SK Atmospheric Neutrino Results

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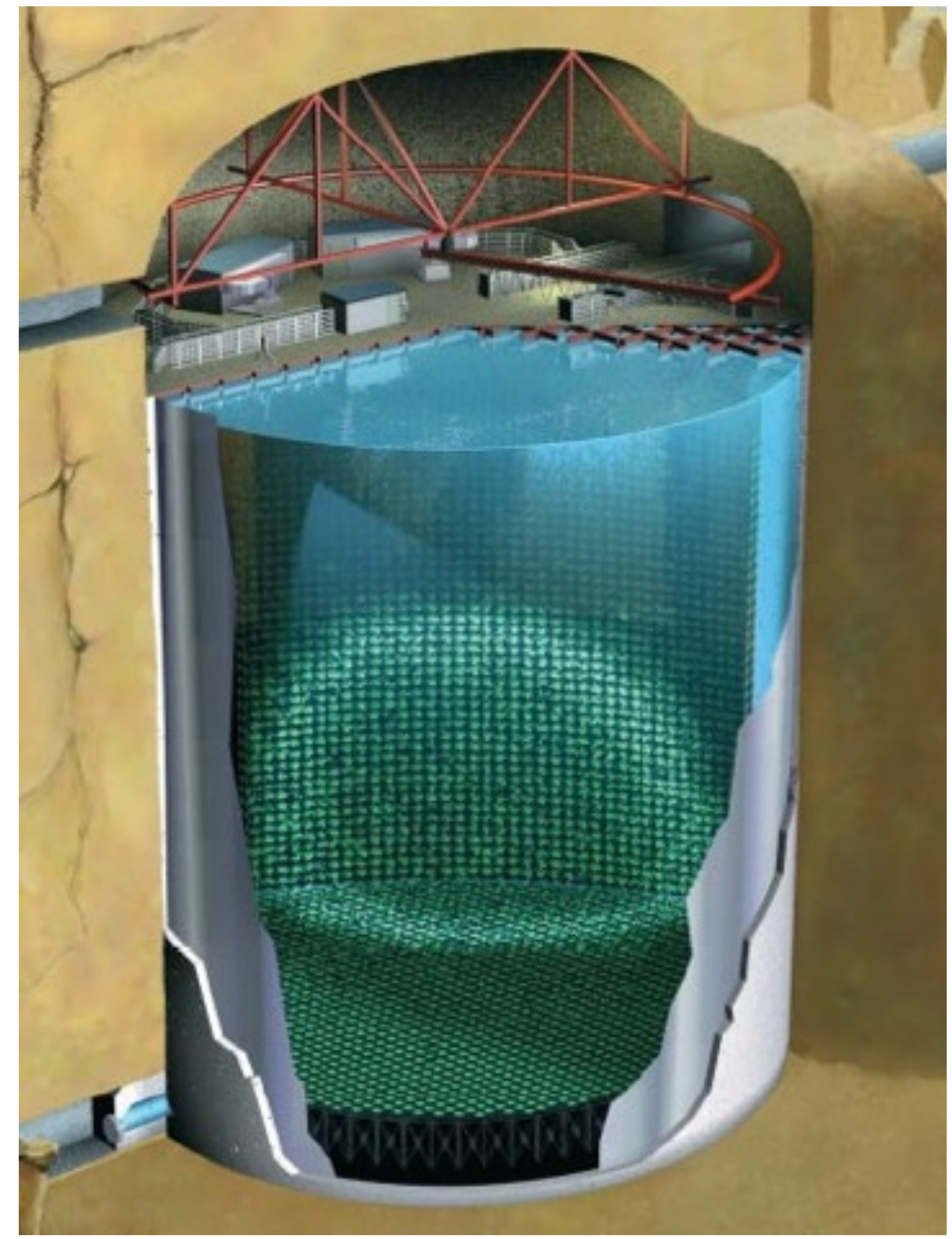
For the Super Kamiokande Collaboration

The Super Kamiokande Detector

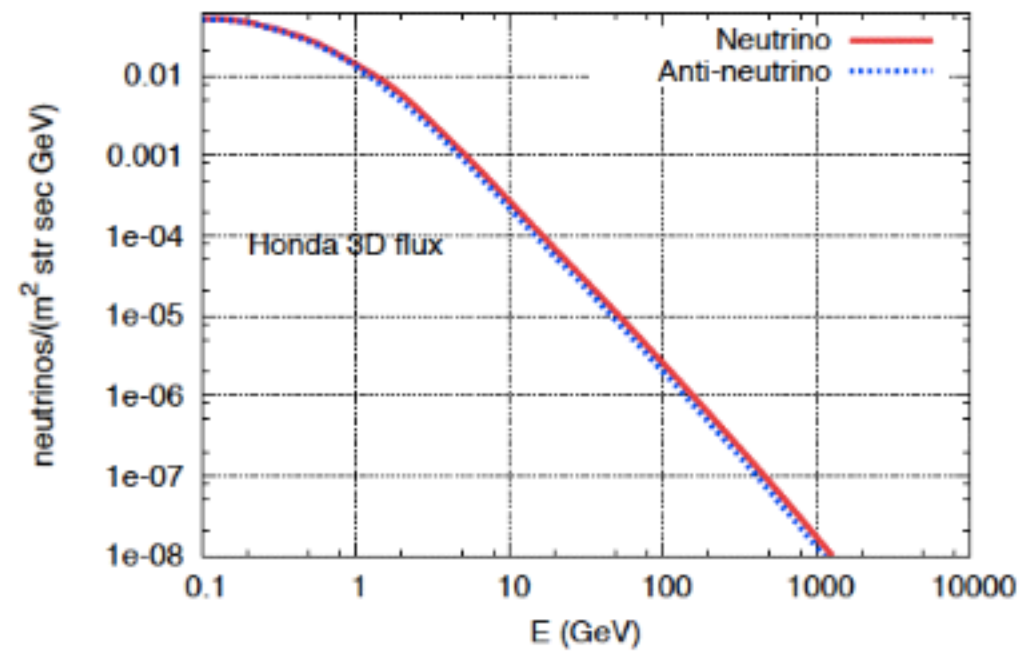


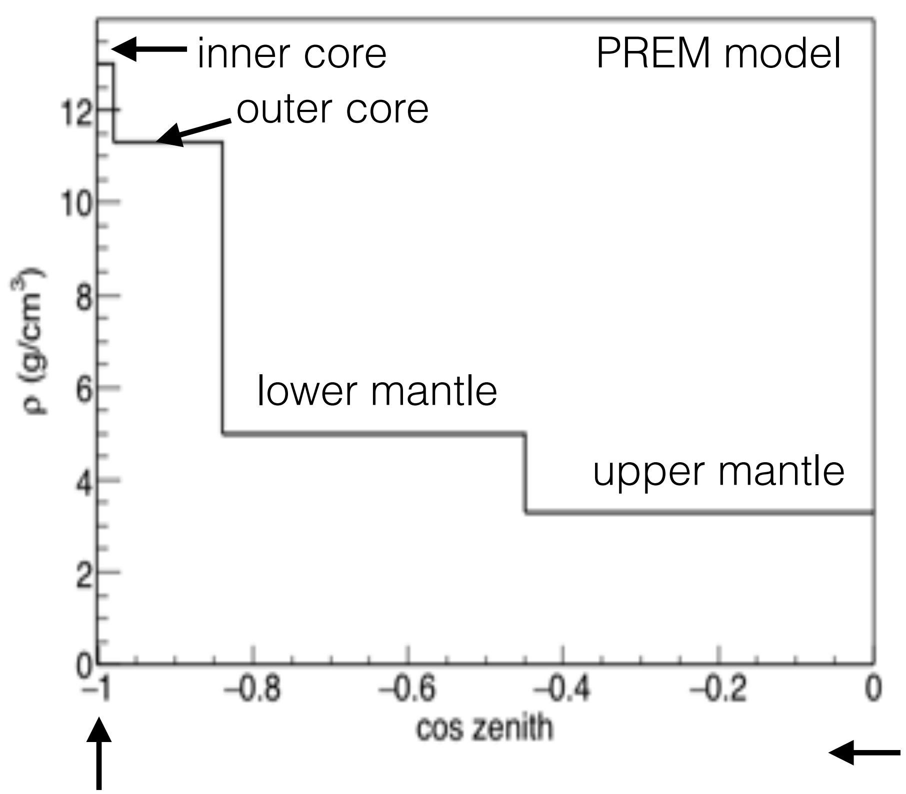
- 50 kT (22.5 kT fiducial) water cherenkov detector
  - ✦ Inner Detector: 11,146 20-inch PMTs facing inward
  - ✦ Outer Detector: 1,885 8-inch PMTs facing outward, optically separated from ID, provides cosmic ray veto
- Under Mt. Ikenoyama in Gifu, Japan
  - ✦ 1000 m rock overburden provides cosmic ray shielding
- 4 running periods (306 kT years)
  - ✦ SK-I: 1996-2001
  - ✦ SK-II: 2002-2005 (reduced photo-coverage due to SK accident)
  - ✦ SK-III: 2006-2008 (full photo-coverage recovered)
  - ✦ SK-IV: 2008-present (improved electronics)
- Multipurpose detector
  - ✦ Solar, supernova, and astrophysical neutrinos
  - ✦ Nucleon decay searches
  - ✦ T2K far detector
  - ✦ **Atmospheric neutrinos** ⟵ **this talk**

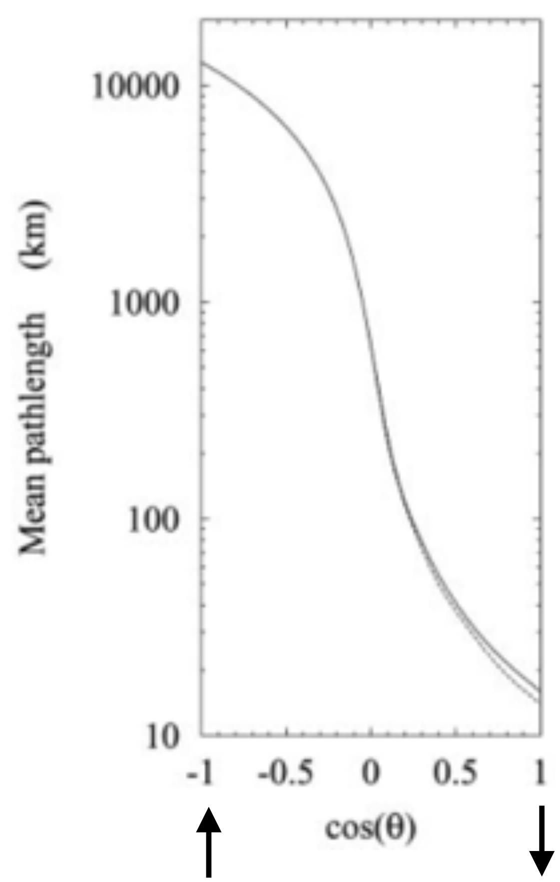
Atmospheric Neutrinos

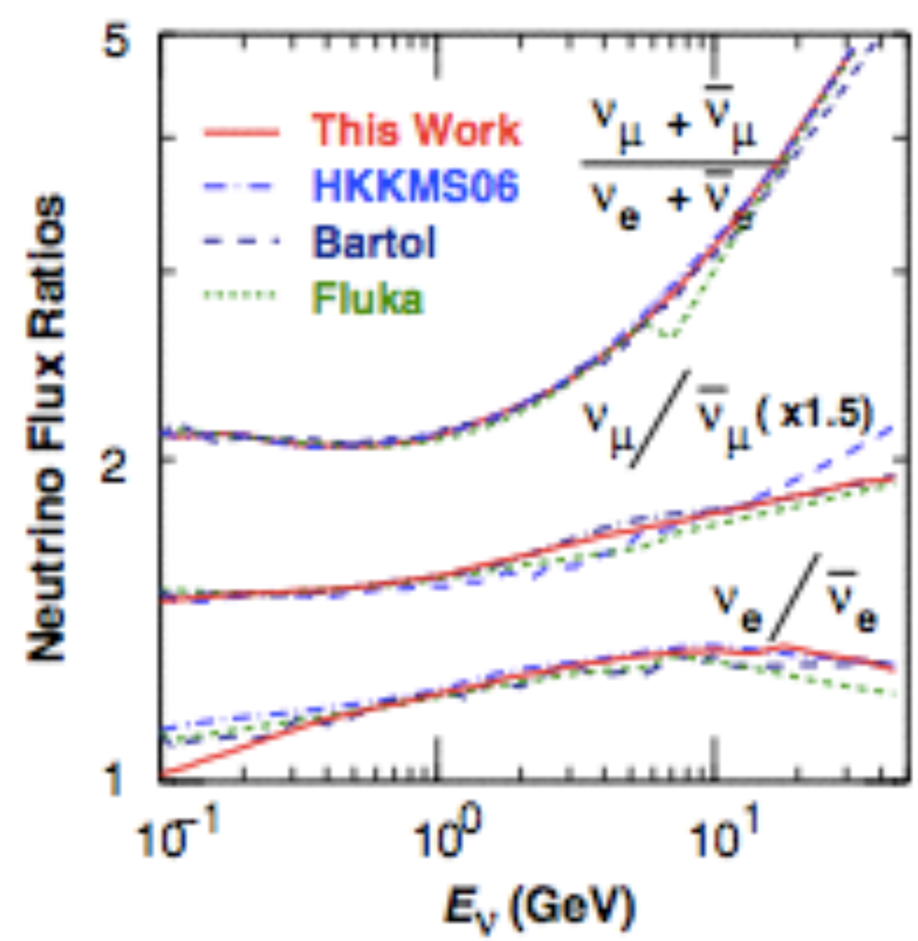
A constant, FREE, neutrino source (detectors cost $$)

- Exponential energy spectrum
- ν_μ/ν_e, $\nu/\bar{\nu}$, in well estimated ratios (<5% uncertainties on ratios)
- Baselines range from **10 to 10,000 km**
- Various densities of matter









M. Honda, et al. Phys. Rev. D **75**, 043006 (2007)

New : Measurement of the Atmospheric Neutrino Flux

For oscillation analyses we have used a model from Honda, et al.

