Atmospheric Neutrino Update

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Hyper-K 2[nd] Open Meeting, Kashiwa

Introduction

- Atmospheric neutrino and Proton Decay working group (HK-ATMPD)
  - Working group activities have now started
  - "ATMPD" is a blanket description for higher energy physics (>100 MeV) that is not specifically from the beam
  - Many of the studies presented at the last meeting are based on analyses at Super-K
  - However, there are still improvements to be made and customizations necessary
  - Plenty of physics work to be done for HK

- Today :
  - Improvements to proton decay searches (M.Miura and V.Takhistov)
  - Atmospheric ν sign discrimination potential (C.Mauger)
  - Atmospheric ν oscillation update (This talk)

The Next Year and Beyond for HK-ATMPD

- Advance and improve physics studies as much as possible
- More of these topics on the horizon
  - Continue existing topics from the LOI
    - BG reduction, efficiency increases for Proton Decay studies
    - Neutrino and antineutrino discrimination methods
  - Starting work on other topics
    - Sterile oscillations
    - Tau physics
    - Sensitivity to indirect dark matter
    - More PDK modes …. Your ideas welcome

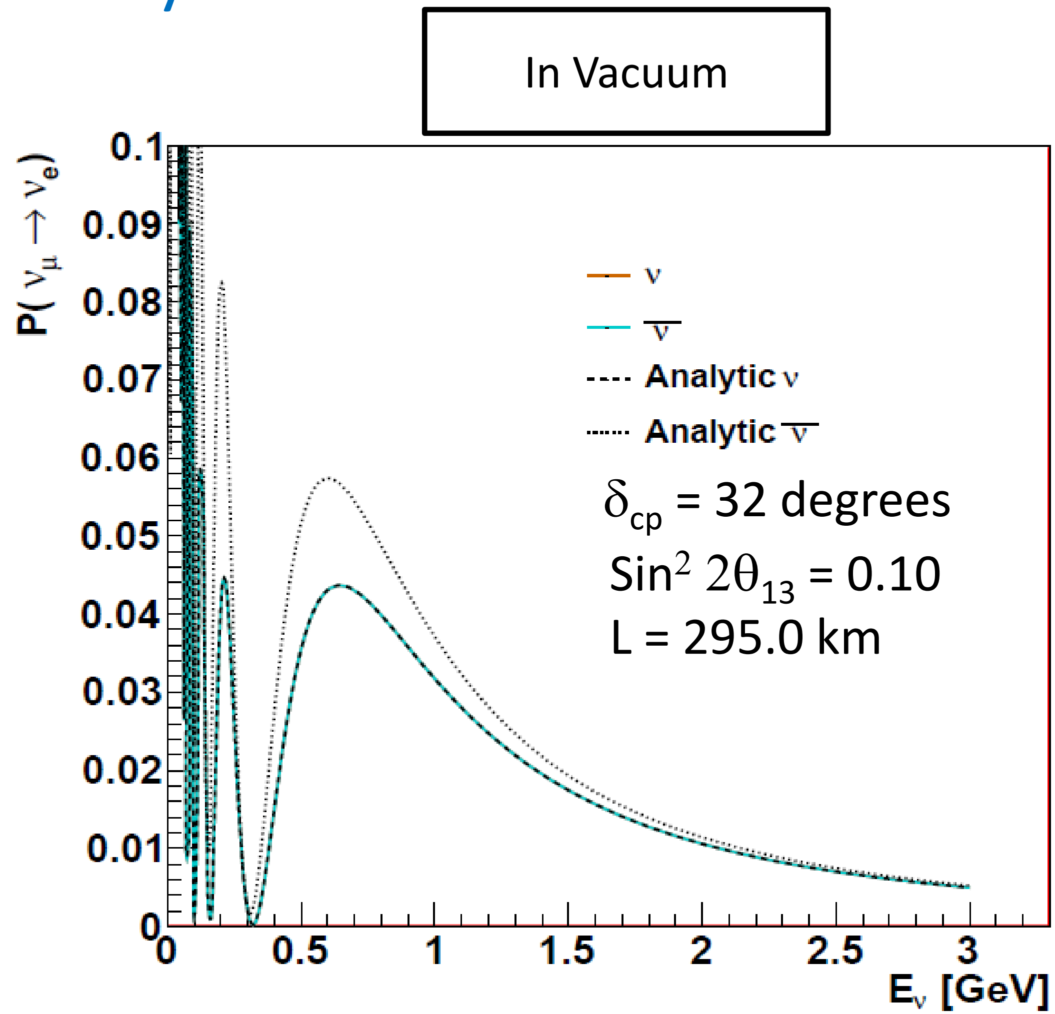
- Prepare documentation for these studies
  - Important input for the next formal proposal to funding agencies
  - Useful for the community at large (LBNE, LBNO efforts)
  - Some cross-pollination between Hyper-K and Super-K is expected (and appreciated)
  - Good advertising for future collaborators

- Please let me (or conveners) know what you are interested in working on and we can get you or your students/postdocs started

Atmospheric Neutrino Update

Updates to Neutrino Oscillation Study

- Input value of θ_{13} updated to global best fit after PDG Global fit
  - $\sin^2 2\theta_{13} = 0.10 \rightarrow 0.098$
  - Does not include latest measurement from Daya Bay (Dec. 2012)



- Oscillation bug
  - Antineutrinos were mistakenly assigned oscillation probabilities for δ_{cp} values shifted by π.
  - Fix improves hierarchy sensitivity slightly, degrades CPV sensitivity slightly

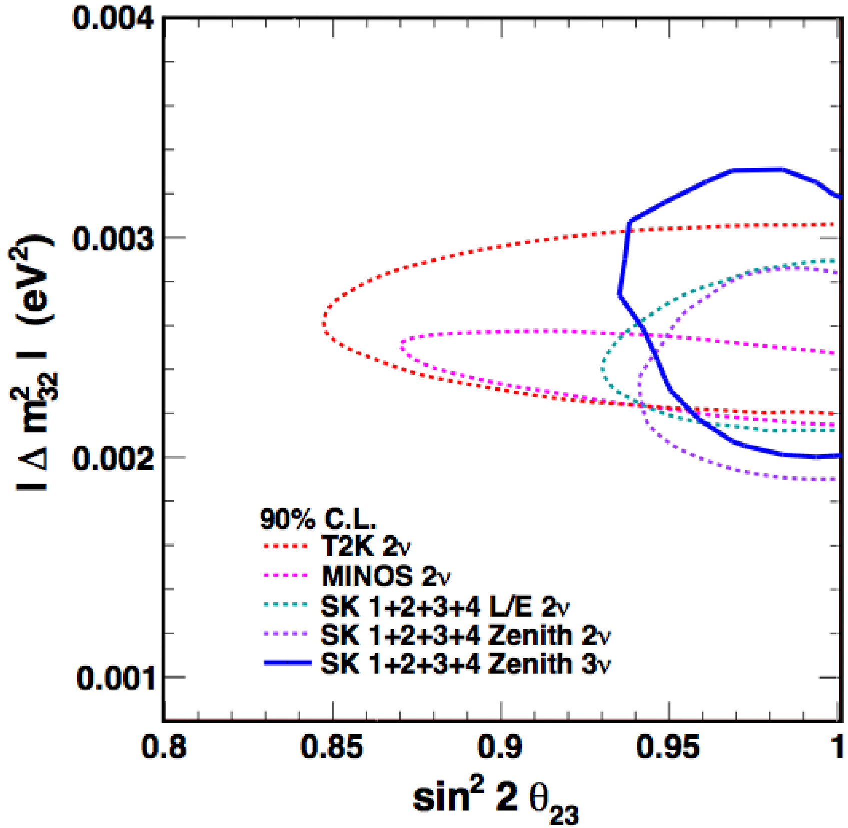
- In general the conclusions of the atmospheric neutrino study presented at the last open meeting have not changed

Notes about Parameter Values

- In the studies below, unless specified otherwise the following inputs have been used to compute sensitivities

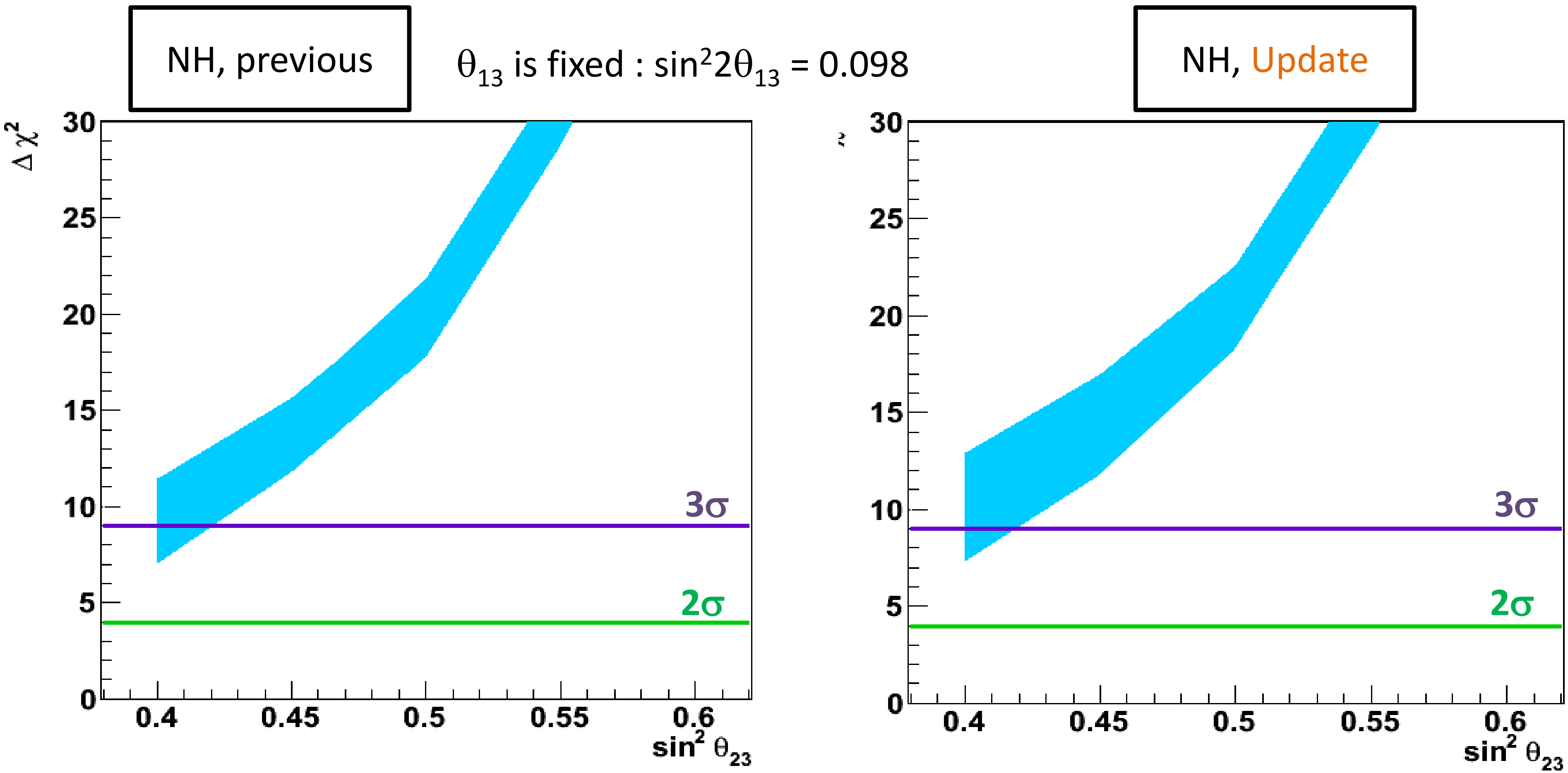
Parameter	Value	$\sin^2(2x)$	Comment
Δm^2_{32}	2.4×10^{-3} eV^2		Global Fit
$\sin^2\theta_{23}$	0.4-0.6	0.96 - 1.0	**
$\sin^2\theta_{13}$	0.025	0.10	Reactor Data
δ_{cp}	40 degrees		Min.$P(\nu_\mu \rightarrow \nu_e)$
$\sin^2\theta_{21}$	0.31	0.85	Global Solar
Δm^2_{21}	7.6×10^{-5} eV^2		Global Solar
Hierarchy	Normal		Assumption

