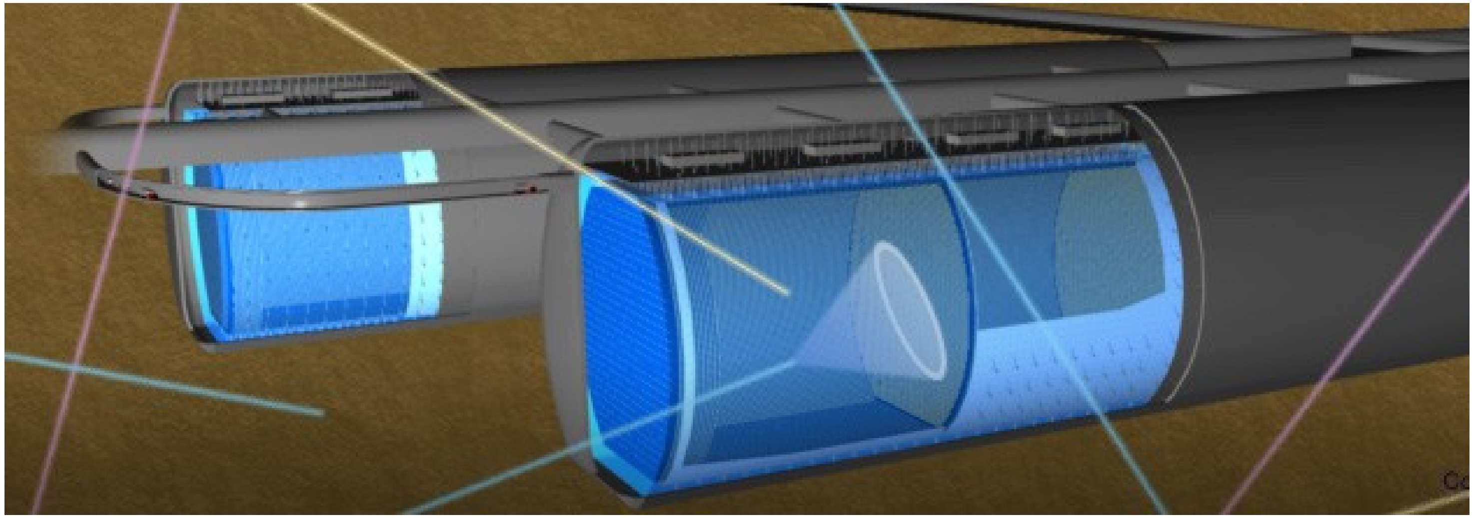


- 22.5 kton fiducial volume
- Optically separated into
  - Inner Detector 11,146 20” PMTs
  - Outer Detector 1885 8” PMTs
- No net electric or magnetic fields
- Excellent PID between showering (e-like) and non-showering (m-like)
  - < 1% MIS ID at 1 GeV

Atm ν	Super-K
σ_{mom} e / μ	5.6% /3.6%
σ_{dir} e / μ	3.0° / 1.8°
ν CC Purity :	
FC e-like	94.2 %
FC μ-like	95.7 %
PC μ-like	98.7 %

- Today: 4581 days of atmospheric neutrino data
  - 40,000 Events
  - **Statistics limited**
- Use a total of ~60 independent error sources (157 errors among all SK periods) including
  - Flux, Cross Section, Detector Response

Hyper-Kamiokande: Introduction



- Present studies are performed assuming
  - 560 kton fiducial volume
  - Equivalent detector performance for SK
- No additional improvements relative to Super-K analyses
  - Ie, expected improvements in event reconstruction with upcoming reconstruction algoritms are <u>not</u> included
- Similarly no extrapolation of flux and cross section systematics

Atm ν	Hyper-K
σ_{mom} e / μ	5.6% /3.6%
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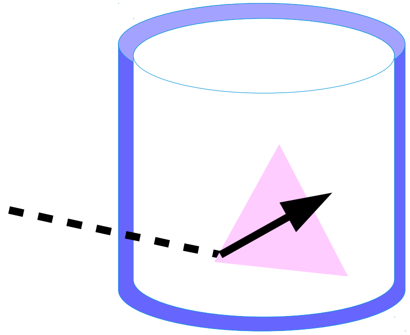
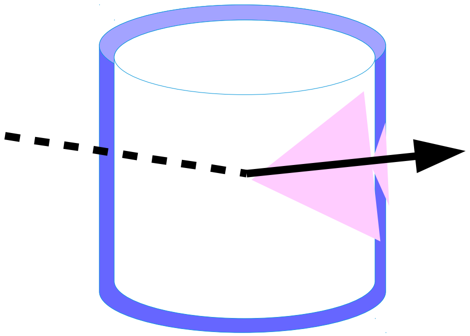
Super-K Atmospheric ν Analysis Samples

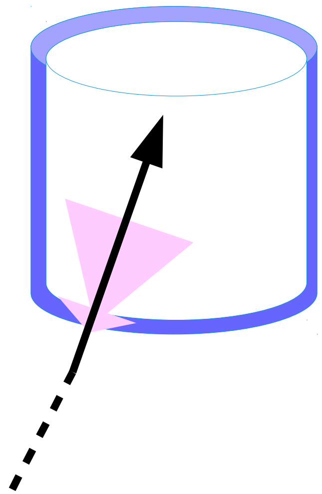
Fully Contained (FC)

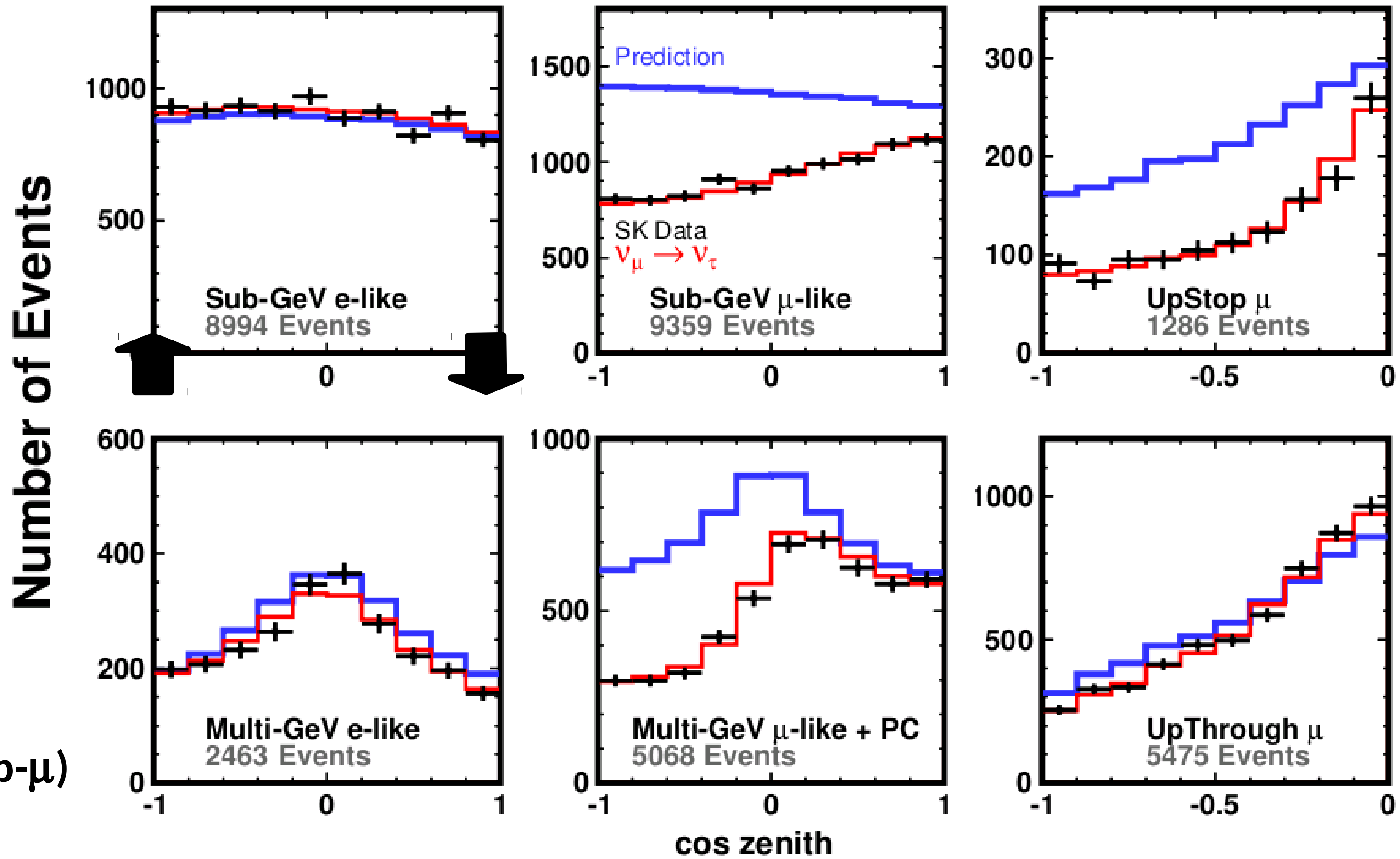


Partially Contained (PC)



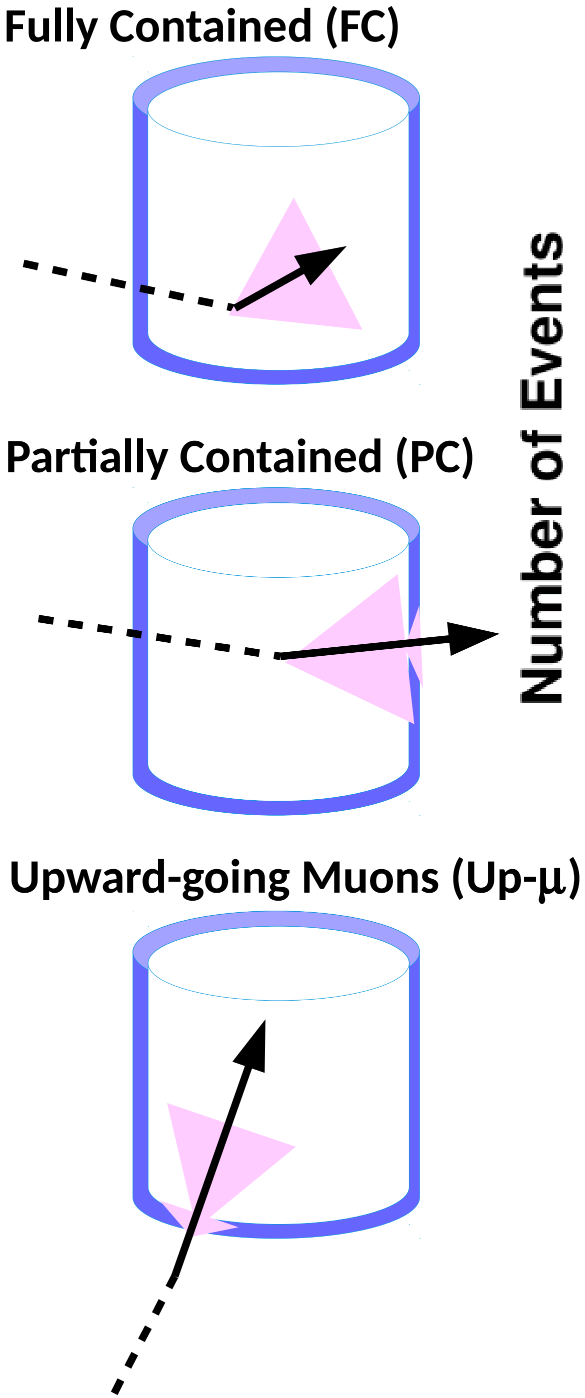
Upward-going Muons (Up-μ)

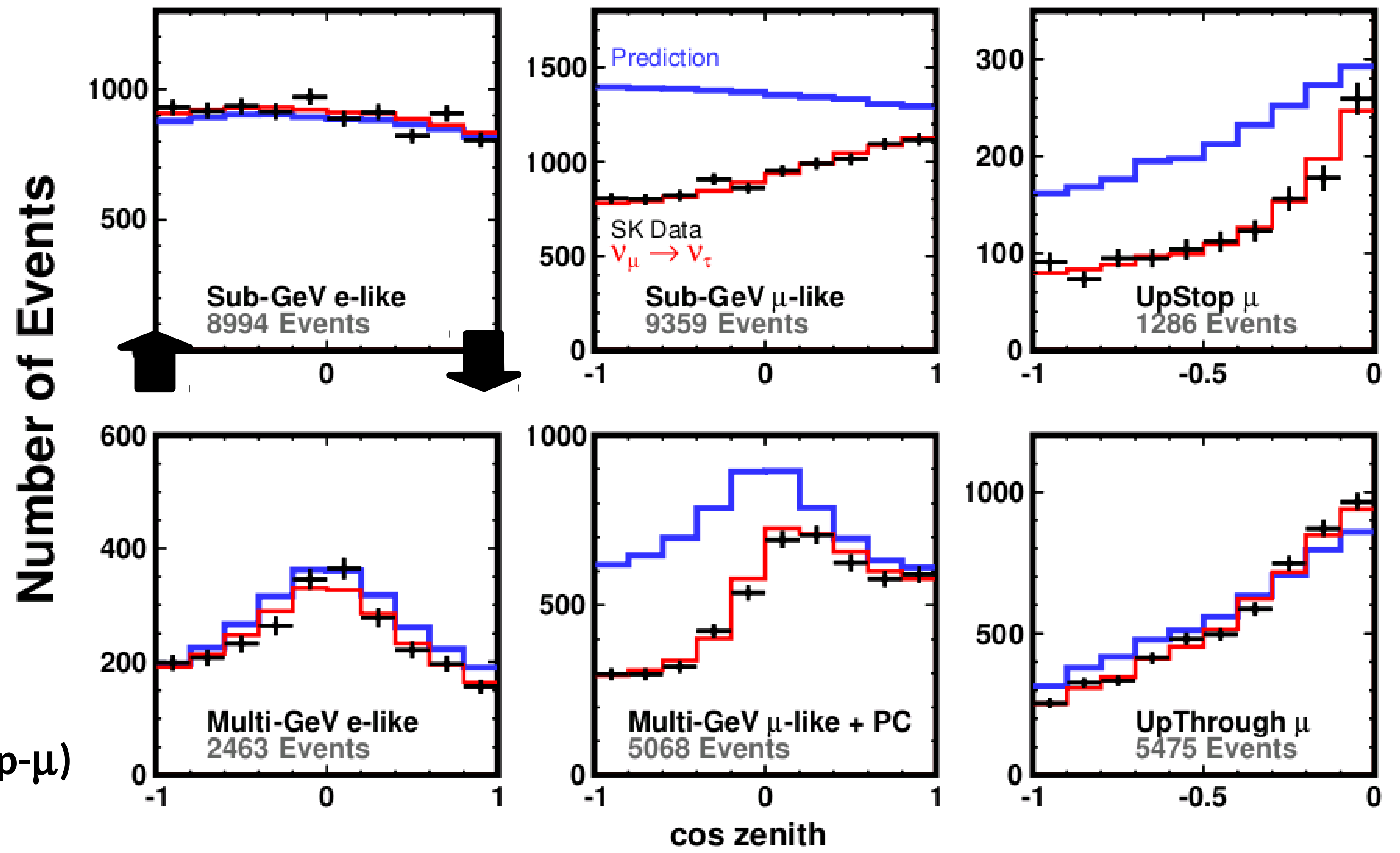




- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and $\bar{\nu}$-like subsamples
- Dominated by ν_μ->ν_τ oscillations
  - We thus expect (and find) ντ interaction to appear somewhere in the data at energies above the τ threshold

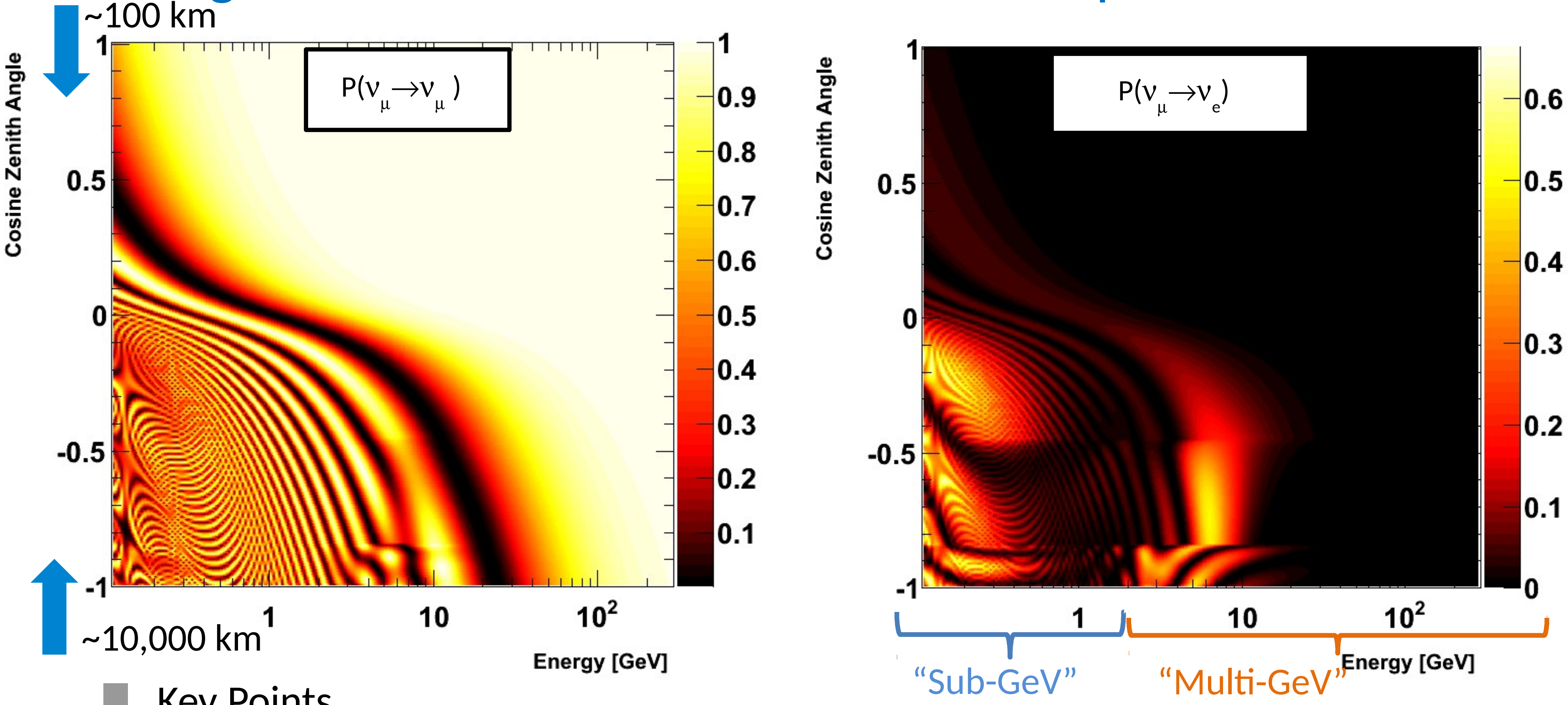
Super-K Atmospheric ν Analysis Samples





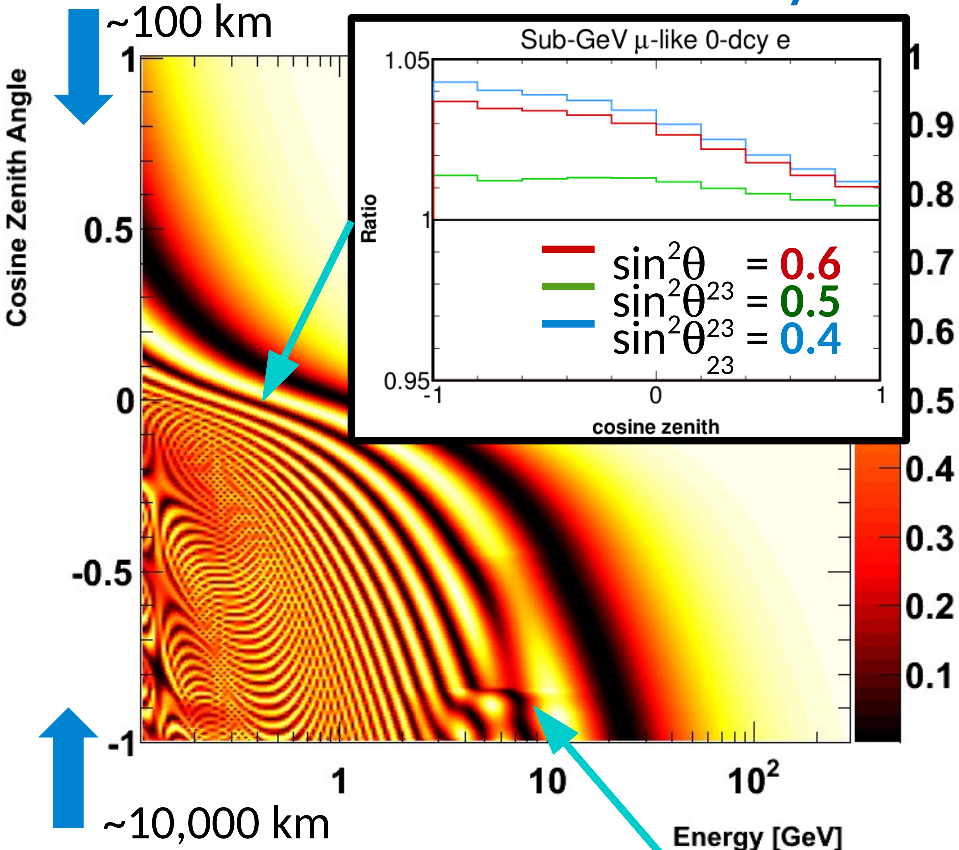
- Generally the data themselves off several ways of constraining uncertainties:
  - 4-π detector, constrain Up/Down (0.1~2%) Horizontal/Vertical ratio (0.3~3%) systematics
  - Several “Sidebands” : NC π^0, DIS-enhanced samples

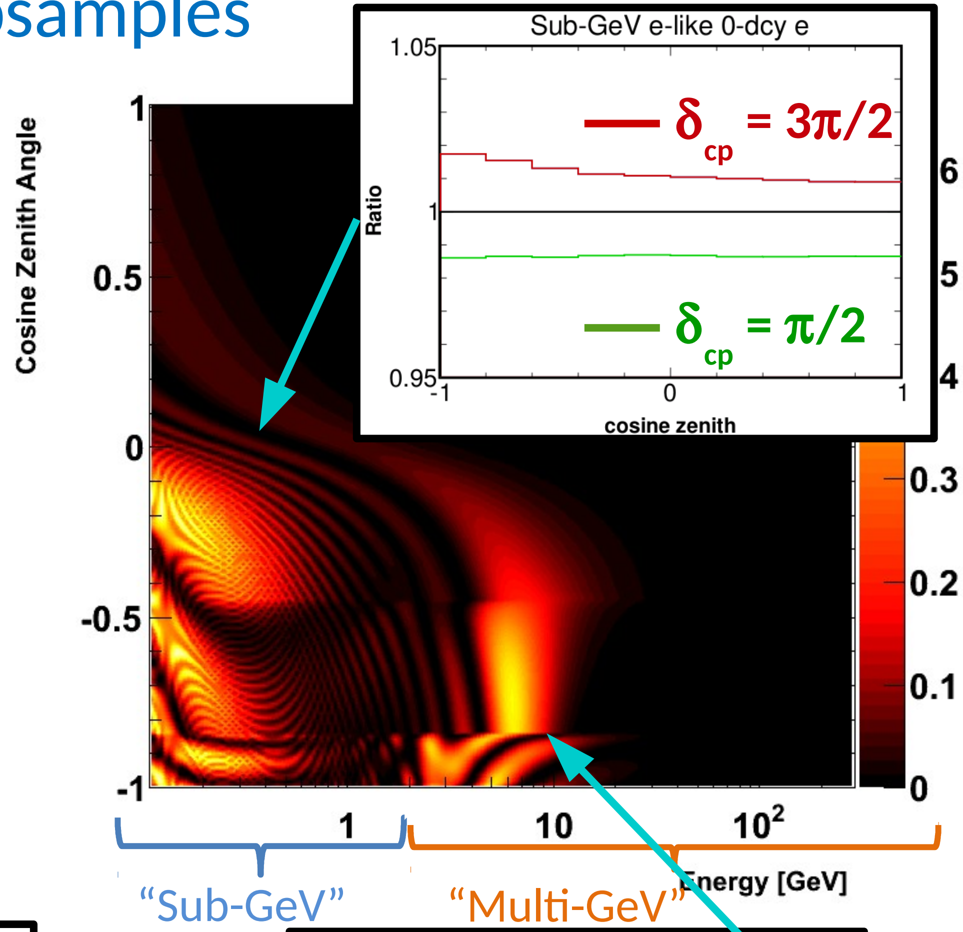
Searching for Three-Flavor Effects: Oscillation probabilities



- Key Points
  - No $\nu_\mu \rightarrow \nu_e$ Appearance above ~20 GeV,
  - Resonant oscillations between 2-10 GeV (for ν or $\bar{\nu}$ depending upon MH)
  - No oscillations above 200 GeV
  - No oscillations from downward-going neutrinos above ~5 GeV
  - Expect effects in most analysis samples, largest in upward-going ν_e

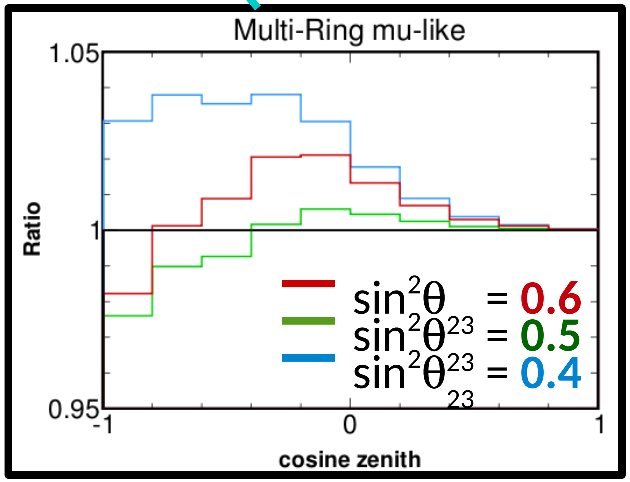
Oscillation Effects on Analysis Subsamples