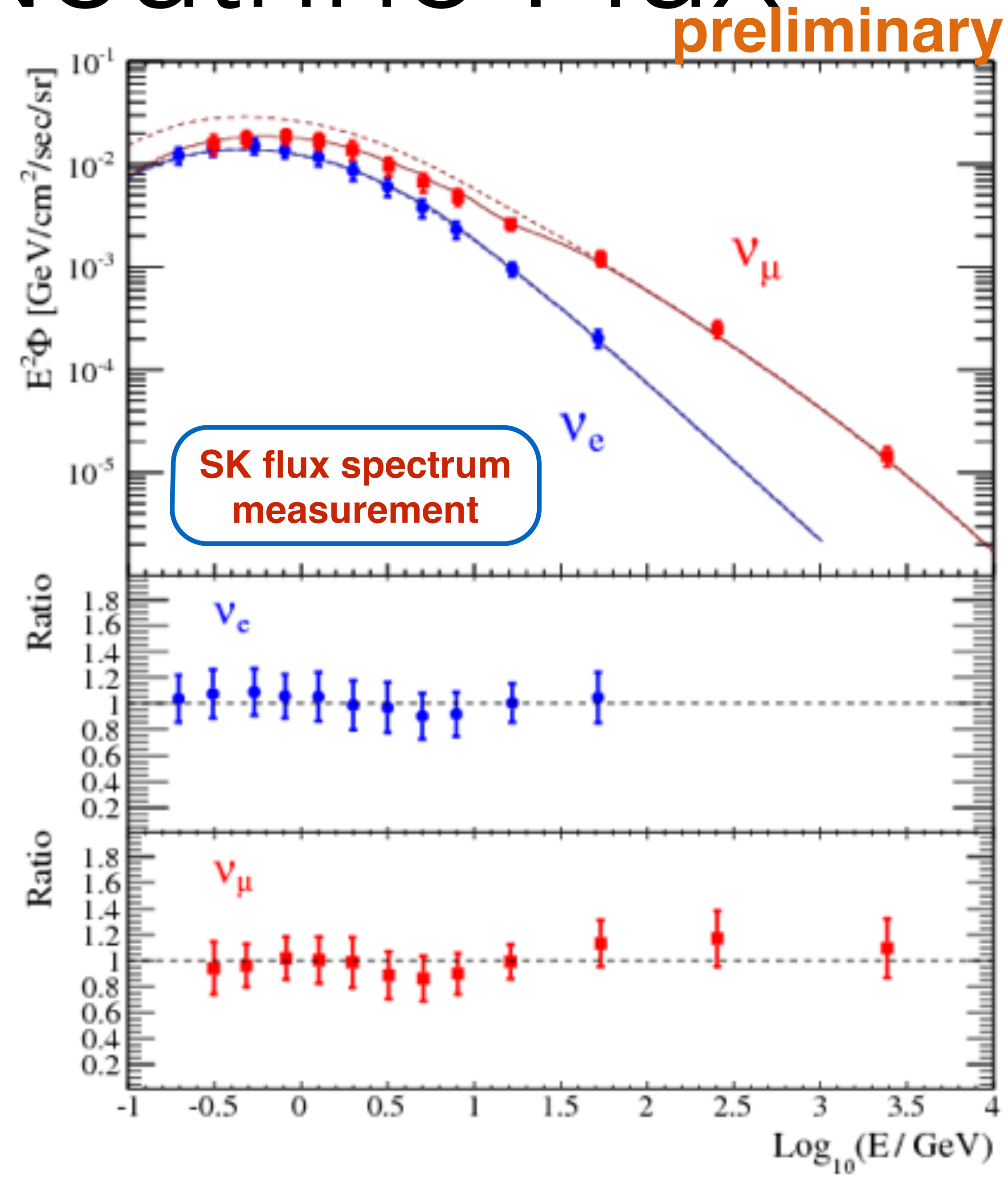
- primary cosmic rays + hadron production in atmosphere + transport to detector
- 7-25% absolute flux uncertainty
- 2-5% flux ratio uncertainties

Now we have measured the flux spectrum

- Bayesian unfolding: transpose reconstructed variable bins into true variable bins
- ~20% uncertainty in measurements

Also try to observe predicted effects

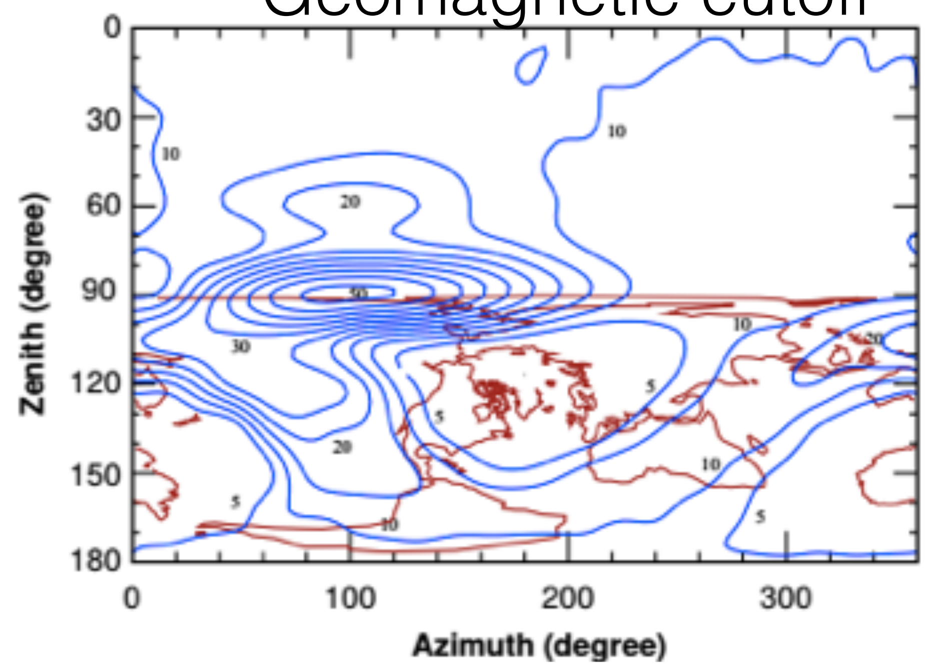
- Earth's magnetic field
- solar activity



Example: Earth's Magnetic Field

- Azimuthal asymmetry predicted in flux due to azimuthal asymmetry in geomagnetic cutoff
- Should be zenith and energy dependent
- We see azimuthal asymmetry with zenith and energy dependence consistent with this effect