Neutrino 2012



** MINOS central value from Neutrino 2012: $\sin^2(2\theta_{23}) = 0.96$

Hierarchy sensitivity, 10 years of Atmospheric data



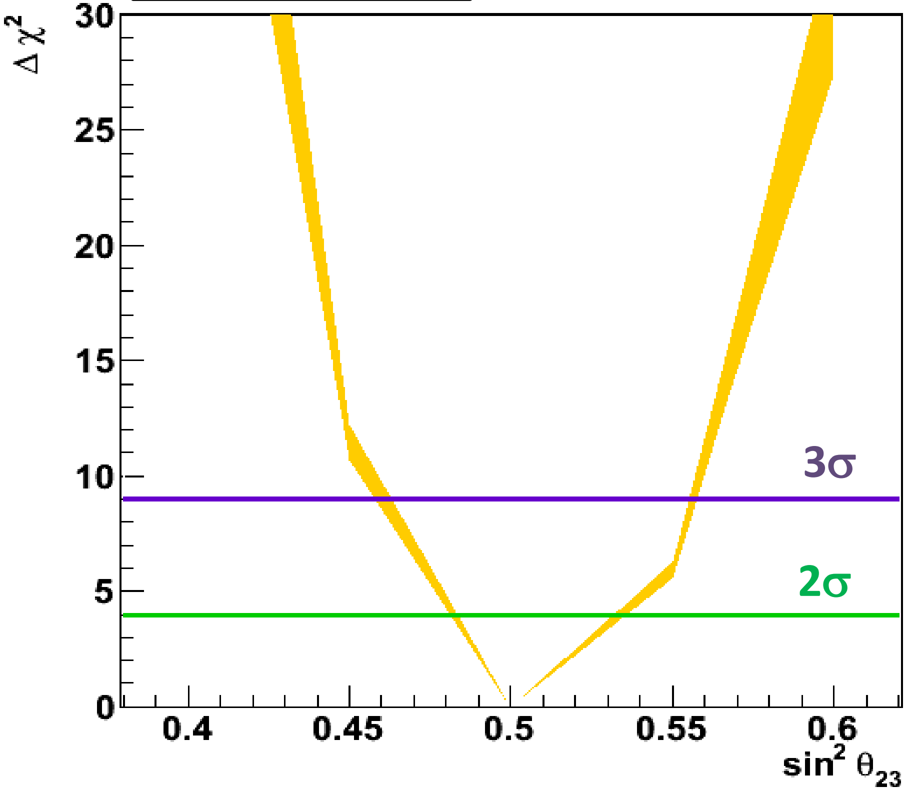
- Thickness of the band corresponds to uncertainty induced from δ_{cp}
- Weakest sensitivity overall in the tail of the first octant
- Hierarchy sensitivity is improved slightly after update
    - True for both hierarchies

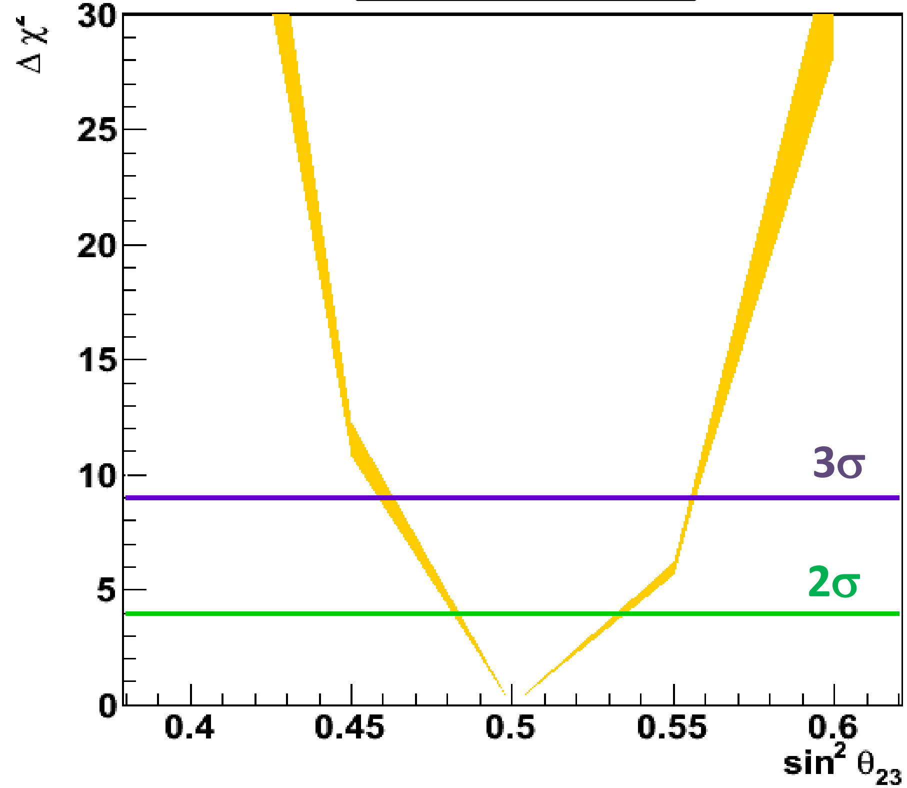
Octant sensitivity, 10 years of Atmospheric data

NH, previous

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.098$

NH, Update





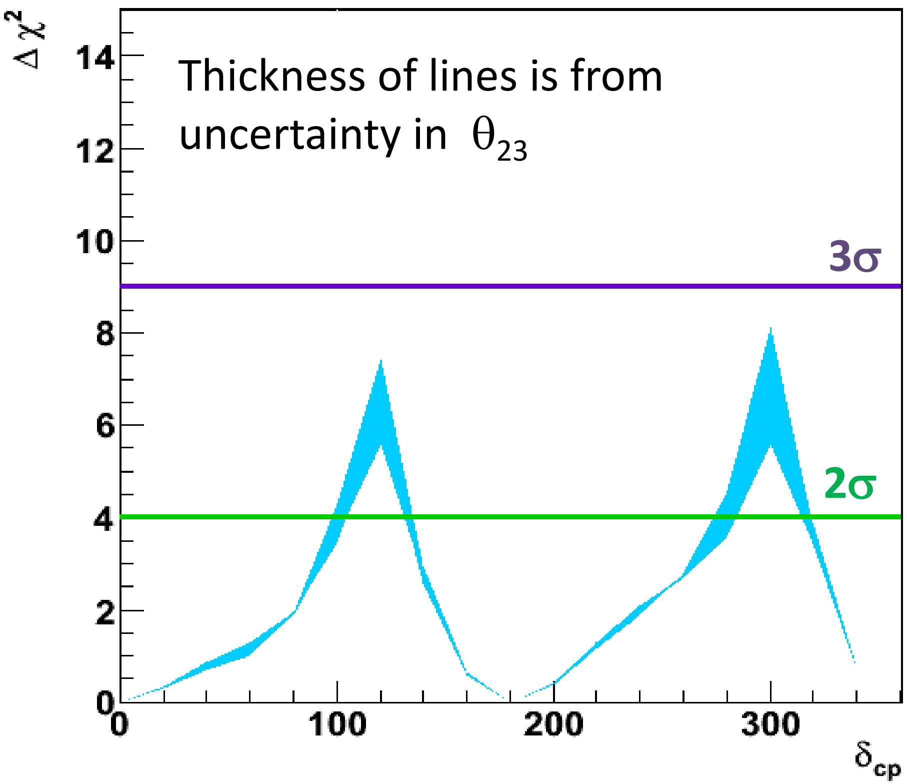
- Thickness of the band corresponds to the uncertainty from δ_{cp}
- Best value of δ_{cp} = 40 degrees
- Worst value of δ_{cp} = 140 (260) degrees, for 1st (2nd) octant
- Change after update is imperceptible

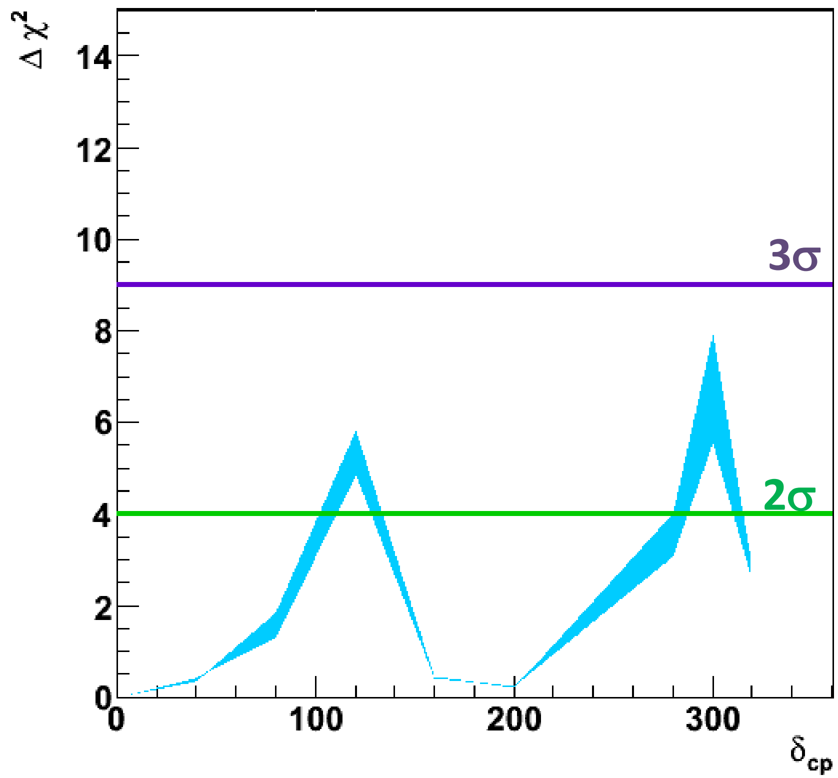
CP-Violation Sensitivity - Exclusion of sin δ_{cp} = 0

NH, previous

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.099$

NH, Update





- Sensitivity to CP-violation is limited under both hierarchy assumptions but is decreased slightly after the update
- The addition of this information to the beam data does not make much of an impact
- Complementarity of beam and atmospheric samples unaffected after update

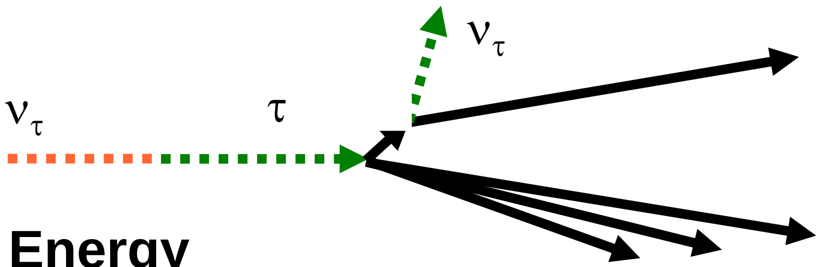
Summary

- HK-ATPMD working group has started
- Atmospheric Neutrino sensitivity has been updated, with small impact on the expected sensitivity of Hyper-K

Objective		Normal	Inverted	Comment
Hierarchy	2σ	$\sin^2 2\theta_{23} > 0.96$	$\sin^2 2\theta_{23} > 0.96$	5 years
	3σ	$\sin^2\theta_{23} > 0.4$	$\sin^2 \theta_{23} > 0.4$	10 years
Octant	2σ	$\sin^2 2\theta_{23} > 0.997$	$\sin^2 2\theta_{23} > 0.99$	5 years
	3σ	$\sin^2 2\theta_{23} > 0.99$	$\sin^2 2\theta_{23} > 0.97$	5 years