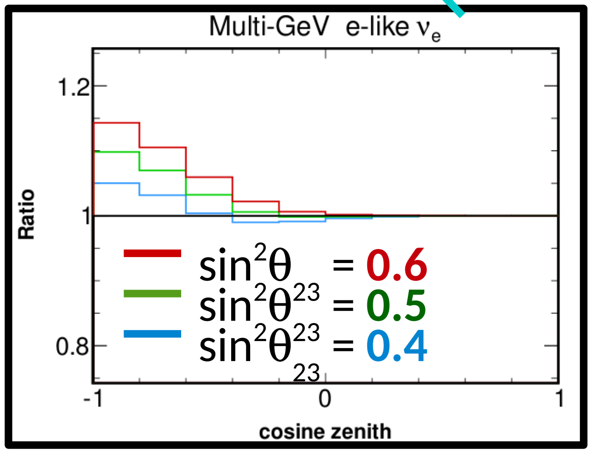




Ratio to two-flavor oscillations

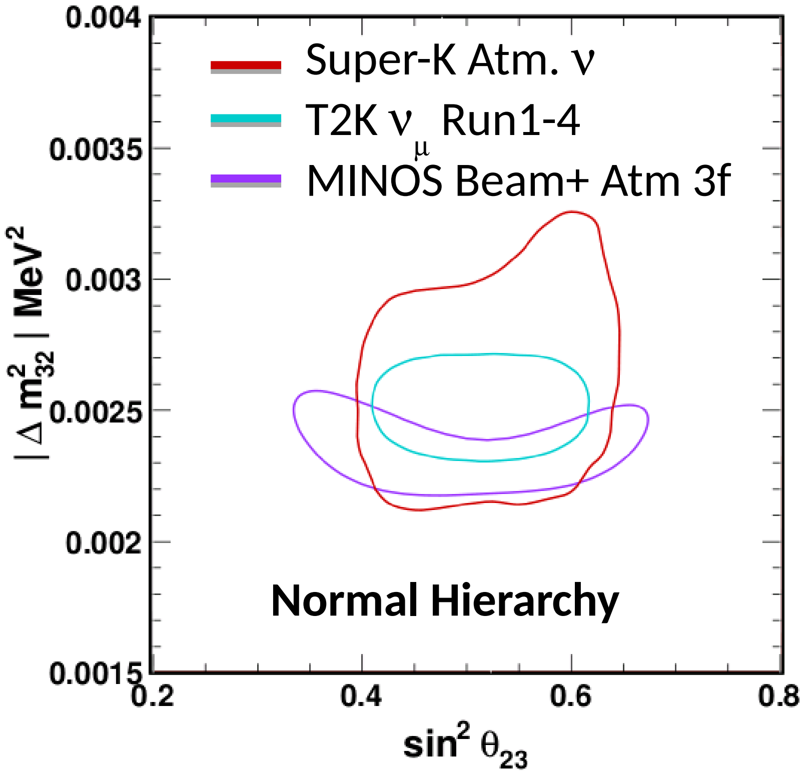
Appearance effects are halved in the IH

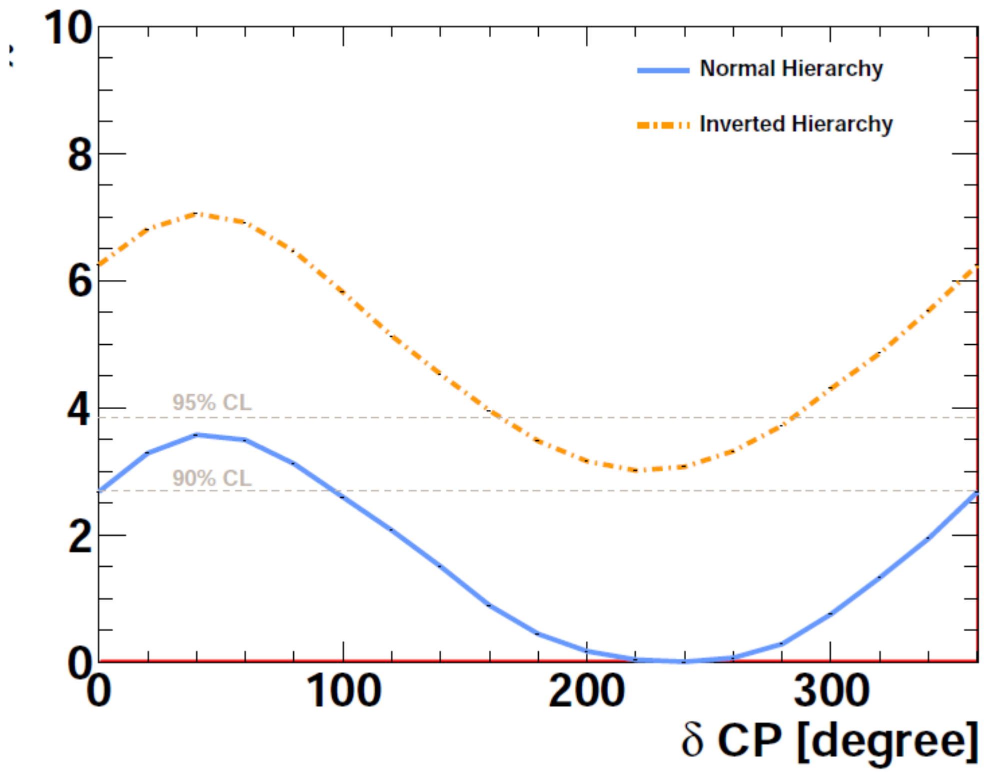




Super-Kamiokande Atmospheric ν Analysis Results

Preliminary

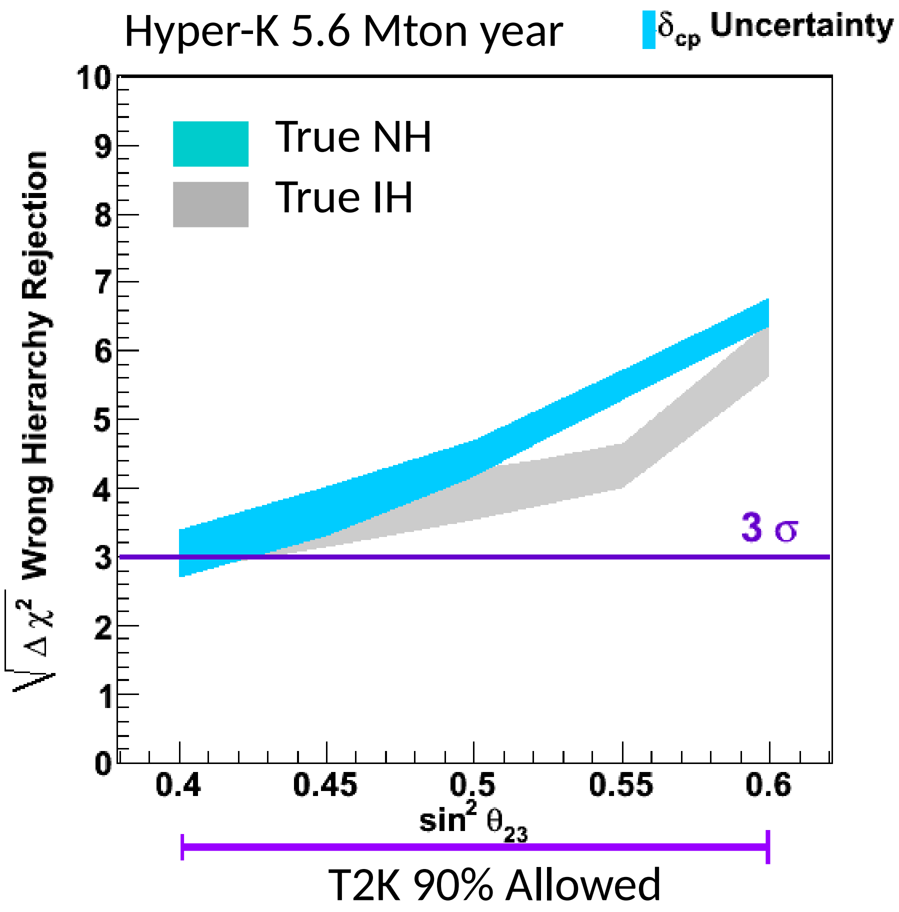


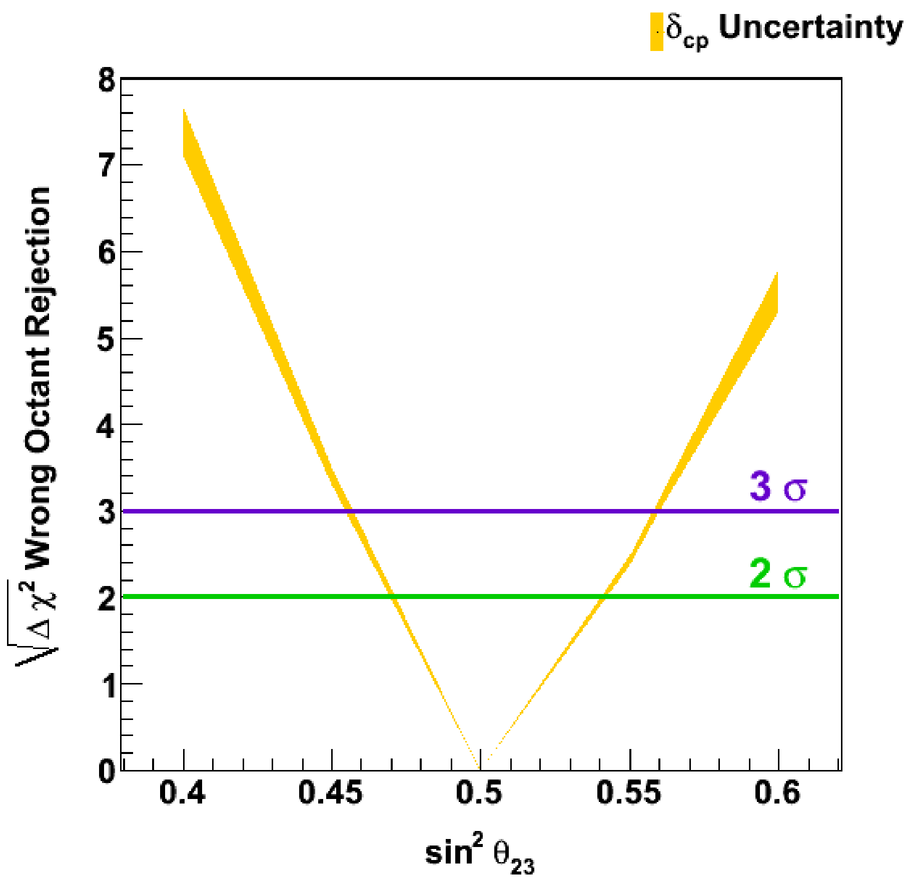


Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} $(\mathrm{x}10^{-3})$
SK (NH)	582.4	0.0238	4.19	0.575	2.6
SK (IH)	585.4	0.0238	3.84	0.575	2.3

- **Normal** hierarchy favored at: $\boxed{\chi^2_{NH} - \chi^2_{IH} = \mathbf{-3.0}}$, not significant

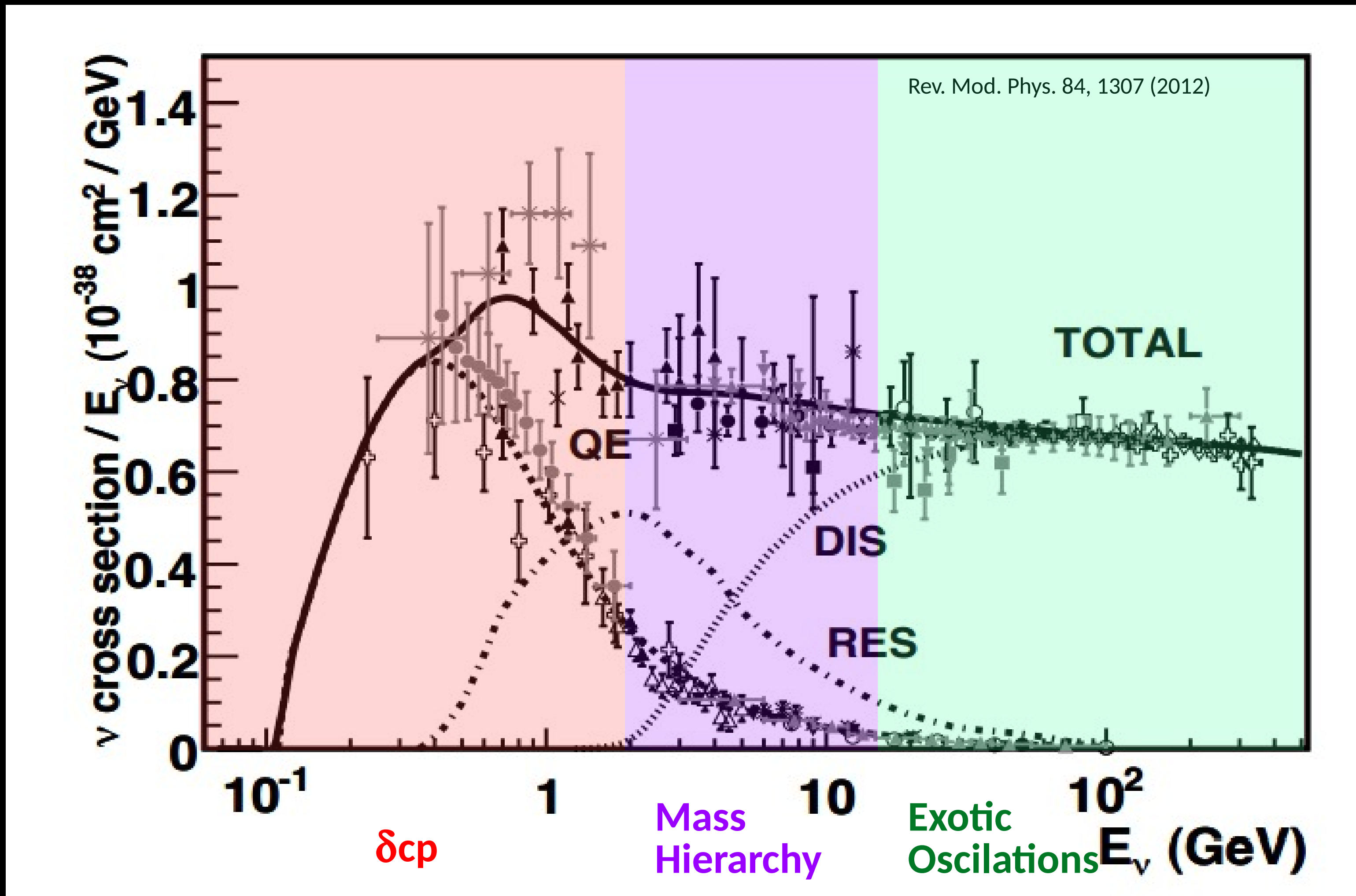
Hyper-Kamiokande Atmospheric ν Sensitivity



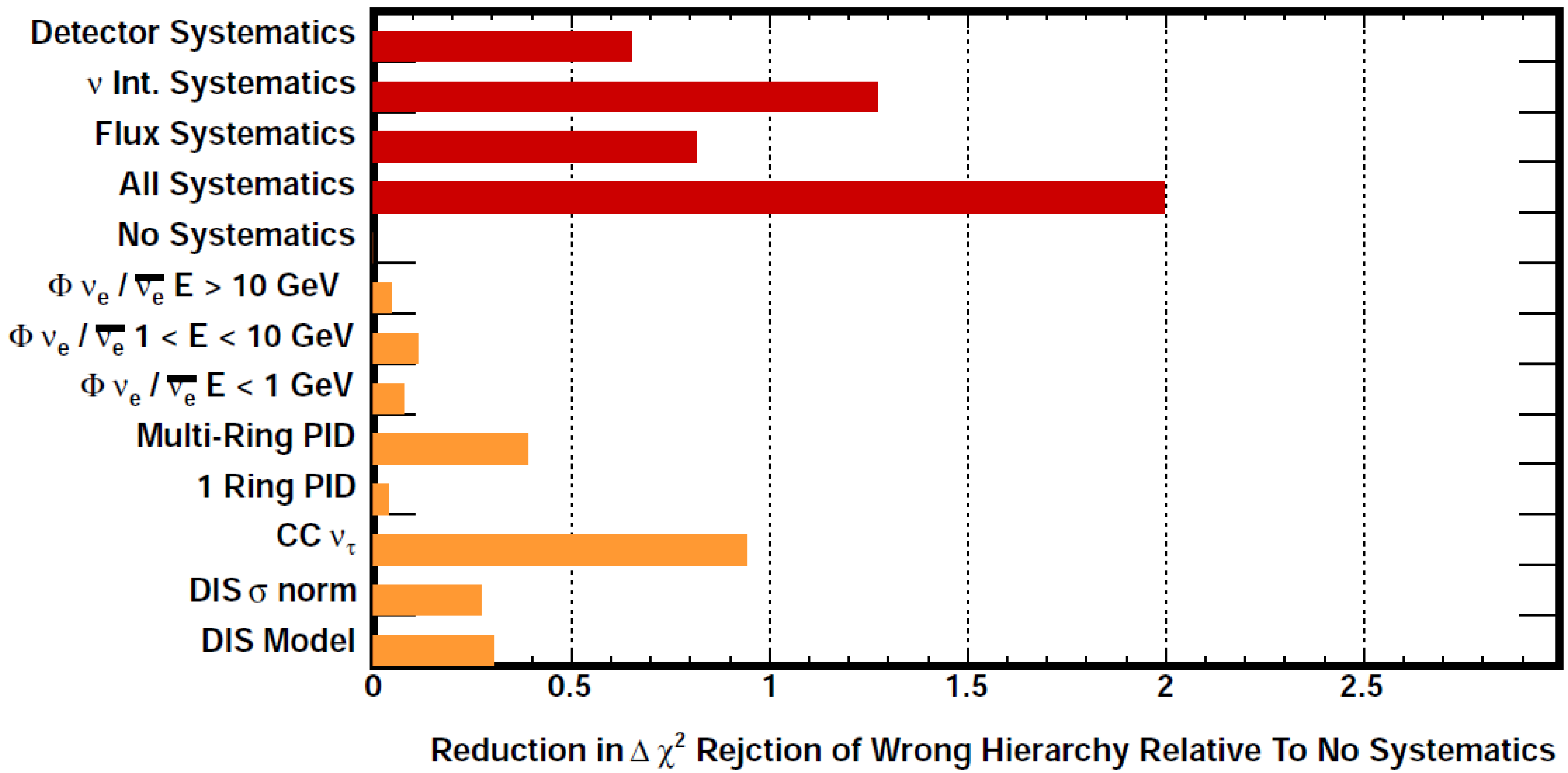


- Expect better than ~3σ sensitivity to the mass hierarchy using atmospheric neutrinos alone
- 3σ Octant determination possible if $\sin^2 2\theta_{23} < 0.99$
- Oscillation parameter uncertainties are significant

Neutrino Interactions Relevant for Atmospheric Neutrinos



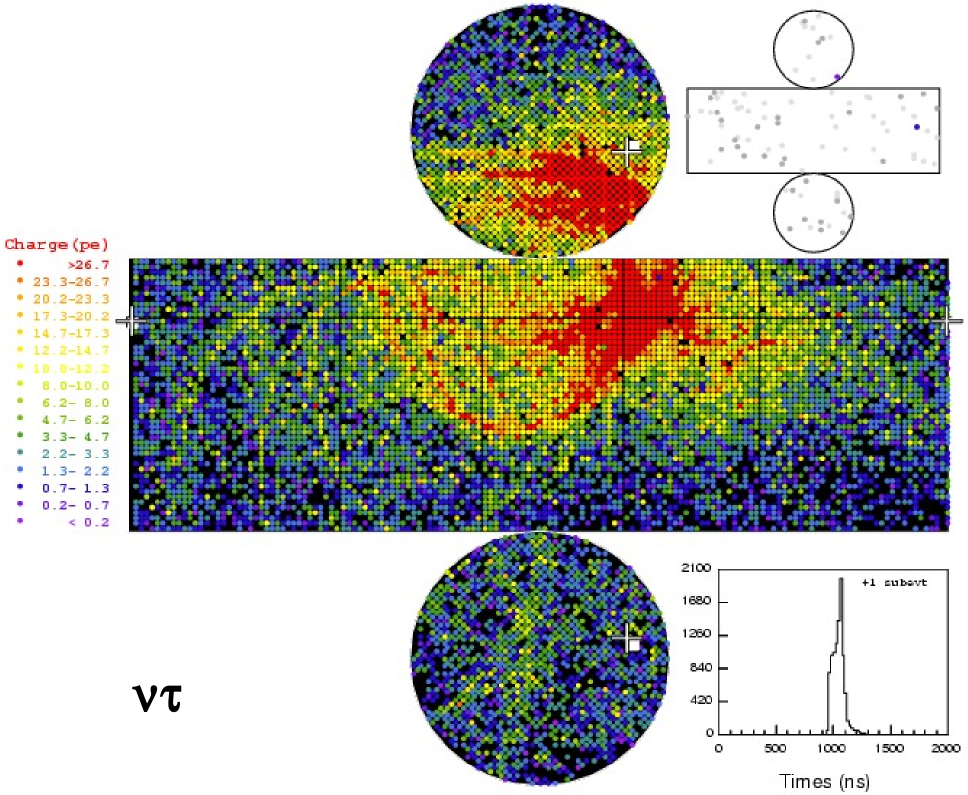
Systematic Effect on Hierarchy Sensitivity at Super-K

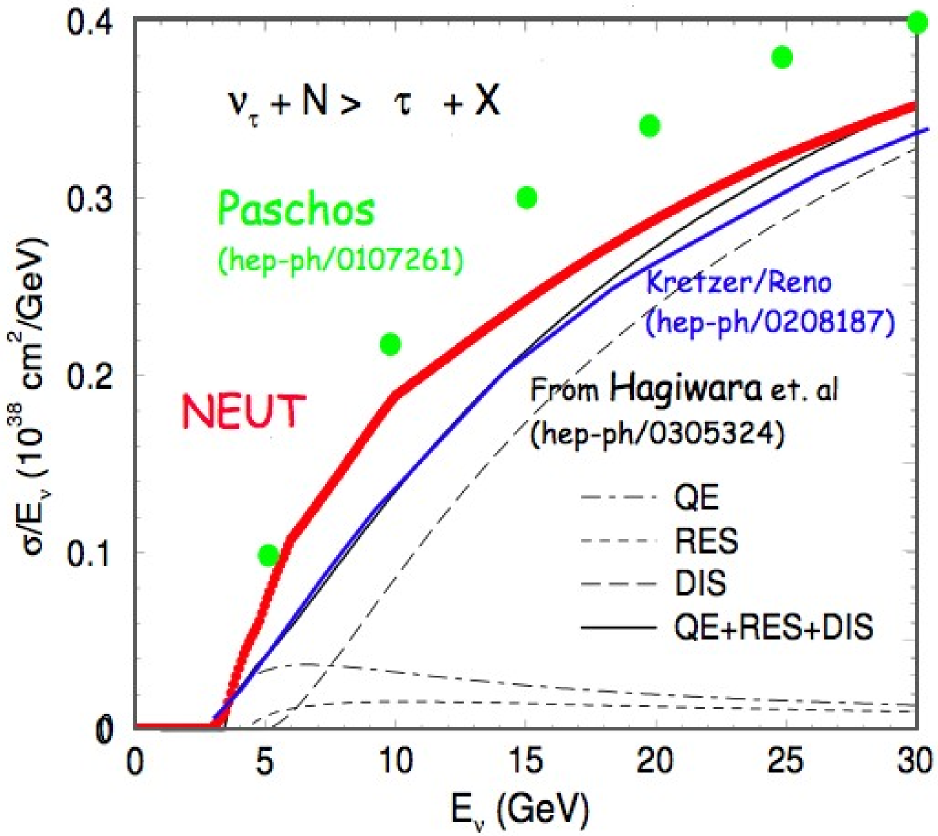


- Sensitivity to the hierarchy is largely affected by uncertainties interaction of high energy neutrinos
  - particularly the CC $\nu\tau$ background component
- The situation is compounded at Hyper-K

$\Delta\chi 2$, $\theta 23$	0.40	0.60
No Syst.	0.81	4.7
Full Syst.	0.59	2.7

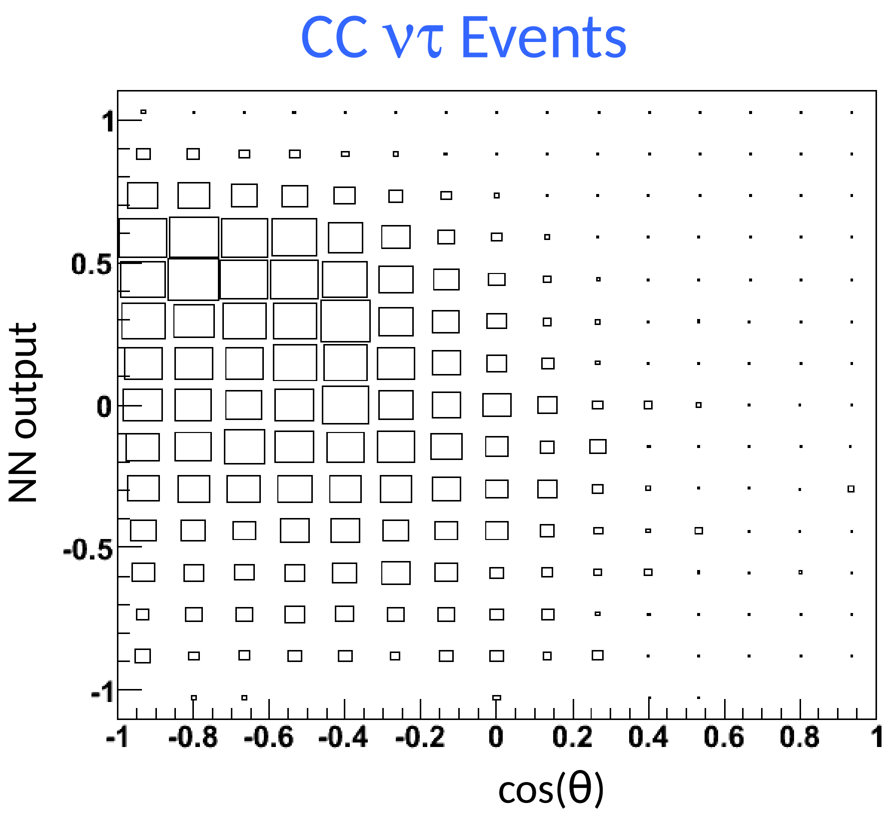
Tau Background For Mass Hierarchy Error

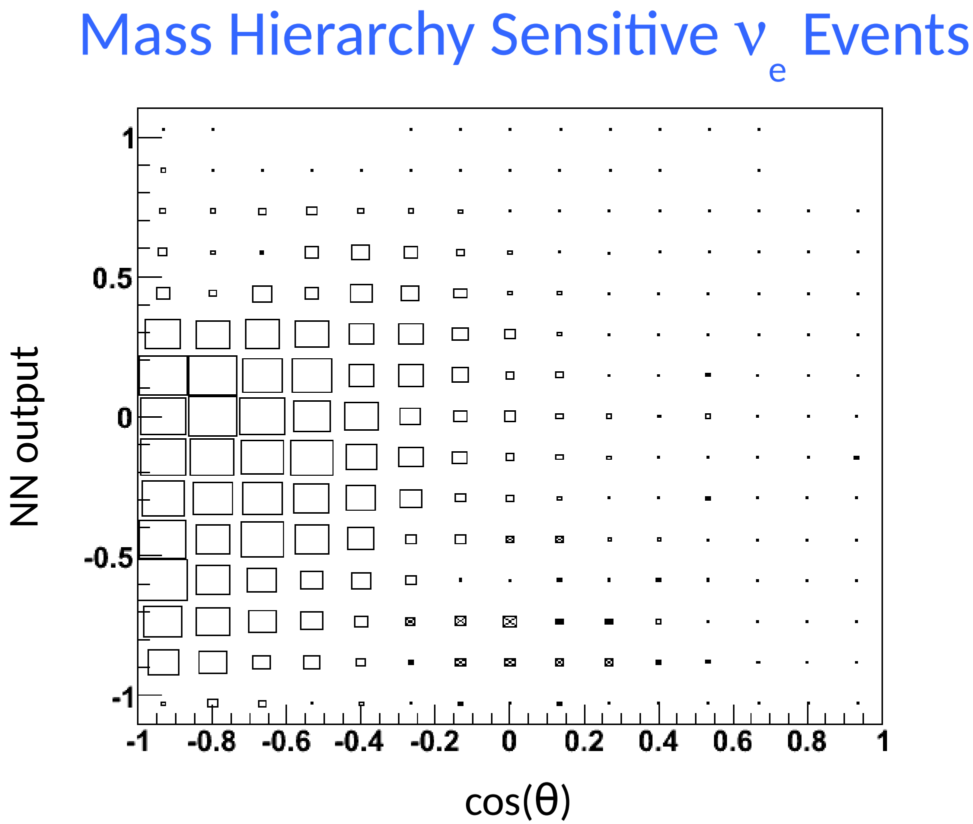




- Many events in the MH energy region are DIS
  - Means many rings
- Hadronic tau decays will produce many visible particles
  - decay is prompt and granularity of the detector is not enough to resolve the tau
  - Many overlapping rings tend to look like electron neutrinos
- Currently the cross section is assigned an uncertainty of 25%, based on model comparisons

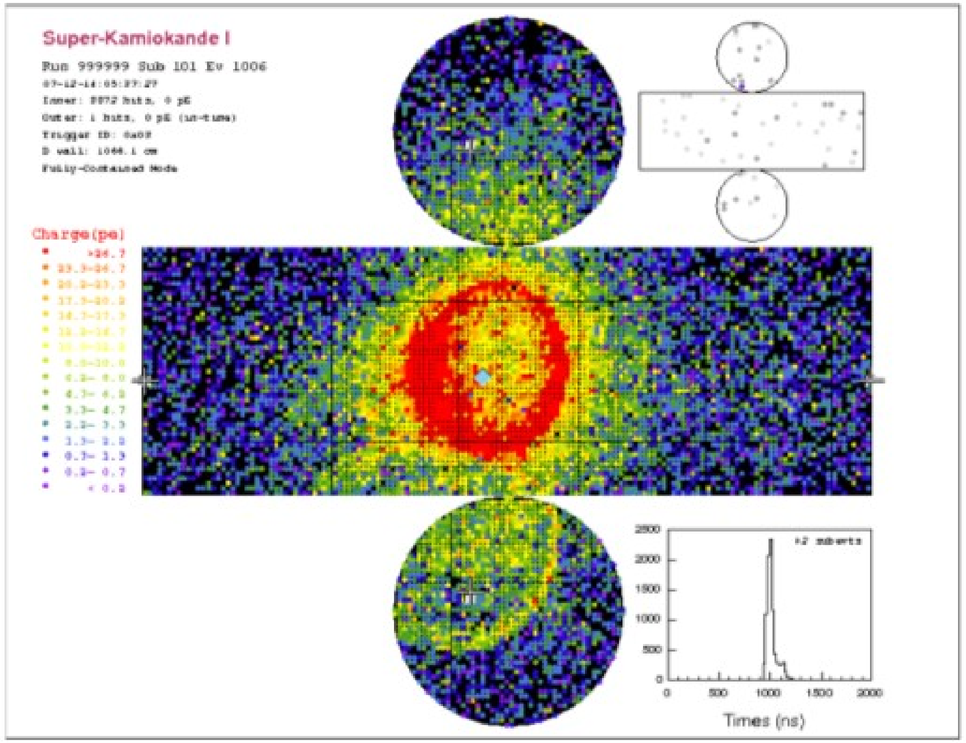
Tau Cross Section Error Mitigation

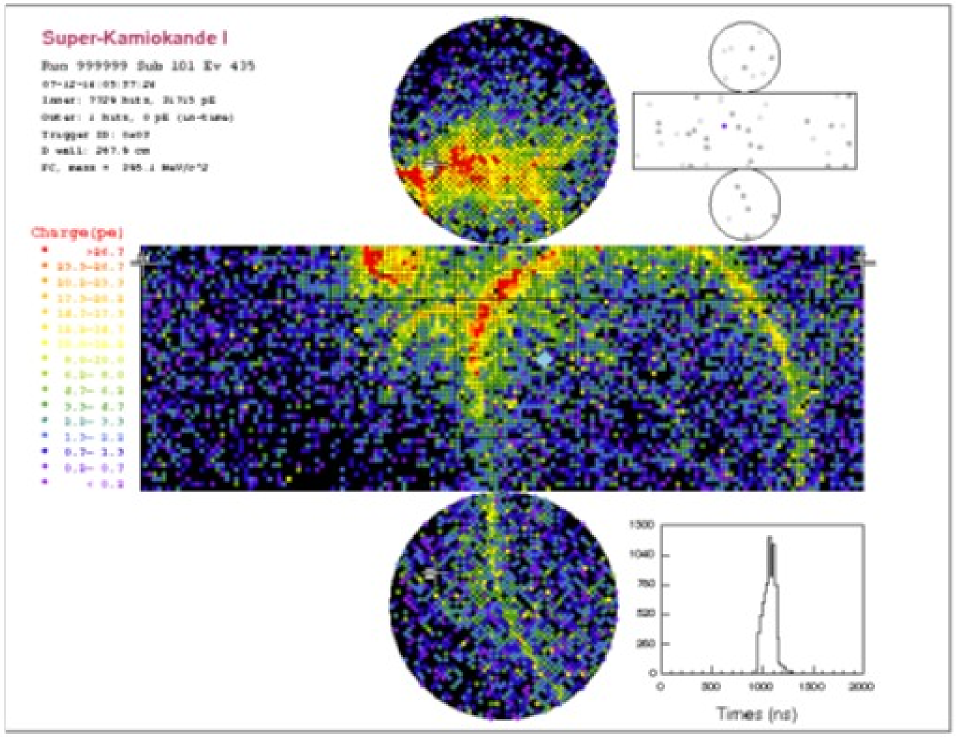




- Currently this error is constrained only somewhat using sidebands in the SK analysis
- However, in a separate analysis CC $\nu\tau$ interactions have been identified in the SK data at 3.8σ
  - Method is based on a neural network which works to identify hadronic τ decays
- This information can be incorporated into the oscillation analysis to further mitigate the effected of these events (work in progress)

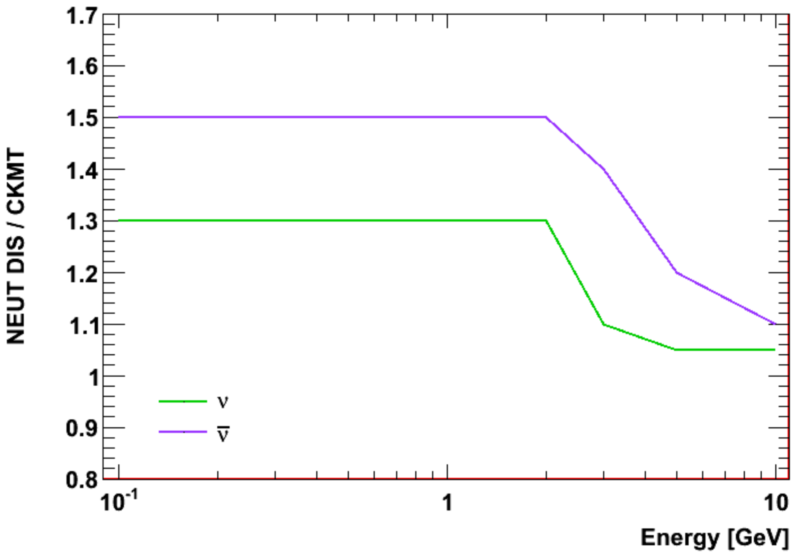
Particle Identification for Multiple Ring Topologies