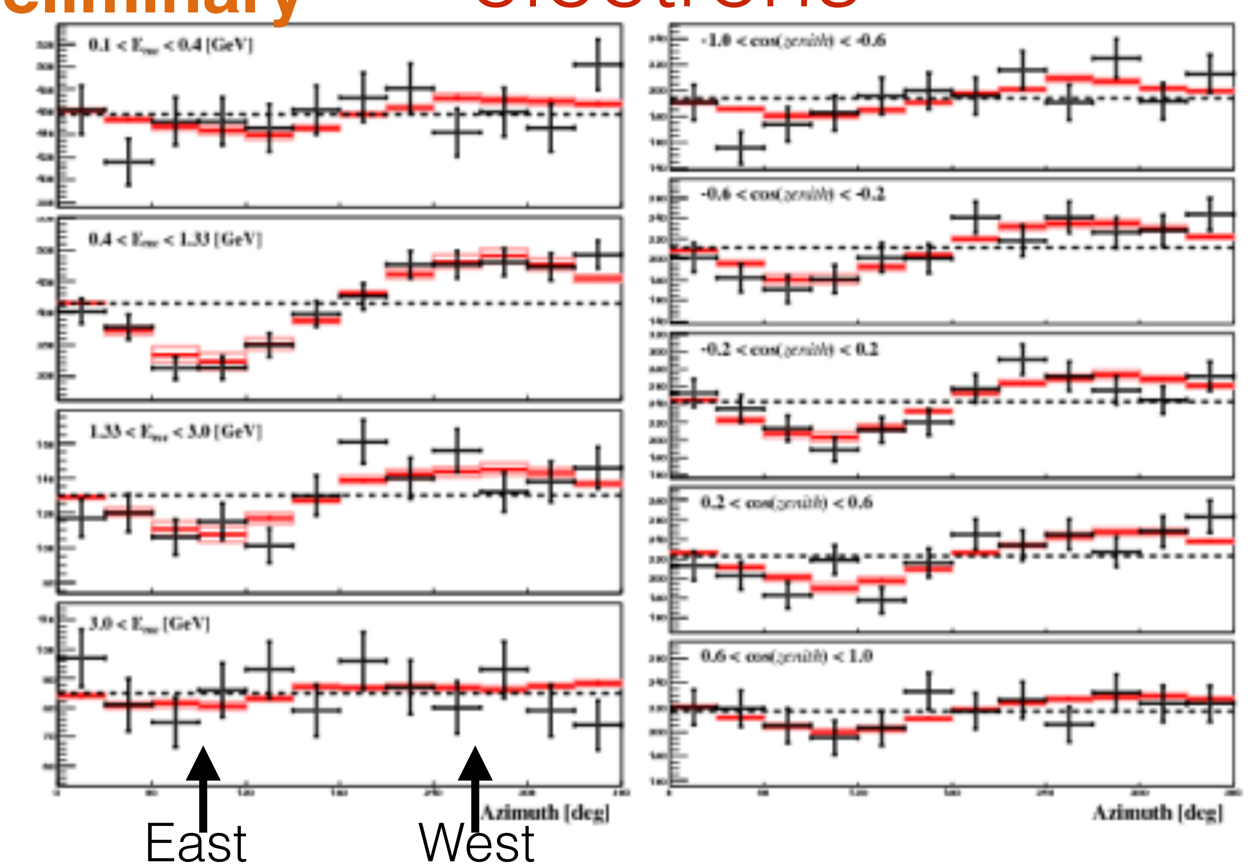
Geomagnetic cutoff



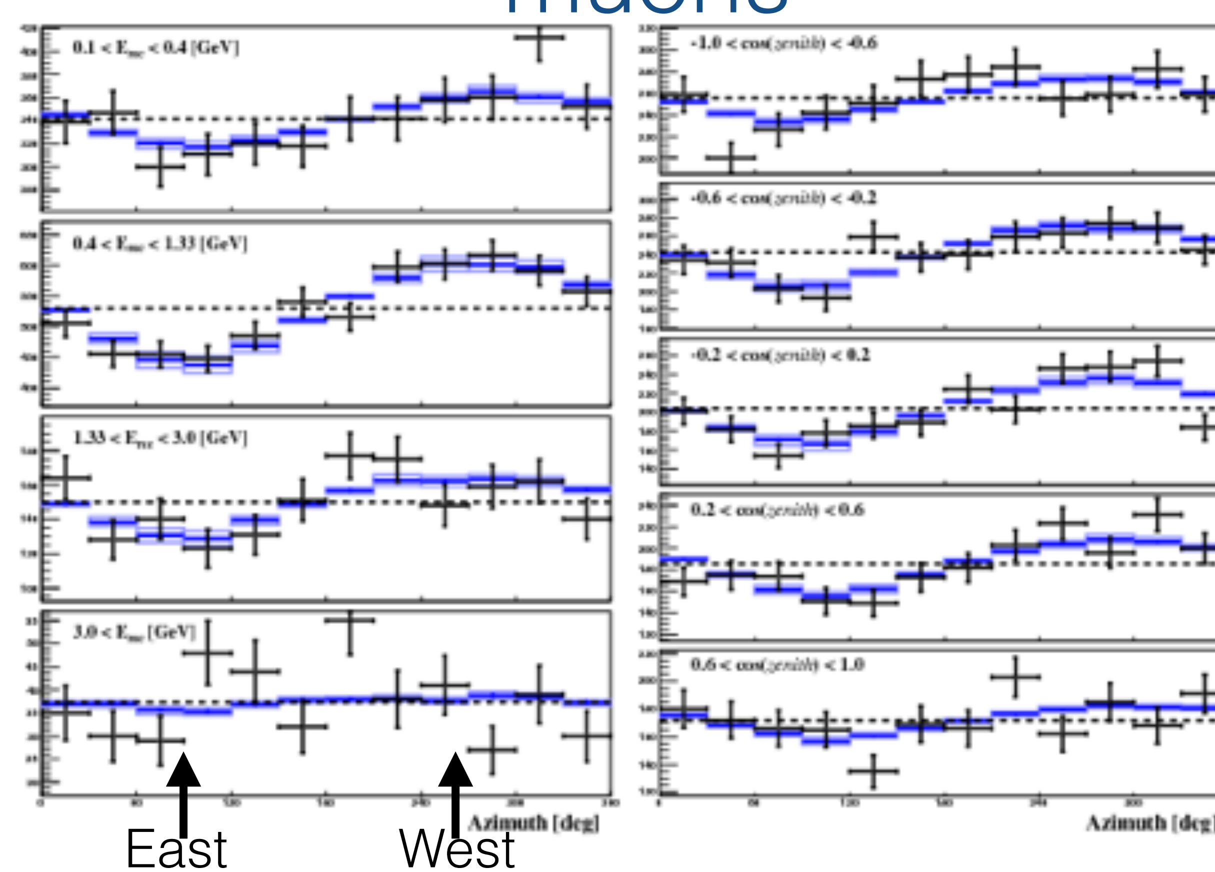
T.K. Gaisser and M. Honda, Annu. Rev. Nucl. Part. **52**, 153 (2002)