- ν_τ sensitivity studies next time

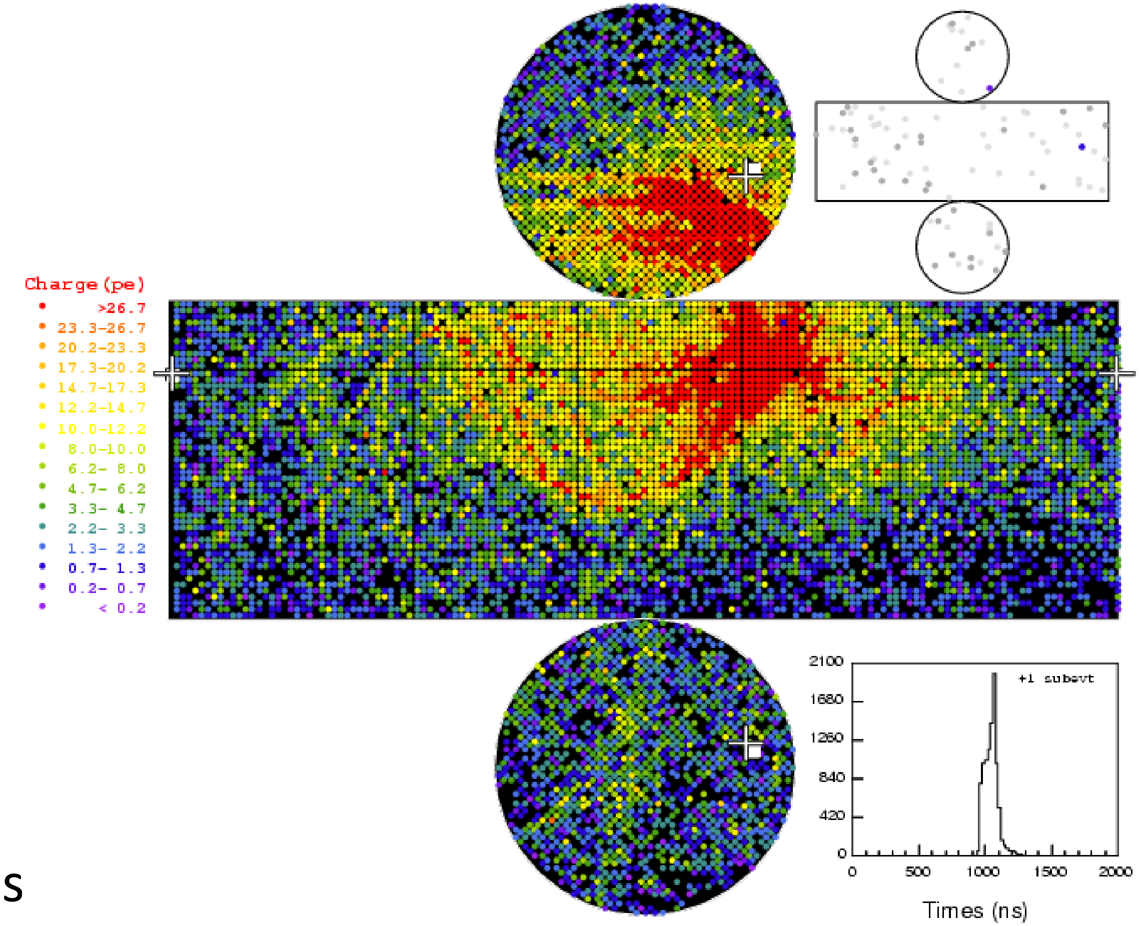
ν_τ Events



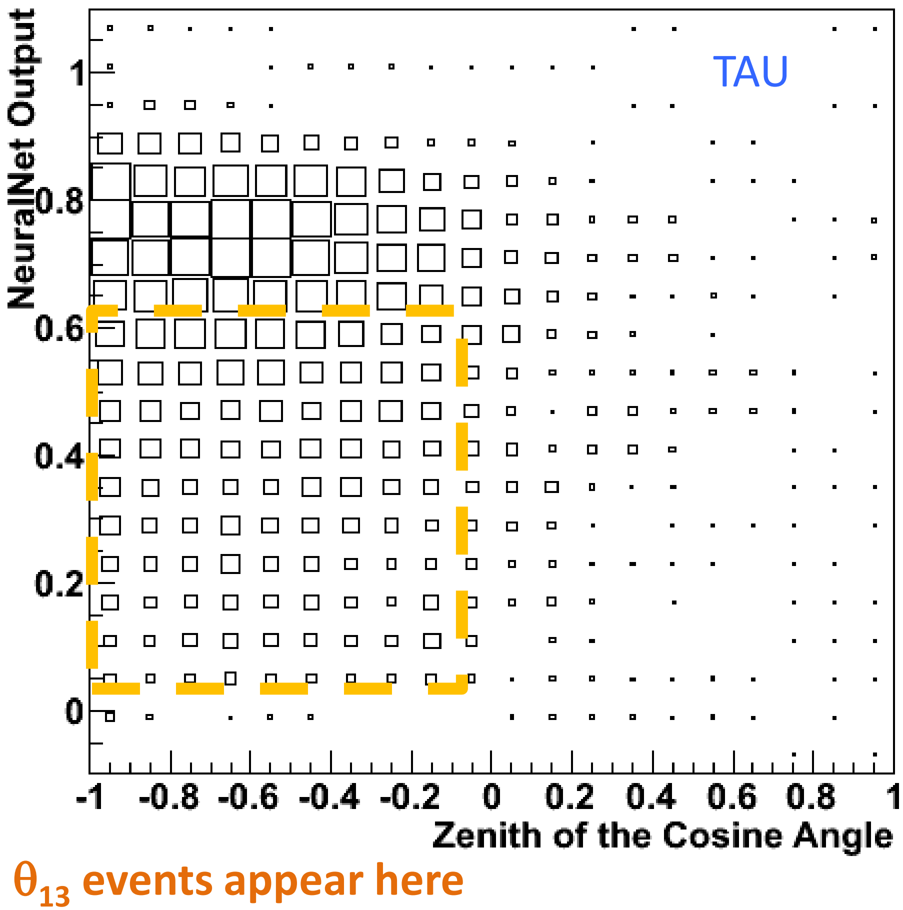
Energy Threshold: 3.5 GeV

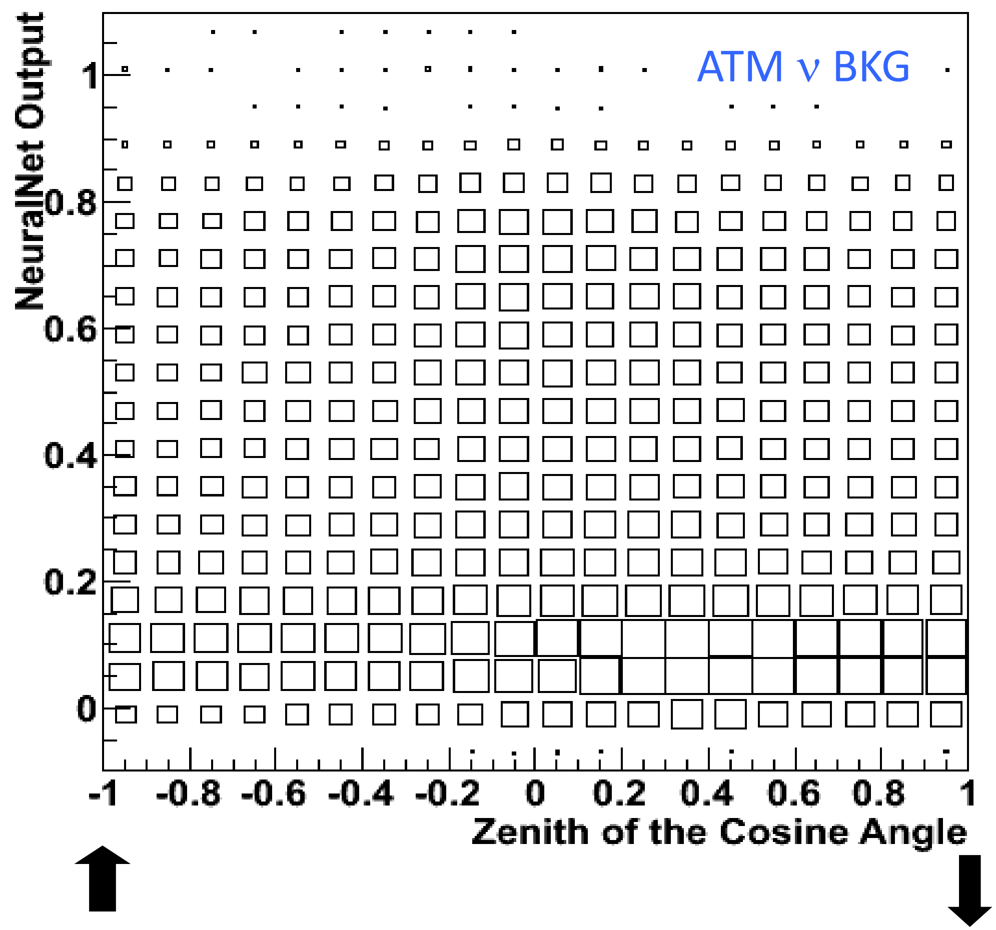
Leptons + Hadrons

- Expect ~1 ev/kton/year from oscillations
  - High-energy upward-going events
- Cross section measurement
- Background to θ_{13} induced oscillation effects in e-like samples
  - 5-25% of the background



Neural Network and Unbinned likelihood fit

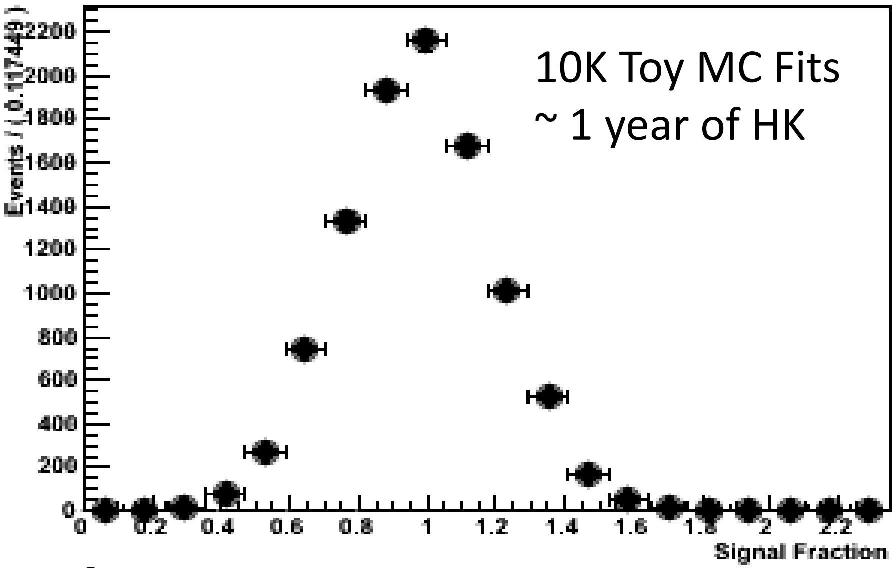




- Neural Network is built to separate tau events from NC and CC_x events
- Fit normalization of signal and bacground PDFs as a function of of NN output and Zenith Angle

Expectations at Hyper-K

$$\beta(\gamma) \times signal$$



[redacted]	[redacted]
SK ν_τ appearance search	3.8 σ observation (2.7σ expected)
Signal Efficiency	81%
Observed	180.1 $\pm$ 44.3 (stat) $^{+17.8}_{-15.2}$ (sys)
HK σ 1 yr	5.0 σ
HK 10 years	**3745.3** τ events