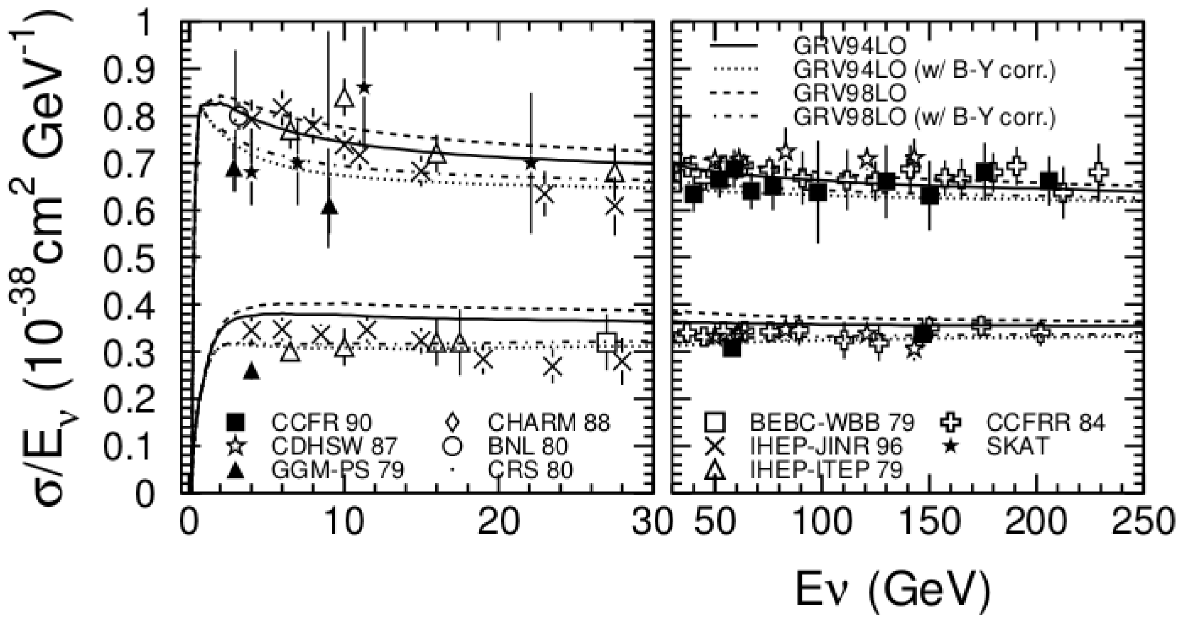




- Just the same as ντ events DIS events with multiple rings often look like electrons
  - Both of these events were classified as electrons and fall in the hierarchy signal sample
  - The one on the left is DIS νμ event
- Ring PID uncertainty is estimated to be between 3 and 6% depending upon the sample
- This systematic can be mitigated by making improvements to the reconstruction
  - Addition of hit timing to original PID algorithm underway (short term)
  - New maximum likelihood-based reconstruction (fiTQun) with both q,t, unhit probability, and many other features nearly ready (mid term, base reconstruction for Hyper-K)

Deep Inelastic Scattering

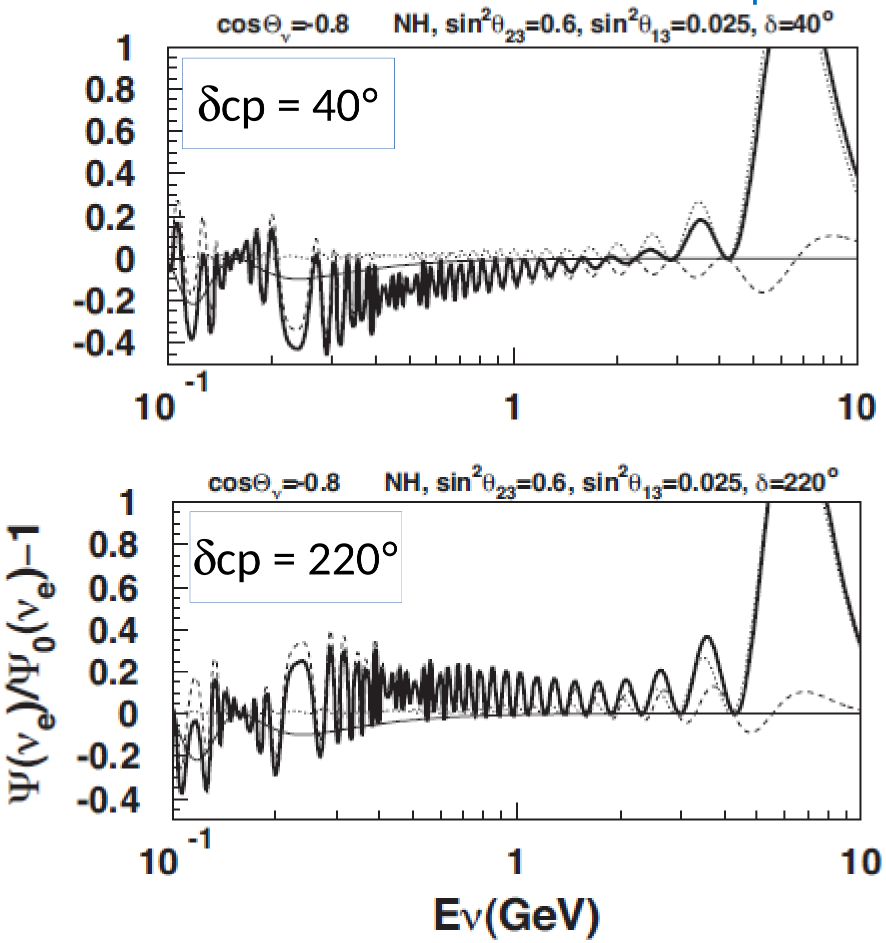


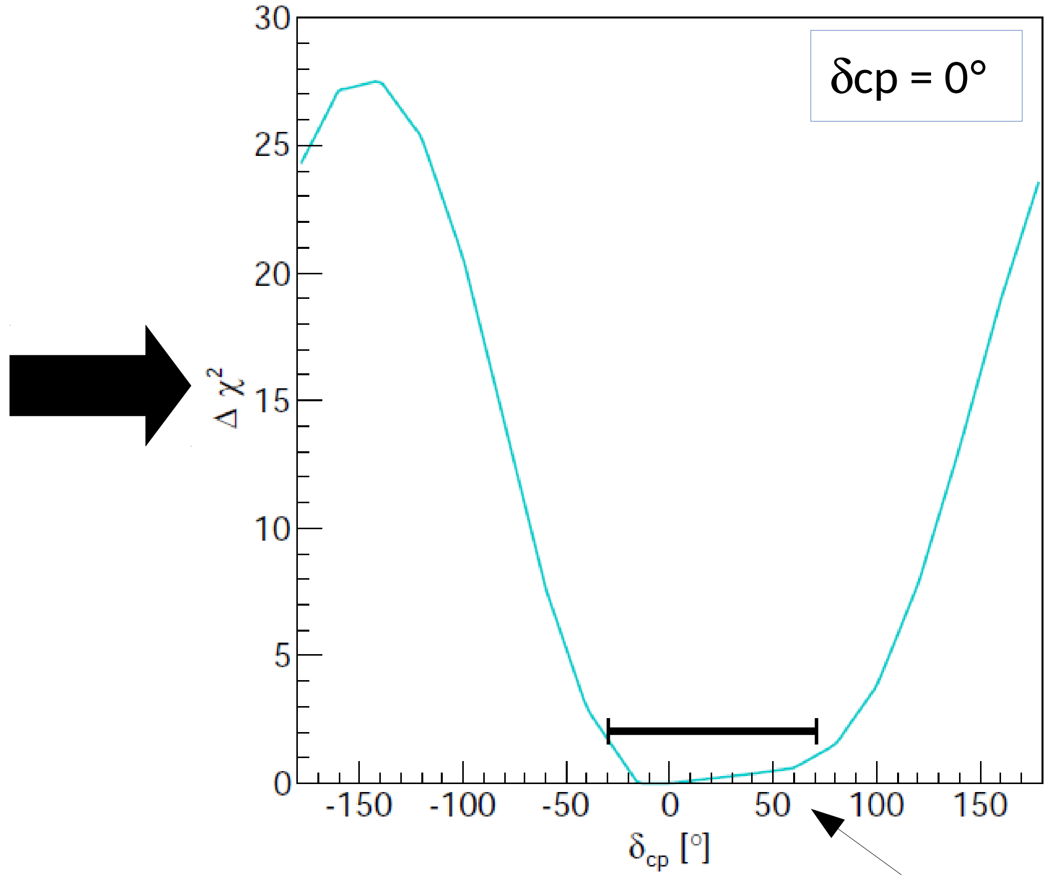


- DIS Cross section systematics are taken from comparison of the default NEUT model with the “CKMT” parameterization below 10 GeV
  - Difference between these two model ranges from 10~50%

- In addition an overall 5% normalization uncertainty is assumed at all energies

Hyper-K's Sensitivity to δ_{cp} Atmospheric neutrinos (5.6 Mton yr)

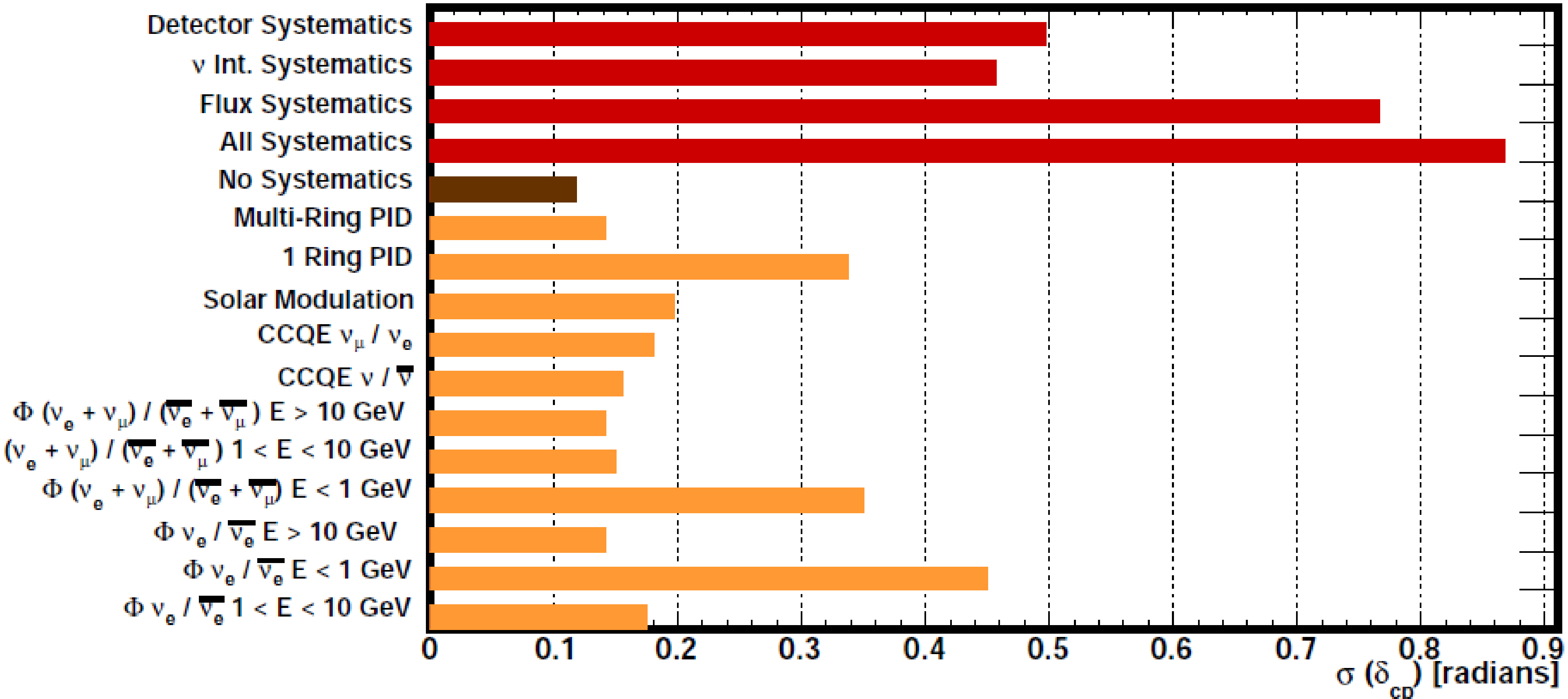




1 σ error on dcp
reported next page

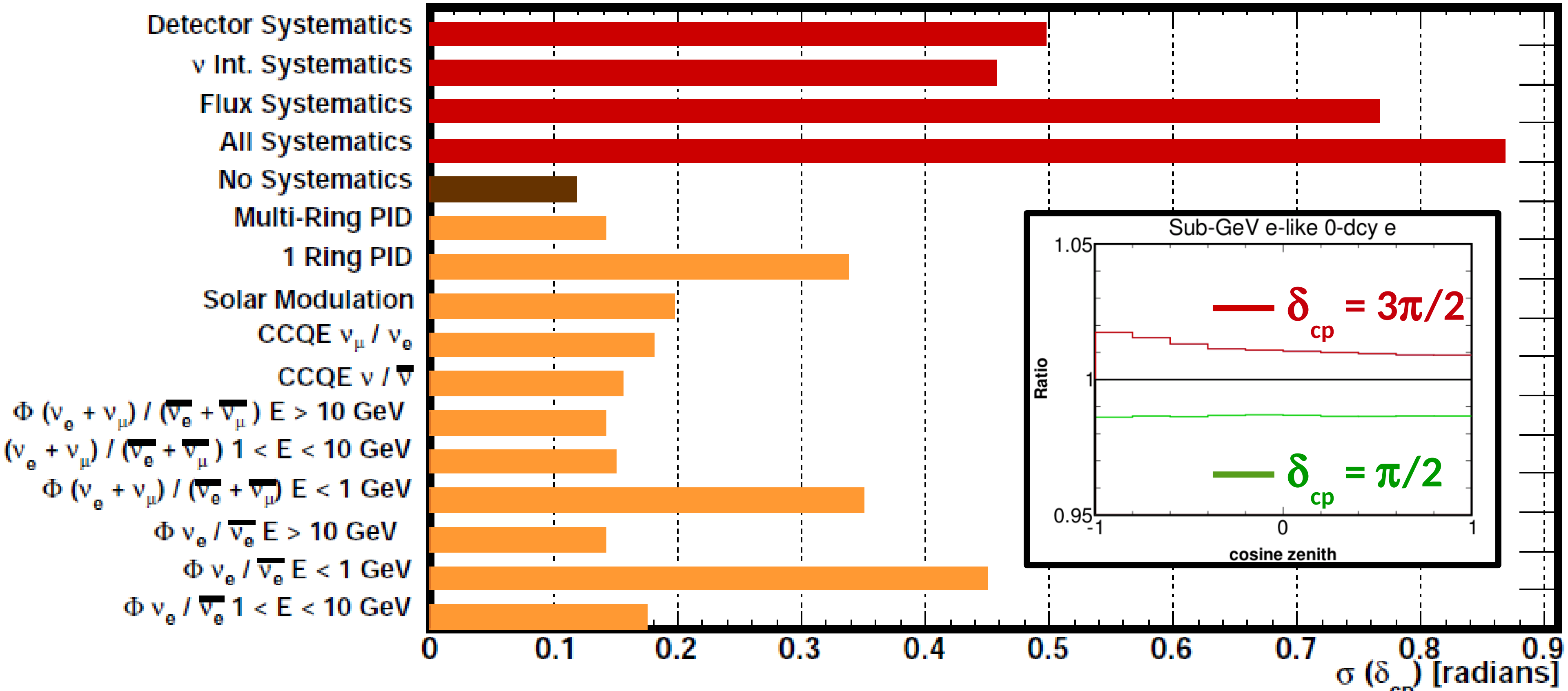
- Sensitivity to δcp is mostly through νe ↔νμ oscillations below 1 GeV
  - Though mostly QE interactions, lack of pointing and systematic errors hamper measurements
  - Improved separation between neutrino and antineutrino components desired

Hyper-K's Sensitivity to δ_{cp} with Atmospheric neutrinos



- Generally sensitivity is affected by systematics directly connected to the low energy neutrino flux
  - To a lesser extent the low energy interaction model:
    - CCQE $\nu/\bar{\nu}$: 5~15% below 500 MeV, CCQE νμ /νe : 2~10% below 500 MeV
- Note that the detector performance also becomes important
  - Single ring mis-PID uncertainty is 1~2% below 1330 MeV

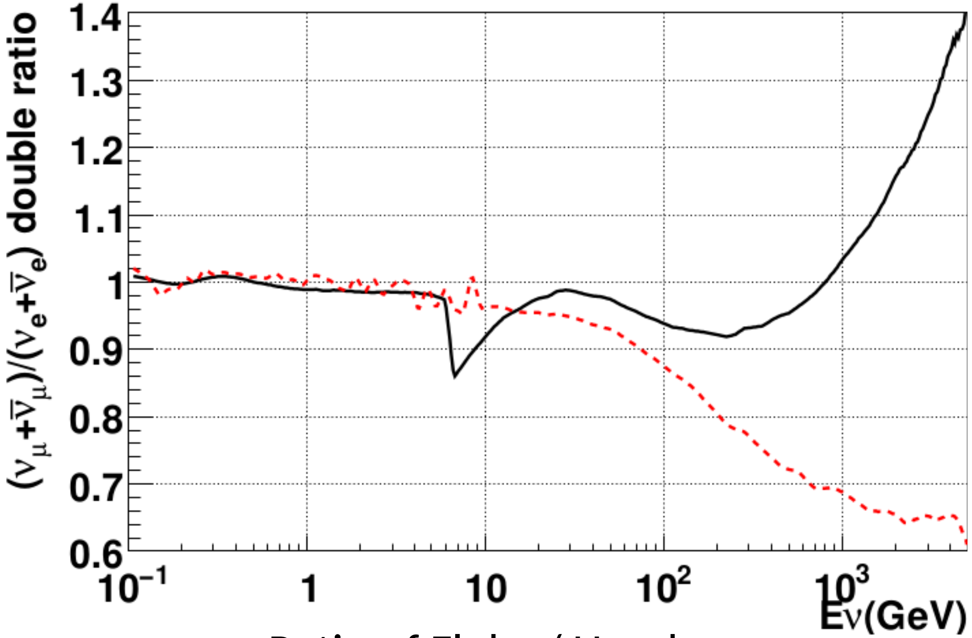
Hyper-K's Sensitivity to δ_{cp} with Atmospheric neutrinos



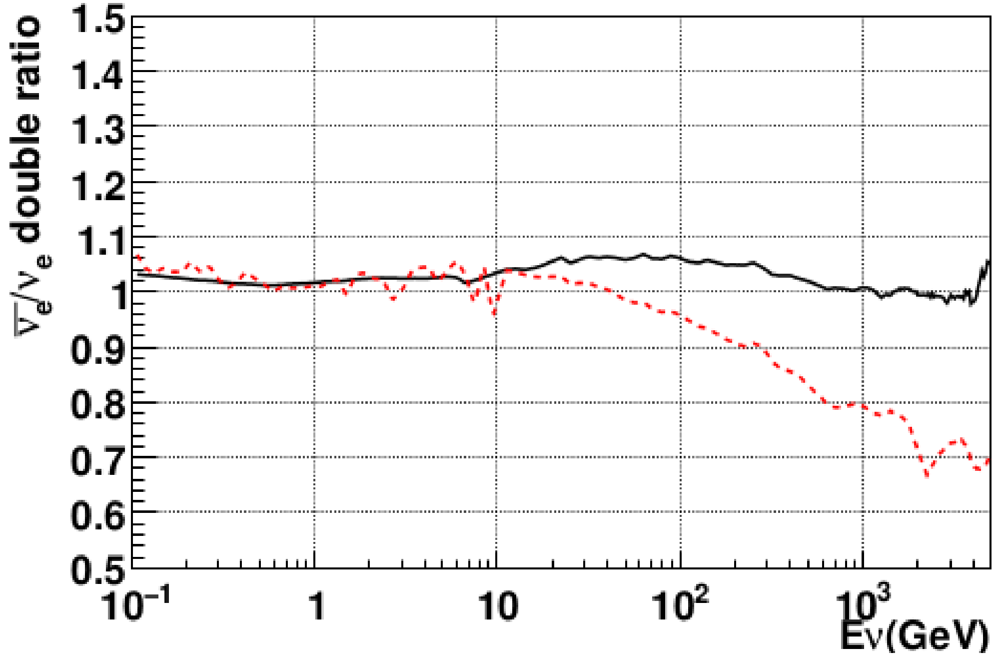
- Generally sensitivity is affected by systematics directly connected to the low energy neutrino flux
  - To a lesser extent the low energy interaction model:
    - CCQE $\nu/\bar{\nu}$: 5~15% below 500 MeV, CCQE $\nu\mu$ /νe : 2~10% below 500 MeV
    - Improved measurements will help
- Note that the detector performance also becomes important
  - Single ring mis-PID uncertainty is 1~2% below 1330 MeV

Atmospheric Neutrino Flux Uncertainties (Honda 2011)

Flavor Ratio Comparison



Electron to Antielectron Neurino Ratio

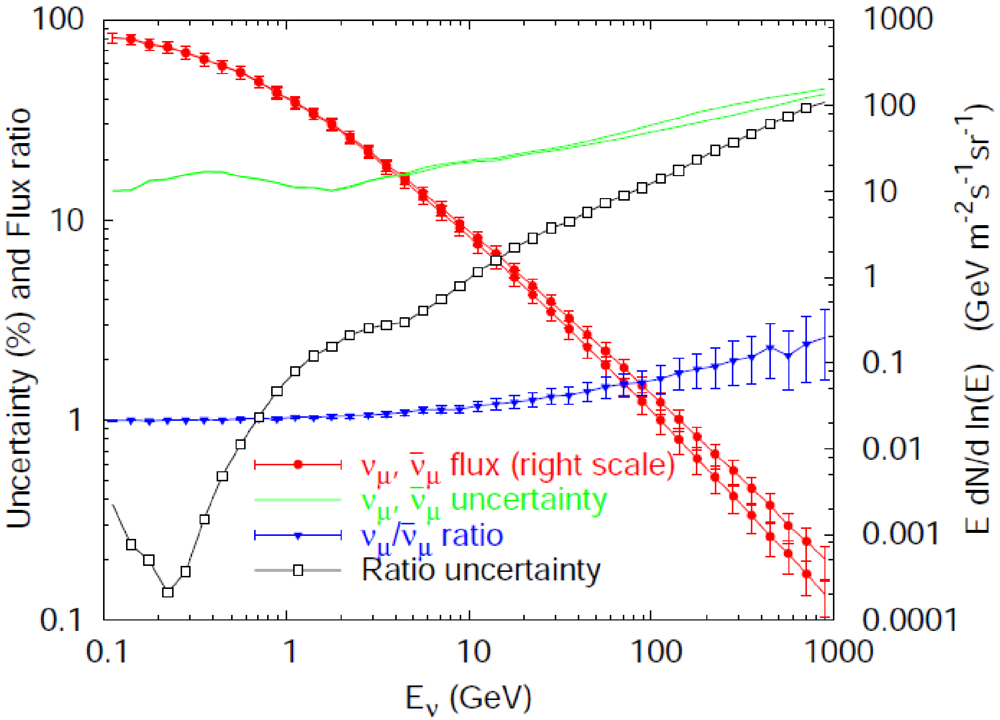


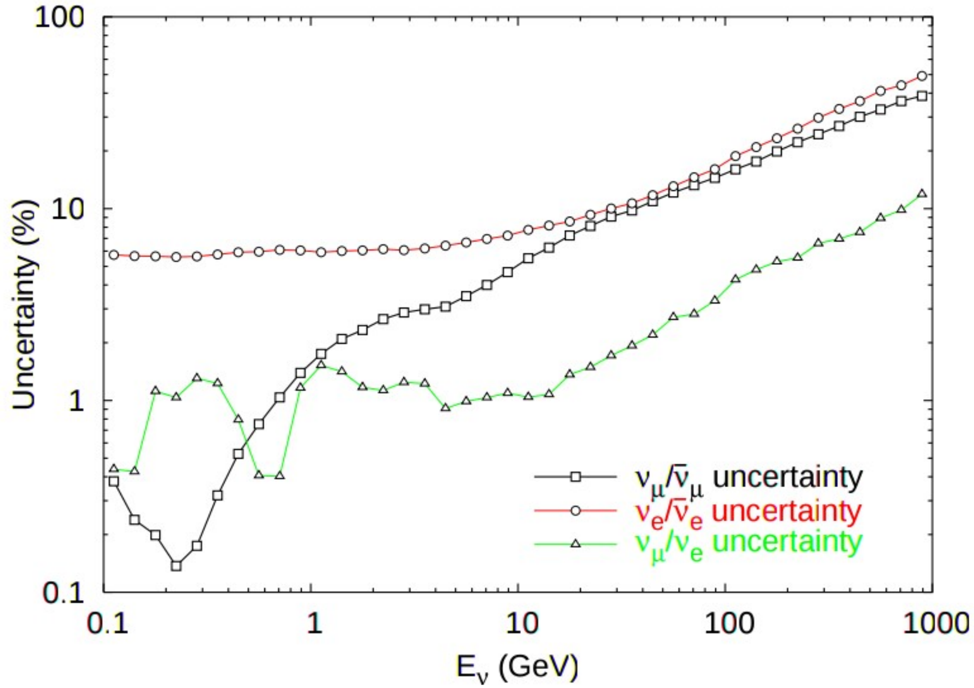
Ratio of Fluka / Honda

Ratio of Bartol / Honda

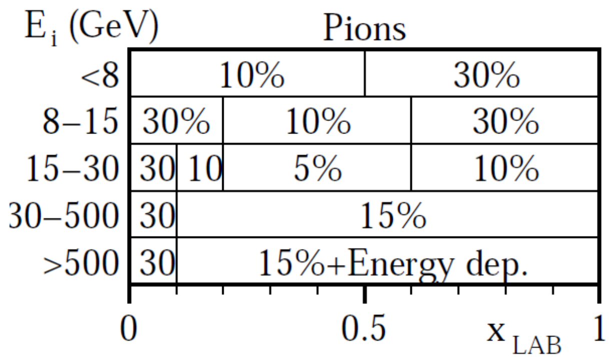
- Systematic Errors on the Neutrino flux at Super-K (Hyper-K) are based on both direct estimates from the authors of the Honda 2011 Flux and by comparisons with other models
  - Flavor Ratio uncertainty is 2% below 1 GeV
  - Electron ratio uncertainty is 5% below 10 GeV
- Changes in solar activity affect the low energy neutrino flux, but the exact magnitude depends on the real experimental run
  - Here 10% uncertainty is assumed on a run with 35% (65%) 'high' ('low') activity

Other Systematic Error Estimates





- Systematic errors for the Bartol flux have been estimated using variations in the hadron production model
  - Electron ratio uncertainty between 5% and 7% below 5 GeV
  - Differing approaches with basically consistent results



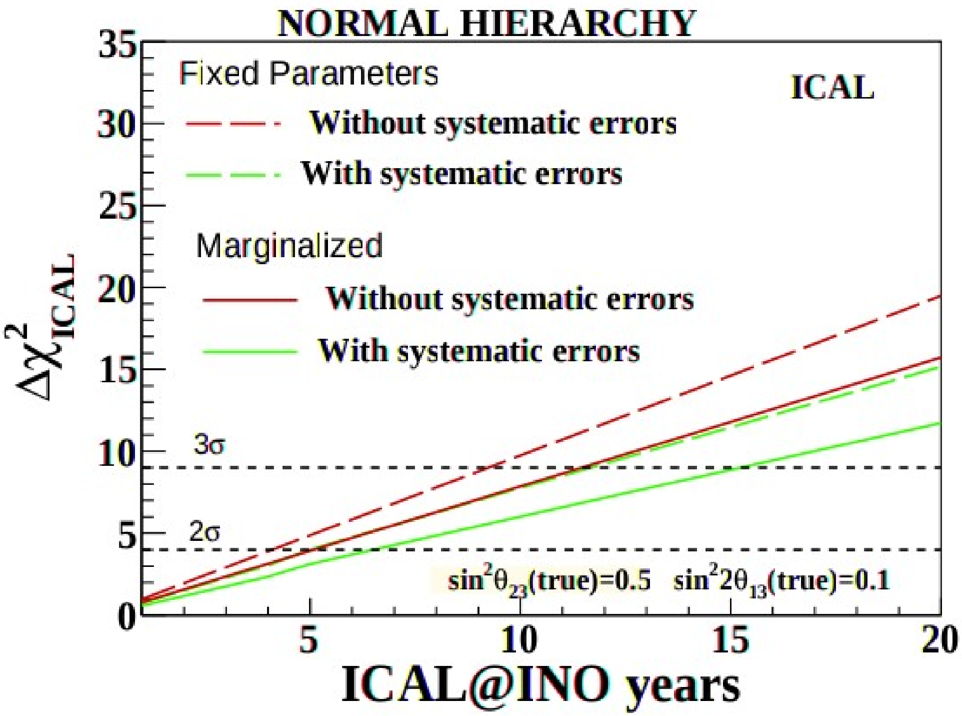
- Atmospheric neutrino flux models at low can be improved by
  - Better hadron production measurements at low momenta
    - Most 500 MeV ν are produced by cosmic ray protons with between 3 and 30 GeV
  - Better muon measurements at momenta around 500 MeV

Some Brief Comments

- Many of the above statements are not specific to water Cherenkov detectors, but with appropriate switch from electron to muon neutrino-specific errors.
  - Notable exceptions include $\nu\tau$ cross section

- MINOS(+), collected(s) atmospheric neutrino data, but due to its smaller size (5.4kton) and lower efficiency for tagging electron neutrinos, its limited heavily by statistics
  - The systematics with the largest impact on their oscillation analyses were absolute flux normalization errors (the least well known part of the flux)

- The ICAL experiment intends to make mass hierarchy measurements using atmospheric muon neutrinos, predominantly
  - So far using a simplified error model they find the biggest impact on sensitivity from the zenith spectrum shape (5%) of the flux and its energy dependence (5%)
  - full analysis is under development



Conclusion

- For the most part, atmospheric neutrino measurements are primarily limited by statistics

- However, the future (Hyper-K, DUNE, PINGU) is coming
  - while atmospheric neutrino measurements may not be competitive with long-baseline experiments in measuring θ23 and Δm223
  - They offer strong, complementary sensitivity to sub-leading oscillation effects

- Making the most of atmospheric neutrinos requires better handle over systematic errors, particularly those from the flux and interaction model