preliminary

electrons

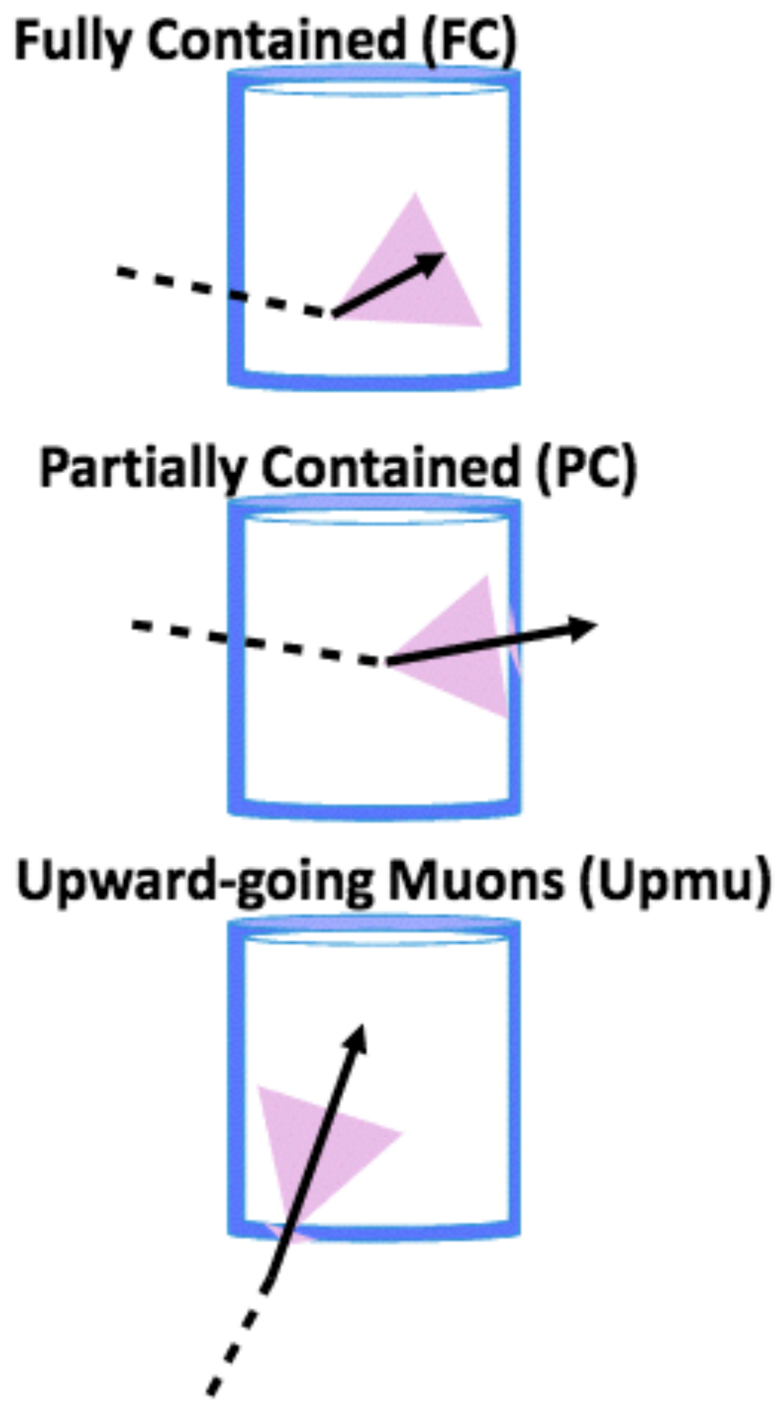


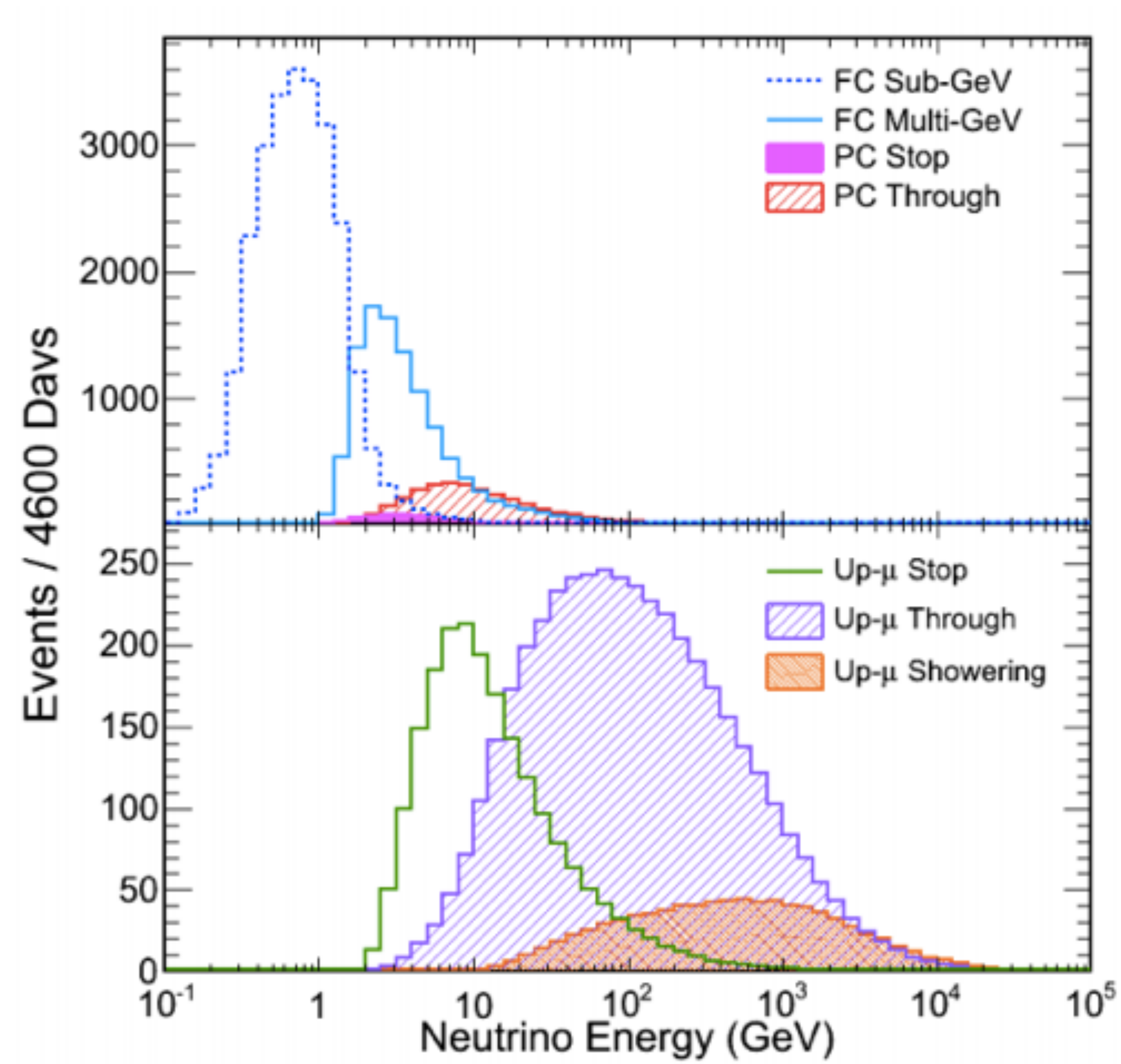
muons



Super-K Data Samples

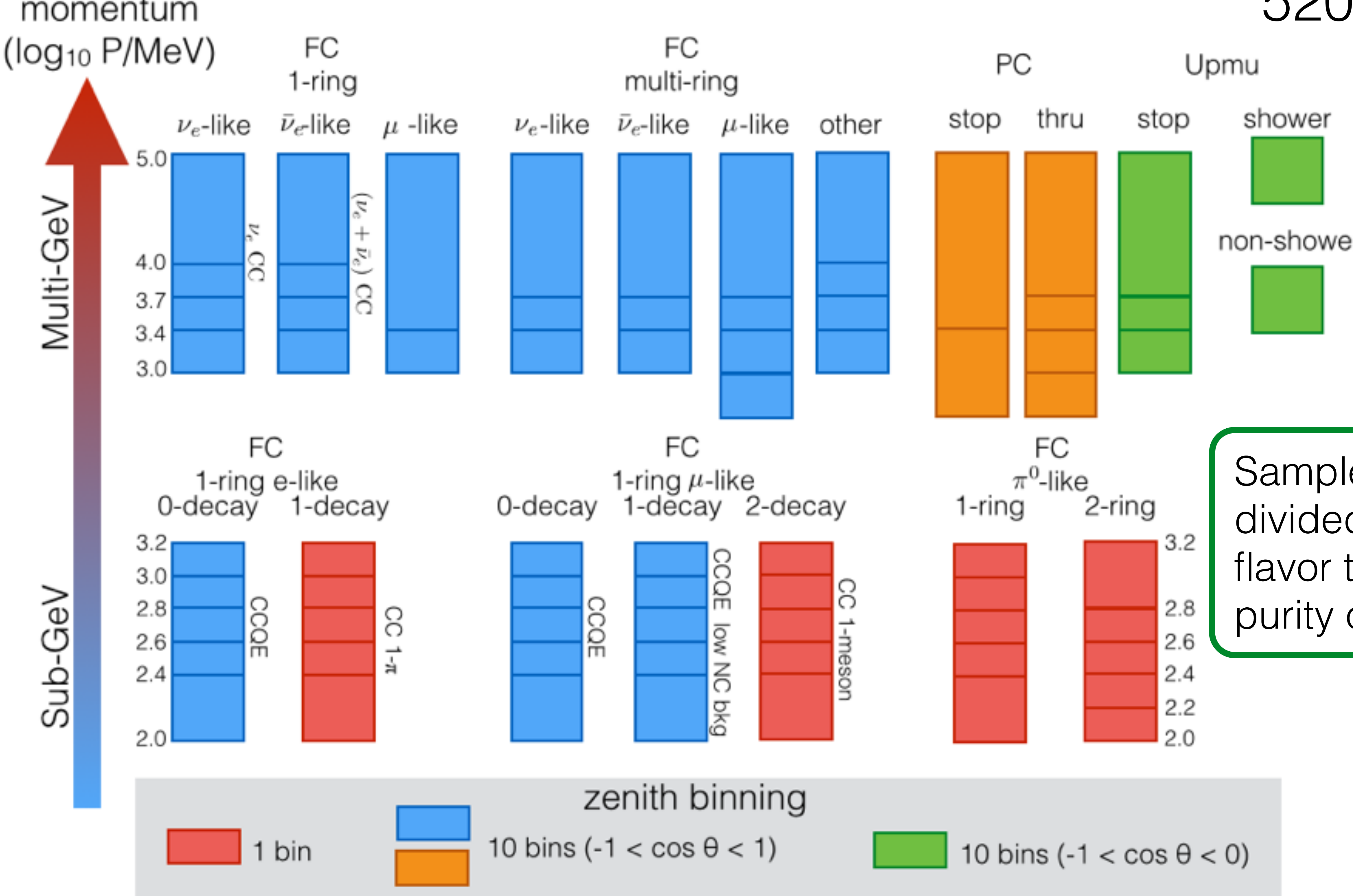
coarse event types





Finer separation into analysis samples

19 samples
520 bins



Samples are divided beyond flavor to improve purity of signals

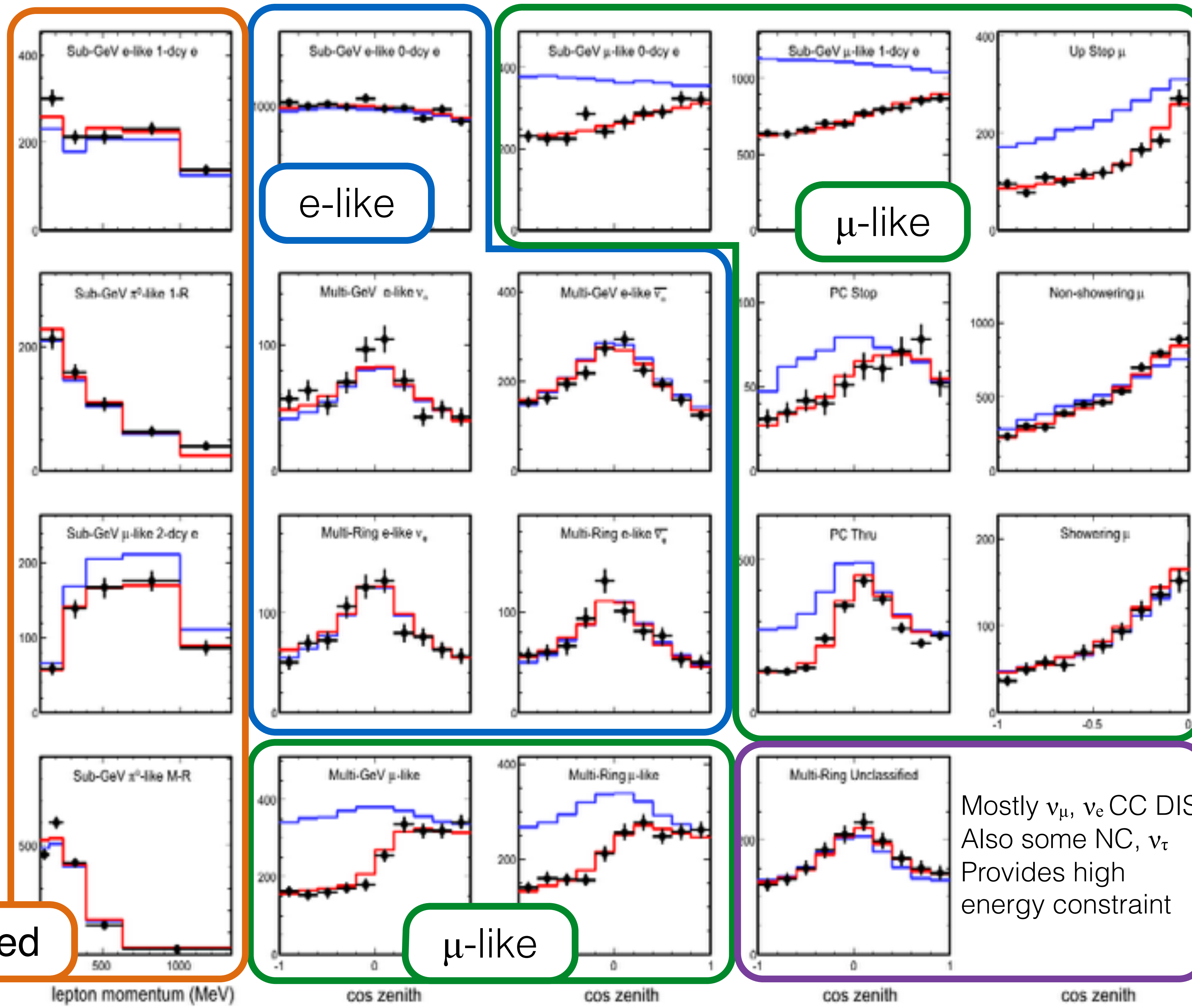
Analysis Samples

Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations

- Obvious zenith dependent atmospheric ν_μ disappearance

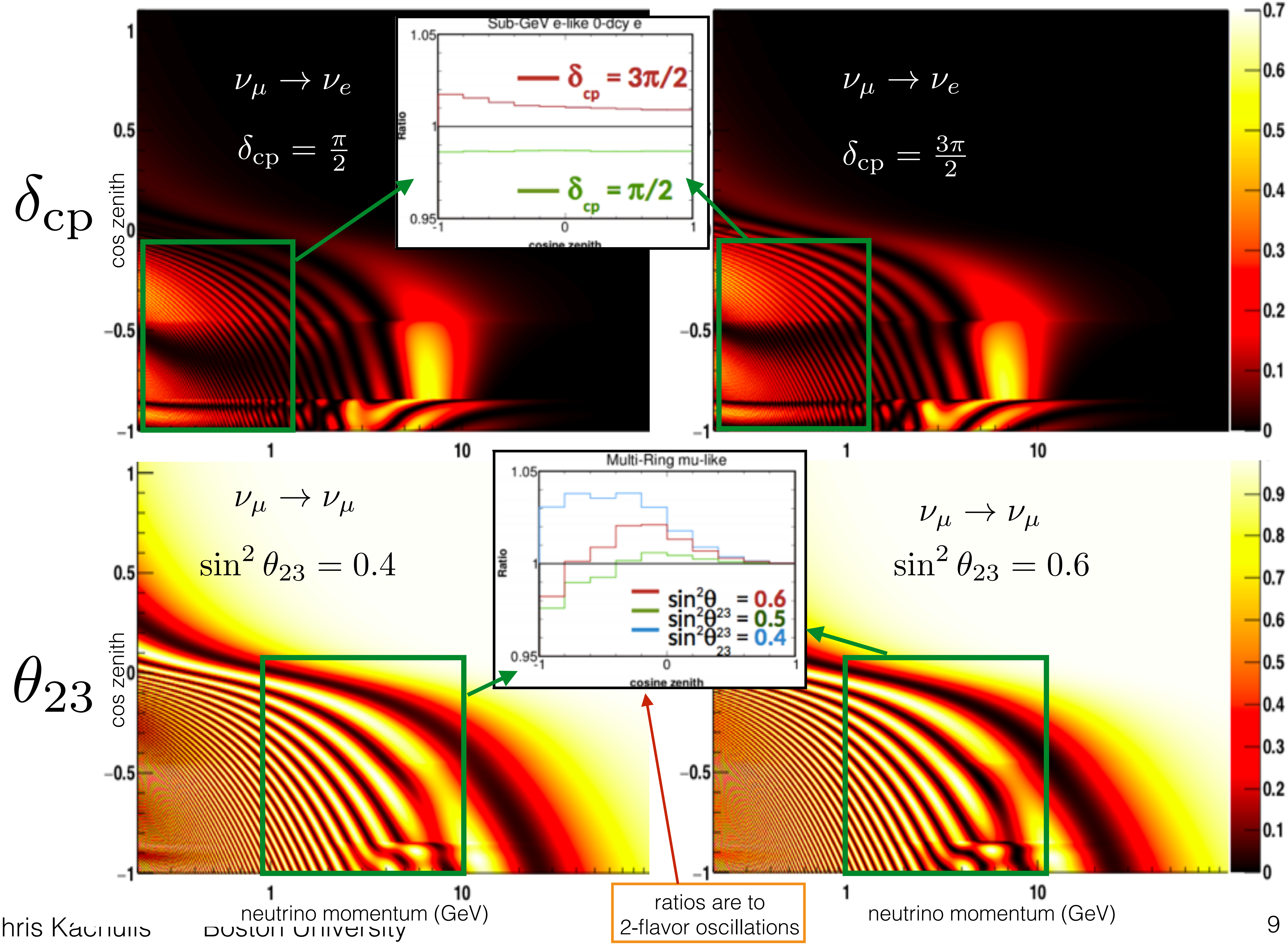
We are now interested in subdominant effects

- Hierarchy, δ_{cp}, θ_{23} octant sensitivities are all based on subdominant 3-flavor effects



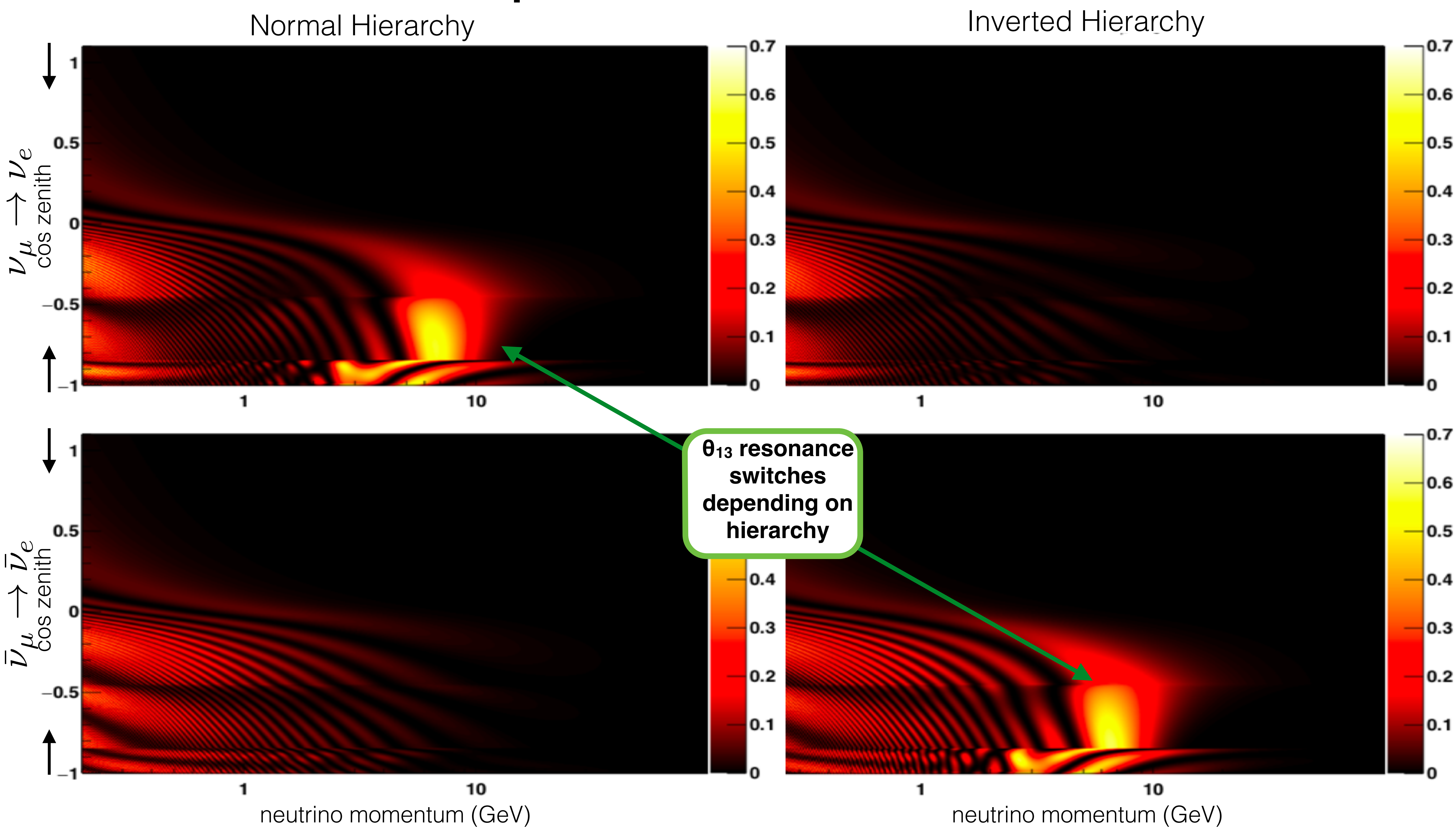
3-flavor best fit   No oscillation

~50 K events



δ_{cp}
θ_{23}
$\nu_\mu \rightarrow \nu_e$
$\delta_{cp} = \frac{\pi}{2}$
$\delta_{cp} = \frac{3\pi}{2}$
$\nu_\mu \rightarrow \nu_\mu$
$\sin^2\theta_{23} = 0.4$
$\sin^2\theta_{23} = 0.6$
Sub-GeV e-like 0-dcy e
$\delta_{cp} = 3\pi/2$
$\delta_{cp} = \pi/2$
Multi-Ring mu-like
$\sin^2\theta_{23} = 0.6$
$\sin^2\theta_{23} = 0.5$
$\sin^2\theta_{23} = 0.4$
Ratio
cosine zenith
cos zenith
neutrino momentum (GeV)
ratios are to 2-flavor oscillations