If no ν_τ appearance , $\beta = 0$

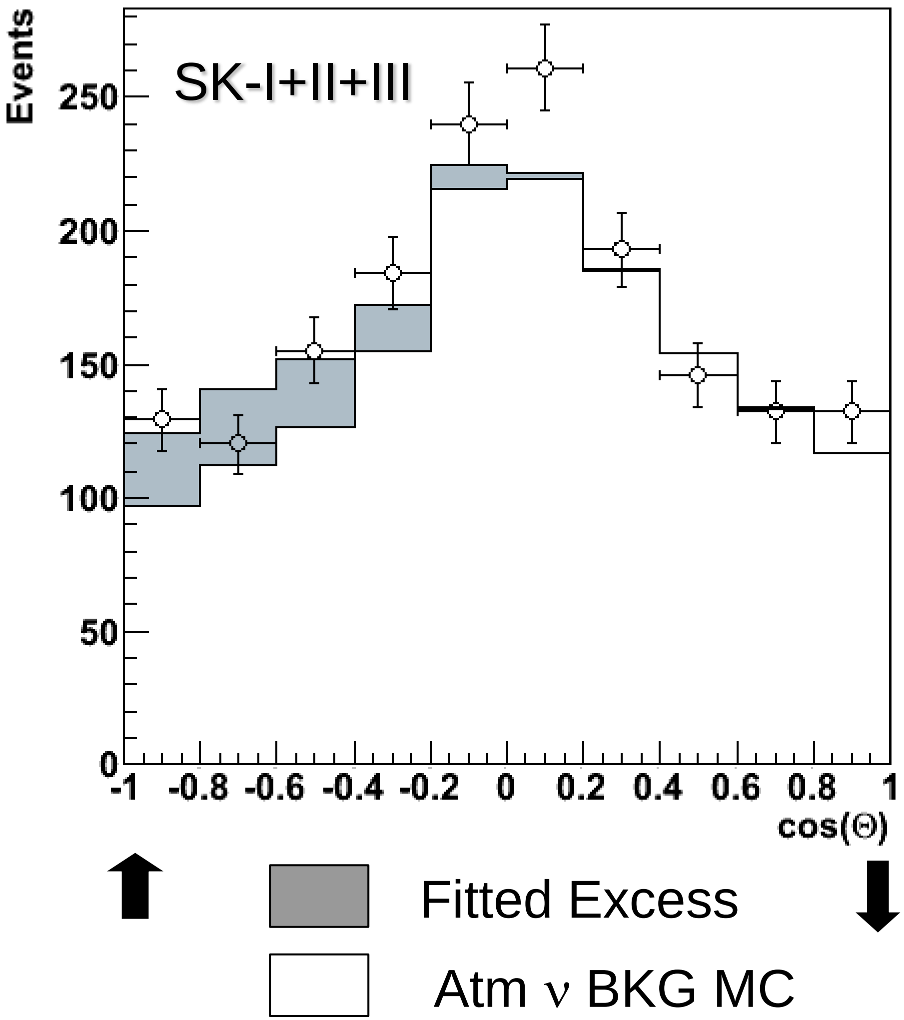
- A large number of ν_τ events are anticipated at Hyper-K
- Significant appearance signal within a year or two of running
- In the future:
  - Investigate cross section measurement possibilities
  - Investigate removing these events from the oscillation analysis to improve sensitivity

Supplements

Super-K Results, 2806 days

If no ν_τ appearance, $\beta = 0$

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



Result	Background	Signal
SK-I	0.95	1.27
SK-II	0.96	1.47
SK-III	0.94	2.16
SK-I+II+III	0.94 ± 0.02	**1.42 ± 0.35**
DIS γ	1.10 ± 0.05	

- Tau signal clearly appears in upward-going region
- Tau normalization fits to $1.42 \times$ expectation

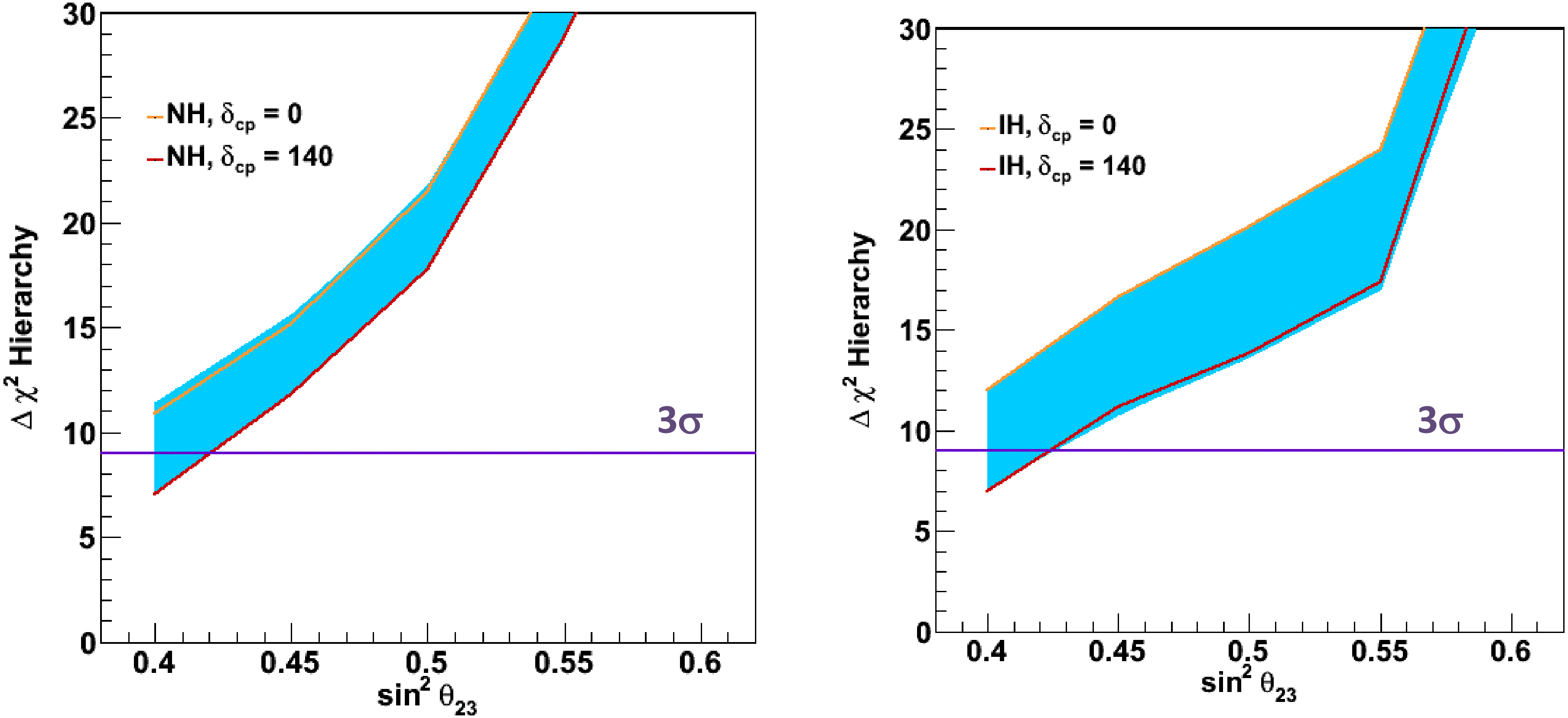
This corresponds to **180.1** $\pm$ 44.3 (stat) $^{+17.8}_{-15.2}$ (sys) events a **3.8 σ** excess
(Expected 2.7 σ significance)

Hierarchy sensitivity, 10 years of Atmospheric neutrino data (Previous meeting)

NH, unknown

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.10$

IH, Unknown



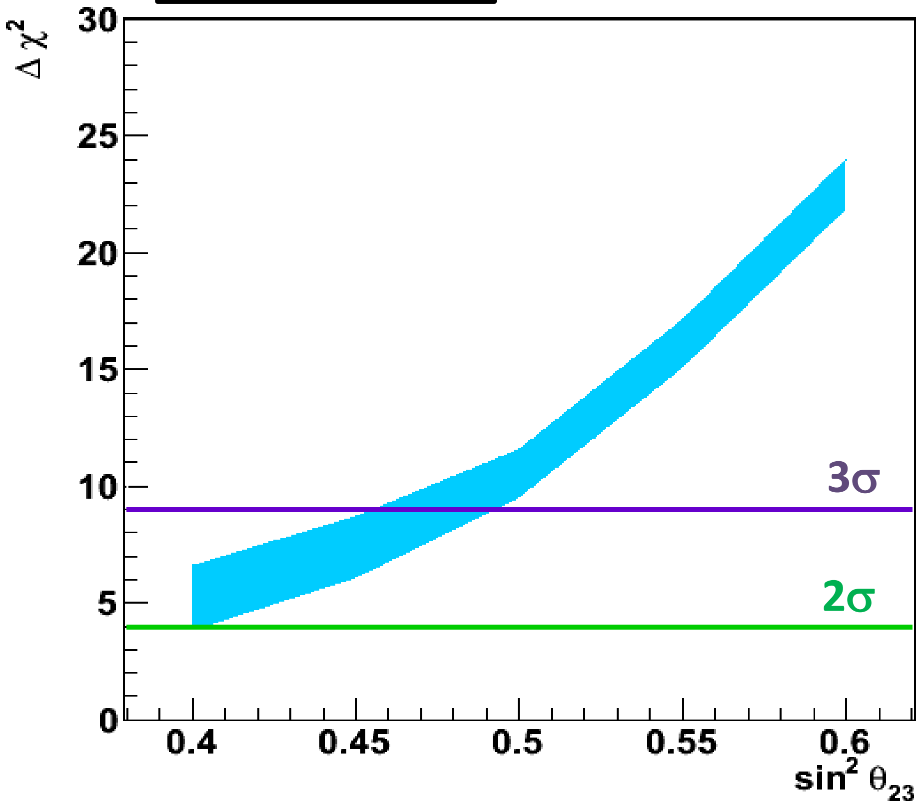
- Thickness of the band corresponds to range of δ_{cp}
- Weakest sensitivity overall in the tail of the first octant

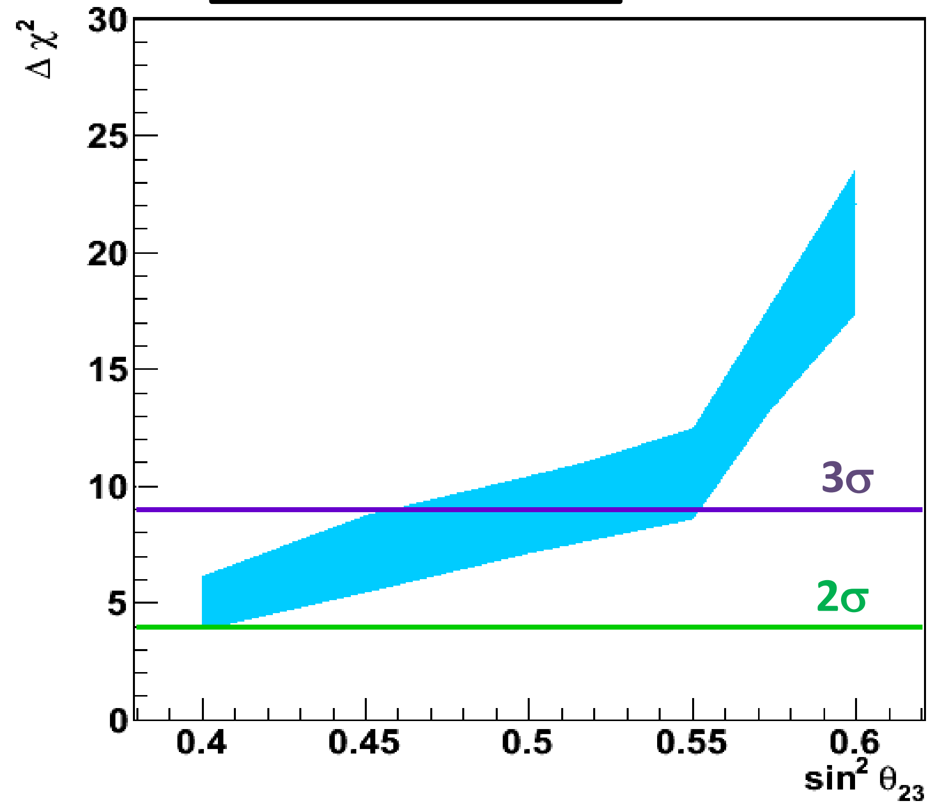
Hierarchy sensitivity, 5 years of Atmospheric data