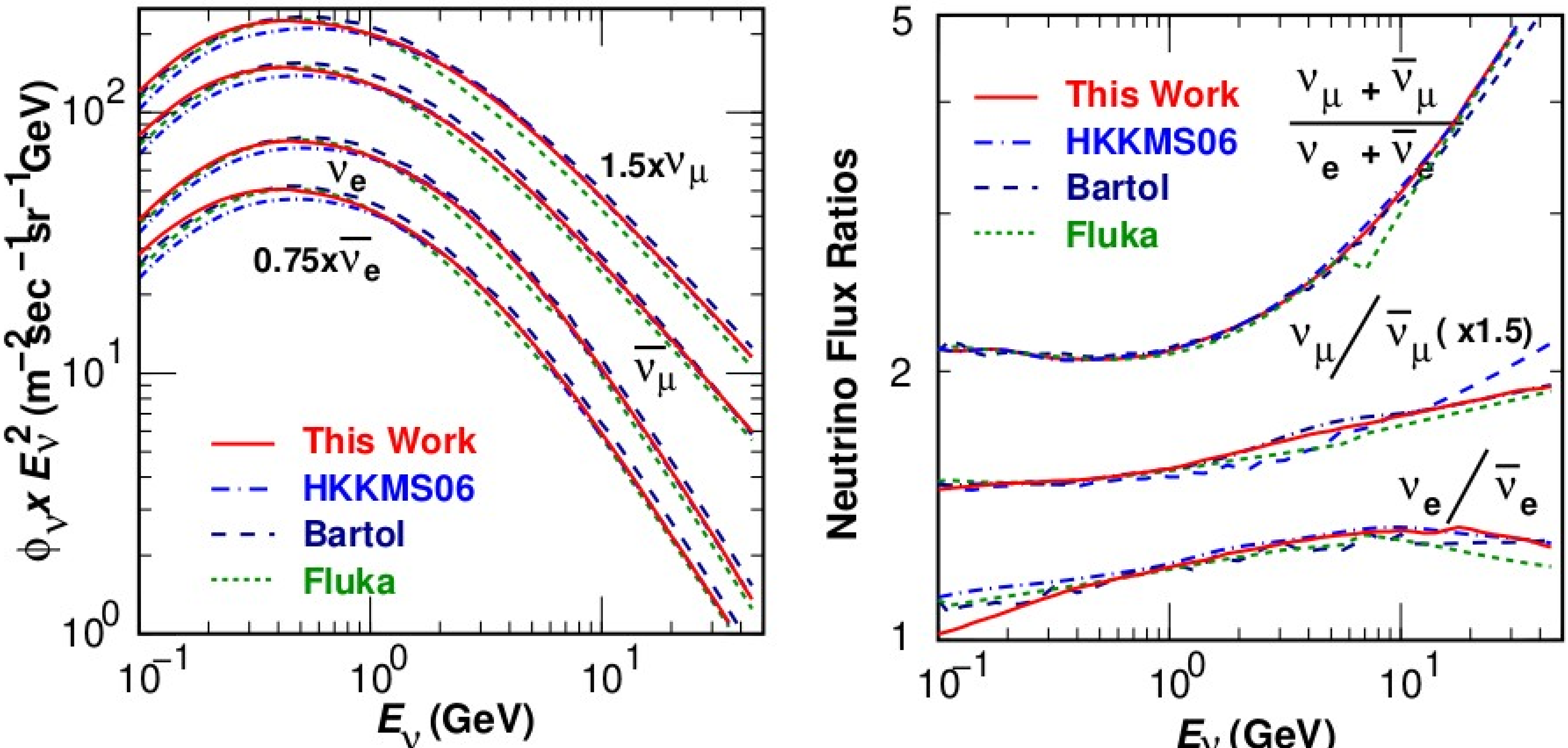
Supplements

Primary Systematics for Measurements with Atmospheric ν

- Measurements of δcp
  - Flux Systematics
    - Nue bar / nue ratio
    - Nubar /Nu ratio generall
  - Cross-Section and Reconstruction Errors have about the same impact
    - Single-Ring PID

- Neutrino Mass Hierarchy
  - Flux Uncertainties
    - Flux above 1 GeV
  - Cross Section Uncertainties
    - CC nu tau
    - DIS Cross section
  - Detector Uncertainties
    - PID for Multi Event topologies

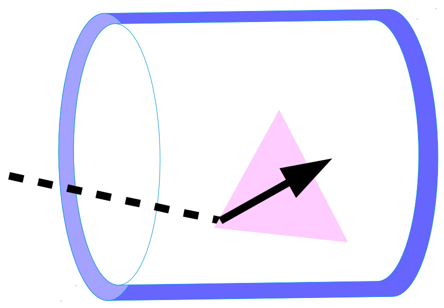
- Measurement of Δm^2



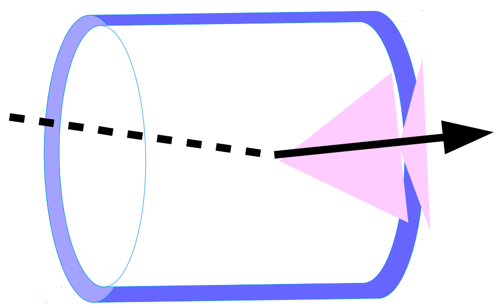
$\phi_\nu x\, E_\nu^2$ ($m^{-2}sec^{-1}sr^{-1}GeV$)
10^2
10^1
10^0
10^{-1}
10^0
10^1
E_ν (GeV)
$1.5x\nu_\mu$
ν_e
$\overline{\nu}_\mu$
$0.75x\overline{\nu}_e$
This Work
HKKMS06
Bartol
Fluka
Neutrino Flux Ratios
5
2
1
10^{-1}
10^0
10^1
E_ν (GeV)
This Work
HKKMS06
Bartol
Fluka
$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e}$
$\nu_\mu / \overline{\nu}_\mu$ (x1.5)
$\nu_e / \overline{\nu}_e$

Super-K Atmospheric ν Analysis Samples

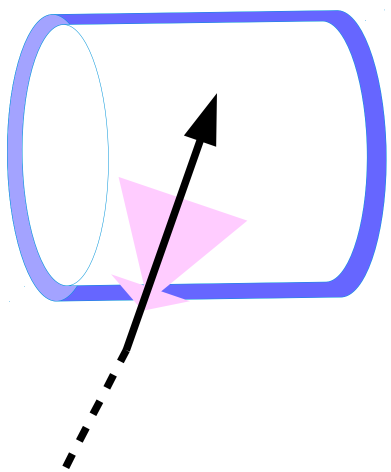
Fully Contained (FC)

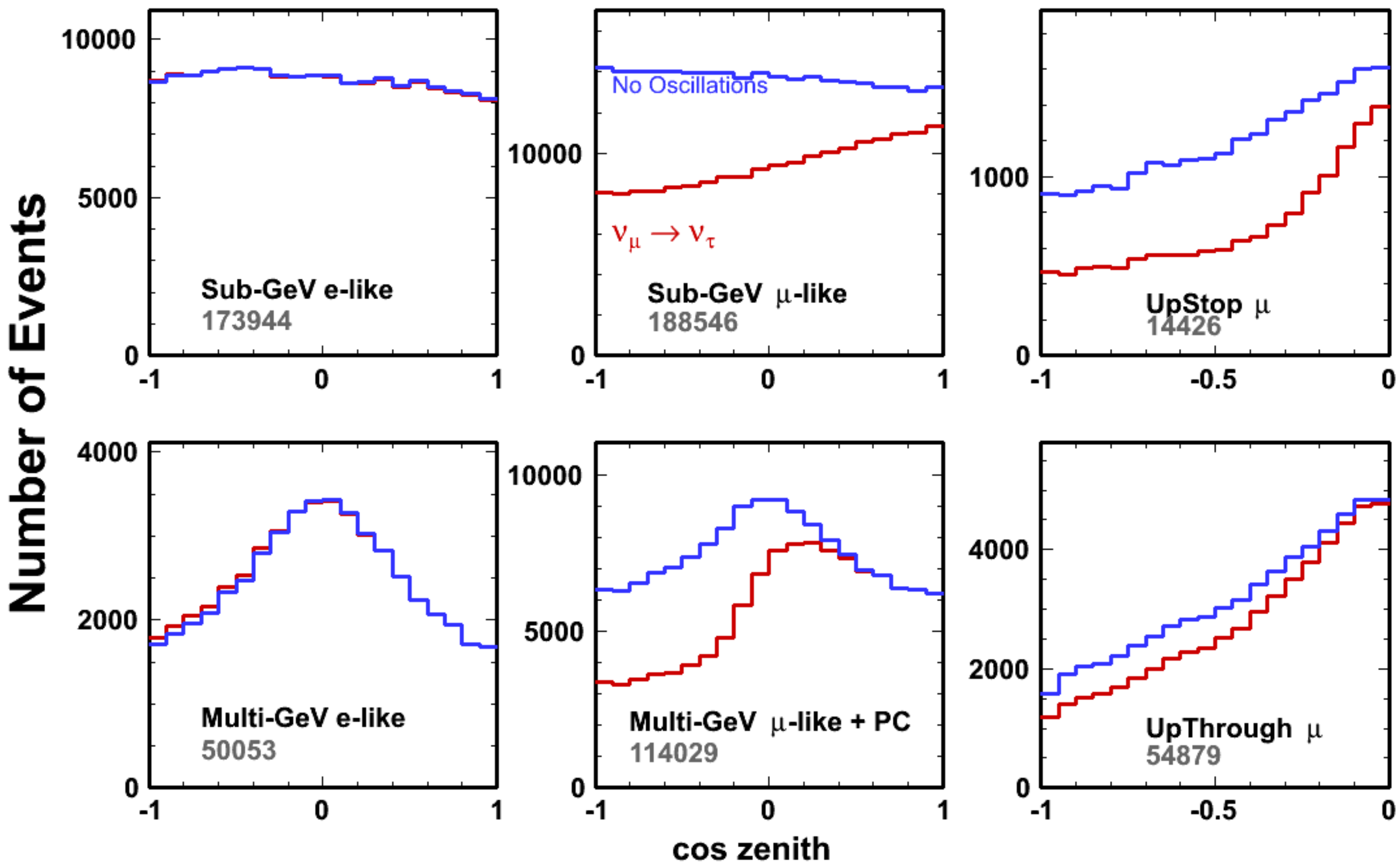


Partially Contained (PC)



Upward-going Muons (Up-



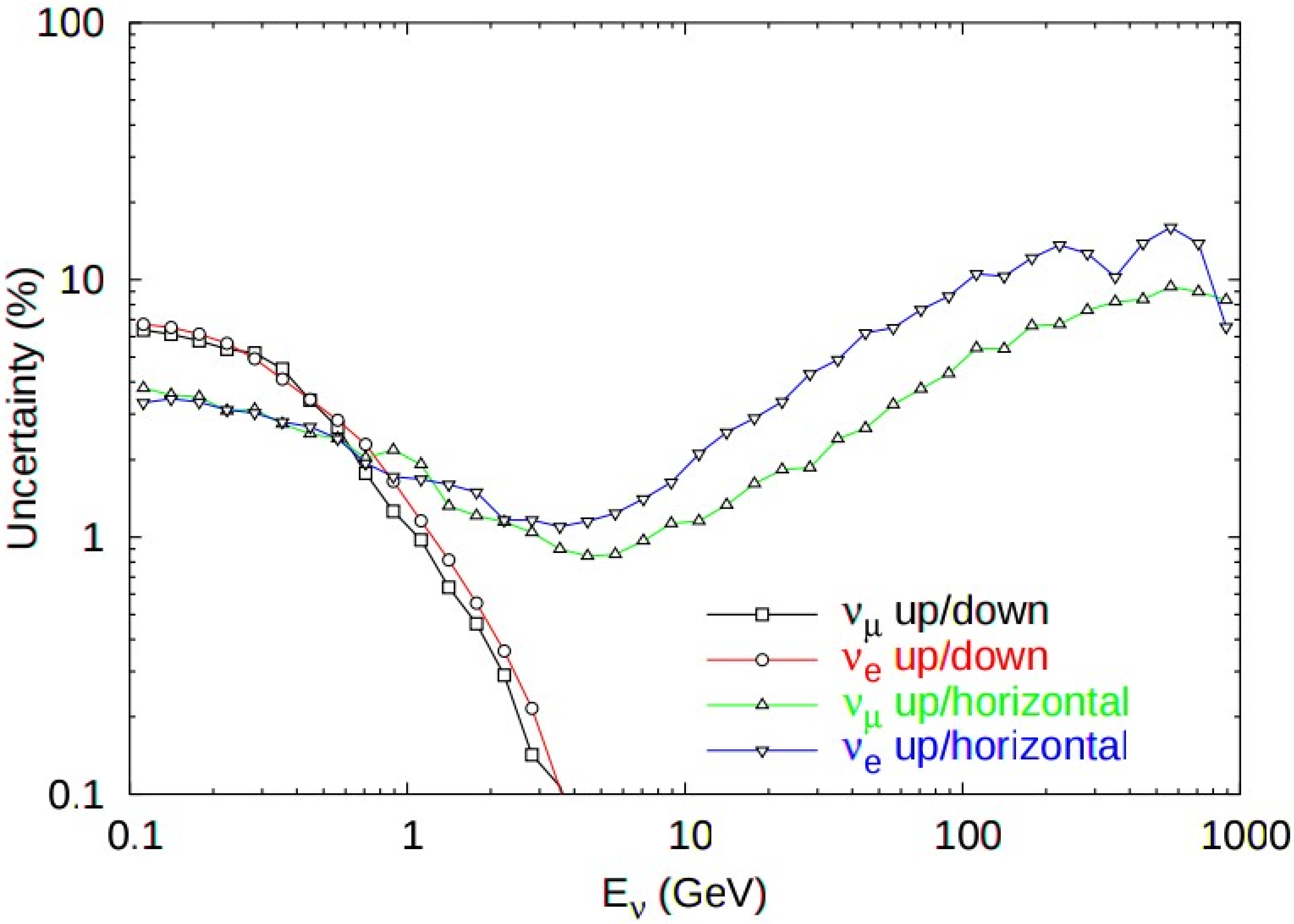


- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and $\bar{\nu}$-like subsamples
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in subdominant contributions to this picture
  - Ie three-flavor effects, Sterile Neutrinos, LIV, etc.

Comparison to Current Super-K Exposure

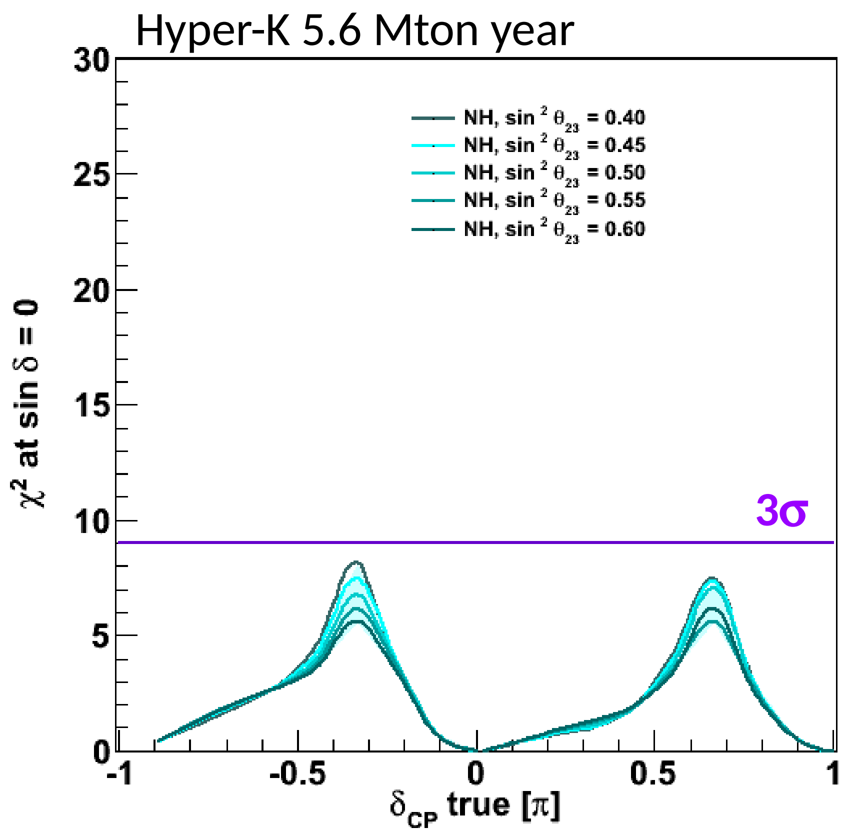
	Hyper-K	SK-IV
Fiducial Vol.	**560 kton**	22.5 kton
Eff. Area	**22,000 m^2**	1500 m^2
Protons	**1.8×10^{35}**	7.5×10^{33}
Neutrons	**1.4×10^{35}**	6.0×10^{33}
Fully Contained μ-/e-like	**740,200**	41,000
Partially Contained μ-like	**64,400**	3,100
Upward-Going μ	**83,400**	7,400

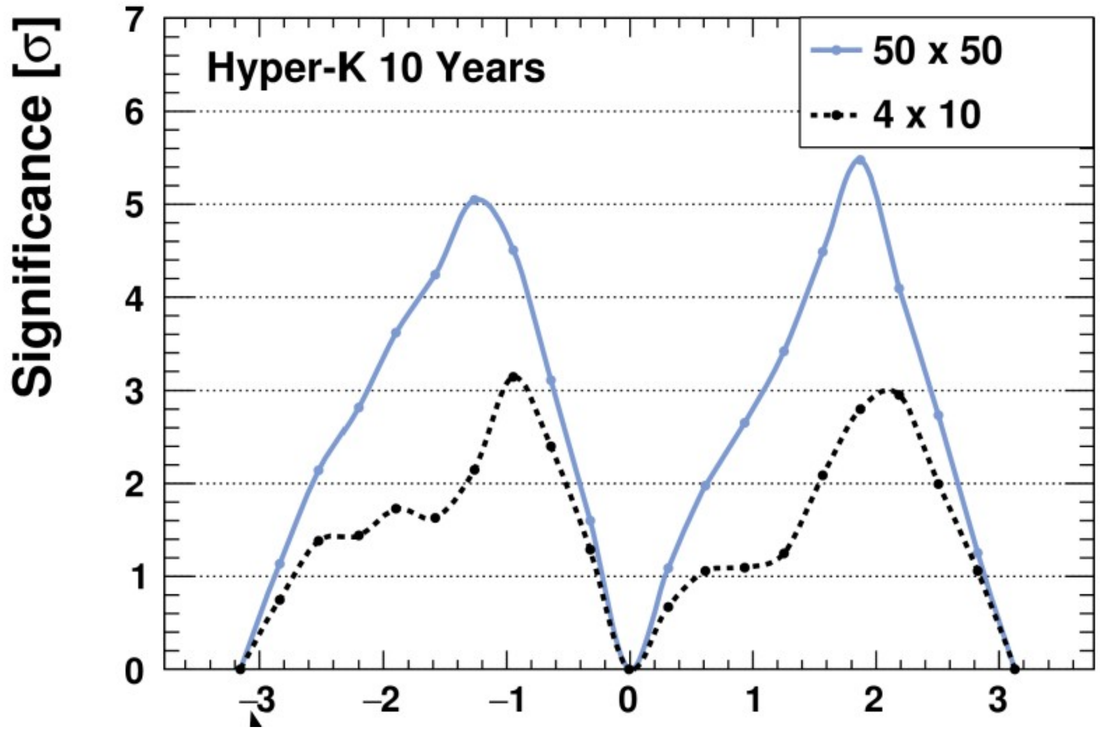
- Event rates are a comparison between 10 years of Hyper-K and 12.8 years of SK
  - Compare: HK beam events 42,000 ν_μ and 7,000 ν_e
- Analyses exposures have been adjusted to account for difference in fiducial volume and effective area between Hyper-K and Super-K



100
10
1
0.1
Uncertainty (%)
0.1
1
10
100
1000
E_ν (GeV)
ν_μ up/down
ν_e up/down
ν_μ up/horizontal
ν_e up/horizontal

CP Violation Sensitivity

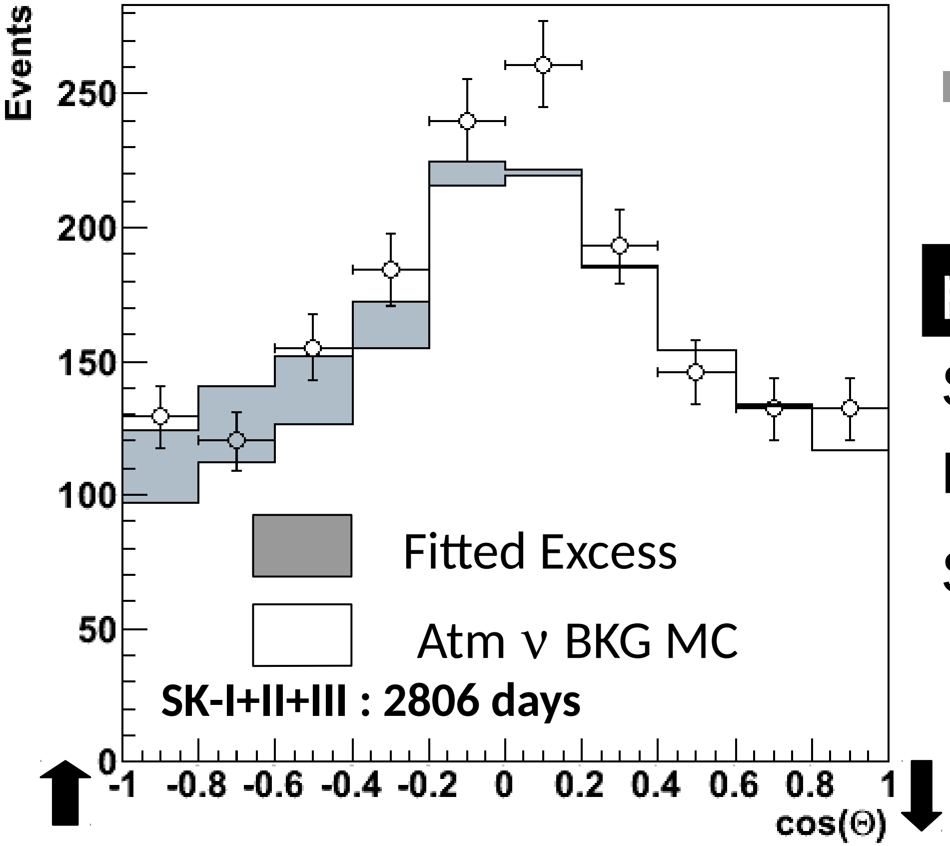




- Limited sensitivity to CP-violation with atmospheric ν alone
- Hyper-K can constrain only about 50% of δ_{cp} space at 3σ, so one of the CP-conserving points is allowed at that C.L.
- Sensitivity from SubGeV e-like samples becomes limited due to flux and cross section systematics
  - Reconstruction, systematic, and analysis improvements possible and expected to help considerably

Oscillation-induced ν_τ measurements

Phys. Rev. Lett. **110**, 181802 (2013)



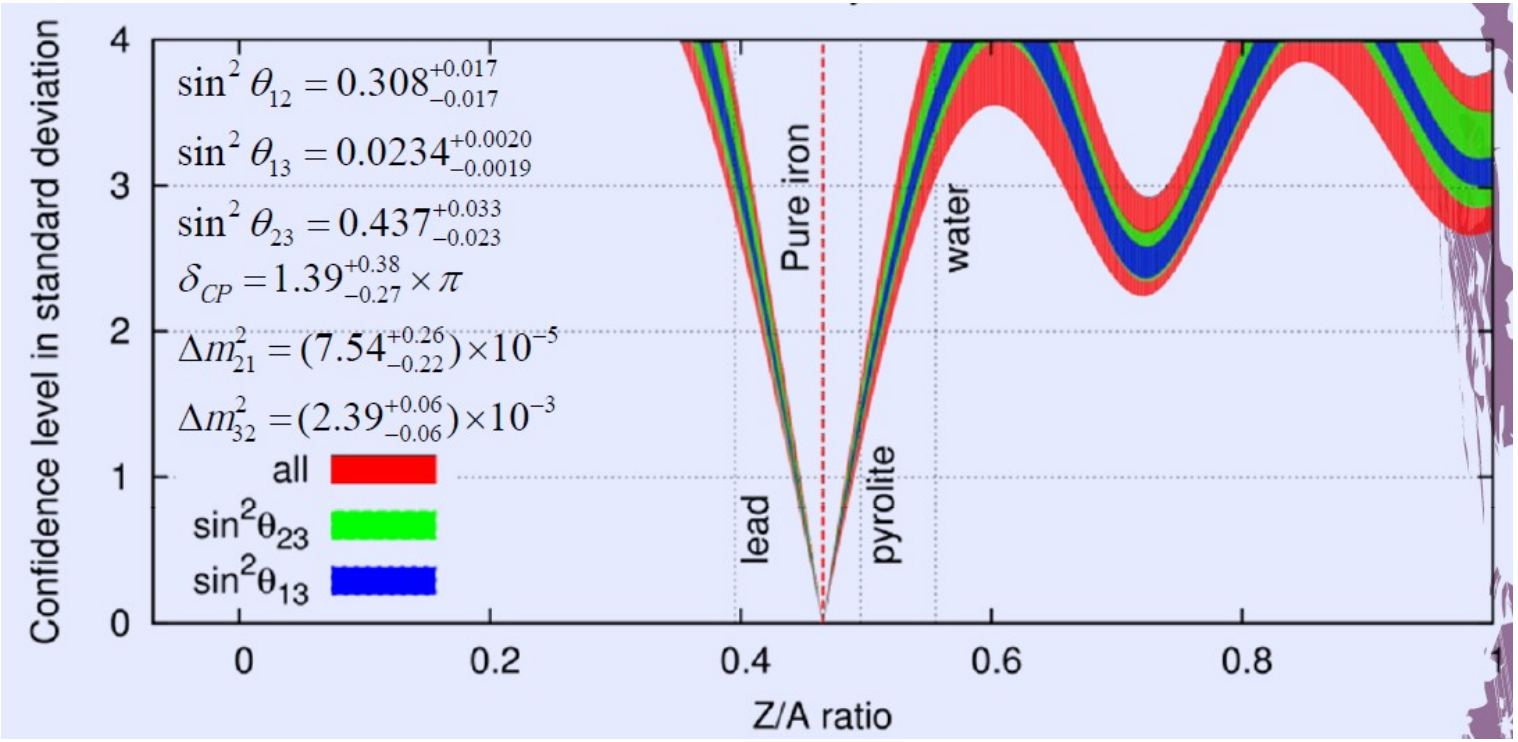
- Pre-cuts + NN
  - Total selection efficiency of 60%

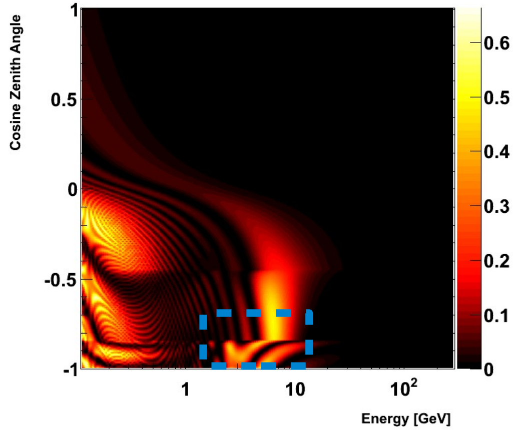
per/ 100 kton yr.	Hyper-K	LBNE
Signal CC $\nu\tau$	40.2	28.5
Background	448.7	44.8
S /√B , 10 years	~14	~8

- HK Numbers are upward-going event rate
- LBNE based on PRD82, 093012

- Super-K has demonstrated the ability to identify ν_τ events in the atmospheric neutrino data (3.8σ)
- After 10 years Hyper-K will have O(2,000) $\nu\tau$ events that can be used to study
  - CC ν_τ cross section, leptonic universality, etc.