Mass Hierarchy in Atmospheric Neutrinos



$\nu_e/\bar{\nu}_e$ Differences

Pion charge/decay electrons - used in MultiGeV 1-ring e-like

~~$\nu_e + n \rightarrow e^- + \pi^0 + p$~~	~~$\bar{\nu}_e + p \rightarrow e^+ + \pi^0 + n$~~
$\nu_e + n \rightarrow e^- + \boxed{\pi^+} + n$	$\bar{\nu}_e + n \rightarrow e^+ + \boxed{\pi^-} + n$
$\nu_e + p \rightarrow e^- + \boxed{\pi^+} + p$	$\bar{\nu}_e + p \rightarrow e^+ + \boxed{\pi^-} + p$
↓ decay electron	↓ captured— no decay electron

Kinematic differences - used in MutliGeV Multi-ring e-like

- ✦ ν_e gives larger energy fraction to hadrons
  →more decay electrons, more rings, larger fraction transverse energy

$\sigma_\nu \sim 3 \times \sigma_{\bar{\nu}}$ → Larger resonance for normal hierarchy

MultiGev 1-Ring

	CC-ν_e	CC-$\bar{\nu}_e$	background
ν_e-like	71%	7%	22 %
$\bar{\nu}_e$-like	57%	34%	9%
no separation	59%	30%	11%

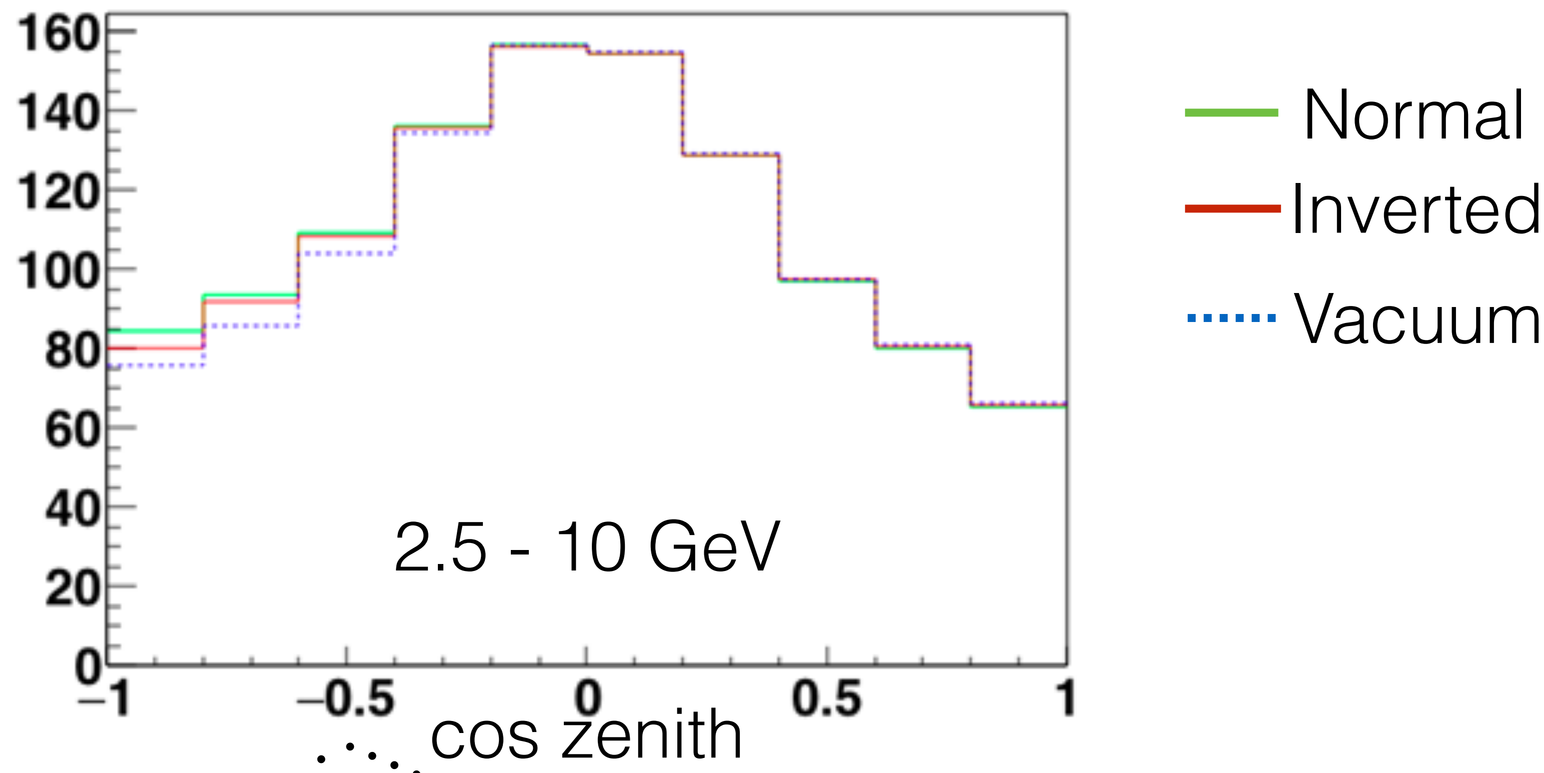
MultiGev Multi-Ring

	CC-ν_e	CC-$\bar{\nu}_e$	background
ν_e-like	53%	12%	35 %
$\bar{\nu}_e$-like	52%	27%	21%
no separation	53%	19%	28%

ν_e enriched samples

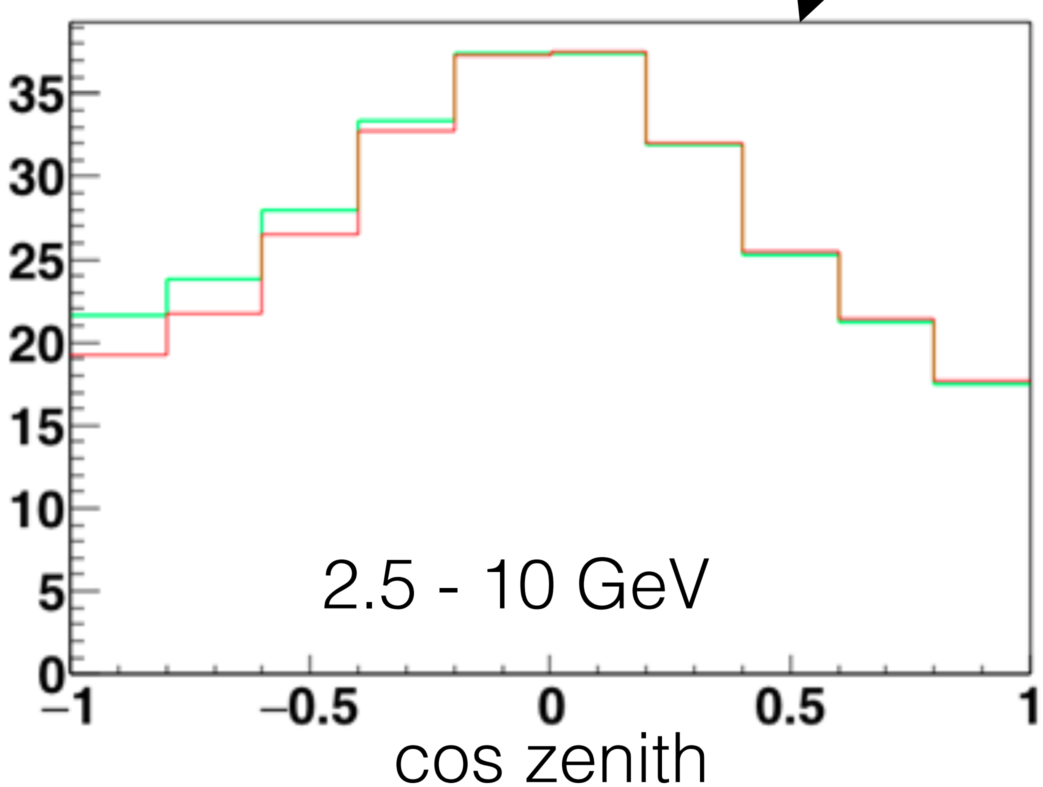
MultiGev 1-Ring e-like

ν_e-like + $\bar{\nu}_e$-like

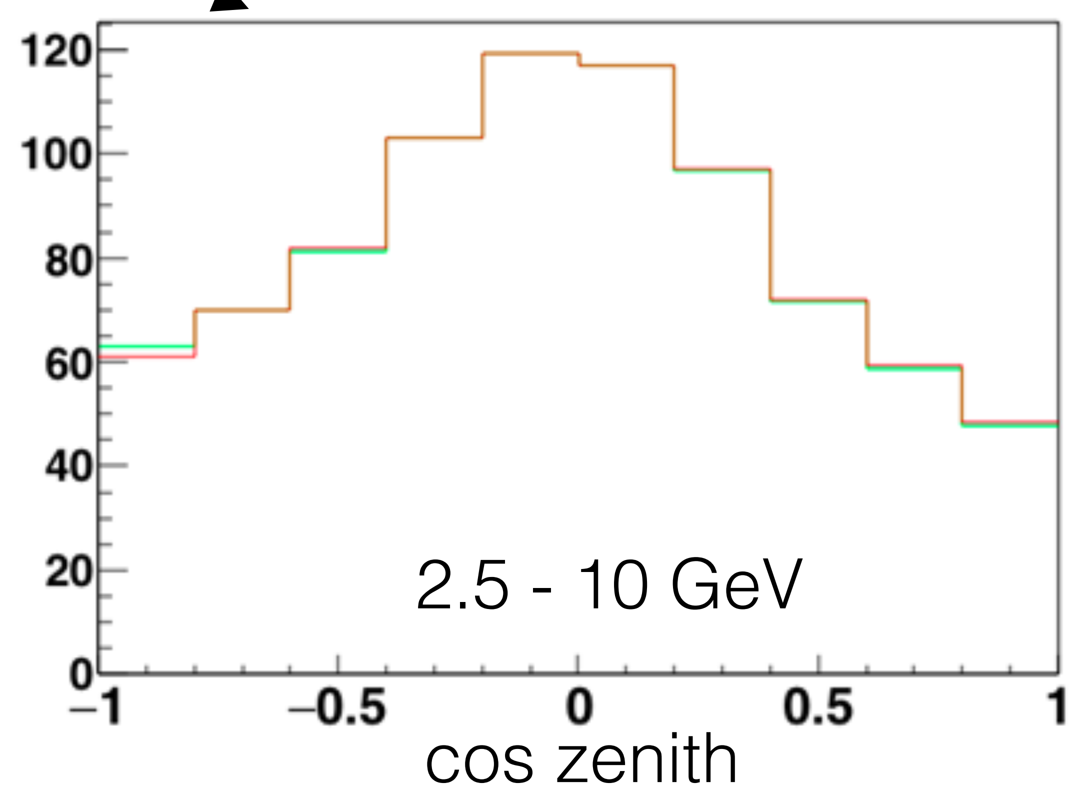


Hierarchy sensitivity concentrated in ν_e-like sample

ν_e-like



$\bar{\nu}_e$-like



Analysis Details

$$\chi^2 = \underbrace{\chi^2_{\text{data-mc}}}_{\text{mc is adjusted by systematic pulls}} + \underbrace{\chi^2_{\text{systematics}}}_{\text{cross sections, flux, detector effects (156 total)}} + \underbrace{\chi^2_{\text{nuisance.osc.parms}}}$$