NH, unknown

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.098$

IH, Unknown





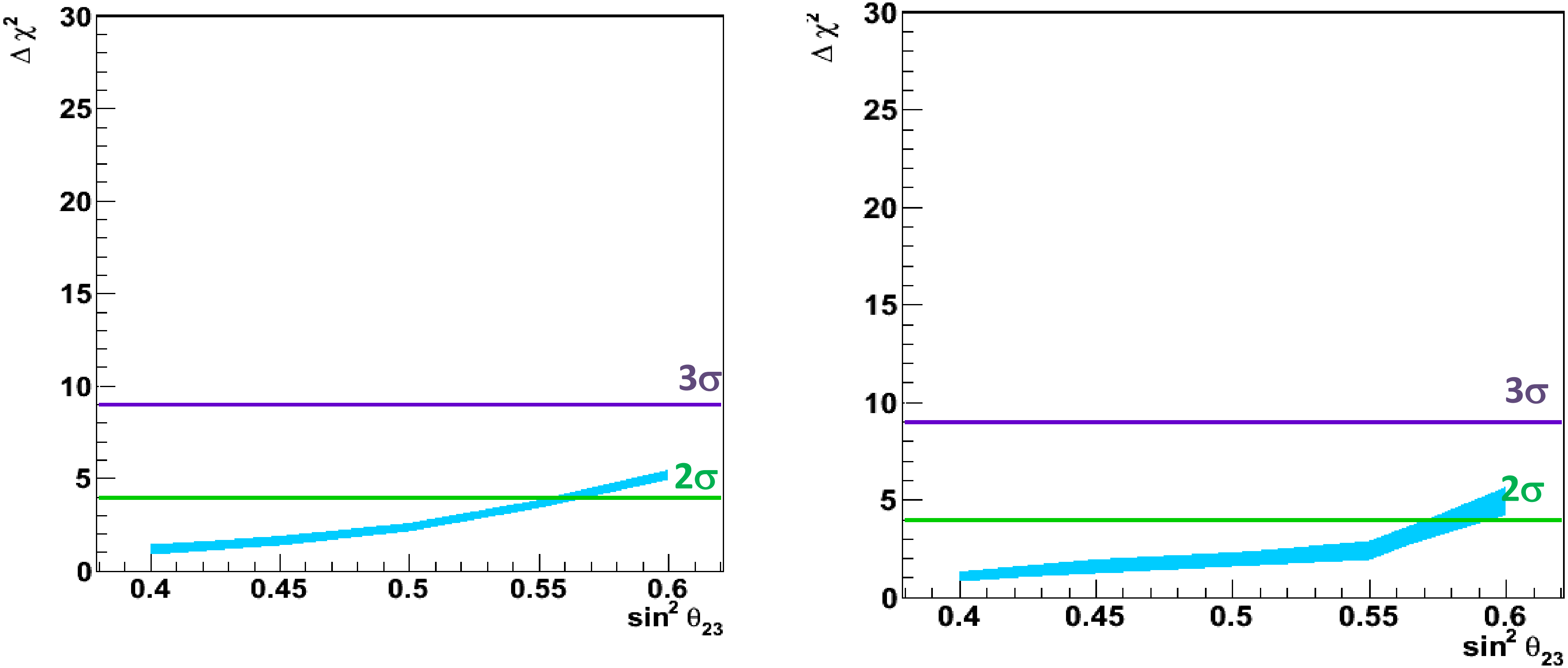
- With 5 years of data 2σ sensitivity to the hierarchy for all values of δ_{cp} and either hierarchy assumption
- 3σ sensitivity for the second octant of θ_{23}

Hierarchy sensitivity, 1 year of Atmospheric data

NH, unknown

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.099$

IH, Unknown



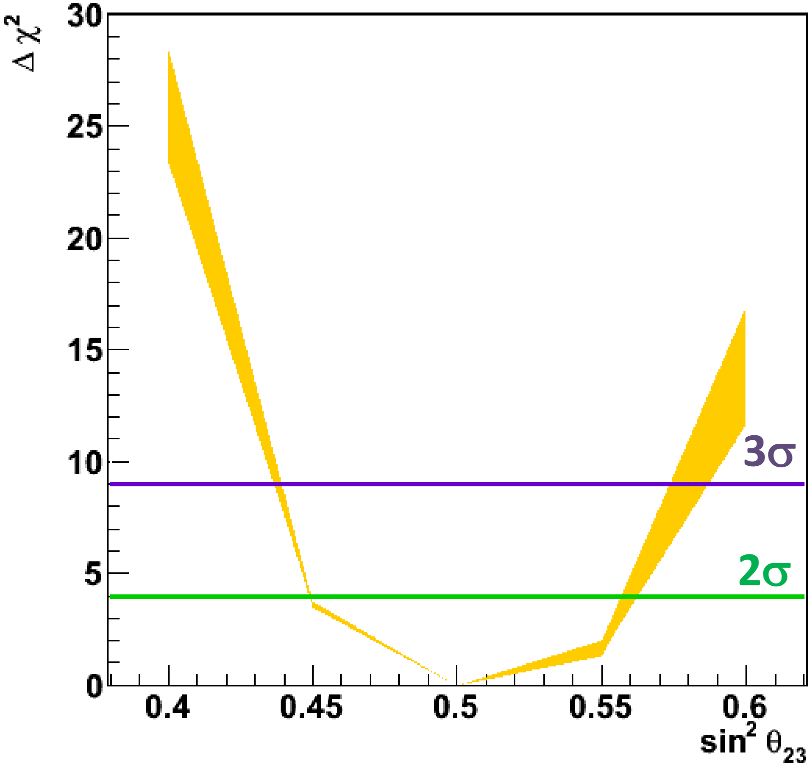
- With 1 year of data 2σ sensitivity to the hierarchy for all values of δ_{cp} and either hierarchy assumption
- 3σ sensitivity for the second octant of θ_{23}

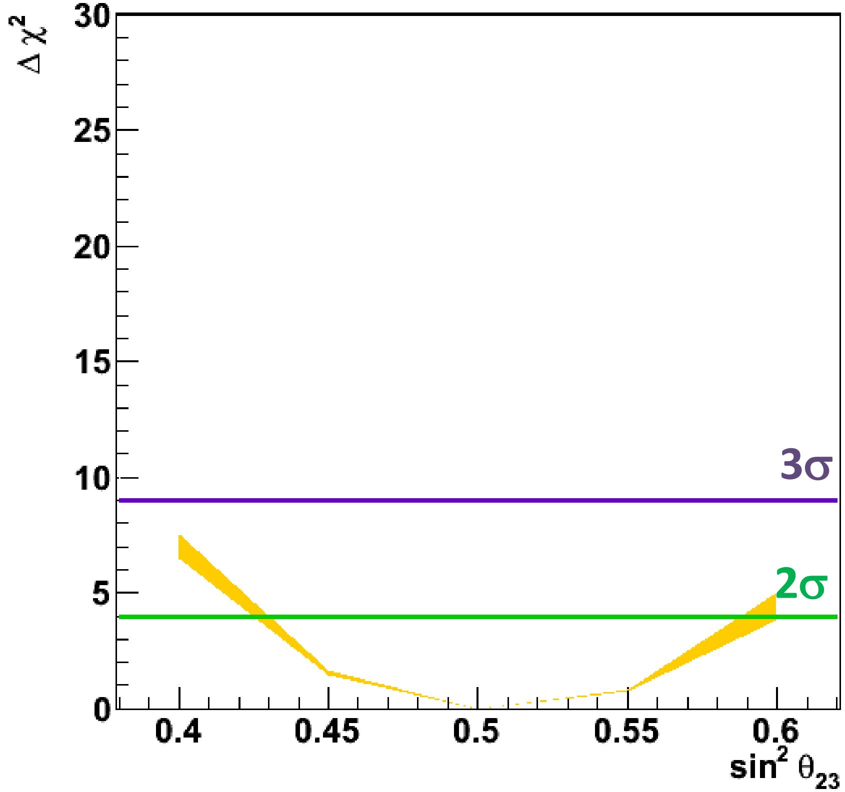
Octant sensitivity, 5 years of Atmospheric data