Geophysics: Chemical Composition of Earth's Outer Core





- Density profile of the Earth is well known from seismic measurements
  - Outer core is thought to be liquid iron+Ni and another light element (Unmeasured!)
- Z/A ratio is important to understanding formation of Earth and its magnetic field
- With 10 years of data Hyper-K can open the field of Earth Spectroscopy
  - First Z/A measurement, can exclude lead-based and water-based outer core
  - Longer exposures more useful (want to discriminate iron from pyrolite)

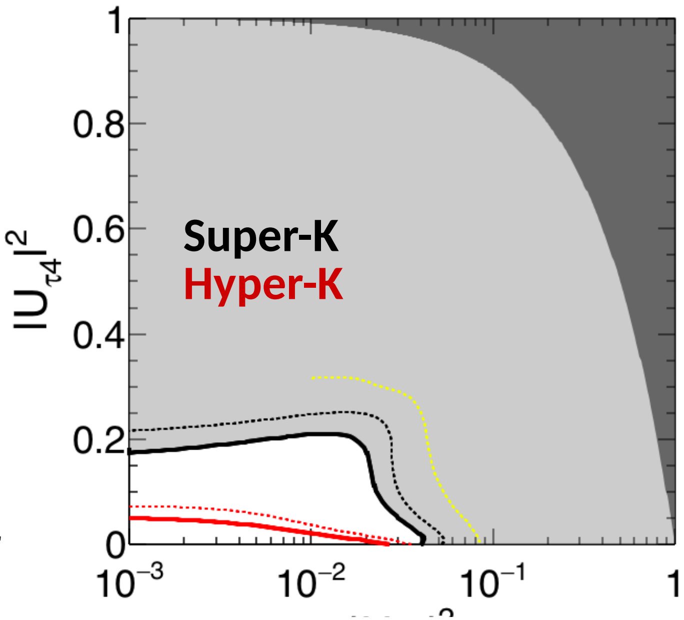
Hyper-K's sensitivity to Sterile Neutrino Mixing

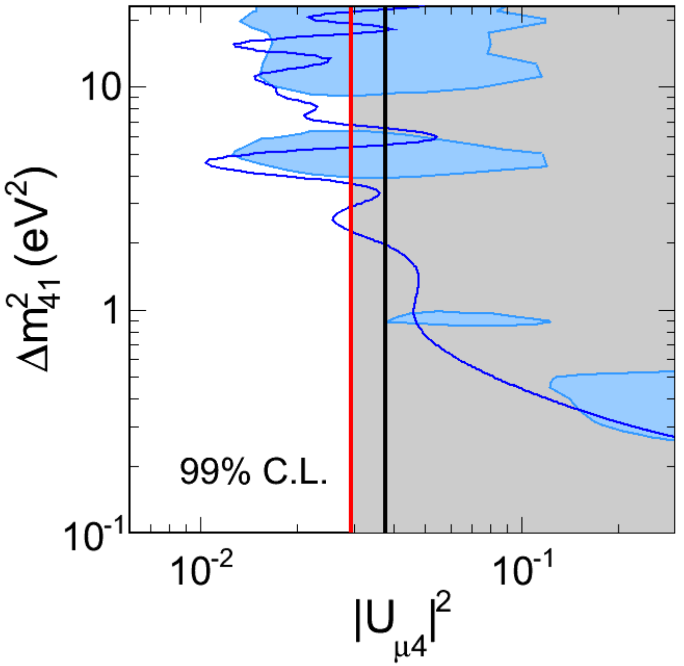
- Searches for sterile neutrinos with the atmospheric neutrinos are independent of the sterile Δm^2 and the number sterile neutrinos
  - For $\Delta m_s^2 \sim 1\ eV^2$ oscillations appear fast

- $|U_{\mu 4}|^2$ Induces a decrease in event rate of μ-like data of all energies and zenith angles
- $|U_{\tau 4}|^2$ Shape distortion of angular distribution of higher energy μ-like data

- Sensitivity gains are limited by
  - flux and cross section errors
  - Better knowledge during actual hyper-K running can improve these constraints

	Hyper-K	SK-IV
$\lvert U_{\mu 4}\rvert^2$	**0.029**	0.038
$\lvert U_{\tau 4}\rvert^2$	**0.066**	0.164



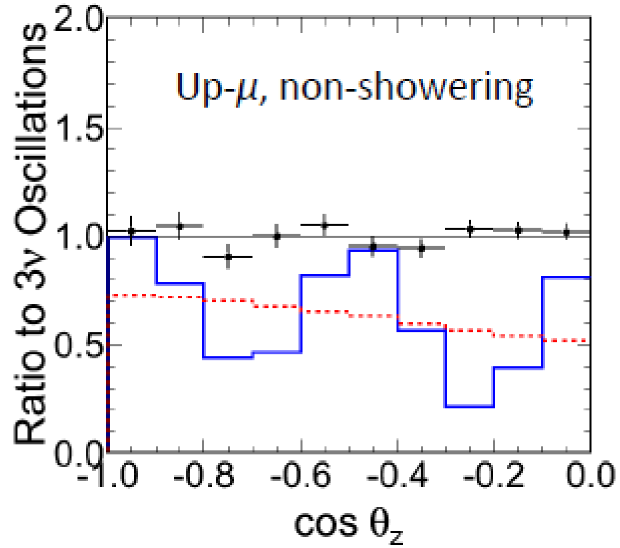


Lorentz-invariance violating oscillations

$$H = UMU^\dagger + V_e + H_{LV}$$

$$H_{LV} = \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - \frac{4E}{3} \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$

- Lorentz invariance violating effects can be probed using atmopsheric neutrinos
- Analysis using the Standard Model Extension (SME)
- Effects of LIV controlled by two sets of complex parameters
  - $a^T_{\alpha\beta}$ dim = 3 induces oscillation effects ~ **L**
  - $c^{TT}_{\alpha\beta}$ dim = 4 induces oscillation effects ~ **L × E**
- Hyper-K Sensitivity will be ~ 3× better than Super-K

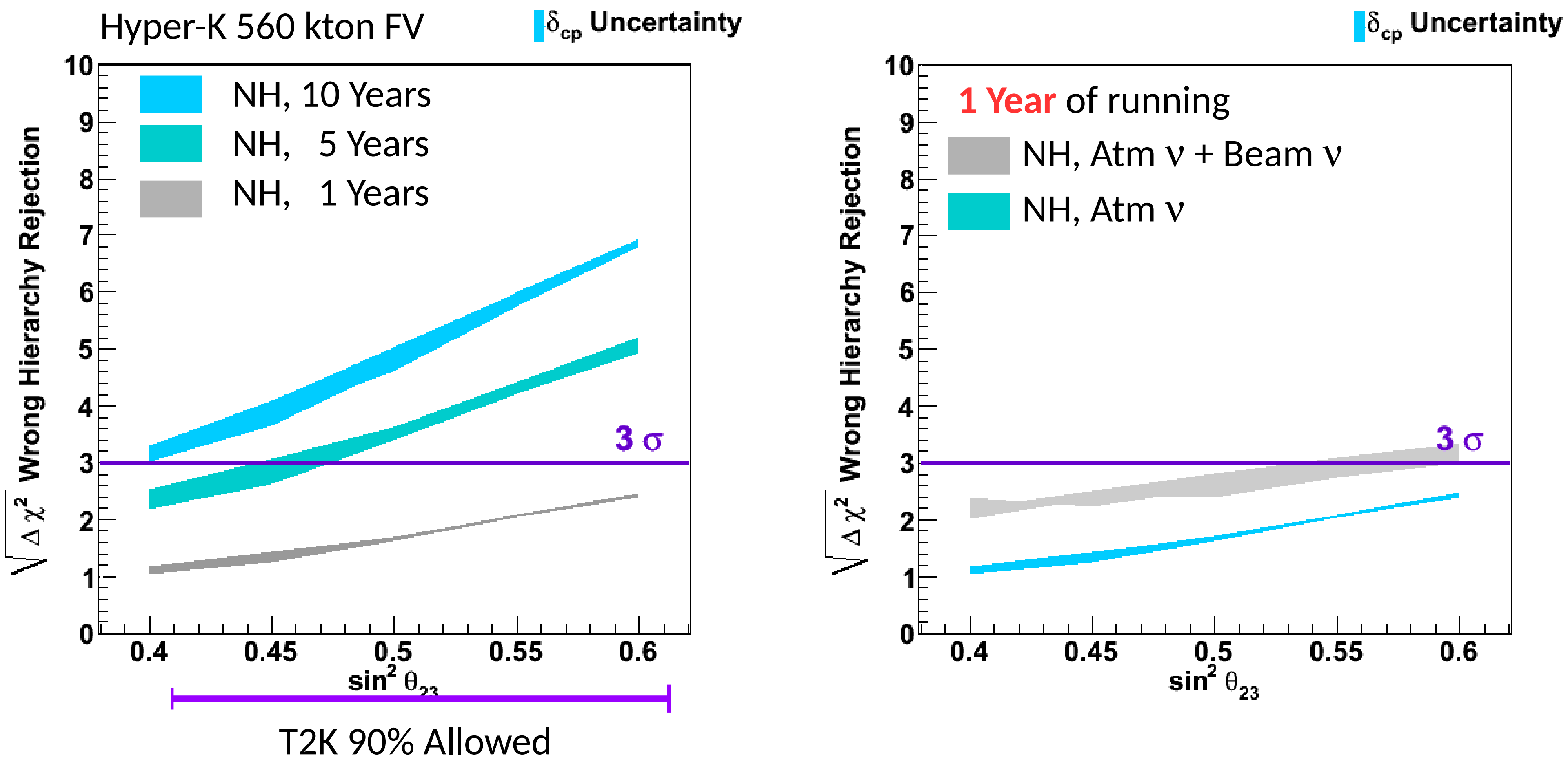


	$e\mu$	$e\tau$	$\mu\tau$		$e\mu$	$e\tau$	$\mu\tau$
$\Re(a^T)$ (GeV)	4×10^{-20} MiniBooNE	8×10^{-20} Double Chooz	-	$\Re(c^{TT})$	1×10^{-19} MiniBooNE	1×10^{-17} Double Chooz	-
SK:	2×10^{-23}	4×10^{-23}	6×10^{-24}		2×10^{-26}	1×10^{-24}	5×10^{-27}
HK:	7×10^{-24}	2×10^{-23}	2×10^{-24}		6×10^{-27}	7×10^{-25}	2×10^{-27}

Combination of Beam and Atmospheric Neutrinos

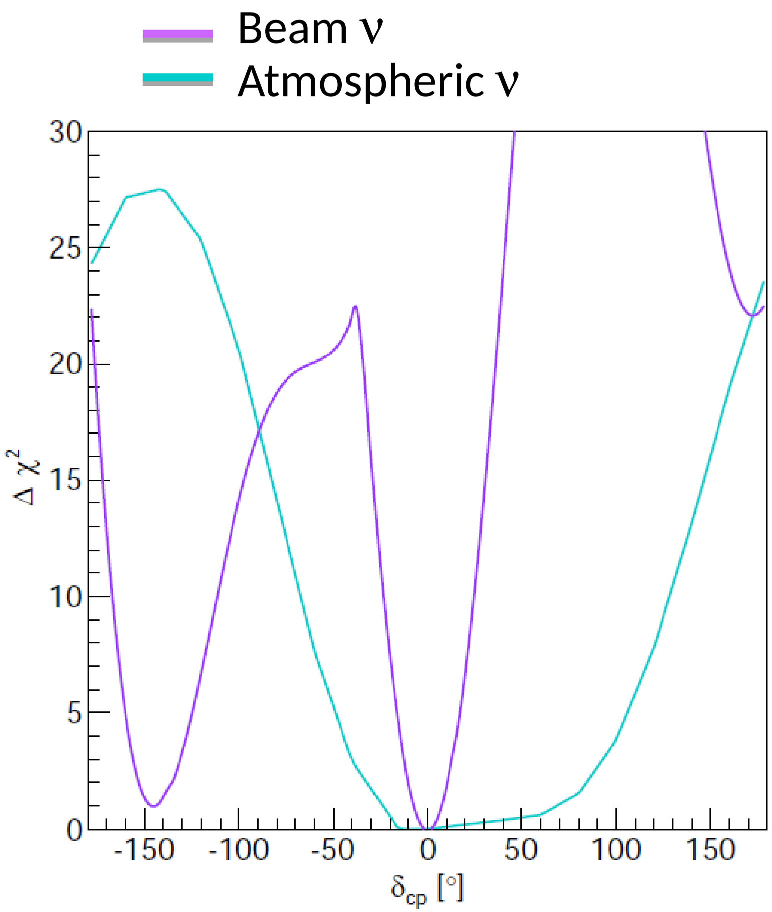
Beam and atmospheric neutrino data provide largely complimentary sensitivity with several common systematic error sources (cross section, detector)

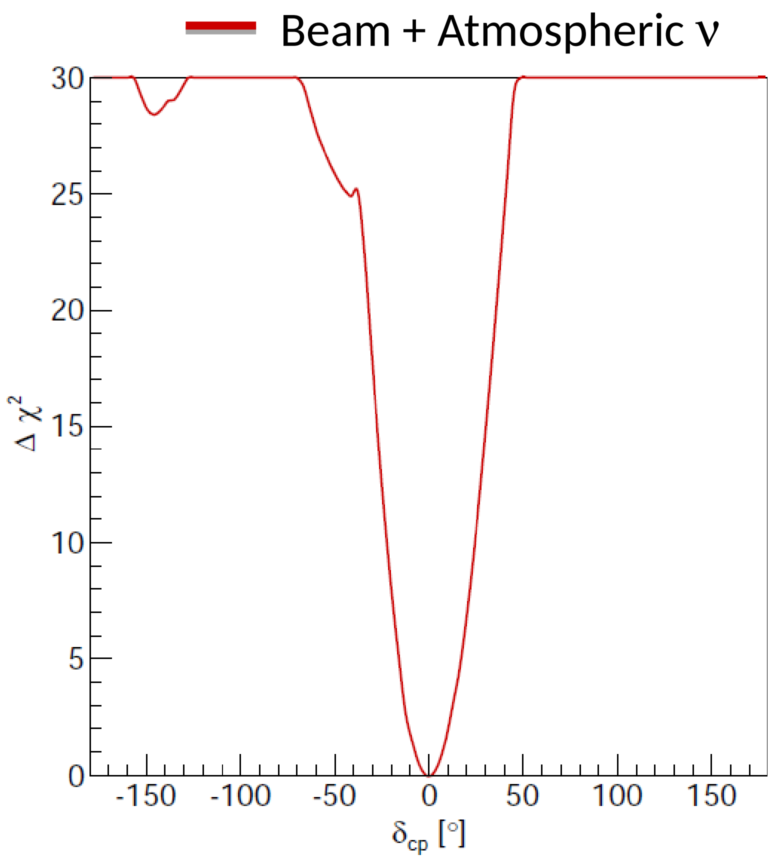
Hyper-K Hierarchy Sensitivity With Beam Inputs



- Plots for true inverted hierarchy are similar
- Large benefit of precise determination of θ_{23} and Δm^2_{23} from the beam
  - Example of benefit of combination with beam (neutrino mode only)
  - 1 Year of running: 1.5×10^{21} POT, with 560 kton FV

Combination With Beam Neutrinos





- Though atmospheric neutrinos have limited sensitivity to CP-violation relative to the beam measurement, the sensitivity is largely complementary
  - Multiple baselines and matter effects give weaker degeneracies
- Addition of atmospheric neutrino data to the beam measurement can improve the δ_{cp} measurement, particularly in regions of limited sensitivity for the beam

Comment on Leptonic Unitarity

500 km/GeV

15,000 km/GeV

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor states

Mass Eigenstates

If the PMNS matrix is unitary we expect these relations (for l = e, μ, τ)

Normalization $$N_l \equiv \sum_{i=1,2,3} |U_{li}|^2 = 1$$

Triangle $$T_{lm} \equiv \sum_{i=1,2,3} U_{li} U^*_{mi} = 0$$

- The pieces of the matrix that can be probed depend on L and E of neutrino source
  - Hyper-K will have both “fixed” L/E (beam) and “varying” L/E (atmospheric ν)
- Computations assume that the U_{pmns} is unitary, but this can be tested
  - Models of new physics (SeeSaw, SUSY) predict U_{pmns} is piece of a larger matrix
- For LBL νμ disappearance: $|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|\right) \rightarrow \frac{|U_{\mu 3}|^2 \left(|U_{\mu 1}|^2 + |U_{\mu 2}|^2|\right)}{\sum_i |U_{\mu i}|^2|}$
- Hyper-Kamiokande can probe many elements of this matrix *by itself* with combined beam and atmospheric neutrino measurements

Comment on Leptonic Unitarity

If Unitarity is NOT assumed, then to first order

$$\left\{\begin{array}{ll}
\text{LBL } \nu_\mu \to \nu_\mu & \boxed{|U_{\mu 3}|^2}\left(|U_{\mu 1}|^2 + |U_{\mu 2}|^2|\right) \\
\text{LBL } \nu_\mu \to \nu_e & \mathbb{R}\left\{U_{\mu 3}U_{e3}^* \left(U_{\mu 1}U_{e2}^* + U_{\mu 3}U_{e2}^*\right)\right\} \\
\text{ATM } \nu_\mu \to \nu_\tau & \mathbb{R}\left\{\boxed{U_{\mu 3}U_{\tau 3}^*}\left(U_{\mu 1}U_{\tau 2}^* + U_{\mu 3}U_{\tau 2}^*\right)\right\} \\
\text{ATM Reson } \nu_\mu \to \nu_e & \left(r\boxed{U_{\mu 3}|^2} - 1\right) \\
\text{ATM Sub-GeV } \nu_\mu \to \nu_\mu & \boxed{|U_{\mu 1}|^2|U_{\mu 2}|^2}
\end{array}\right.$$

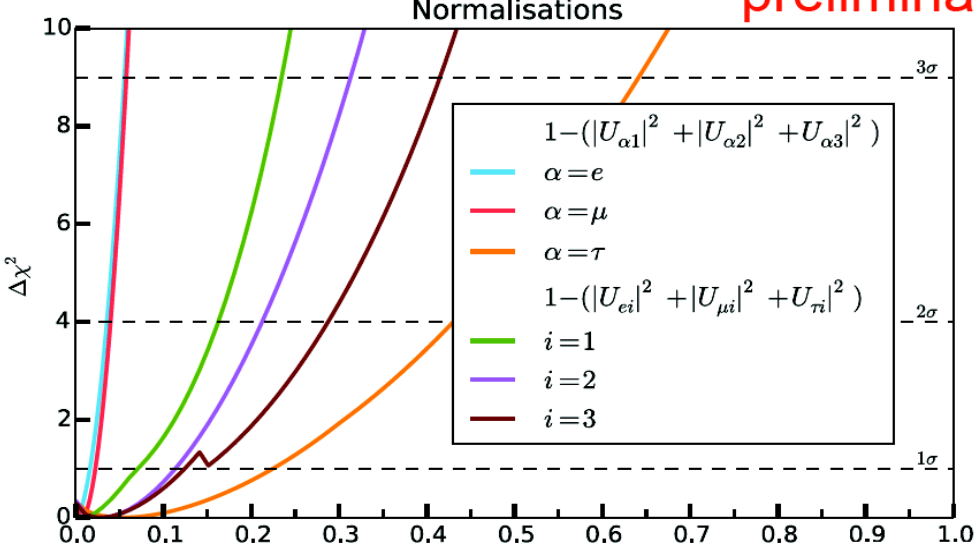
- Typically single oscillation channels are sensitive to multiple parts of the mixing matrix
  - true for any experiment
- However atmospheric neutrino measurements have sufficient breadth in L/E to have some sensitivity to both “1-2” and “2-3” columns of the mixing matrix (in principle)
  - separating $U_{\mu 1}$ and $U_{\mu 2}$ with (1.0~3.0 GeV data)
- To really make progress improvements in detector performance and systematic errors (flux, cross-section) will be essential

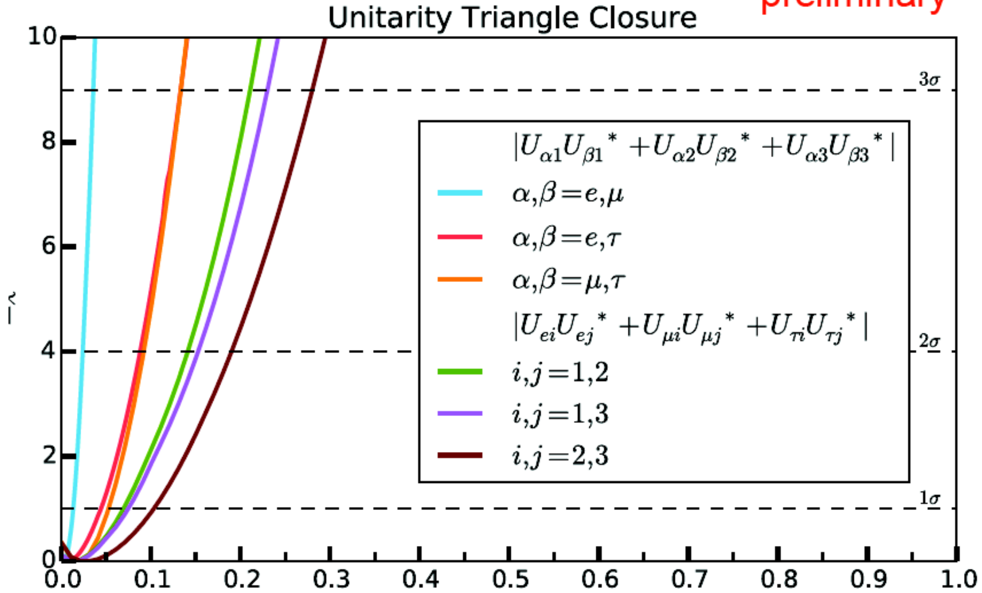
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Global Study of Leptonic Unitarity

Plots from S.Parke@WIN15



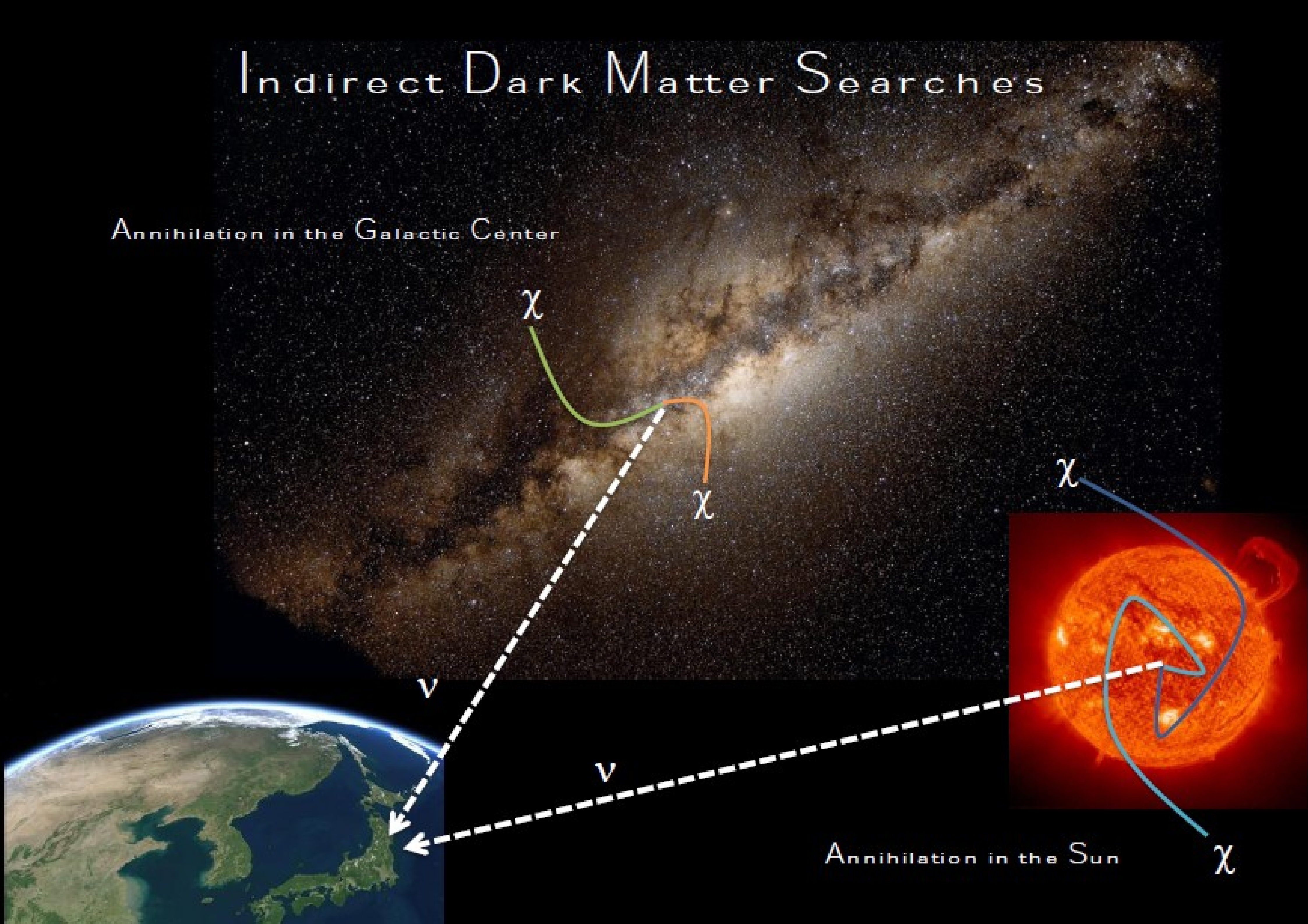


- Hyper-K Beam + Atmospheric measurements:
- Contribute to normalizations
  - $\alpha = \mu$ (red line)
  - $\alpha = \tau$ (orange line)
  - i = 3 (brown line)

- Contribute to closure of triangles
  - α,β = e,μ (cyan line)
  - $\alpha,\beta = \mu,\tau$ (orange line)
  - i,j = 2,3 (brown line)

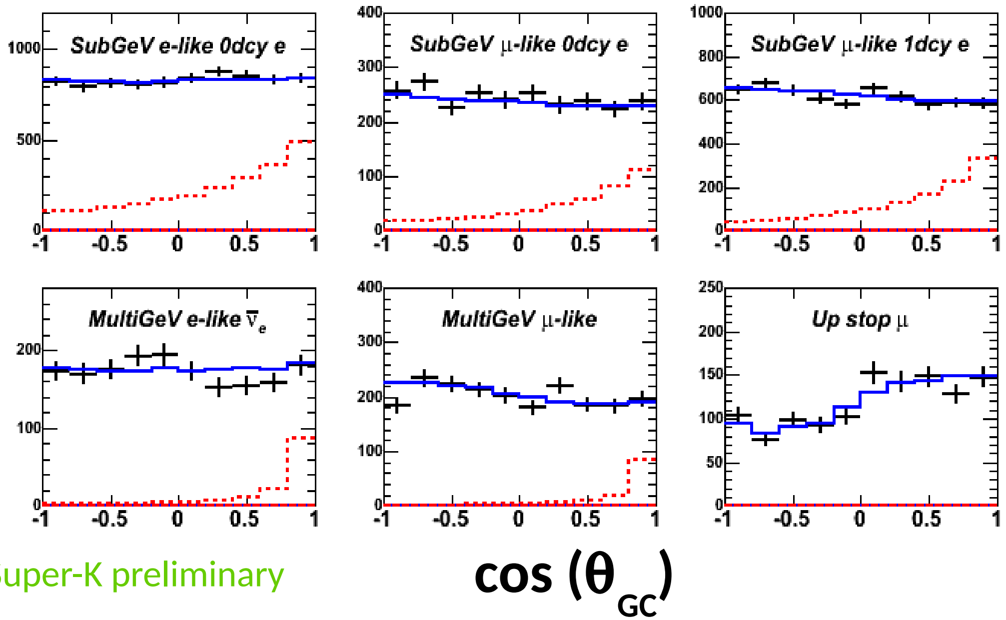
- Hyper-K can provide high statistics measurements with full systematic correlations to improve (overconstrain) our understanding of these relations

Atmospheric Neutrinos As Background


Indirect Dark Matter Searches
Annihilation in the Galactic Center
χ
χ
ν
χ
ν
Annihilation in the Sun
χ

Search for WIMP Annihilations in the Galactic Center

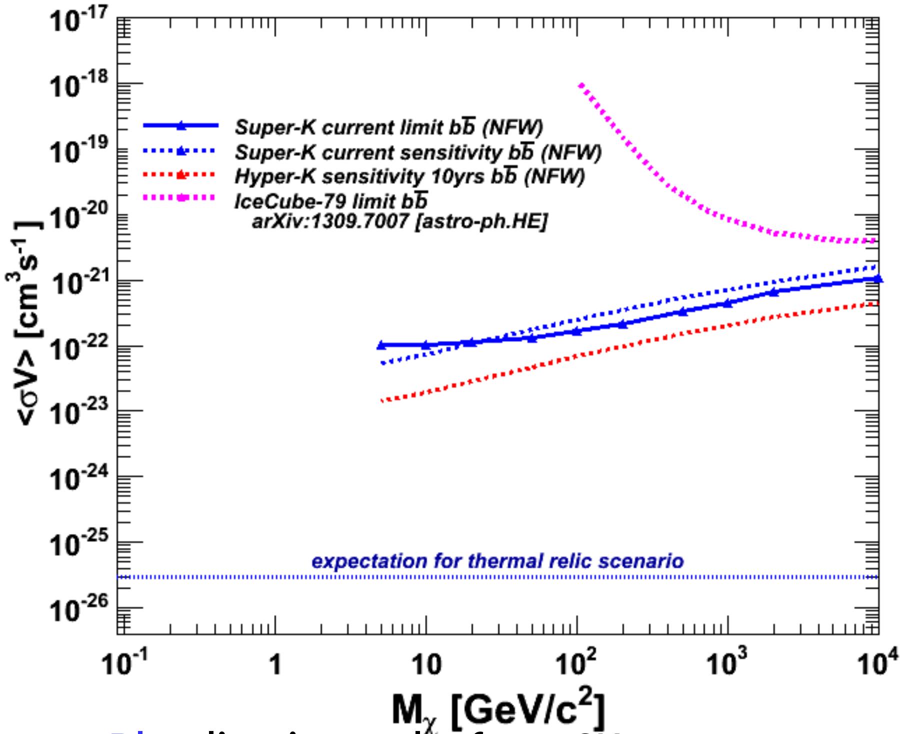
$\chi\chi \rightarrow b\bar{b}$ $M(\chi) =$ **5 GeV / c²**



Super-K preliminary

WIMP Signal, **Best Fit × 15**

ATM ν Background + WIMP

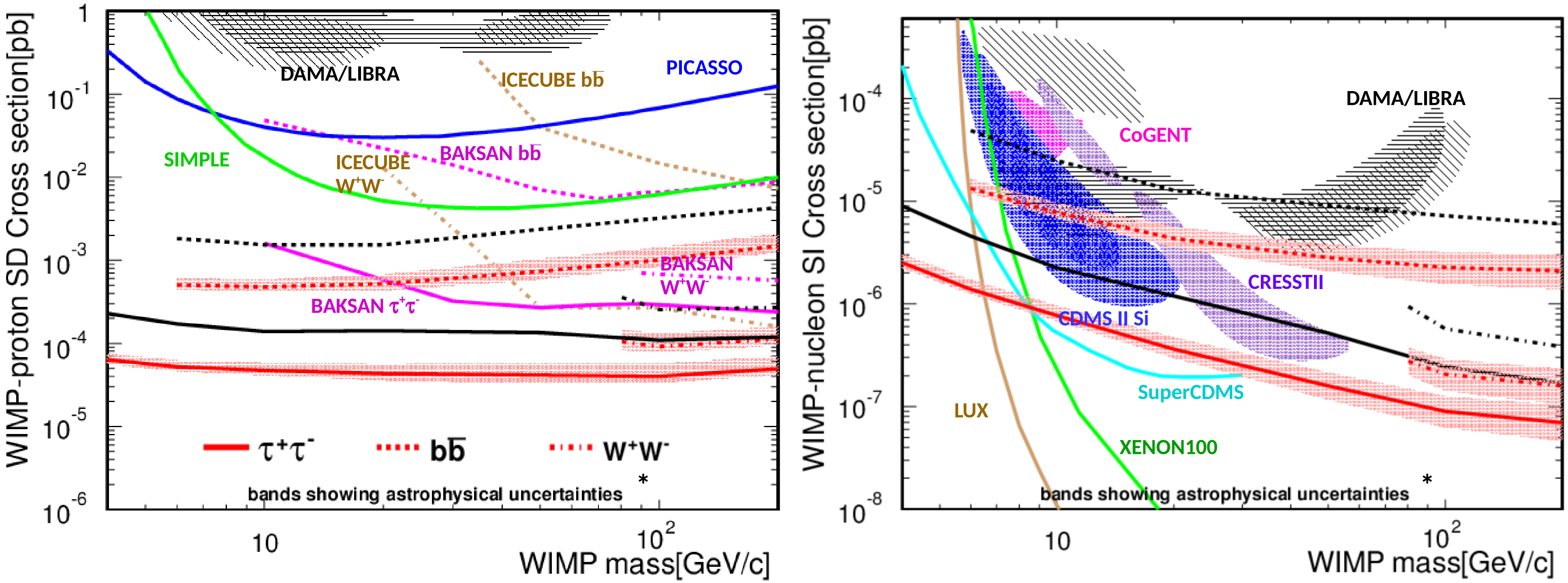


Blue line is results from SK
Red line is Hyper-K 5.6 Mton year sensitivity

- Data and MC are binned in momentum and direction to the galactic center
- Signal for a given WIMP mass appears in only some of analysis samples, but is peaked towards the galactic center
  - Remaining analysis samples help control background and its uncertainty
- Hyper-K's sensitivity should exceed Super-K's limits by a factor of 4~5

Search for WIMP Annihilations in the **Sun**

*Solar composition, VDF, Nuclear form factor



Black lines are results from SK
Red lines are Hyper-K 5.6 Mton year sensitivity

- Similarly the data can be binned in the direction to the sun
- Hyper-K limits are expected to be a factor of 3~5 stronger than Super-K in the absence of a signal
  - Strongest limits on SD interactions at low WIMP masses
  - Possible to exclude hints for SI interactions with hardest channel ($\tau^+\tau^-$)

Other Physics at *Hyper-K*

- Atmospheric neutrino flux measurements
- Tau neutrino studies (oscillation-induced, cross section)
- Non-standard Neutrino Interactions in atmospheric neutrinos
- Search for WIMP annihilation at the center of the Earth
- Various nucleon decay modes
  - $p \to \nu\, \pi^+$, $n \to \nu\, \pi^0$
  - $p \to l^+ M^0$ (other antilepton + meson modes)
  - $n \to l^- M^+$ (Recent theoretical interest)
  - B+L modes
  - dinucleon decay modes
- $n \leftrightarrow \bar{n}$ oscillations
- Astrophysical neutrino source search
- ...