mc is adjusted by
systematic pulls

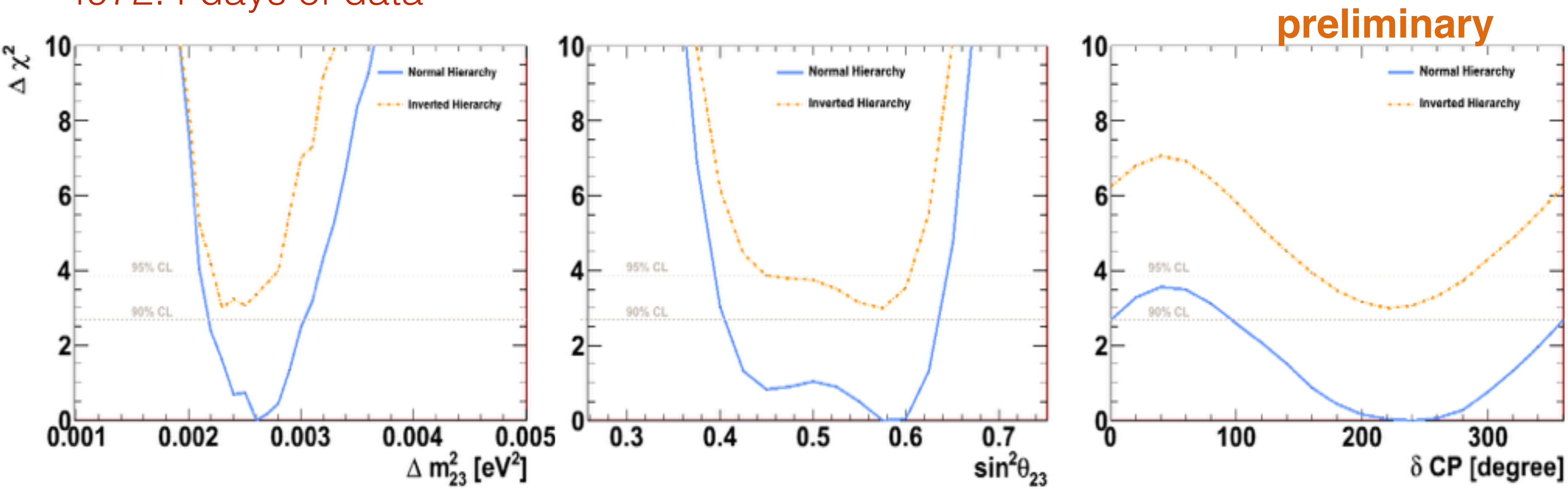
cross sections
flux
detector effects
(156 total)

$\sin^2 2\theta_{13}=0.093\pm0.010$
$\Delta m^2_{12}=7.65\pm0.19$ ($\times10^{-5}$ eV^2)
$\sin^2 2\theta_{12}=0.854\pm0.021$

Minimize χ^2 over systematics/nuisance parameters and θ_{23}, Δm^2_{13}, δ_{cp} → profile likelihood

SK Atmospheric Only Fit

4972.4 days of data



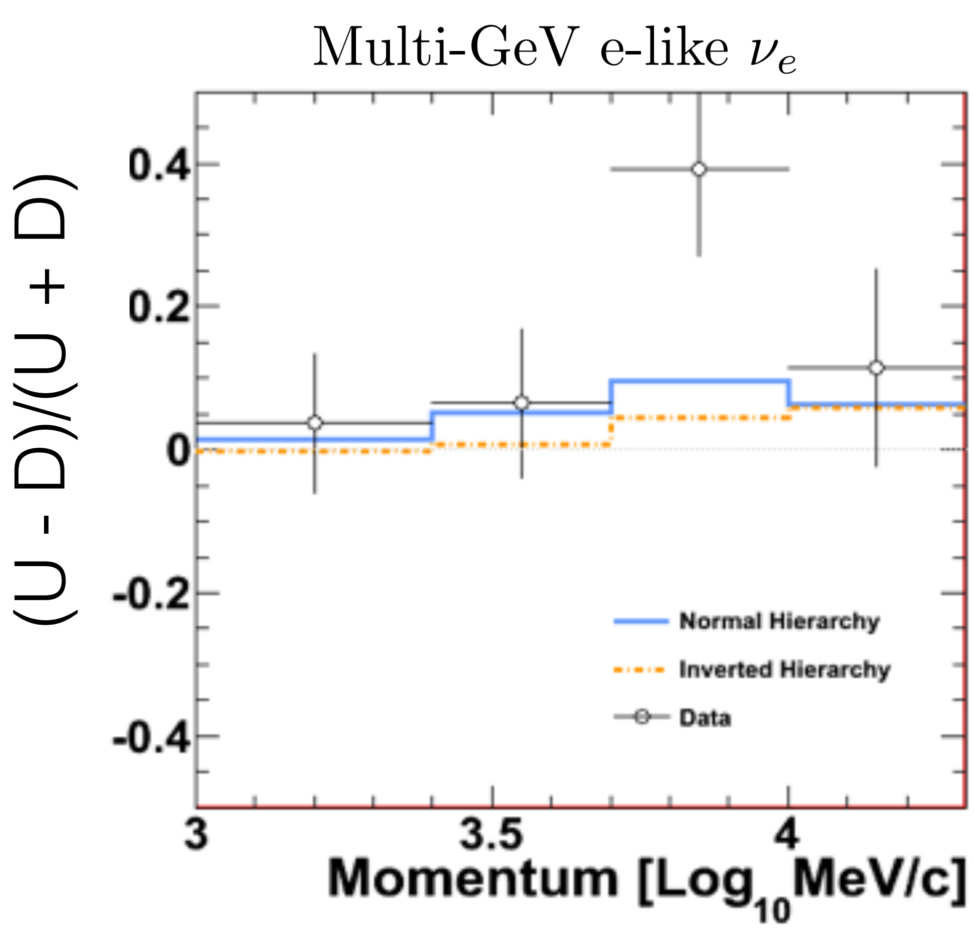
★ Hierarchy: $\chi^2_{IH} - \chi^2_{NH} = 3.0$

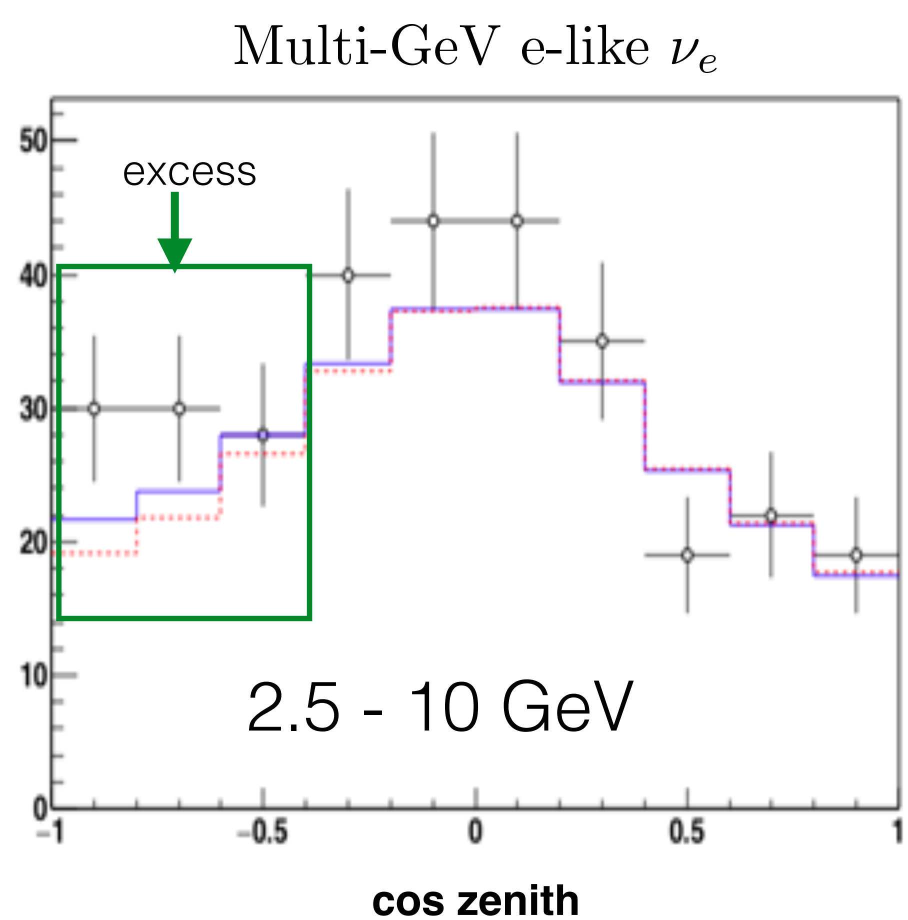
Fit Result (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{cp}	$\sin^2\theta_{23}$	Δm^2_{23} $(\times 10^{-3} eV^2)$
NH	582.4	0.0238	4.2	0.575	2.6
IH	585.4	0.0238	3.8	0.575	2.3

Hierarchy Preference

Fit weakly favors normal hierarchy at $\chi^2_{IH} - \chi^2_{NH} = 3.0$

- Preference driven by excess upward going ν_e-like events, as expected from θ_{13} resonance.
- Increase in preference (was 0.9 at Neutrino 2014) driven by excess of these events in new data. Excess in new data is statistically reasonable.





More About Result

δ_{cp} ~240° preferred

- Preference driven by excesses in multiple SubGeV e-like samples
- Additional preference from deficit of SubGeV μ-like events
- sin δ_{cp}=0 allowed at 68% C.L.
- Agrees with T2K ν_e appearance preference

Weak preference for $\theta_{23}>45°$

Matter effects preferred to vacuum oscillations at $\chi^2_{matter} - \chi^2_{vac} = 3.0$

- Preference driven by same excess in MultiGeV ν_e-like sample as hierarchy preference

Combined Fit with Data from other Experiments

SK Only Fit

SK atmospheric data

520 Bins

solar, reactor KamLand results

fix values of Δm^2_{12}, θ_{12}

+

Additional Data

data constraining Δm^2_{23}, θ_{23}

T2K ν_μ disappearance →

data with hierarchy, δ_{cp} sensitivity

T2K ν_e appearance

data not yet included, coming soon

T2K $\bar{\nu}$

NOνA →

Improve hierarchy and δ_{cp} sensitivities by simultaneously fitting data from other experiments

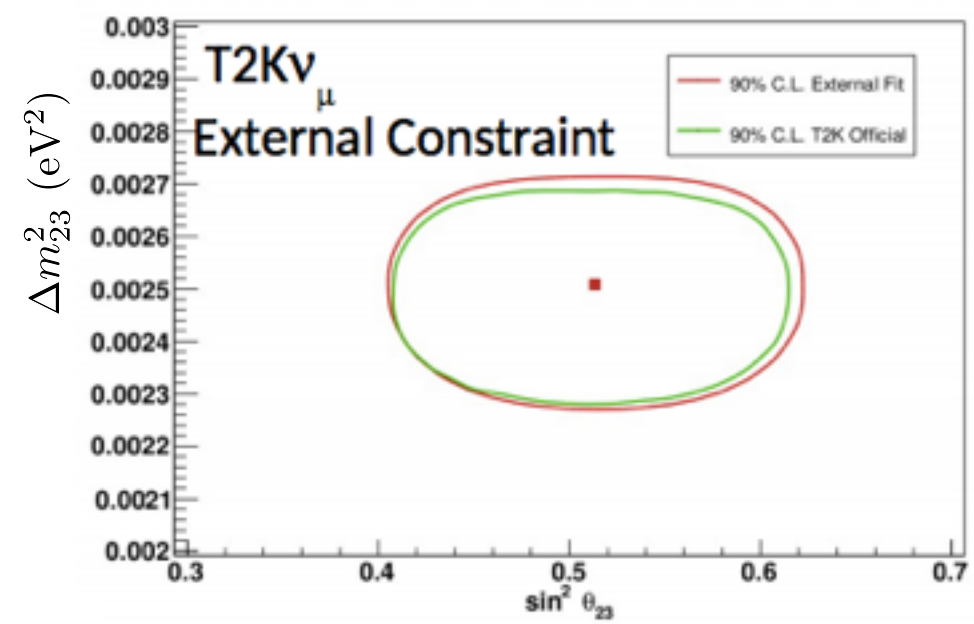
MINOS and T2K provide similar constraints. Including both provides little advantage to hierarchy, δ_{cp} sensitivity over including one or the other. We choose to include T2K because we can cancel shared systematics

NOνA has longer baseline than T2K → more matter effects.