NH, unknown

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.098$

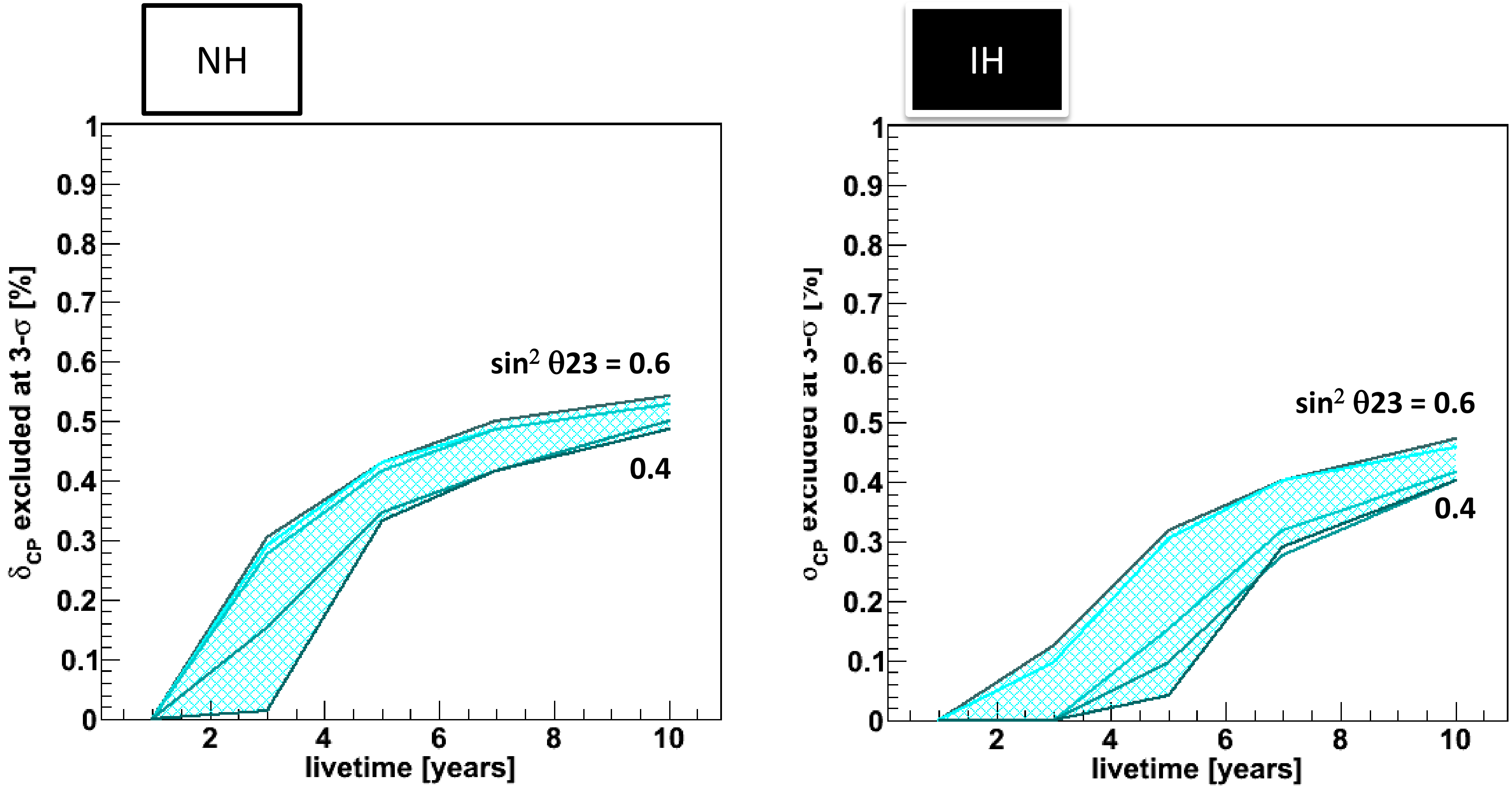
IH, Unknown





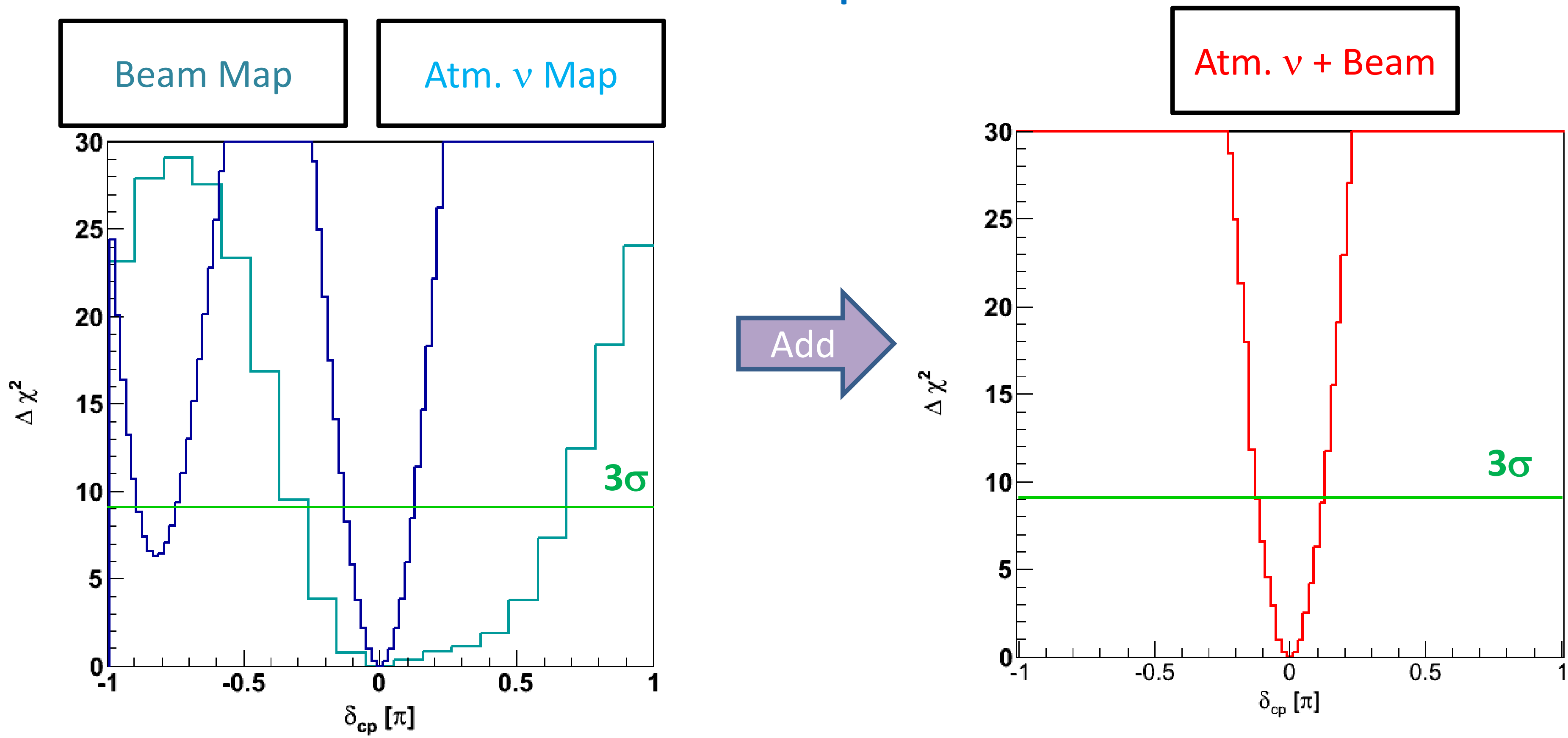
- With 1 year of data 2σ sensitivity to the hierarchy for all values of δ_{cp} and either hierarchy assumption
- 3σ sensitivity for the second octant of θ_{23}

Fraction of δ_{cp} excluded at 3σ for a fixed value of δ_{cp}



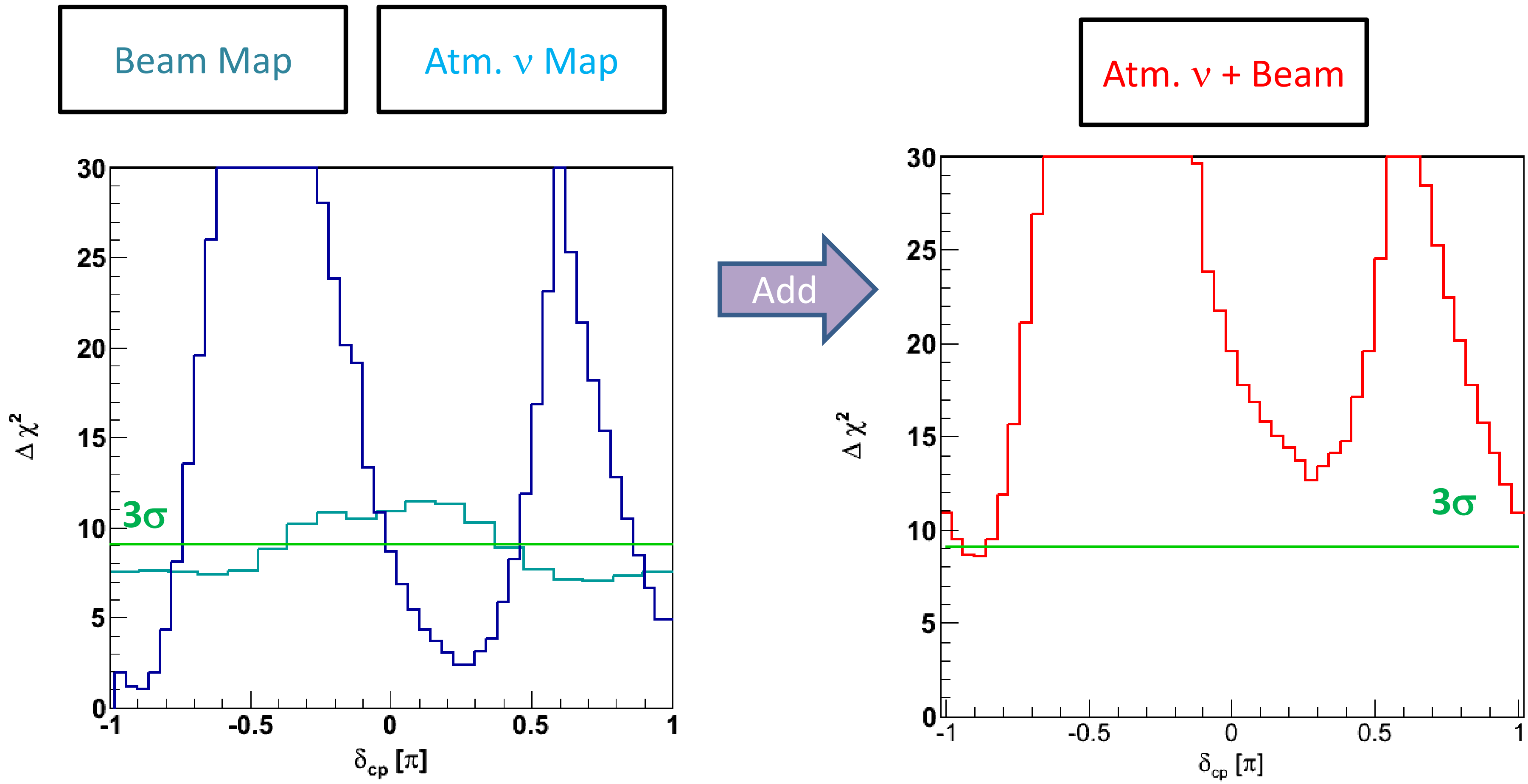
- For this particular input, the constraint atmospheric neutrinos can place on dcp is about 50% of

Combination of Beam and Atmospheric Neutrinos : Allowed δ_{cp}

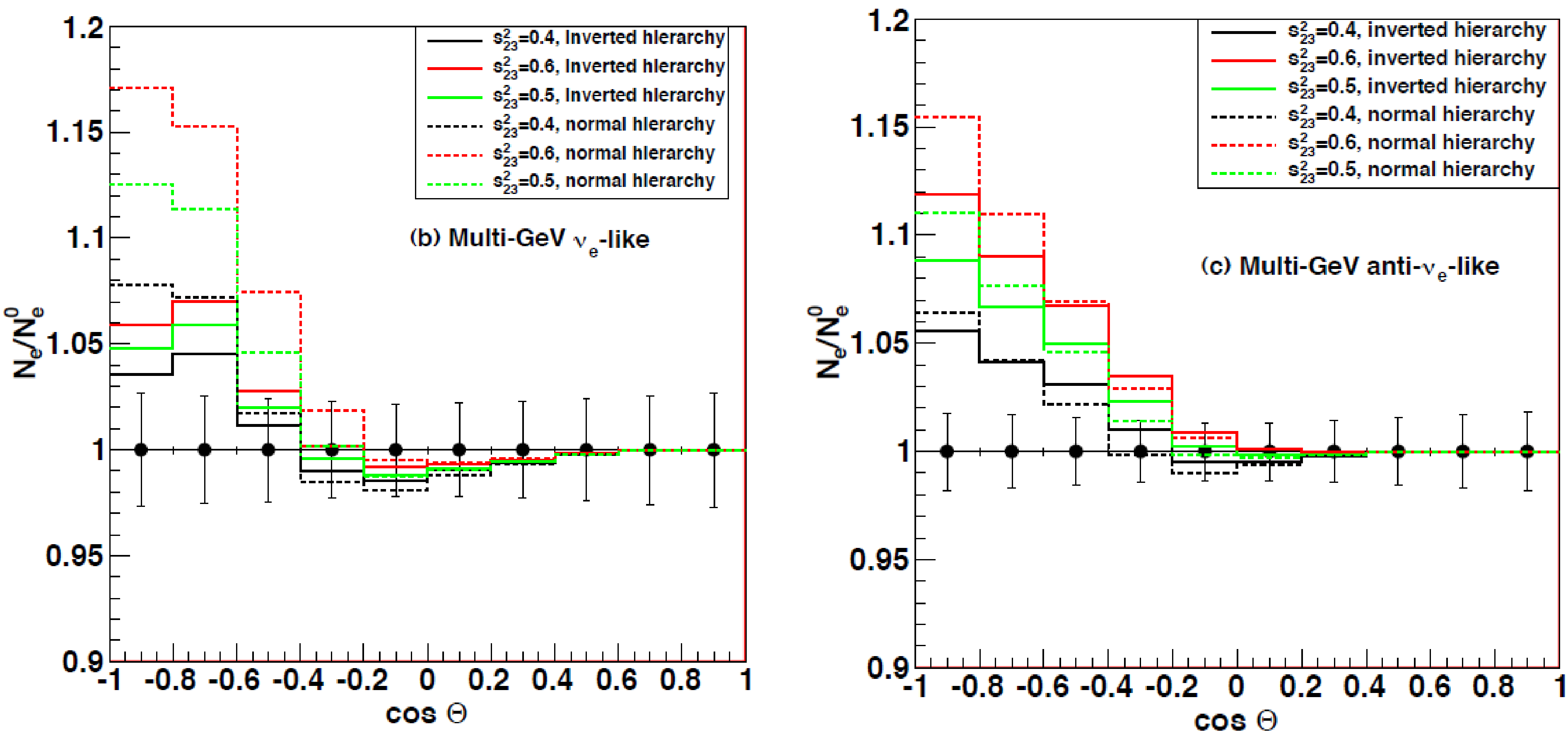


- Hierarchy is unknown, but NH is true
- True $\delta_{cp} = 0.0$
- True $\sin^2 2\theta_{13} = 0.10$
- Maximal mixing , $\sin^2 2\theta_{23} = 1.0$
- Degenerate solution exists at 3σ in the beam only case - just add the χ^2 maps
- In the real world, something more sophisticated is in order