- The statistical uncertainty at Super-K on many of the analyses above is large so generically we can expect improvements at Hyper-K

Summary

- Atmospheric neutrino physics at Hyper-K is expected to be expansive and precise
  - 3σ+ mass hierarchy and octant determination
  - Improved sensitivity to exotic oscillation scenarios
  - New studies of ν_τ physics and lepton unitarity
  - First measurements of Earth core's chemical composition

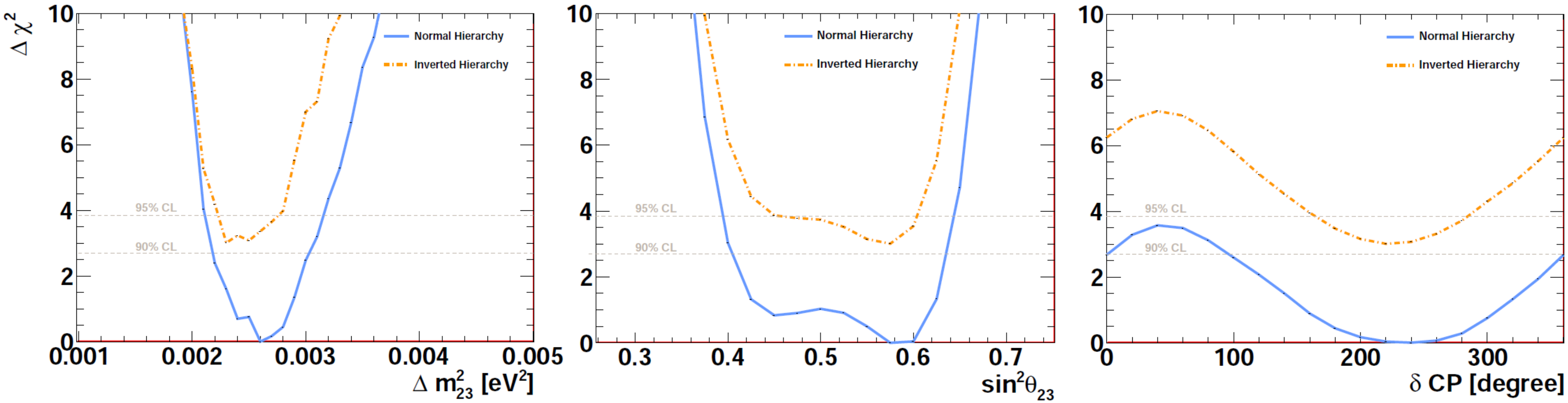
- In combination with the beam neutrino data further precision is expected

- Nucleon decay physics potential is equally promising
  - Sensitivity to $p \rightarrow e^+\pi^0$ at $\tau/B > 10^{35}$ years (only with Hyper-K!)
  - Sensitivity to $p \rightarrow \nu K^+$ at $\tau/B > 10^{34}$ years and beyond
  - Order of magnitude increase in sensitivity in many other modes

- The future of non-accelerator measurements at Hyper-K is bright

θ_{13} Fixed Analysis (NH+IH) SK Only

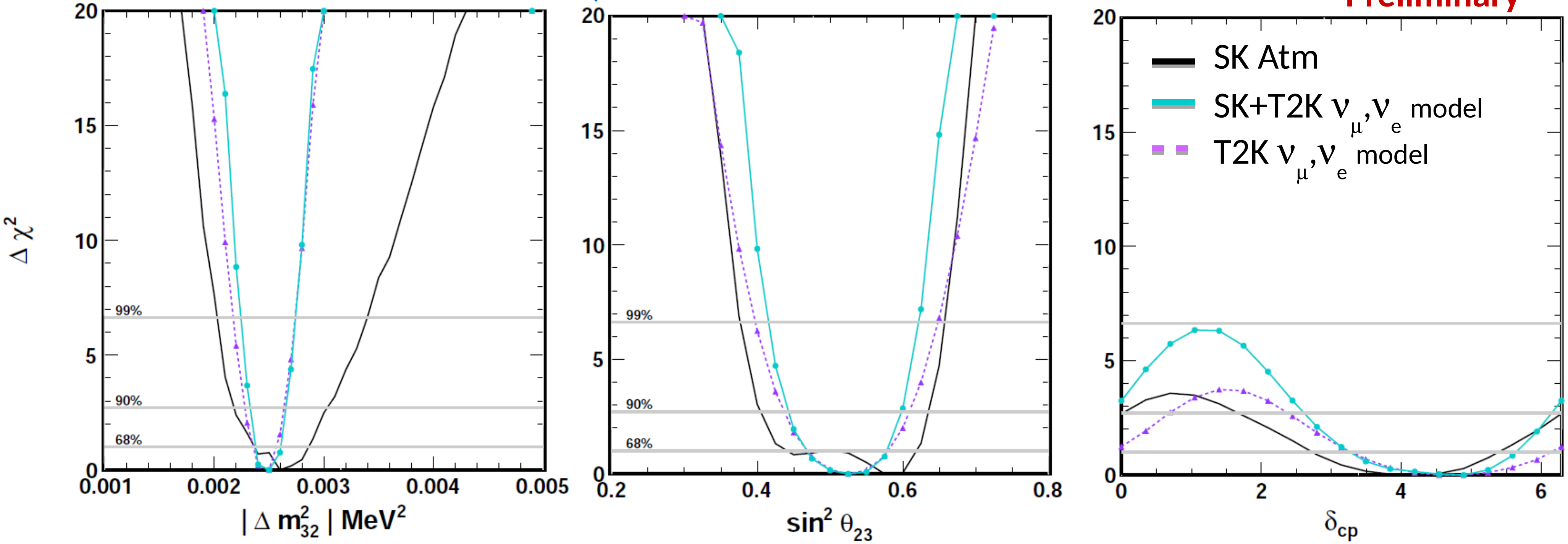
Preliminary



Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	582.4	0.0238	4.19	0.575	2.6
SK (IH)	585.4	0.0238	3.84	0.575	2.3

- Offset in these curves shows the difference in the hierarchies
- Normal hierarchy favored at: $\boxed{\chi^2_{NH} - \chi^2_{IH} = -3.0}$, not significant
  - Preference for matter over vacuum oscillations at ~1 σ (82% C.L.)

Theta13 **Fixed** SK + T2K ν_μ, ν_e Model, Normal Hierarchy

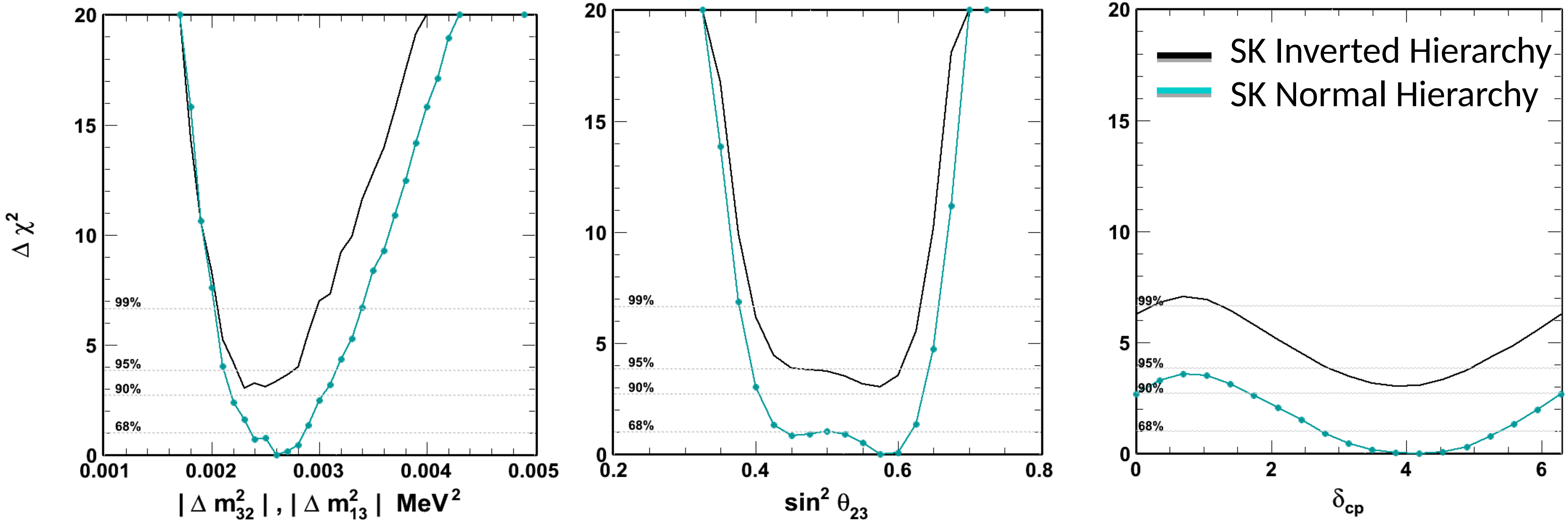


Fit (585 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK + T2K (NH)	651.5	0.0238	4.89	0.525	2.5
SK + T2K (IH)	654.7	0.0238	4.19	0.550	2.4

- $\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (-3.0 SK only)
- CP Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

θ_{13} Fixed Analysis (NH+IH) SK Only

Preliminary



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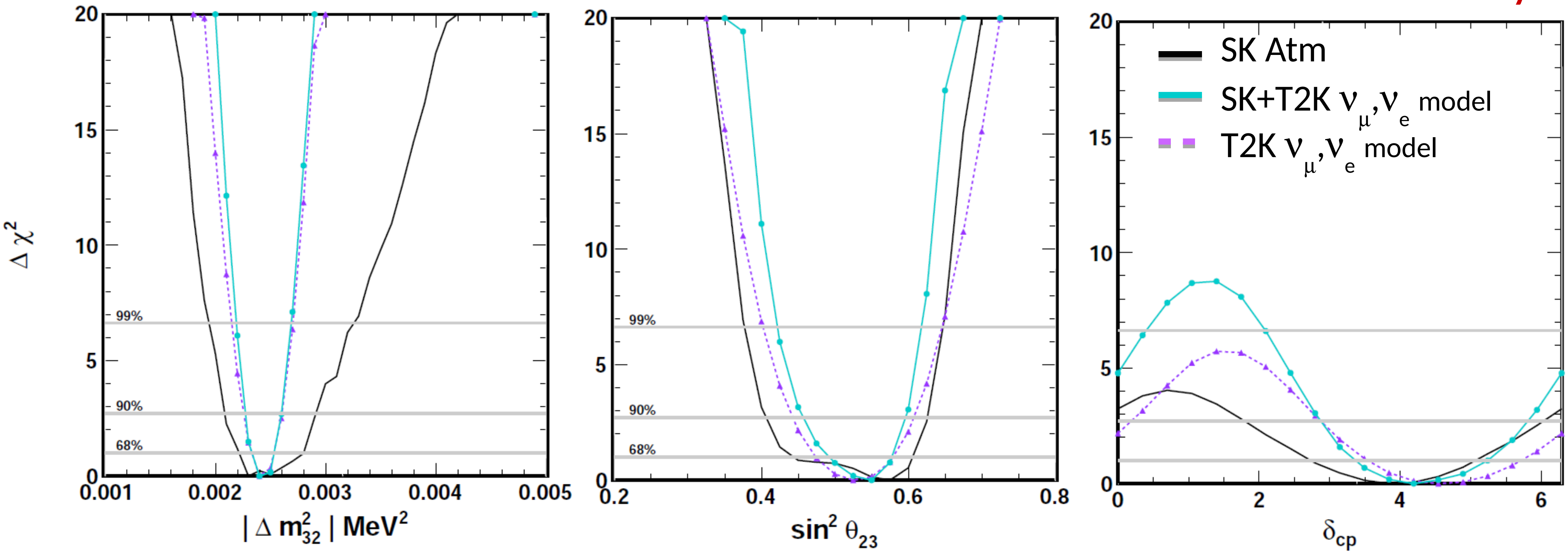
- Offset in these curves shows the difference in the hierarchies
- Normal hierarchy favored at: $\boxed{\chi^2_{NH} - \chi^2_{IH} = -3.0}$, not significant

Theta13 Fixed SK + T2K ν_μ, ν_e Model, Inverted Hierarchy

Preliminary



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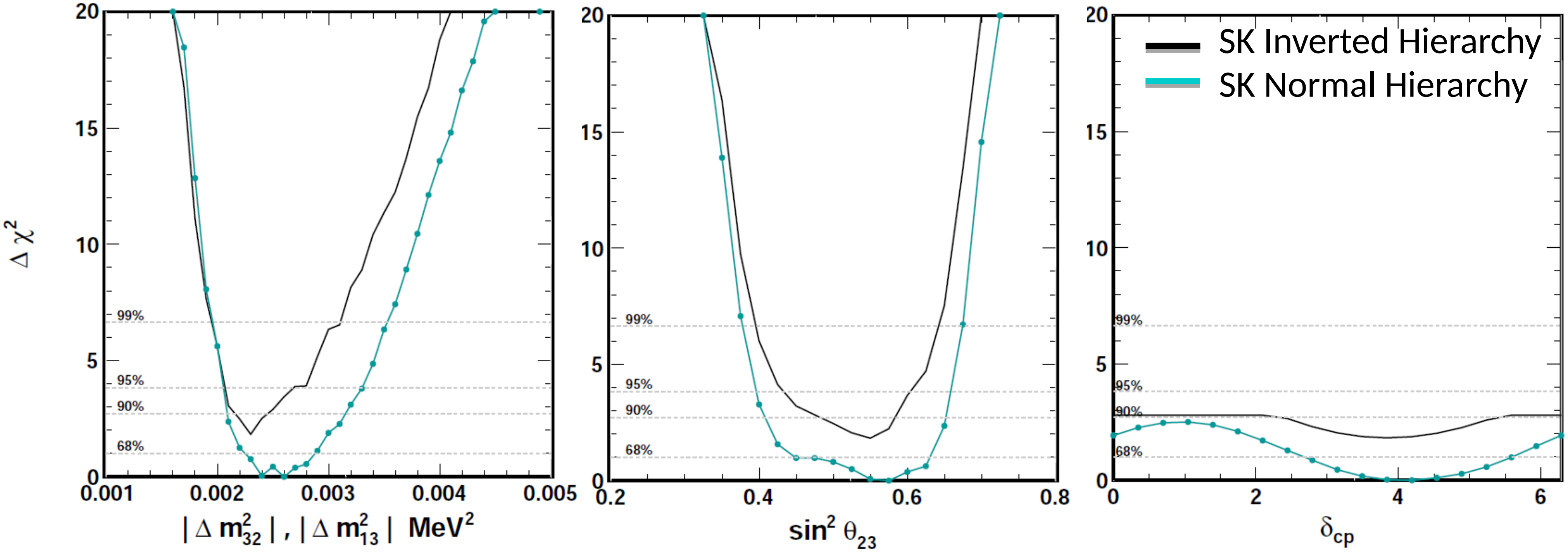
- CP Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

θ_{13} Free Analysis (NH+IH) SK Only

Preliminary

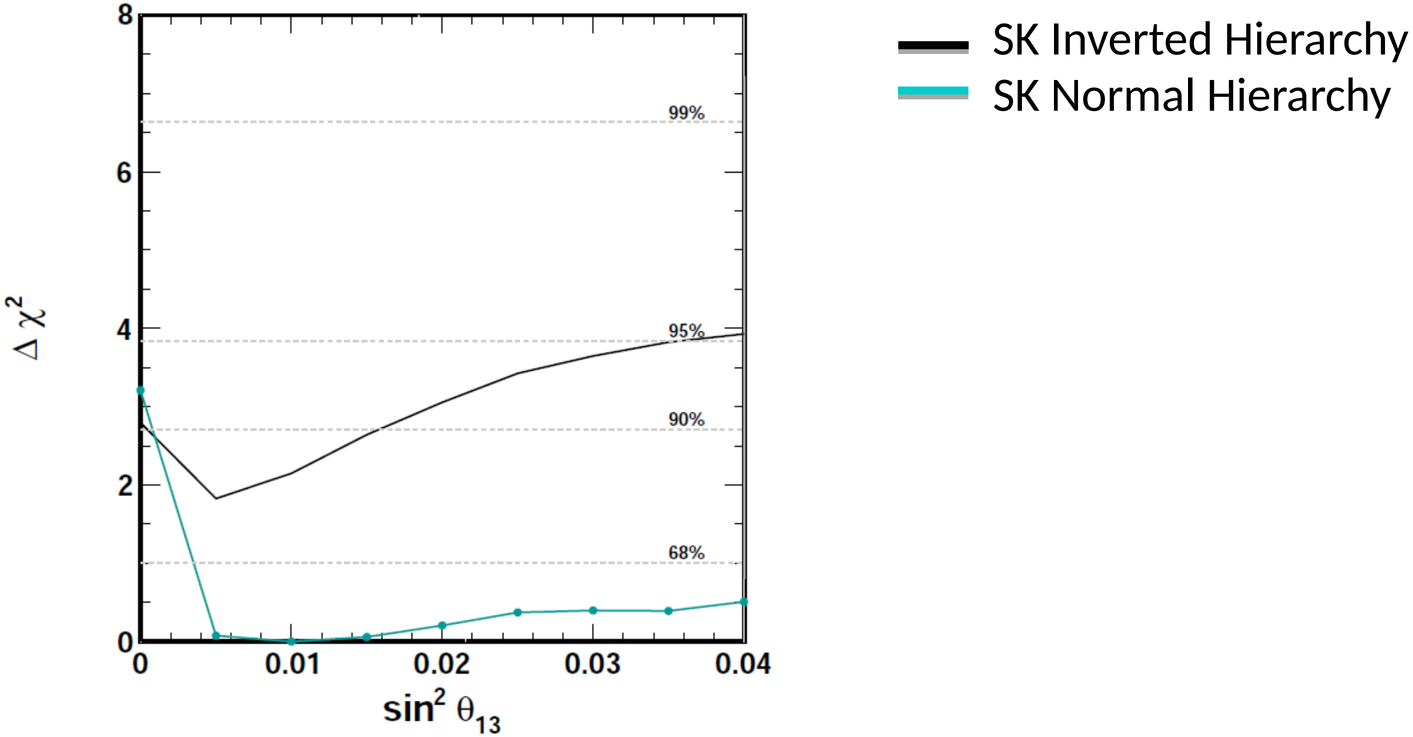


Fit (516 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	582.1	0.010	4.18	0.575	2.6
SK (IH)	583.9	0.005	3.84	0.550	2.3

- Offset in these curves shows the difference in the hierarchies

θ_{13} Free Analysis (NH+IH) SK Only

Preliminary

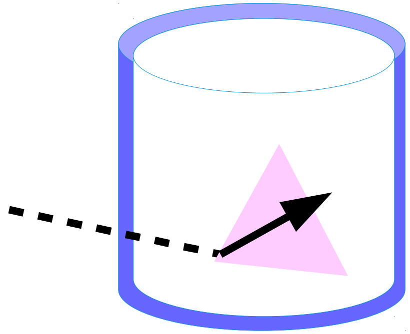


Fit (516 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($\times 10^{-3}$)
SK (NH)	582.1	0.010	4.18	0.575	2.6
SK (IH)	583.9	0.005	3.84	0.550	2.3

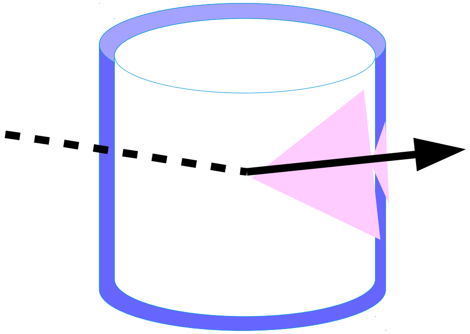
- Offset in these curves shows the difference in the hierarchies

Super-K Atmospheric ν Event Topologies

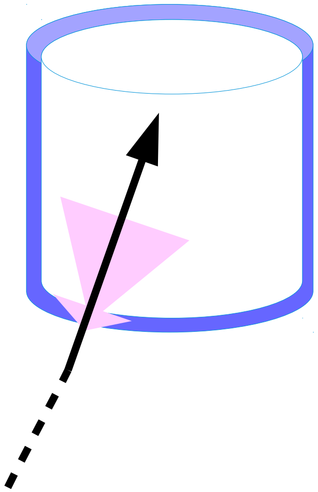
Fully Contained (FC)

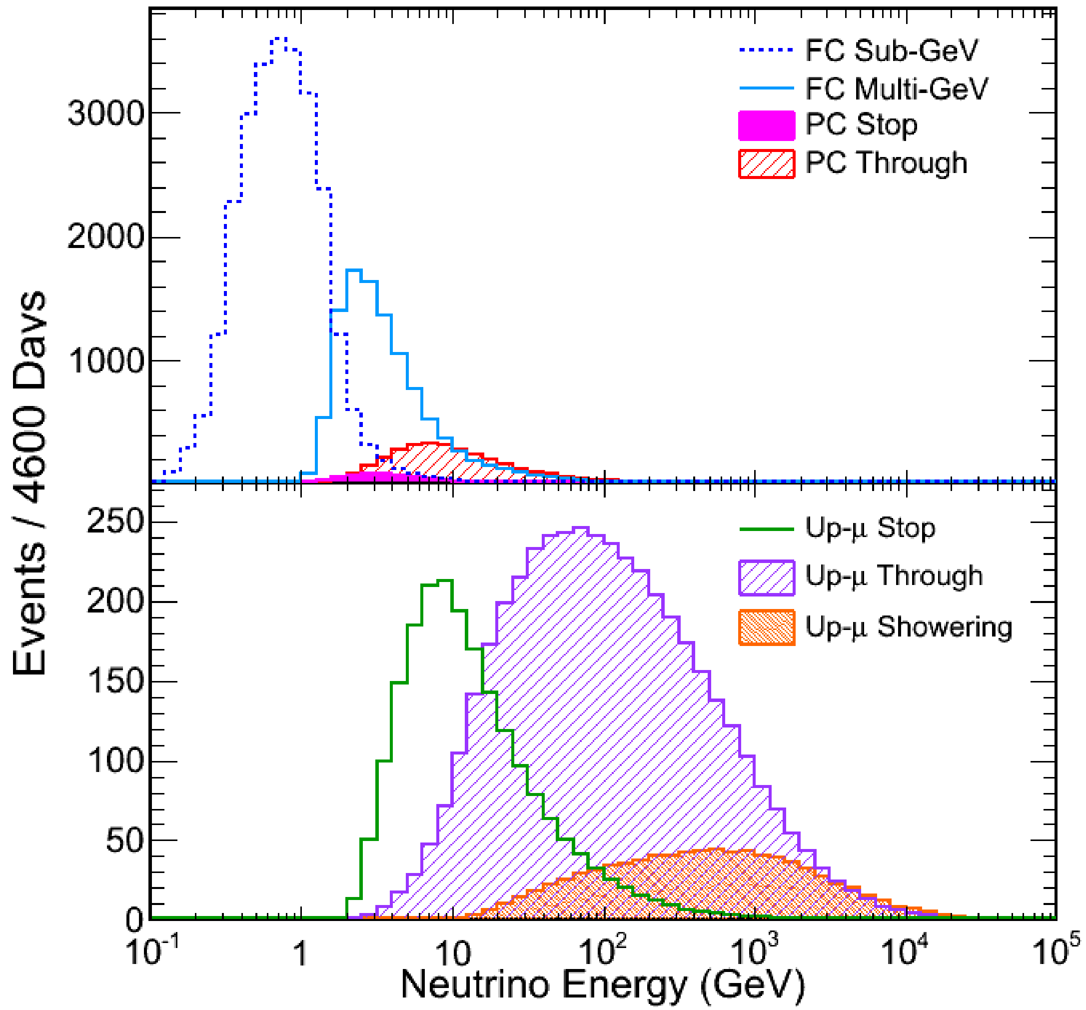


Partially Contained (PC)



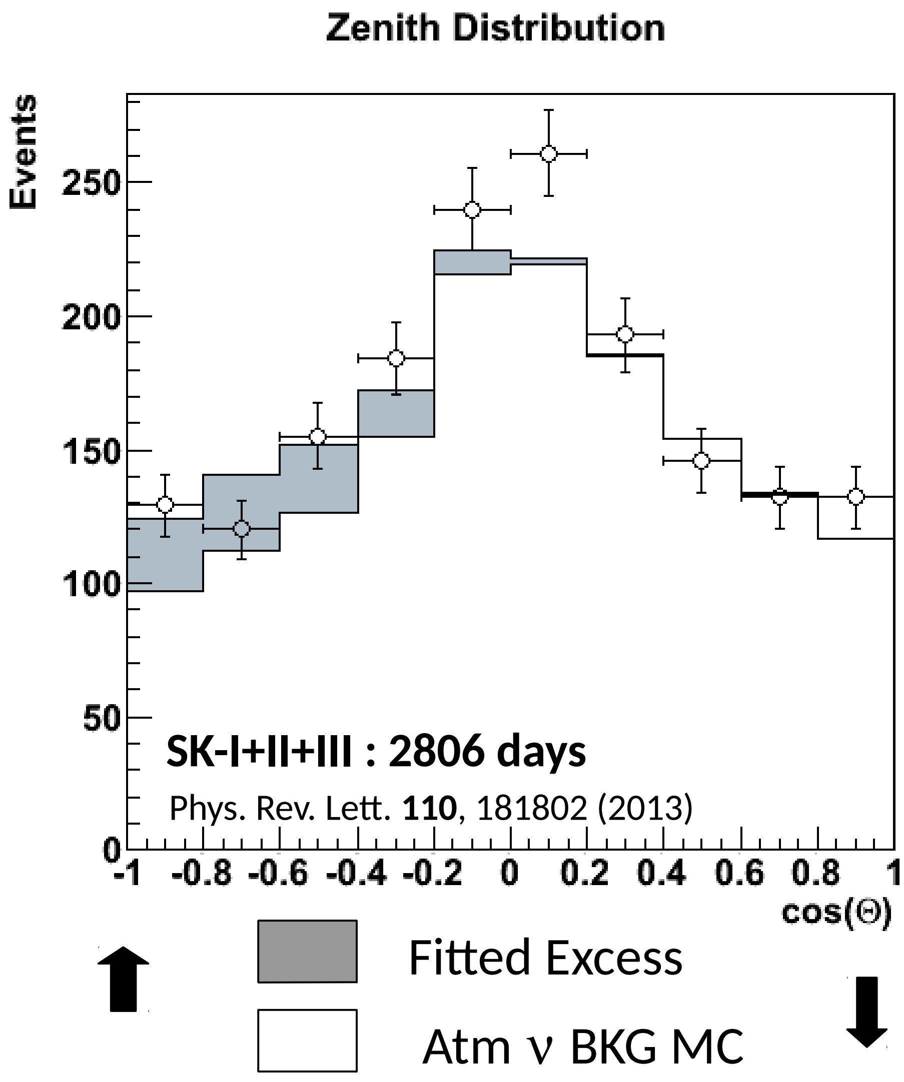
Upward-going Muons (Up-μ)





- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

Evidence for ν_τ Appearance at Super-K



- Search for events consistent with hadronic decays of τ leptons
  - Multi-ring e-like events, mostly DIS interactions
- Negligible primary ν_τ flux so ν_τ must be oscillation-induced : **upward-going**
- Event selection performed by neural network
  - Total efficiency of 60%

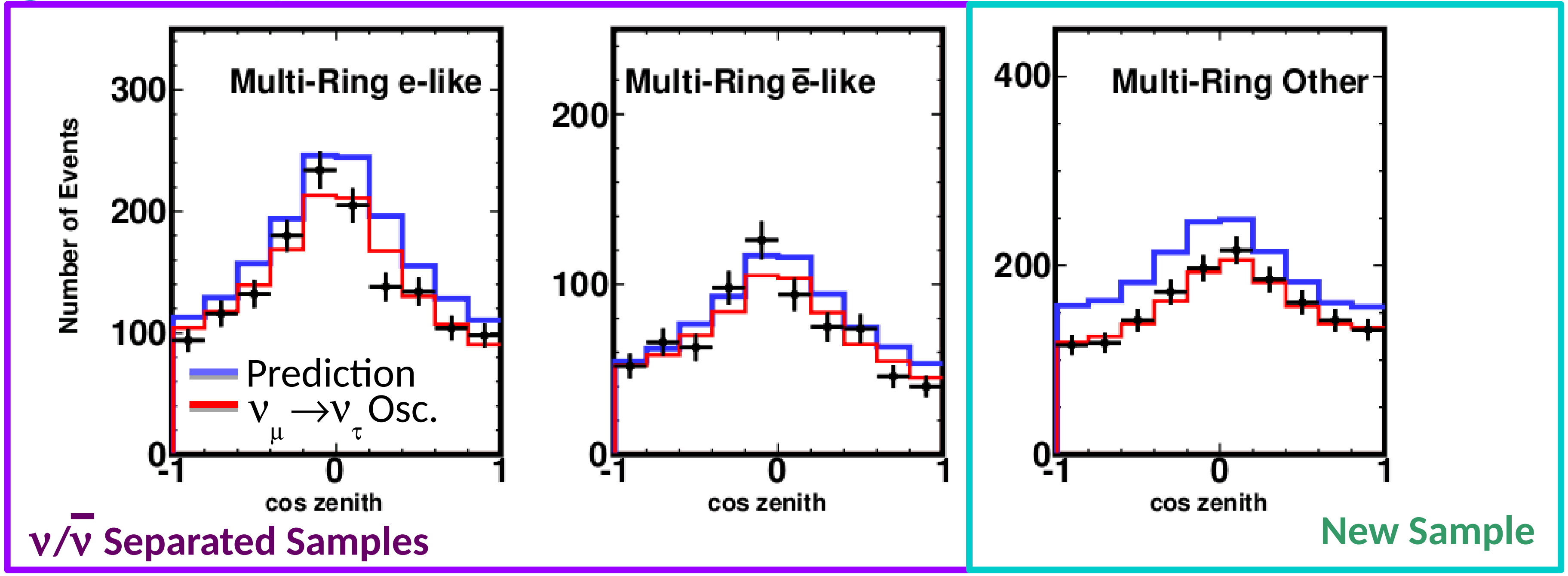
$\beta = 0$: no ν_τ

$$Data = \alpha(\gamma) \times bkg + \boxed{\beta}(\gamma) \times signal$$

Result	Background	DIS (γ)	Signal
SK-I+II+III	0.94 ± 0.02	1.10 ± 0.05	**1.42 ± 0.35**

This corresponds to **180.1** ±44.3 (stat) +17.8-15.2 (sys) events, a **3.8 σ** excess (Expected 2.7 σ significance)

Changes and Updates to Oscillation Analyses



- Addition of a new analysis sample
- Multi-Ring e-like Inclusive (Fully Contained)
  - Events that fail the multi-ring e-like selection
- Improved systematic error treatments
  - Updates to cross-section, FSI, detector systematics, 2p-2h (MEC) uncertainties
- 1775 days of SK-IV data: 4581.4 days total
  - (282.2 kton yrs)

Multi-Ring e-like Sample Purities

Purity	CC ν_e	CCν_μ	CCν_τ	NC
ν-like	72.2%	8.3%	3.2%	16.1%
$\bar{\nu}$-like	75.0%	6.5%	2.8%	15.6%
other	30.9%	33.4%	5.1%	30.5%

Sterile Neutrino Oscillations in Atmospheric Neutrinos

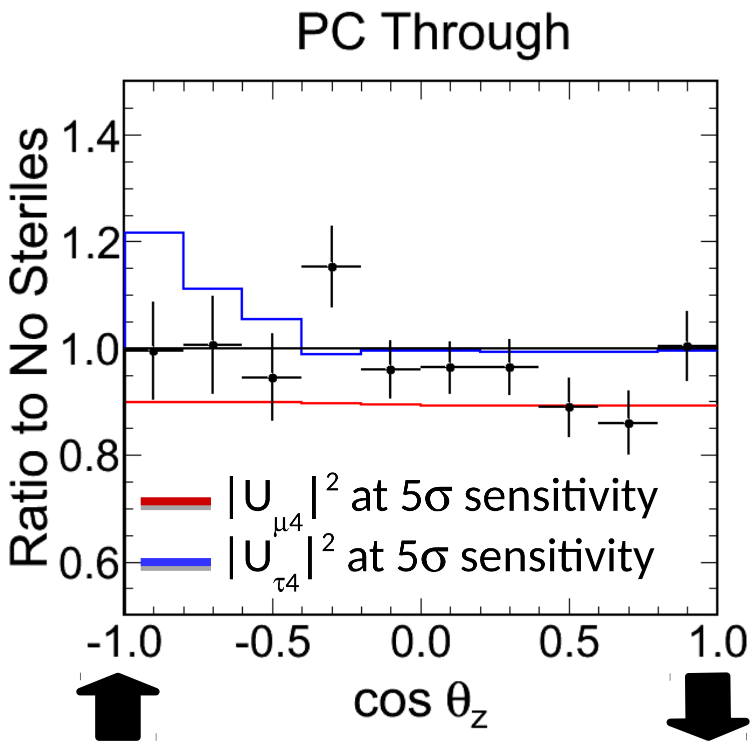
- Sterile Neutrino searches at SK are independent of the sterile Δm^2 and the number sterile neutrinos
  - 3+1 and 3+N models have the same signatures in atmospheric neutrinos
  - For $\Delta m_s^2 \sim 1$ eV^2 oscillations appear fast:

    $< \sin^2 \Delta m^2 L/E > \sim 0.5$

MNS **Sterile**

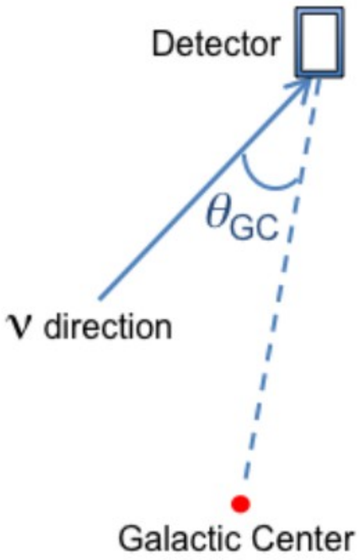
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- $| U_{\mu 4} |^2$
  - Induces a decrease in event rate of μ-like data of all energies and zenith angles
- $| U_{\tau 4} |^2$
  - Shape distortion of angular distribution of higher energy μ-like data

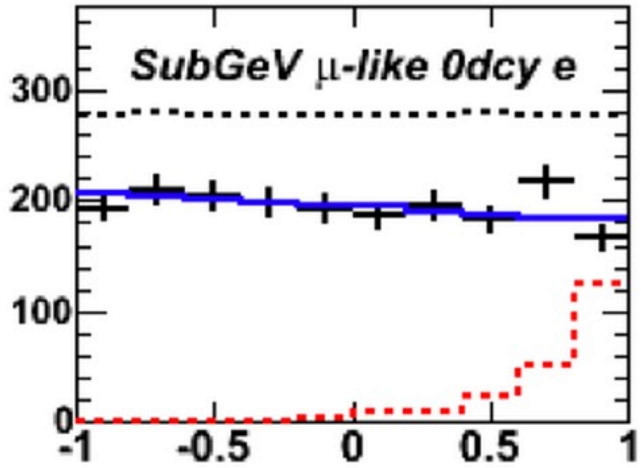


Search for WIMP Annihilations in the Galactic Center and Sun

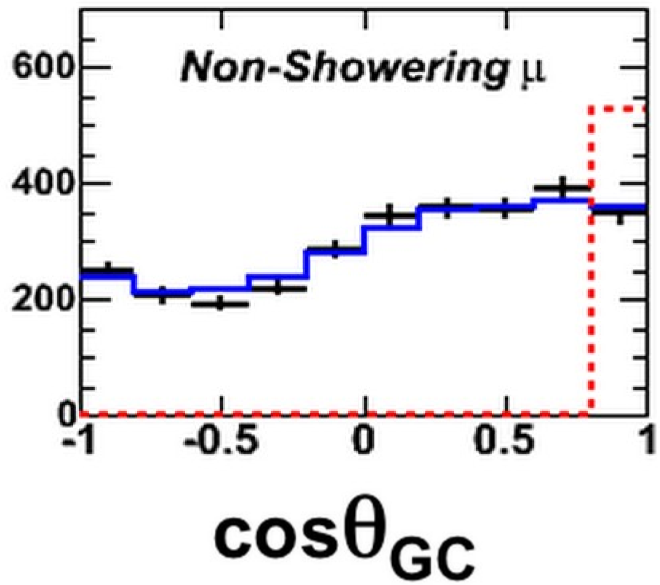
- Search for a signal of WIMP annihilation from the Galactic Halo or solar interior assuming several branching modes
  - $\nu\bar{\nu}$, $b\bar{b}$, $t\bar{t}$, W^+W^-
- Signal would appear atop the ATM ν background, peaked towards either the galactic center or towards the sun
- Simulate **signal** and detector response for all ν flavors
- Same analysis samples as oscillation analyses, but binned in angle to the galactic center
  - Use **all** samples
  - Previous analyses used only Up μ sample
  - Allows probe of both low O(GeV) and high O(TeV) WIMP masses



(Or Sun)

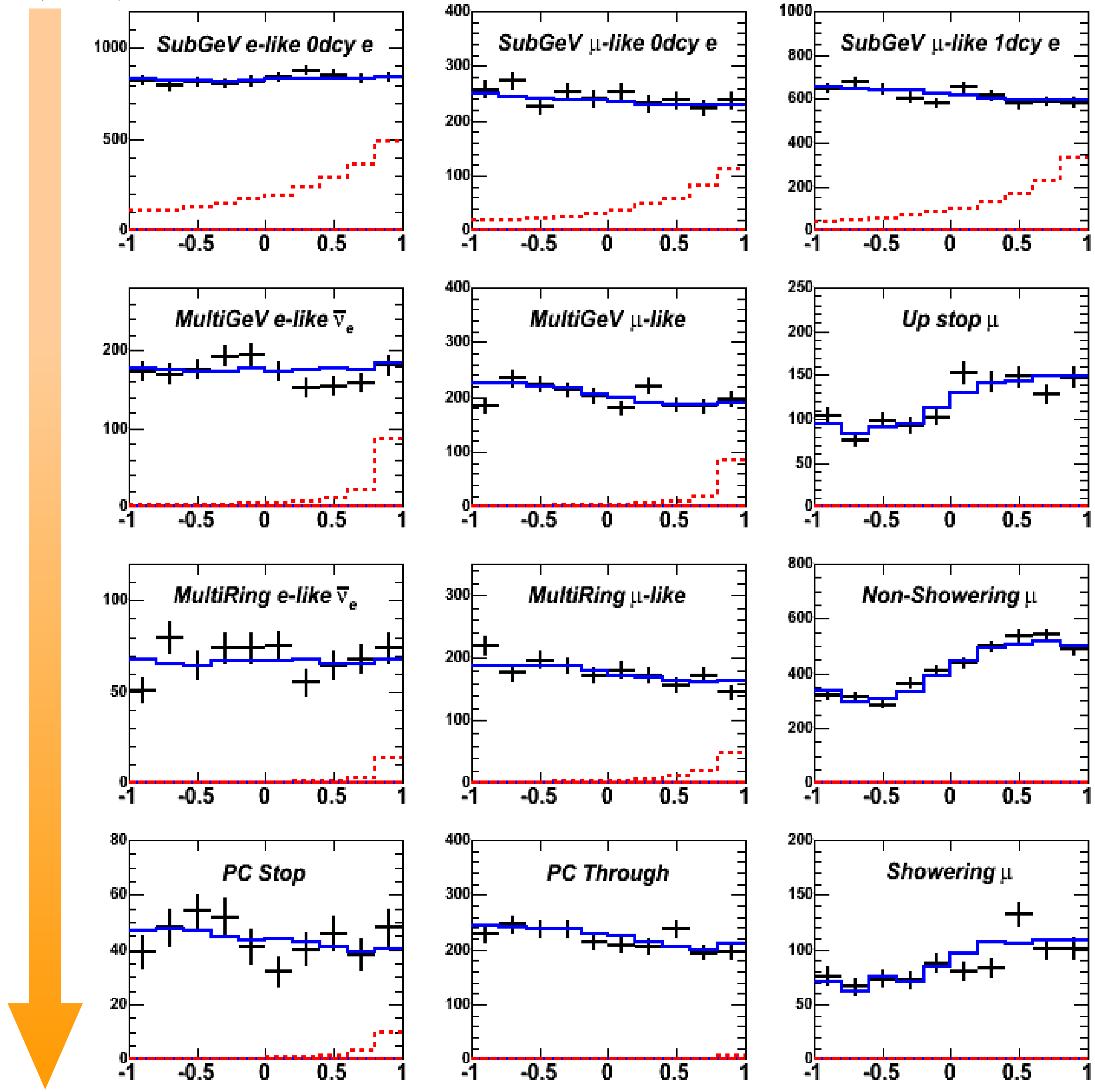


Signal Norm Arbitrary
ATM BG MC



Search for WIMP Annihilations : Signal Demonstration

O(100) MeV



O(10)–O(100+) GeV

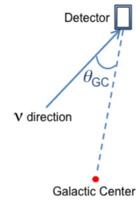
cos (θ_{GC})

$\chi\chi \rightarrow b\bar{b}$

$M(\chi)$ = **5 GeV / c^2**

WIMP Signal, **Best Fit** × 15

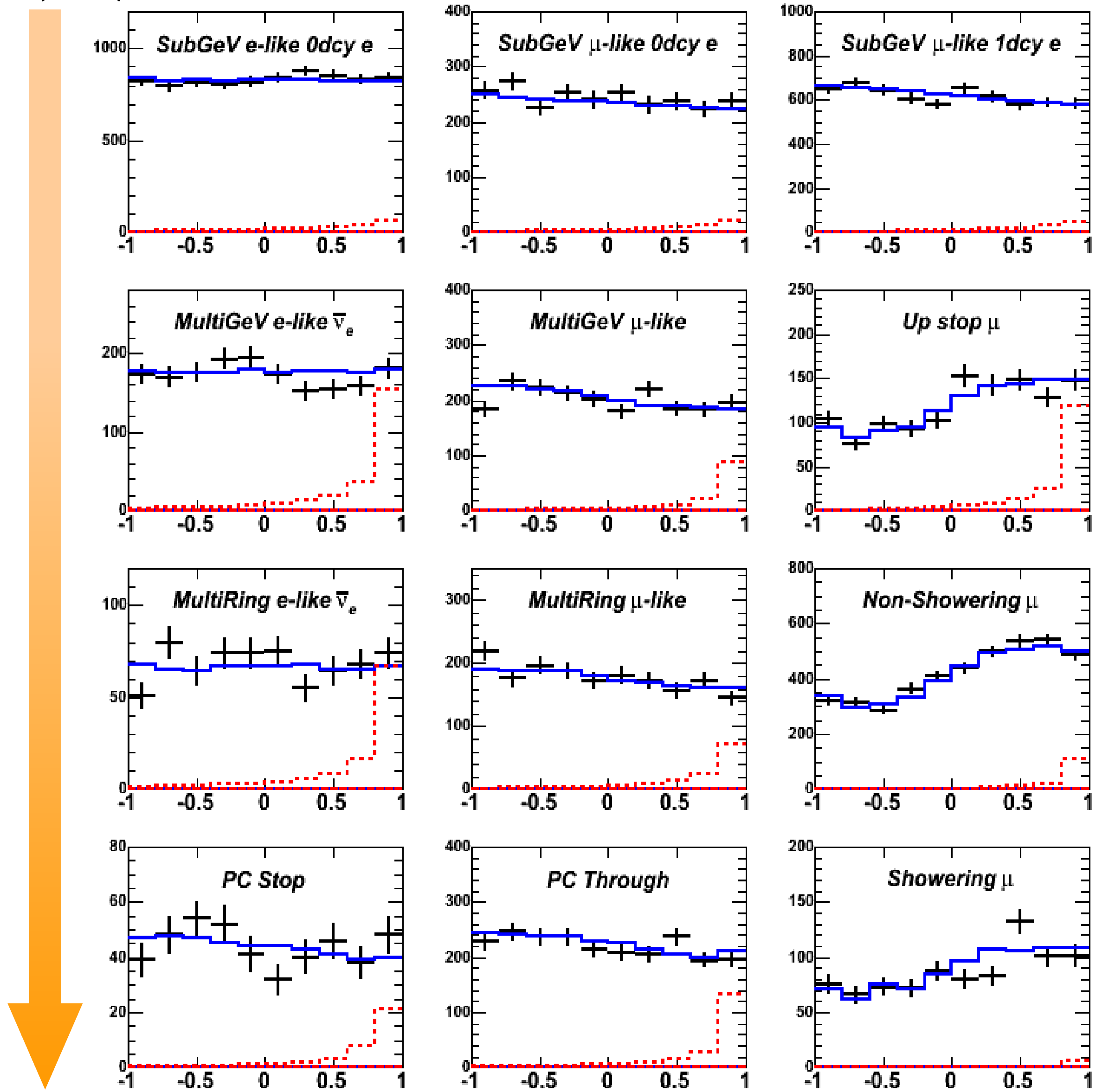
ATM ν Background + WIMP



- Analysis uses all available data
  - Previous analyses used only the upward-going muons
- 100% branching fraction assumed for each tested annihilation channel
- Equal fluxes at detection
  - $\phi(\nu_e) = \phi(\nu_\mu) = \phi(\nu_\tau)$

Search for WIMP Annihilations : Signal Demonstration

O(100) MeV



O(10)–O(100+) GeV

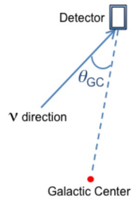
cos (θ_{GC})

$\chi\chi \rightarrow b\bar{b}$

M(χ) = **100 GeV / c^2**

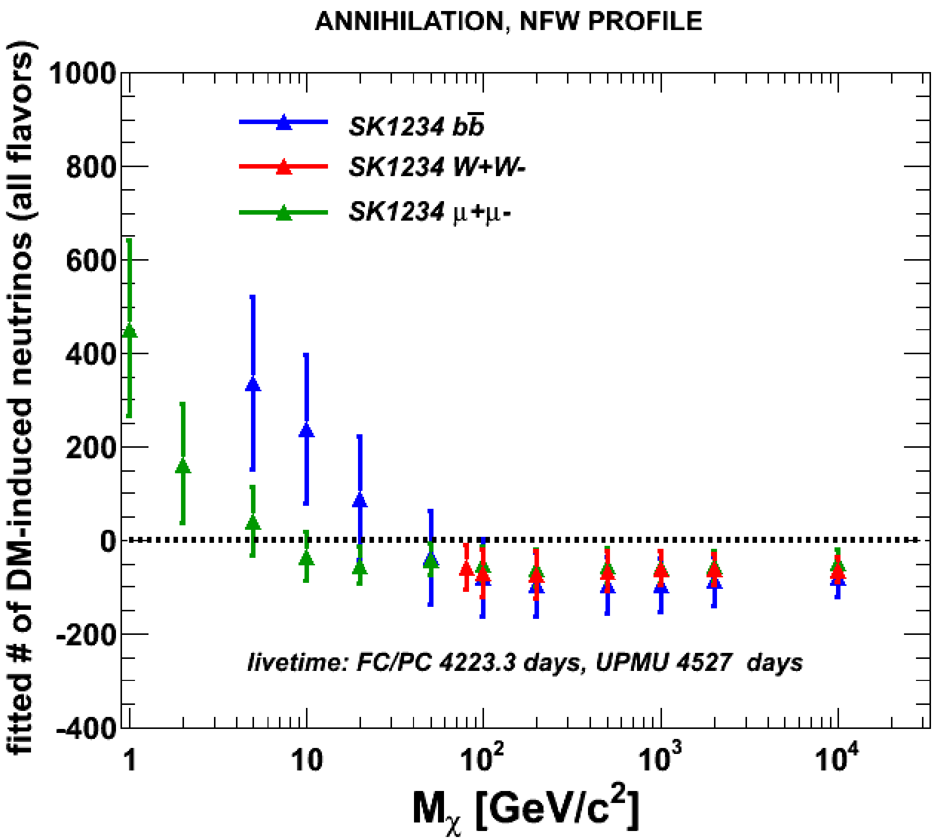
WIMP Signal, **Best Fit** × 15

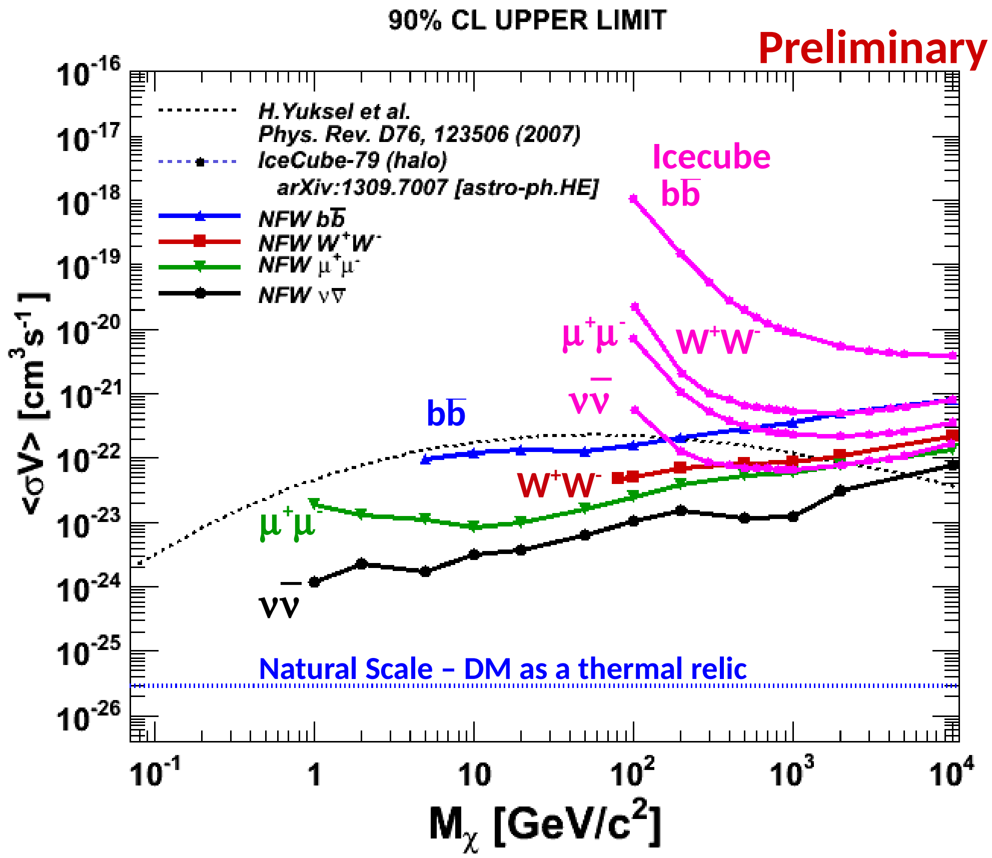
ATM ν Background + WIMP



- Analysis uses all available data
  - Previous analyses used only the upward-going muons
- 100% branching fraction assumed for each tested annihilation channel
- Equal fluxes at detection
  - $\phi(\nu_e) = \phi(\nu_\mu) = \phi(\nu_\tau)$

Search for WIMP Annihilations in the **Galactic Center**: Results

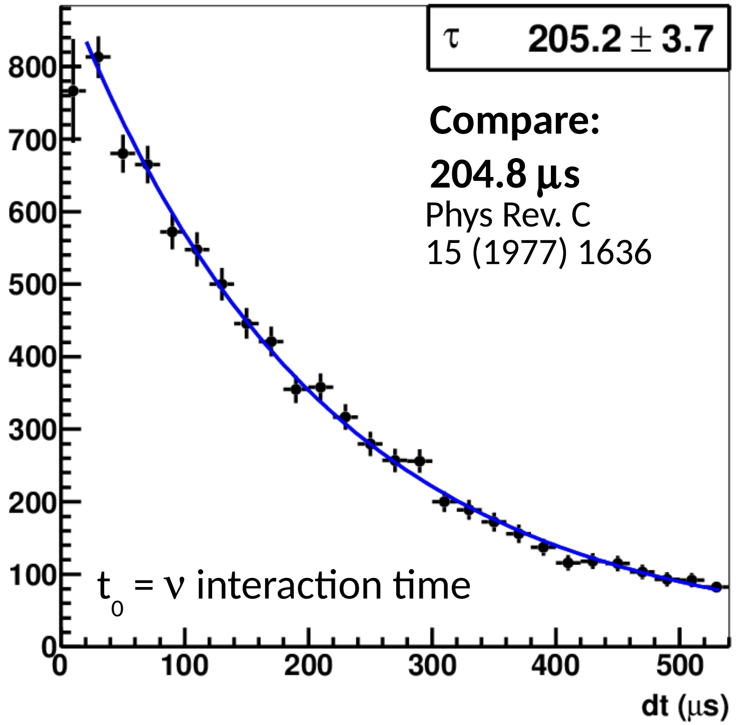


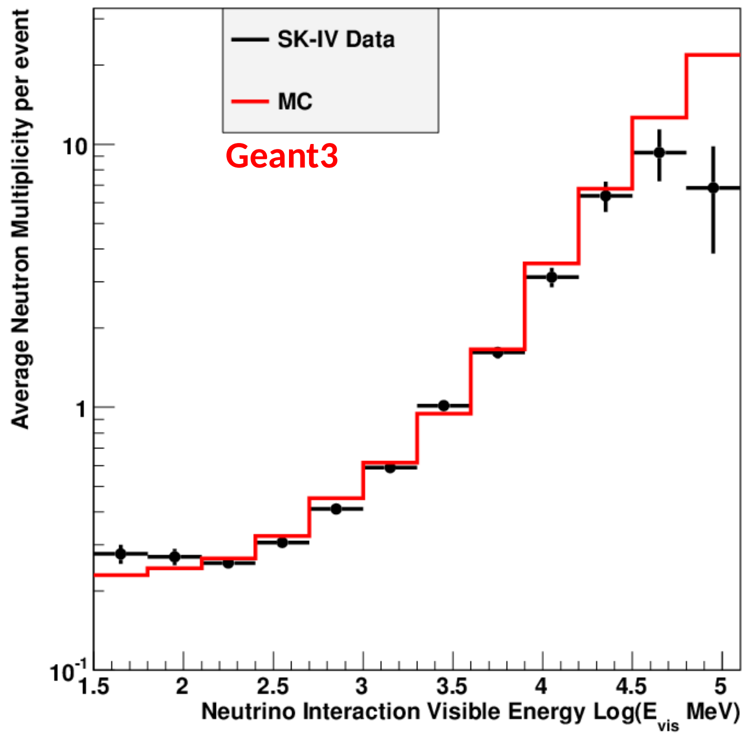


- No evidence for event excess on top of the atmospheric neutrino background
  - N.B. ~300 events allowed at 5 GeV test point are distributed over several analysis bins
- Stringent limits placed on the velocity-averaged annihilation cross section down to WIMP masses of 1 GeV ($\chi\chi \rightarrow \nu\bar{\nu}$)

Neutron Tagging

Preliminary





- Upgraded detector electronics in SK-IV store all PMT hits in a 500 μsec window after a physics trigger
  - Search for the 2.2 MeV gamma from p(n,γ)d
- Search is performed using a neural network built from 16 variables
  - Data and MC show good agreement on atmospheric neutrino sample
- **Future**: Implement neutron tagging to help distinguish $\nu/\bar{\nu}$ interactions and to reduce proton decay backgrounds

2.2 MeV γ Selection	
Efficiency	**20.5%**
Background / Event	**0.018**

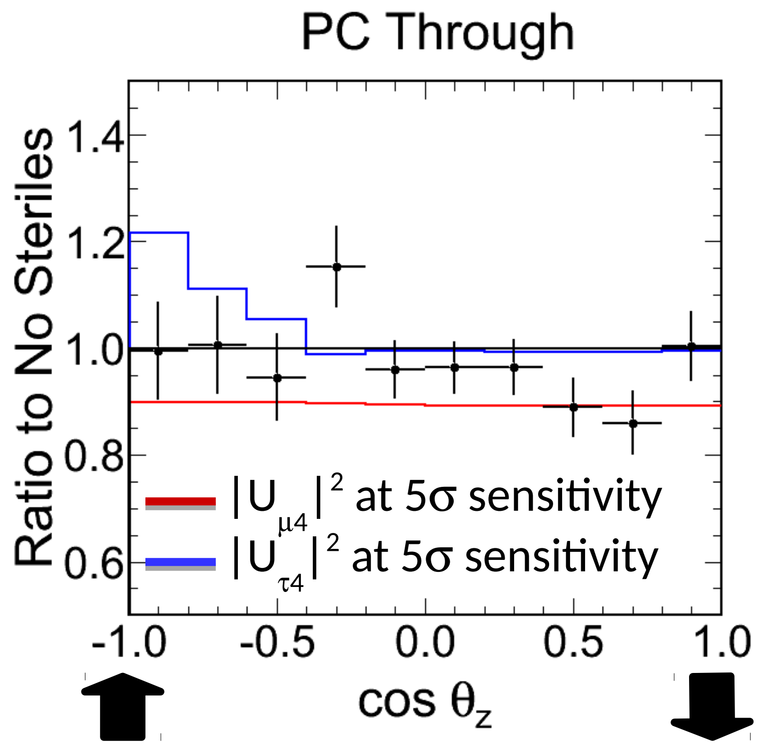
Sterile Neutrino Oscillations in Atmospheric Neutrinos

- Sterile Neutrino searches at SK are independent of the sterile Δm^2 and the number sterile neutrinos
  - 3+1 and 3+N models have the same signatures in atmospheric neutrinos
  - For $\Delta m_s^2 \sim 1$ eV^2 oscillations appear fast:

    $< \sin^2 \Delta m^2 L/E > \sim 0.5$

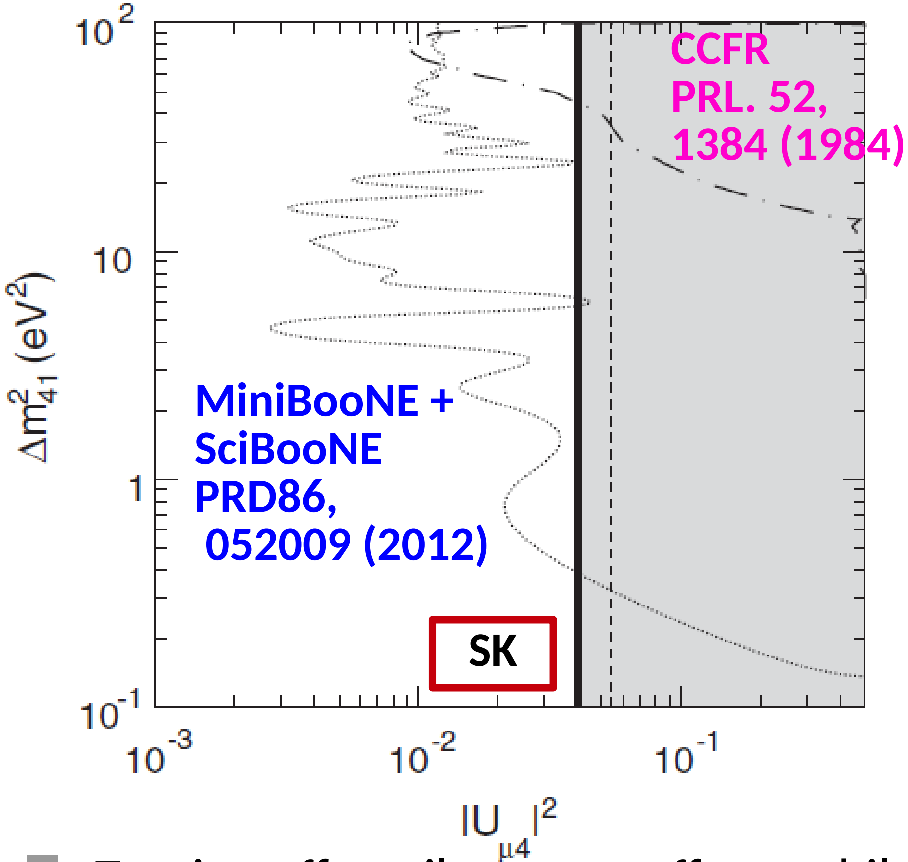
$$
\begin{array}{cc}
 & \begin{array}{ccccc} \text{MNS} & & & \text{Sterile} & \end{array} \\
U = & \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}
\end{array}
$$

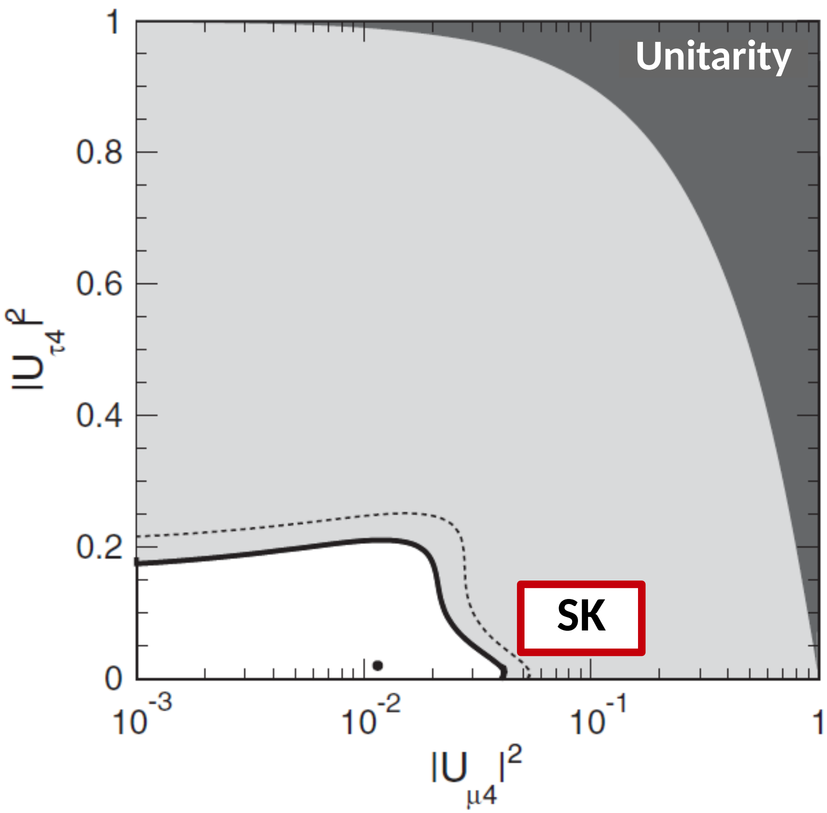
- $|U_{\mu 4}|^2$
  - Induces a decrease in event rate of μ-like data of all energies and zenith angles
- $|U_{\tau 4}|^2$
  - Shape distortion of angular distribution of higher energy μ-like data



Sterile Oscillations Results

PRD.91.052019 (2015)



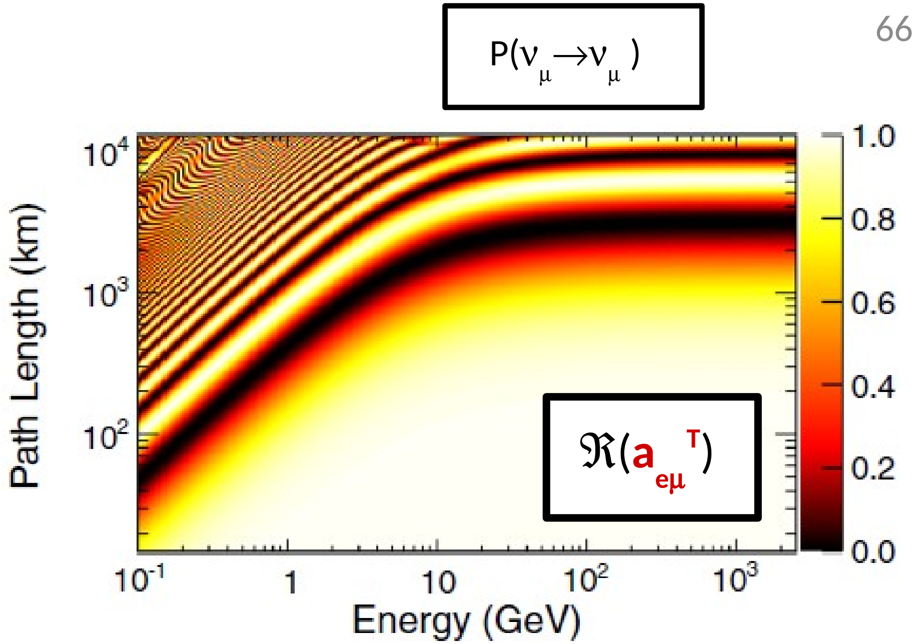


- Turning off sterile matter effects while preserving standard three-flavor oscillations provides a pure measurement of $|U_{\mu4}|^2$
- Using sterile matter effects, but decoupling ν_e oscillations provides a joint measurement of $|U_{\mu4}|^2$ and $|U_{\tau4}|^2$, with a slightly biased estimate of the former
- Using SK-I+II+III+IV data (4438 days)
  $|U_{\mu4}|^2 < 0.041$ at 90% C.L. $|U_{\tau4}|^2 < 0.18$ at 90% C.L.