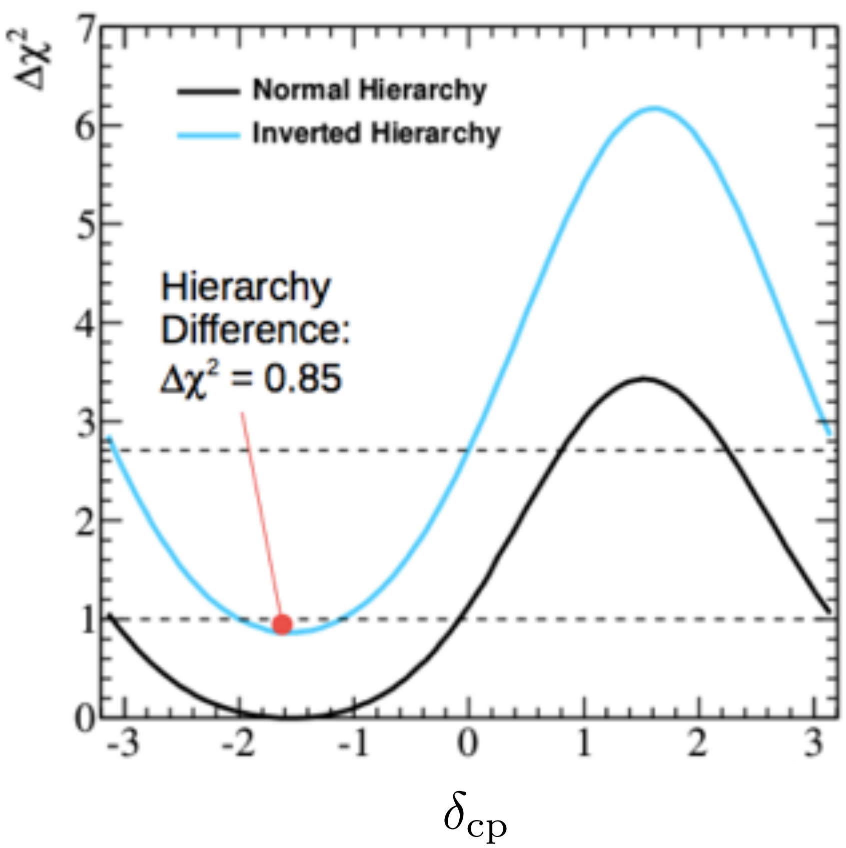
Not a joint analysis by the SK and T2K collaborations. We are treating T2K as an external experiment

Replicating T2K Official Result

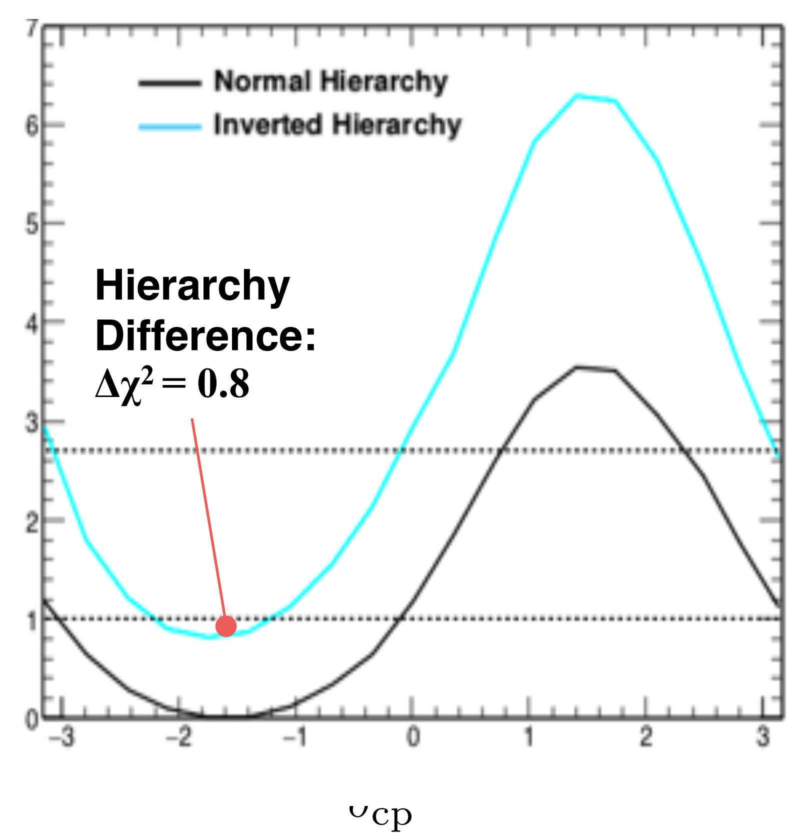
- Since we are treating T2K as an external experiment, we must first reproduce their official results
- We reproduce the T2K contours to a satisfactory level

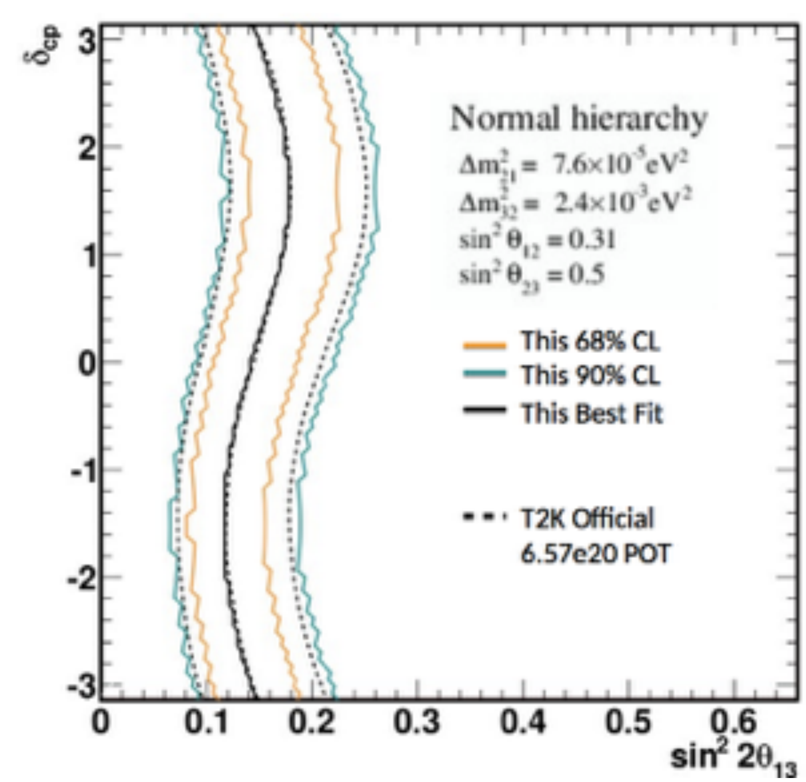


T2K Official Result

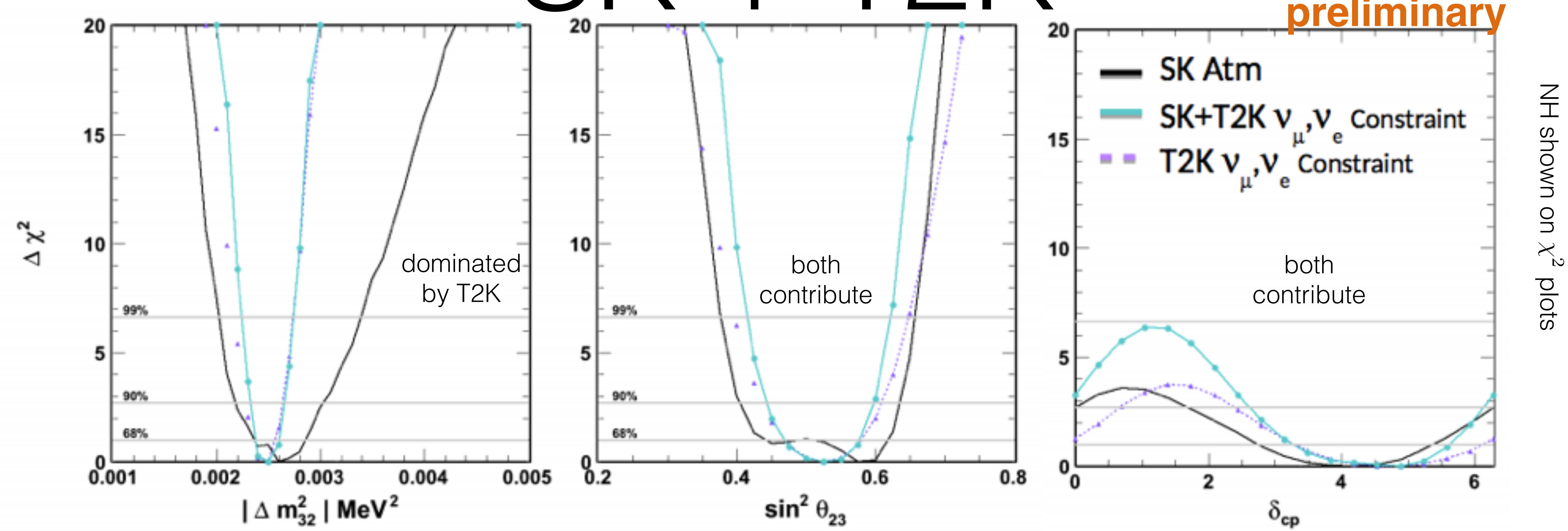


External Analysis





SK + T2K



★Hierarchy: $\chi^2_{IH} - \chi^2_{NH} = 3.2$ (dominated by SK)

Fit Result (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{cp}	$\sin^2\theta_{23}$	Δm^2_{23} $(\times 10^{-3} eV^2)$
NH	651.53	0.0238	4.89	0.525	2.5
IH	654.73	0.0238	4.19	0.550	2.4

Summary

SK + T2K fit prefers normal hierarchy at χ^2_{IH} - χ^2_{NH} = 3.2

SK+T2K fit prefers δ_{cp}~240°

- both SK and T2K separately prefer δ_{cp}~240°, combination strengthens this preference
- sin δ_{cp}=0 is still allowed at 68% confidence

Improvements in mind

Improving Hierarchy Sensitivity

More Data

SK continues to run

T2K $\bar{\nu}$

NOνA

Reduce/Constrain Backgrounds

improve ν_e-ν_μ separation with better MutliGeV PID

constrain ν_τ background with neural net techniques from ν_τ appearance analysis

Improve ν-$\bar{\nu}$ Separation

n-H capture

n-Gd capture (with future addition of Gadolinium)

A recent author list for the Super-Kamiokande Collaboration

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Japan
U.S.A.
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Office of Science
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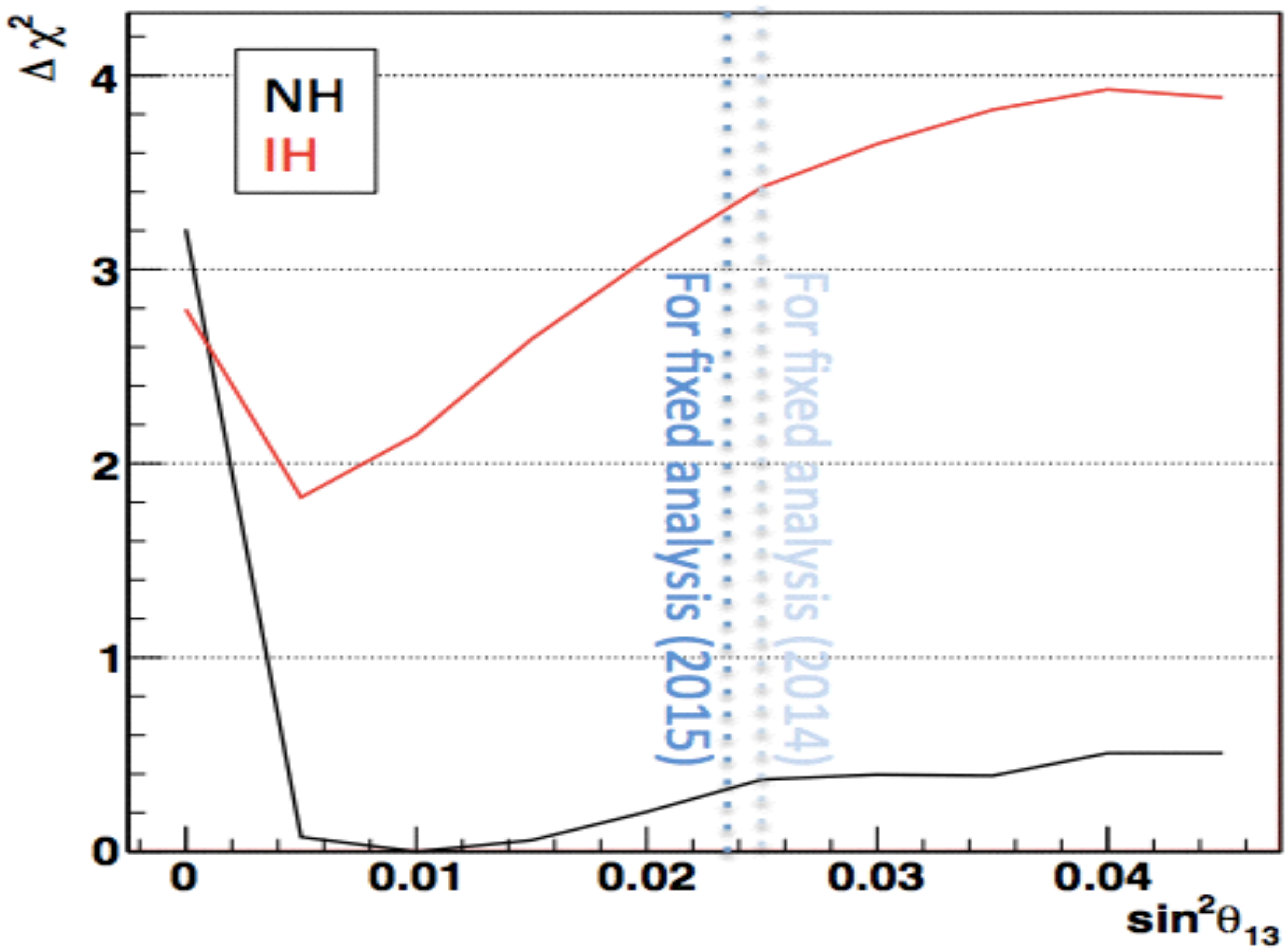
Supplements