Hierarchy sensitivity : Combination of Beam and Atm. Neutrinos

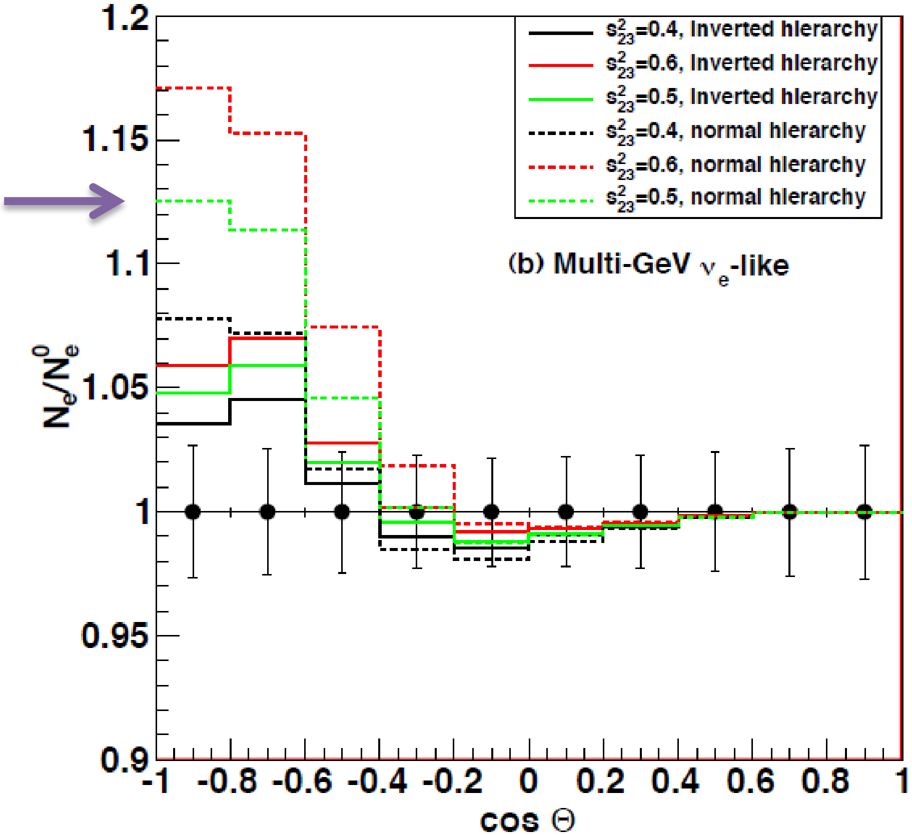


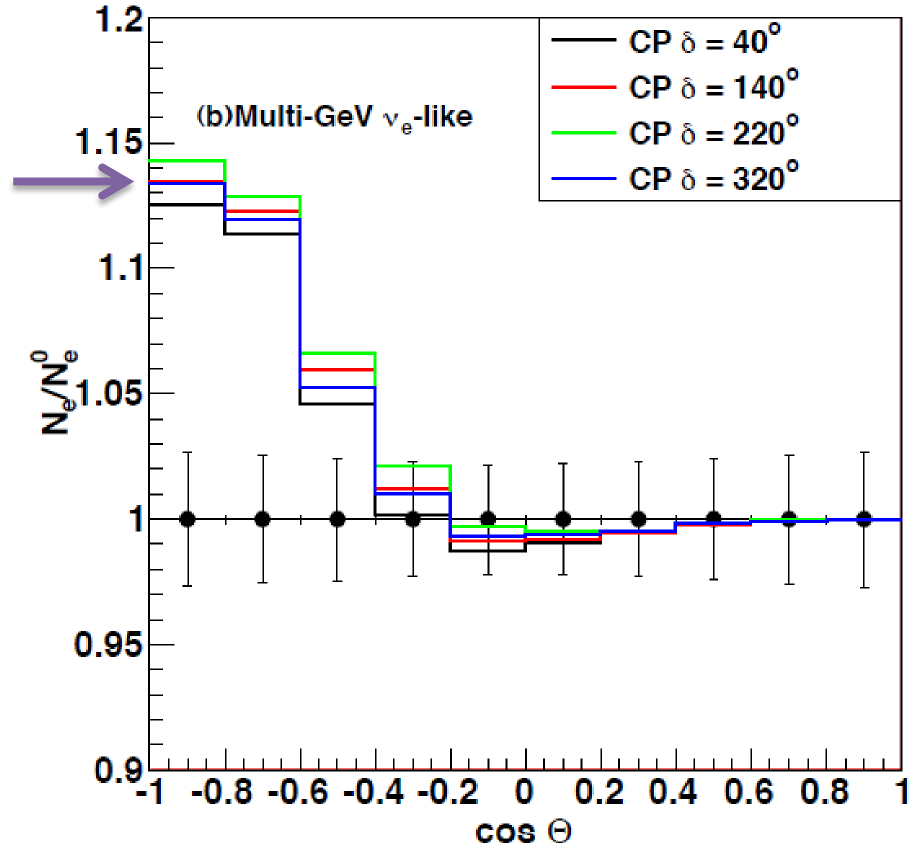
- Hierarchy is unknown, but the NH is true
- True $\sin^2 2\theta_{13} = 0.10$
- Using $\sin^2\theta_{23} = 0.4$
- Even under a conservative assumption its possible to achiev ~3σ discrimination or all values of δ_{cp} if the true hierarchy is normal



s^2_{23}=0.4, inverted hierarchy
s^2_{23}=0.6, inverted hierarchy
s^2_{23}=0.5, inverted hierarchy
s^2_{23}=0.4, normal hierarchy
s^2_{23}=0.6, normal hierarchy
s^2_{23}=0.5, normal hierarchy
(b) Multi-GeV ν_e-like
N_e/N_e^0
cos Θ
(c) Multi-GeV anti-ν_e-like

Expected Effects : electron-like samples

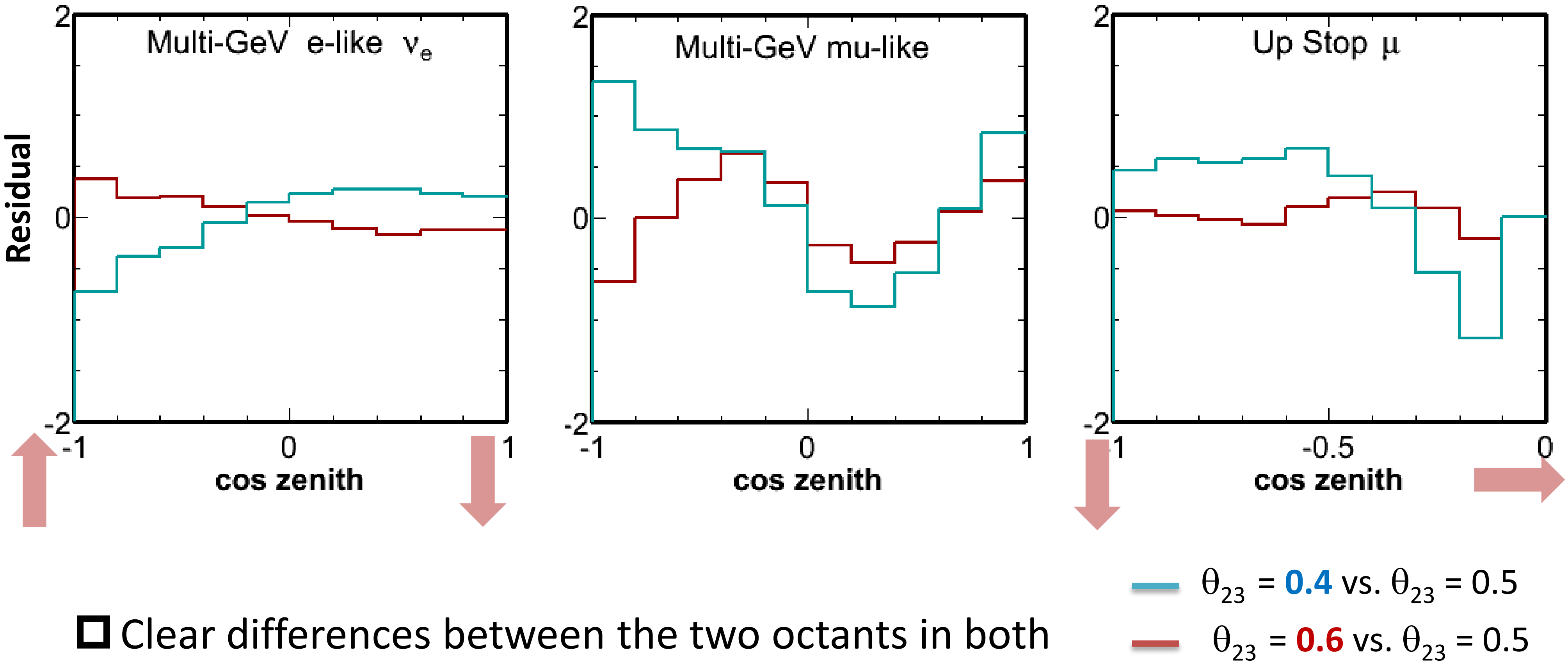




→ Equivalent MC

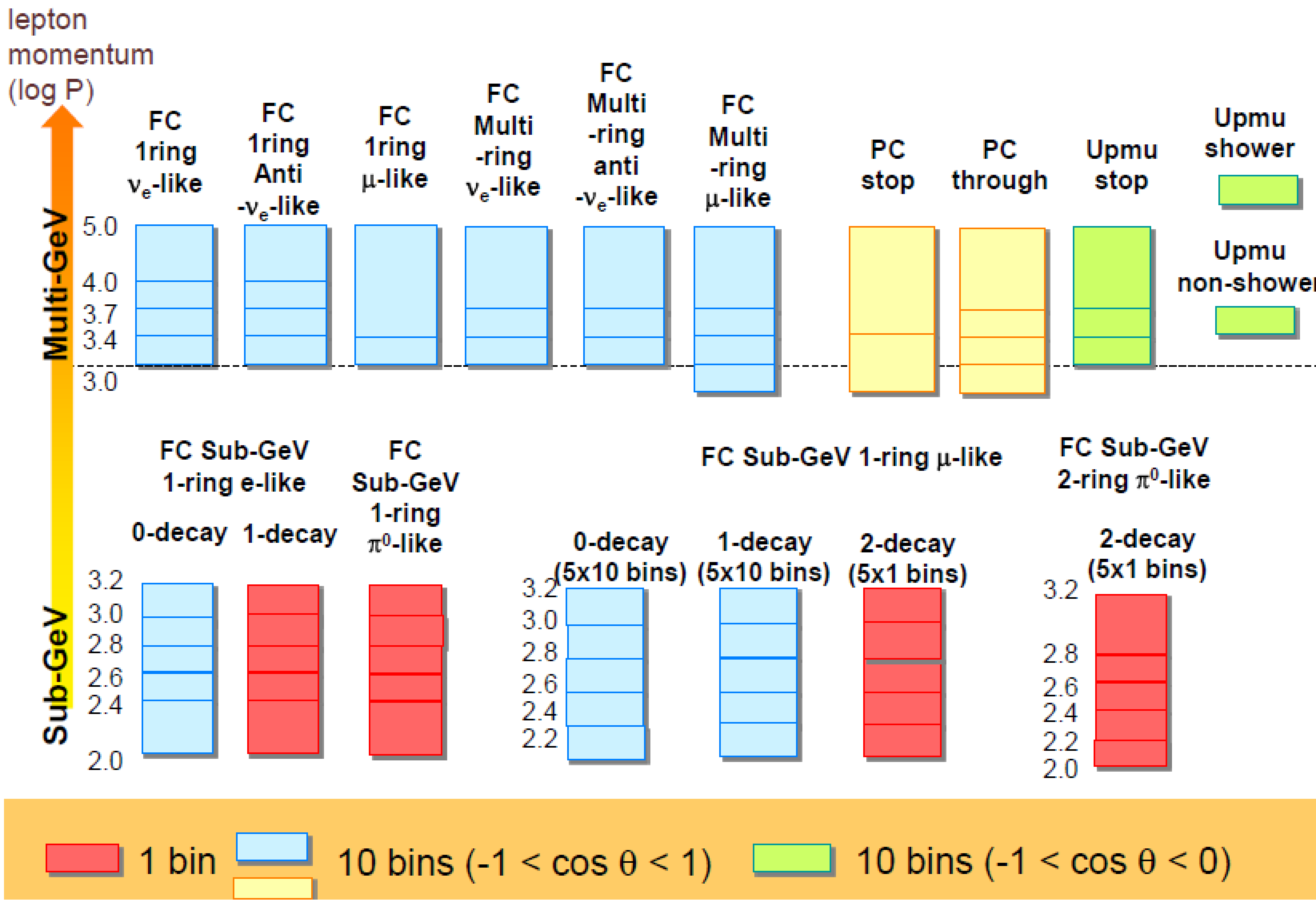
- Effect of the θ_{23} octant can be larger than that from δ_{cp} on electron appearance
- Effect of the latter is smaller than the expected statistical uncertainty in each bin