Tests of Lorentz Invariance

$$H = UMU^\dagger + V_e + H_{LV}$$

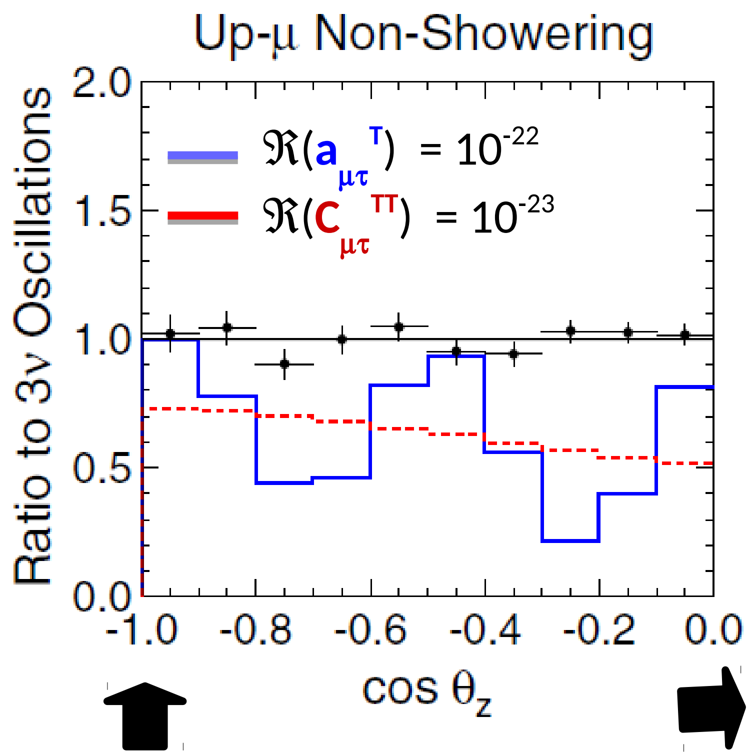
$$\boxed{\pm \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - E \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}}$$



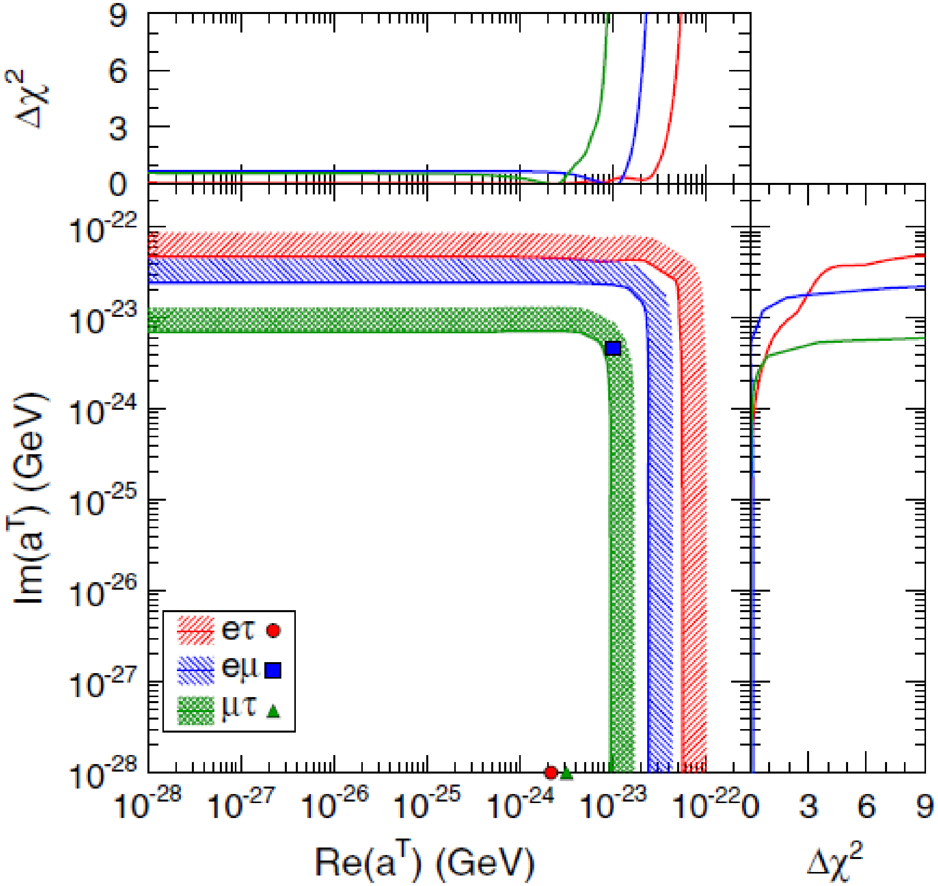
- Lorentz invariance violating effects can be probed using atmopsheric neutrinos
  - Focus here on **isotropic** effects
  - (sensitive to sidereal effects as well…)

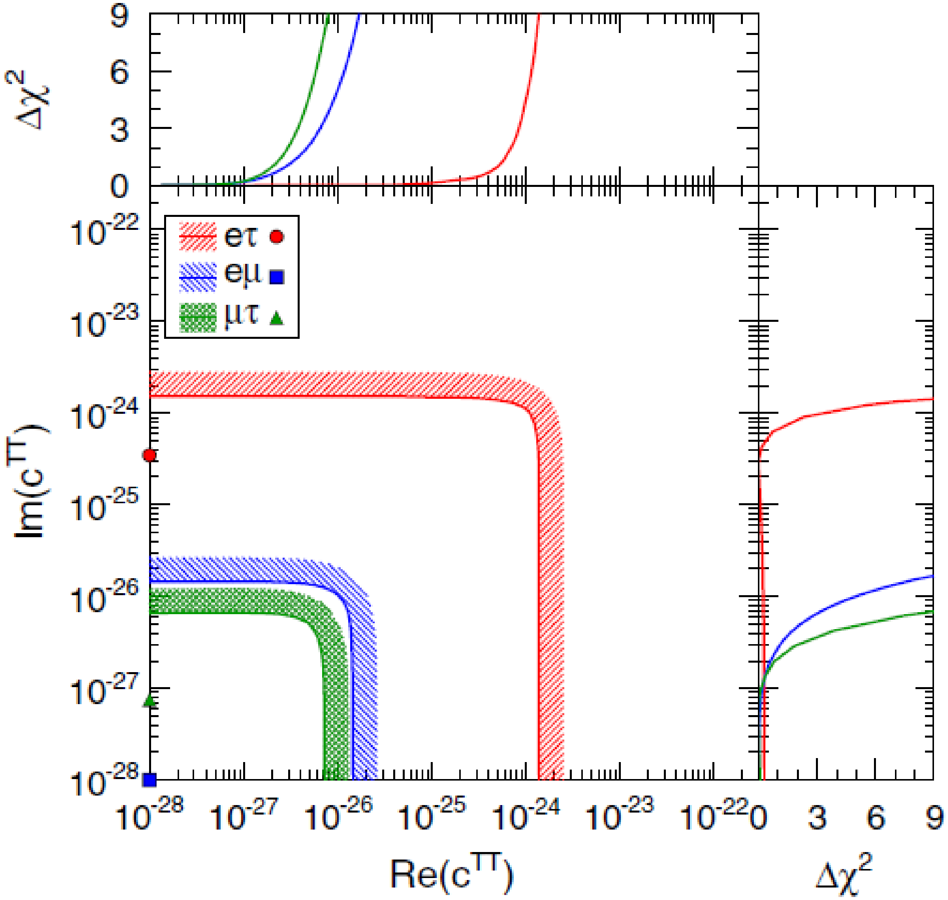
- Analysis using the Standard Model Extension (SME)
  - **Not a perturbative** calculation
  - Effects computed using full solutions of the Hamiltonian

- Effects of LIV controlled by two sets of complex parameters
  - $a^T_{\alpha\beta}$ dim = 3 induces oscillation effects ~ **L**
  - $c^{TT}_{\alpha\beta}$ dim = 4 induces oscillation effects ~ **L × E**



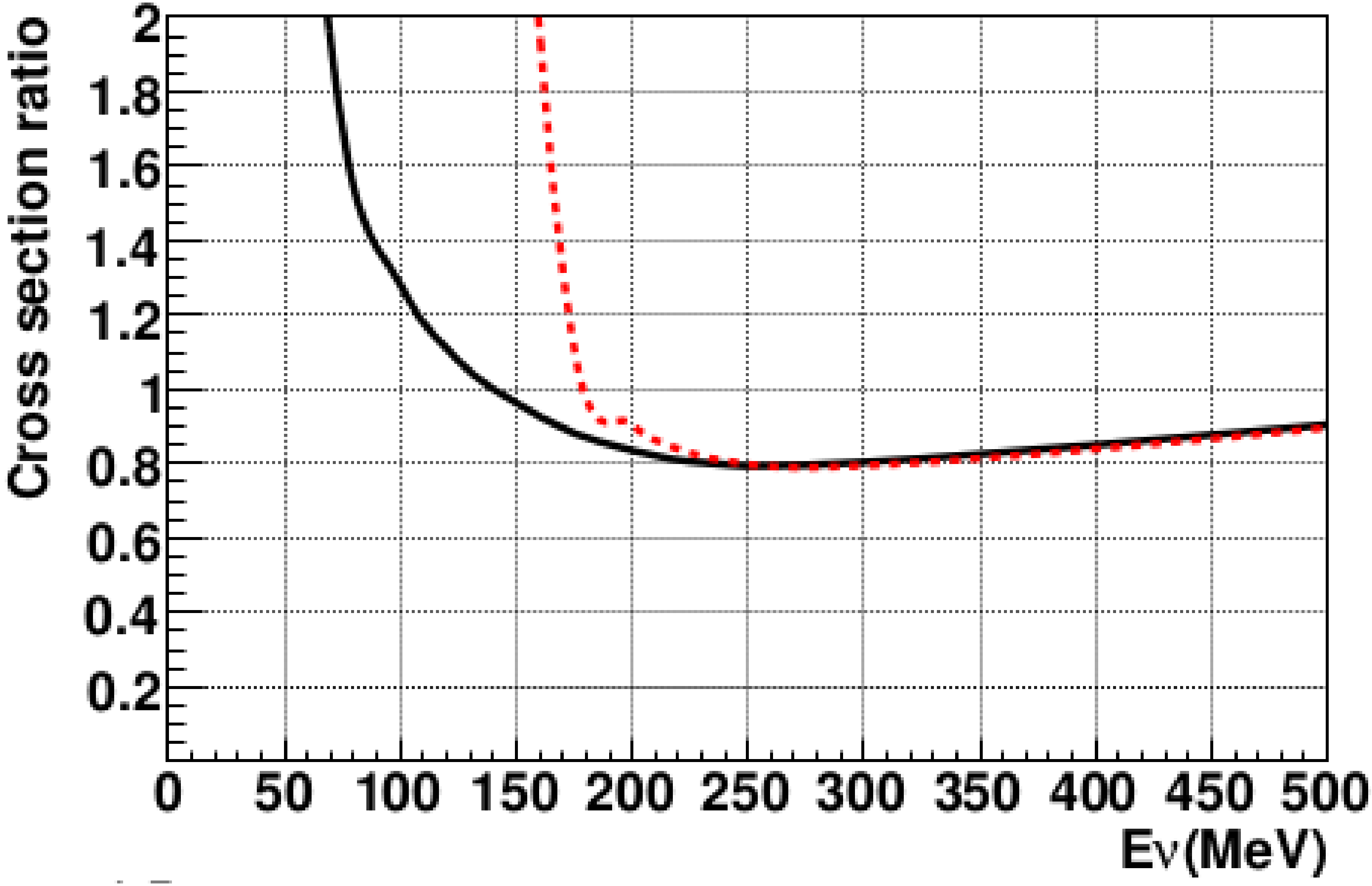
Constraints on Lorentz Invariance Violating Oscillations: **90% C.L.**





PRD.91.052019 (2015)

- SK-I+II+III+IV : 4438 days of data
- Perform separate fits on both hierarchy assumptions for each coefficient and each sector : eμ , eτ, μτ
- No indication of Lorentz invariance violation
  - Limits placed on the real and imaginary parts of **6 parameters** ≤ $O(10^{-23})$
  - New limits on μτ sector, improvements by **3 to 7** orders of magnitude over existing limits


Cross section ratio
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
50
100
150
200
250
300
350
400
450
500
Eν(MeV)

Systematic error			Fit value (%)	σ (%)
Flux normalization	$E_\nu < 1$ GeV[a]		21	25
	$E_\nu > 1$ GeV[b]		1.7	15
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$	$E_\nu < 1$ GeV		−0.25	2
	$1 < E_\nu < 10$ GeV		−0.26	3
	$E_\nu > 10$ GeV[c]		6.7	5
$\bar{\nu}_e/\nu_e$	$E_\nu < 1$ GeV		2.5	5
	$1 < E_\nu < 10$ GeV		2.6	5
	$E_\nu > 10$ GeV[d]		2.6	8
$\bar{\nu}_\mu/\nu_\mu$	$E_\nu < 1$ GeV		0.021	2
	$1 < E_\nu < 10$ GeV		1.9	6
	$E_\nu > 10$ GeV[e]		4.2	15
Up/down ratio	< 400 MeV	e-like	−0.0037	0.1
		μ-like	−0.011	0.3
		0-decay μ-like	−0.041	1.1
	> 400 MeV	e-like	−0.029	0.8
		μ-like	−0.018	0.5
		0-decay μ-like	−0.063	1.7
	Multi-GeV	e-like	−0.026	0.7
		μ-like	−0.0074	0.2
	Multi-ring sub-GeV	e-like	−0.015	0.4
		μ-like	−0.0074	0.2
	Multi-ring multi-GeV	e-like	−0.011	0.3
		μ-like	−0.0074	0.2
	PC		−0.0074	0.2

Horizontal/vertical ratio	< 400 MeV	e-like	0.011	0.1
		μ-like	0.011	0.1
		0-decay μ-like	0.033	0.3
	> 400 MeV	e-like	0.15	1.4
		μ-like	0.21	1.9
		0-decay μ-like	0.15	1.4
	Multi-GeV	e-like	0.35	3.2
		μ-like	0.25	2.3
	Multi-ring sub-GeV	e-like	0.15	1.4
		μ-like	0.14	1.3
	Multi-ring multi-GeV	e-like	0.31	2.8
		μ-like	0.17	1.5
	PC		0.19	1.7
K/π ratio in flux calculation[f]			1.3	10
Neutrino path length			0.094	10
Sample-by-sample	FC multi-GeV		−5.8	5
	PC + stopping UP-μ		0.79	5
Matter effects			1.8	6.8

[a]Uncertainty decreases linearly with $\log E_\nu$ from 25% (0.1 GeV) to 7% (1 GeV).
[b]Uncertainty is 7% up to 10 GeV, linearly increases with $\log E_\nu$ from 7% (10 GeV) to 12% (100 GeV) and then to 20% (1 TeV).
[c]Uncertainty linearly increases with $\log E_\nu$ from 5% (30 GeV) to 30% (1 TeV).
[d]Uncertainty linearly increases with $\log E_\nu$ from 8% (100 GeV) to 20% (1 TeV).
[e]Uncertainty linearly increases with $\log E_\nu$ from 6% (50 GeV) to 40% (1 TeV).
[f]Uncertainty increases linearly from 5% to 20% between 100 GeV and 1 TeV.

Systematic error		Fit value (%)	σ (%)
M_A in QE and single π		−6.4	10
CCQE cross section[a]		1.8	10
CCQE $\bar{\nu}/\nu$ ratio[a]		18	10
CCQE μ/e ratio[a]		0.12	10
Single meson production cross section		14	20
DIS cross section		2.2	5
DIS model comparisons[b]		−1.5	10
DIS Q^2 distribution (high W)[c]		0.003	10
DIS Q^2 distribution (low W)[c]		−3.1	10
Coherent π production		1.8	100
NC/CC		9.8	20
ν_τ cross section		−4.6	25
Single π production, $\pi^0/\pi^\pm$		−35	40
Single π production, $\bar{\nu}_i/\nu_i$ $(i = e, \mu)$[d]		−11	10
NC fraction from hadron simulation		−3	10
π^+ decay uncertainty sub-GeV 1-ring	e-like 0-decay	−0.48	0.6
	μ-like 0-decay	−0.64	0.8
	e-like 1-decay	3.3	4.1
	μ-like 1-decay	0.71	0.9
	μ-like 2-decay	4.5	5.7
$\Delta m^2{}_{32}$ [15]		2	3.98
$\sin^2(\theta_{23})$ [15]		2.8	10.9
$\Delta m^2{}_{21}$ [3]		0.079	2.55
$\sin^2(\theta_{12})$ [3]		0.42	6.89
$\sin^2(2\theta_{13})$ [45]		−0.55	10.5

[a]Difference from the Nieves [67] model is set to 1.0.
[b]Difference from CKMT [71] parametrization is set to 1.0.
[c]Difference from GRV98 [72] is set to 1.0.
[d]Difference from the Hernandez [73] model is set to 1.0.

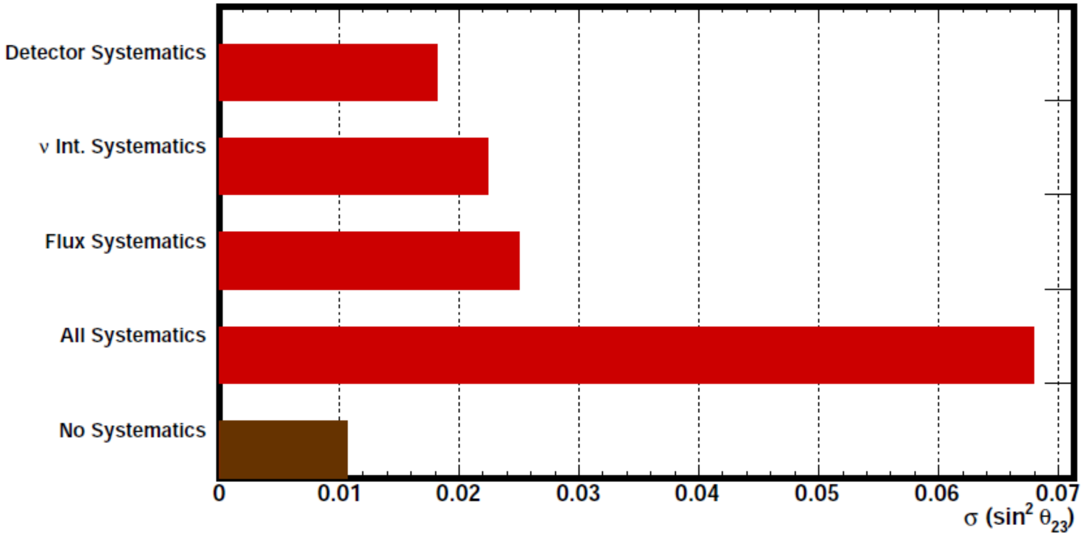
Systematic error		SK-I Fit value	SK-I σ	SK-II Fit value	SK-II σ	SK-III Fit value	SK-III σ	SK-IV Fit value	SK-IV σ
FC reduction		0.006	0.2	0.007	0.2	0.038	0.8	0.030	0.3
PC reduction		−0.99	2.4	−3.47	4.8	−0.041	0.5	−0.24	1
FC/PC separation		−0.027	0.6	0.081	0.5	0.003	0.9	0.0001	0.02
PC stopping/through-going separation (bottom)		−22.4	23	0.2	13	−0.2	12	−1.06	6.8
PC stopping/through-going separation (barrel)		1.88	7	−5.54	9.4	−9.0	29	−0.65	8.5
PC stopping/through-going separation (top)		8.3	46	−3.3	19	16.0	87	−3.3	40
Non-ν background	Sub-GeV μ-like	0.009	0.1	0.009	0.1	−0.009	0.1	−0.026	0.1
	Multi-GeV μ-like	0.036	0.4	0.009	0.1	−0.009	0.1	−0.026	0.1
	Sub-GeV 1-ring 0-decay μ-like	0.009	0.1	0.009	0.1	−0.018	0.2	−0.211	0.8
	PC	0.018	0.2	0.062	0.7	−0.16	1.8	−0.129	0.49
	Sub-GeV e-like	0.016	0.5	0.003	0.2	−0.003	0.1	−0.000	0.1
	Multi-GeV e-like	0.003	0.1	0.002	0.1	−0.013	0.4	−0.000	0.1
	Multi-GeV 1-ring e-like	3.3	13	−15.0	38	5.1	27	1.1	18
	Multi-GeV multiring e-like	1.1	12	2.5	11	−6.1	11	3.1	12
Fiducial volume		−0.04	2	0.08	2	−0.42	2	0.40	2

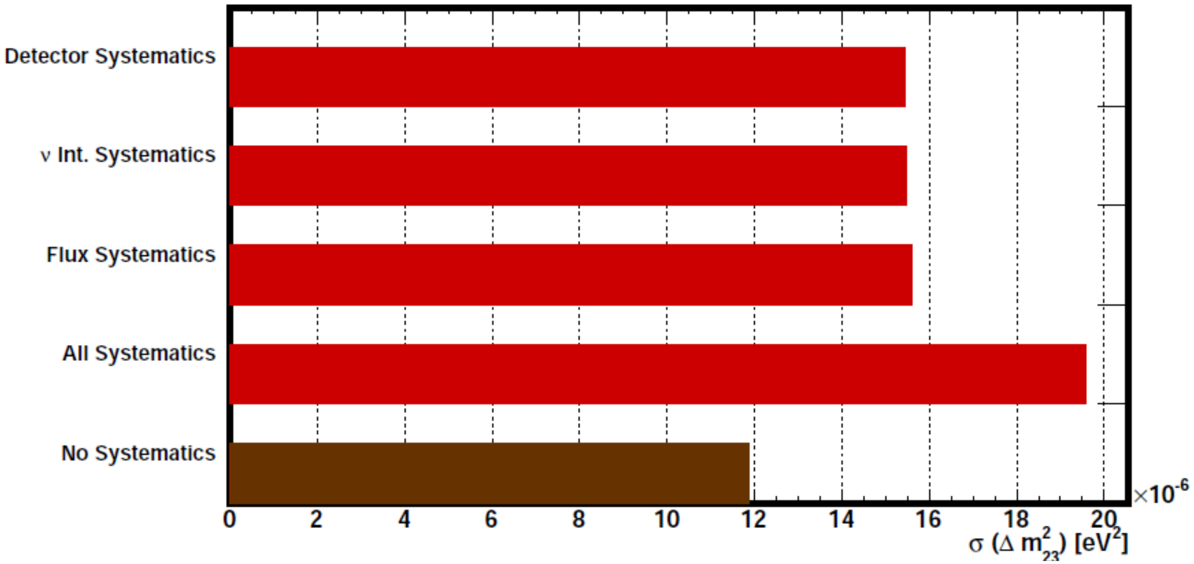
(Table continued)

Systematic error			SK-I Fit value	SK-I σ	SK-II Fit value	SK-II σ	SK-III Fit value	SK-III σ	SK-IV Fit value	SK-IV σ
Ring separation	< 400 MeV	e-like	1.07	2.3	−1.09	1.3	0.79	2.3	0.05	1.6
		μ-like	0.324	0.7	−1.93	2.3	1.03	3	0.09	3
	> 400 MeV	e-like	0.185	0.4	−1.43	1.7	0.44	1.3	−0.03	1
		μ-like	0.324	0.7	−0.588	0.7	0.205	0.6	−0.018	0.6
	Multi-GeV	e-like	1.71	3.7	−2.18	2.6	0.44	1.3	−0.03	1
		μ-like	0.79	1.7	−1.43	1.7	0.34	1	0.04	1.2
	Multiring Sub-GeV	e-like	−1.62	3.5	3.19	3.8	0.44	1.3	0.06	1.9
		μ-like	−2.08	4.5	6.88	8.2	−0.89	2.6	0.07	2.3
	Multiring multi-GeV	e-like	−1.44	3.1	1.59	1.9	−0.38	1.1	0.027	0.9
		μ-like	−1.90	4.1	0.671	0.8	−0.72	2.1	−0.07	2.4
Particle identification (1 ring)	Sub-GeV	e-like	0.016	0.23	0.099	0.66	0.023	0.26	−0.025	0.28
		μ-like	−0.013	0.18	−0.075	0.5	−0.016	0.19	0.020	0.22
	Multi-GeV	e-like	0.013	0.19	0.036	0.24	0.027	0.31	−0.031	0.35
		μ-like	−0.013	0.19	−0.039	0.26	−0.026	0.3	0.031	0.35
Particle identification (multiring)	Sub-GeV	e-like	−0.31	3.1	−3.39	6	5.09	9.5	2.15	4.2
		μ-like	0.066	0.66	1.45	2.5	−2.79	5.2	−0.80	1.6
	Multi-GeV	e-like	0.64	6.5	5.54	9.7	−2.63	4.9	1.71	3.3
		μ-like	−0.29	2.9	−2.24	3.9	1.43	2.7	−0.80	1.6
Energy calibration			0.00	1.1	−0.20	1.7	0.65	2.7	−0.36	2.3
Up/down asymmetry energy calibration			0.293	0.6	−0.070	0.6	0.36	1.3	−0.109	0.3
UP-μ reduction	Stopping		−0.185	0.7	−0.131	0.7	0.111	0.7	0.126	0.5
	Through-going		−0.132	0.5	−0.094	0.5	0.080	0.5	0.075	0.3
UP-μ stopping/through-going separation			0.007	0.4	0.016	0.6	0.034	0.4	−0.109	0.6
Energy cut for stopping UP-μ			0.085	0.9	0.11	1.3	0.87	2	0.01	1.7
Path length cut for through-going UP-μ			0.86	1.5	1.50	2.3	−0.12	2.8	−1.87	1.5
Through-going UP-μ showering separation			3.59	3.4	−2.84	4.4	2.35	2.4	−4.88	3
Background subtraction for UP-μ	Stopping[a]		10.2	16	−4.0	21	−2.2	20	−6.7	17
	Nonshowering[a]		−4.0	18	0.8	14	0.6	24	1.8	17
	Showering[a]		−7.5	18	−12.9	14	2.6	24	9.6	24
$\nu_e/\bar{\nu}_e$ separation			−2.67	7.2	0.08	7.9	−9.19	7.7	−4.07	6.8
Sub-GeV 1-ring π^0 selection	$100 < P_e < 250$ MeV/c		3.47	9	2.9	10	2.23	6.3	1.92	4.6
	$250 < P_e < 400$ MeV/c		3.55	9.2	4.1	14	1.73	4.9	1.25	3
	$400 < P_e < 630$ MeV/c		6.1	16	3.3	11	8.4	24	5.6	13
	$630 < P_e < 1000$ MeV/c		5.2	14	4.8	16	2.90	8.2	7.0	17
	$1000 < P_e < 1330$ MeV/c		4.5	12	2.87	9.8	3.9	11	9.9	24
Sub-GeV 2-ring π^0			0.31	5.6	−2.42	4.4	−1.17	5.9	1.78	5.6
Decay-e tagging			−5.5	10	−2.7	10	1.5	10	1.1	10
Solar activity			0.1	20	17.2	50	2.0	20	0.3	10

[a]The uncertainties in BG subtraction for upward-going muons are only for the most horizontal bin, $-0.1 < \cos\theta < 0$.

Other Systematics





MINOS Atm Nu

Parameter	Uncertainty	Best Fit (2 Osc. Param.)	Best Fit (4 Osc. Param.)
$\|\Delta m^2\|/\mathrm{eV}^2$		1.9×10^{-3}	2.2×10^{-3}
$\|\Delta \overline{m}^2\|/\mathrm{eV}^2$		1.9×10^{-3}	1.6×10^{-3}
$\sin^2 2\theta$		0.99	0.99
$\sin^2 2\overline{\theta}$		0.99	1.00
normalization (contained-vertex ν)	$\sigma = 15\,\%$	$+0.6\,\sigma$	$+0.7\,\sigma$
normalization (ν-induced rock-μ)	$\sigma = 25\,\%$	$+0.1\,\sigma$	$+0.1\,\sigma$
$up/down$ ratio (contained-vertex ν)	$\sigma = 3\,\%$	$-0.1\,\sigma$	$-0.1\,\sigma$
ν_e/ν_μ ratio (contained-vertex ν)	$\sigma = 5\,\%$	$-0.5\,\sigma$	$-0.5\,\sigma$
$\overline{\nu}_\mu/\nu_\mu$ ratio (contained-vertex ν)	$\sigma = 10\,\%$	$-0.5\,\sigma$	$-0.6\,\sigma$
$\overline{\nu}_\mu/\nu_\mu$ ratio (ν-induced rock-μ)	$\sigma = 12.5\,\%$	$+1.1\,\sigma$	$+0.9\,\sigma$
NC/CC ratio (contained-vertex ν)	$\sigma = 20\,\%$	$+0.6\,\sigma$	$+0.6\,\sigma$
ν spectrum parameter	$\sigma = 6\,\%$	$-0.4\,\sigma$	$-0.4\,\sigma$
$\overline{\nu}$ spectrum parameter	$\sigma = 6\,\%$	$+0.3\,\sigma$	$+0.3\,\sigma$
μ momentum (range)	$\sigma = 3\,\%$	$-0.3\,\sigma$	$-0.3\,\sigma$
μ momentum (curvature)	$\sigma = 5\,\%$	$+0.3\,\sigma$	$+0.3\,\sigma$
shower energy	$\sigma = 15\,\%$	$+0.4\,\sigma$	$+0.4\,\sigma$

TABLE III. Summary of systematic uncertainties included in the oscillation fit, along with the best fit oscillation and systematic parameters returned by each fit. For the two-parameter fit, equal oscillation parameters are used for neutrinos and antineutrinos; for the four-parameter fit, separate oscillation parameters are used. The best fit systematic parameters are given in units of standard deviations.