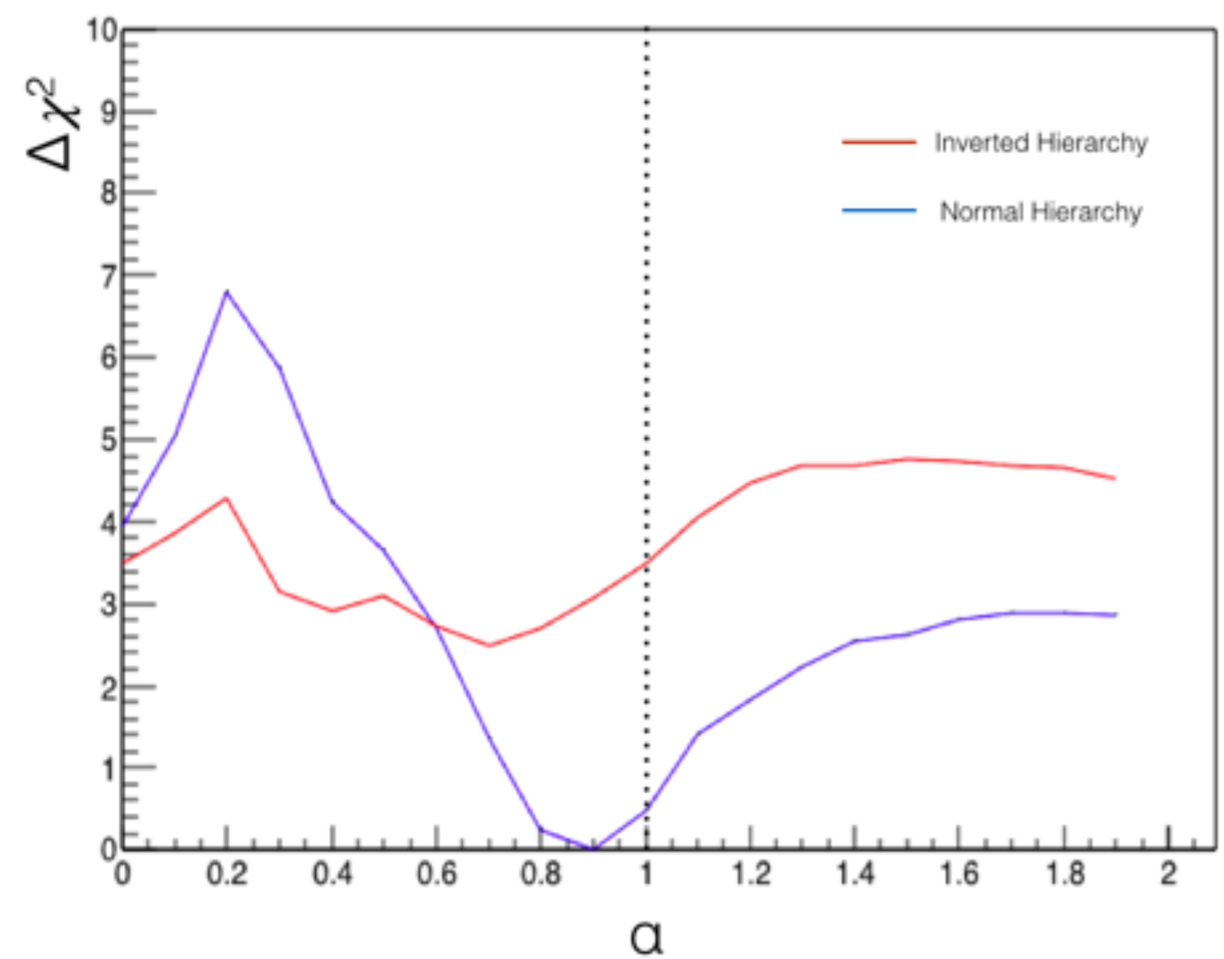
θ_{13} Free



Matter Effects Significance

- Search for evidence of Earth Matter Effects in Atmospheric data
- Parameter α scales density of the Earth from vacuum (α=0) to “standard” matter (α=1)
- “standard” matter is weakly preferred to vacuum at:

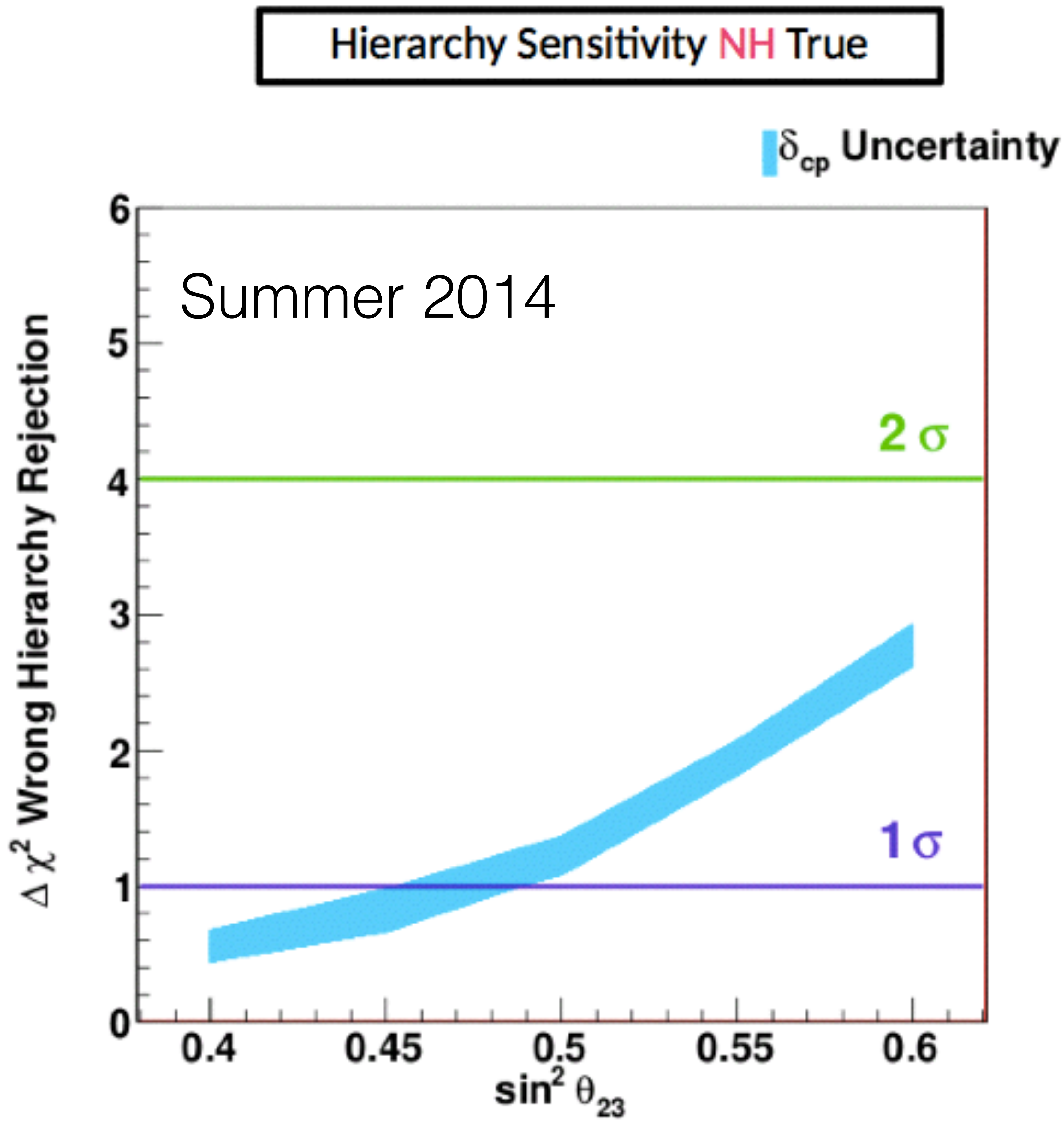
$$\chi^2_{\text{vac}} - \chi^2_{\text{matter}} = 3.0$$



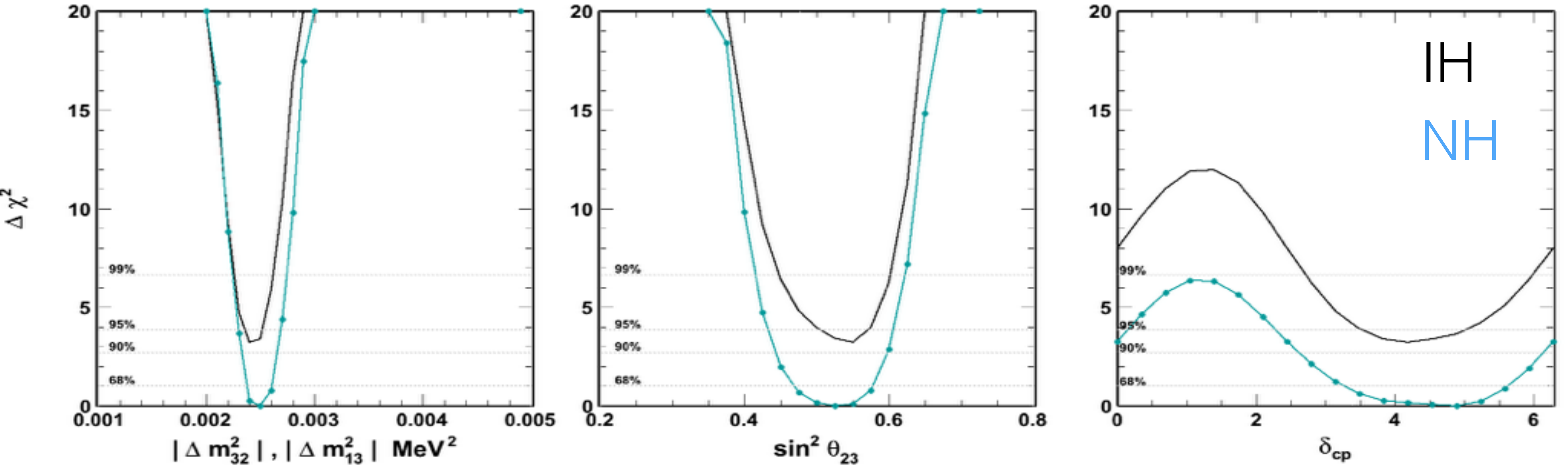
Gadolinium Official Statement

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water.

The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.


Hierarchy Sensitivity NH True
δcp Uncertainty
Summer 2014
2 σ
1σ
Δ χ2 Wrong Hierarchy Rejection
sin2 θ23
0
1
2
3
4
5
6
0.4
0.45
0.5
0.55
0.6

SK + T2K



Fit Result (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{cp}	$\sin^2\theta_{23}$	Δm^2_{23} $(\times 10^{-3} eV^2)$
NH	651.53	0.0238	4.89	0.525	2.5
IH	654.73	0.0238	4.19	0.550	2.4