Octant: Residual at Maximal Mixing (x – $MC^{\theta = 0.5}$)/ sqrt($MC^{\theta = 0.5}$)



- Clear differences between the two octants in both the electron and muon samples
- Overall slightly better sensitivity to the first octant

Zenith Angle Analysis – 480 Bins



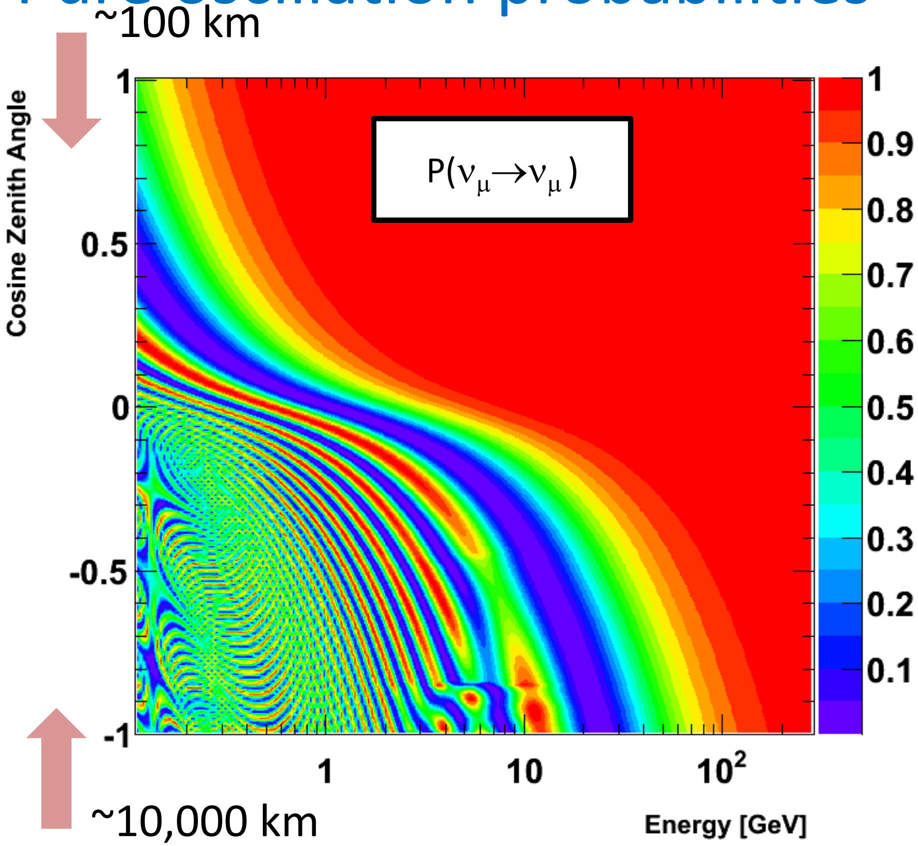
Sample Composition

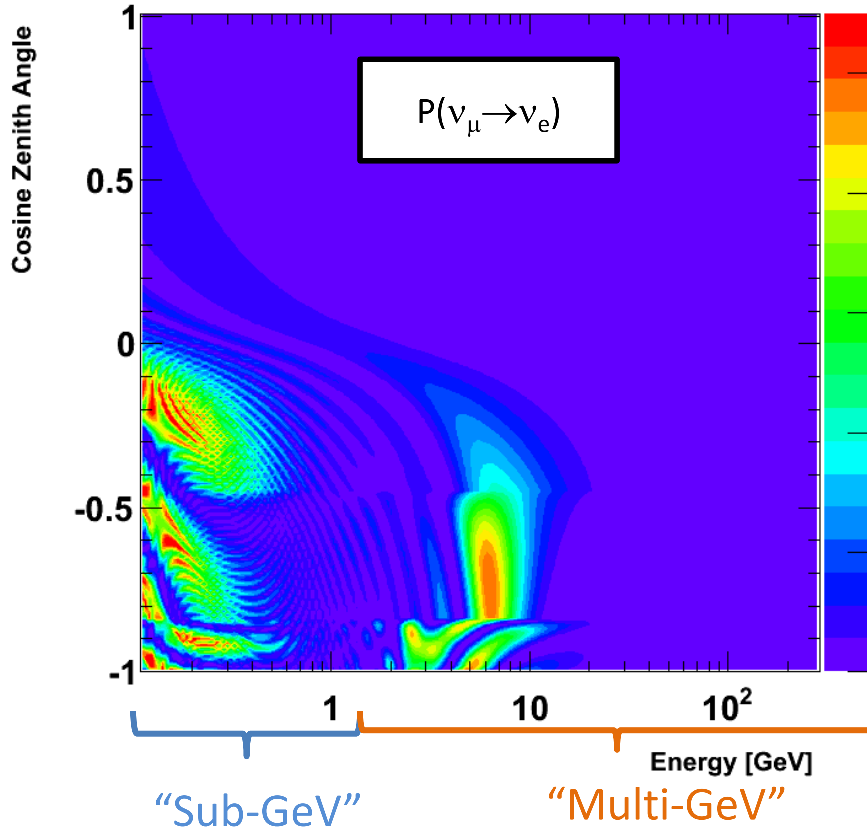
Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_e like	1R	60.2	10.6	13.5	14.8
	MR	57.5	17.4	10.7	13.7
Anti-ν_e like	1R	55.7	36.6	1.1	6.4
	MR	51.9	20.7	8.2	19.7

Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_μ like	1R	0.2	0.08	98.8	0.2
	MR	2.5	0.3	91.7	4.4

- Generally the background component of the e-like signal samples is **~20-30%**
- Muon-like samples on the other hand tend have high-purity and reasonable sensitivity to small effects

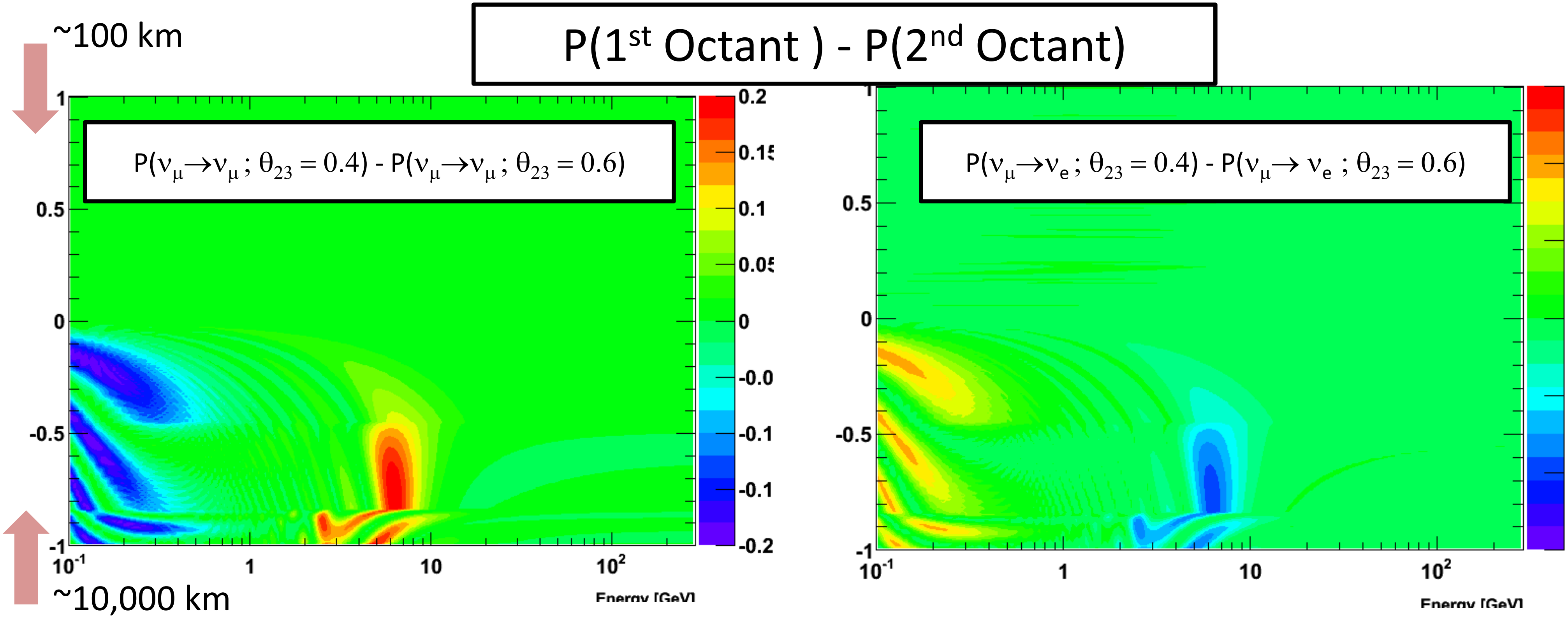
Pure oscillation probabilities





- In the presences of the now large θ_{13} resonant enhancement of the $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability occurs via matter interactions
- Resonance occurs only for (anti-)neutrinos under the Normal (Inverted) Hierarchy
  - Effects are roughly halved going to the IH

Oscillation probability difference between the θ_{23} octants



- Matter effect gives improved sensitivity
  - Mass hierarchy → Asymmetry between neutrinos and antineutrinos
  - size of θ_{13} and δ_{cp} → Magnitude of resonance effect
  - Octant of θ_{23} → Appearance and disappearance interplay

(Trends are Independent of Hierarchy)

Systematic Errors

	+ %	-%
☐ **Flux:** Up/Down Ration, Horizontal/ Vertical ratio , K/p ☐ **X-sec:** NC/CC ratio ☐ **Dectector:** Up/Down Energy cal. Asymmetry	7.9	8.5
☐ **Oscillation Parameters:** 1 - σ allowed atm.	5.4	1.3

$$\beta = 1.42 \pm 0.35 \text{ (stat)} {}^{+0.14}_{-0.12} \text{ (sys)}$$

This corresponds to 180.1 ± 44.3 (stat) $^{+17.8}_{-15.2}$ (sys) events a 3.8 σ excess

(Expected 2.7 σ significance)

SK Data disfavor 'no tau appearance' at 3.8 σ

Interaction Mode	NN < 0.5	NN > 0.5	All
CC ν_e	781.4 (0.40)	381.3 (0.46)	1162.7 (0.42)
CC ν_μ	1070.2 (0.55)	200.2 (0.24)	1270.4 (0.46)
CC ν_τ	12.4 (0.01)	37.2 (0.04)	49.7 (0.02)
NC	95.2 (0.05)	209.3 (0.25)	304.4 (0.11)

Systematics Uncertainties for ν_τ normalization		+ %	− %
Super-K atmospheric ν oscillation errors			
28 error terms	(expected events)	13.4	14.7
5 error terms	(observed events)	7.9	8.5
Tau neutrino cross section	(expected events)	25.0	25.0
Oscillation parameters	(observed events)	5.4	1.3

A note about tools

- Currently the Software WG is working to produce a set of HK-specific tools
  - A realistic detector simulation and reconstruction tools are primary goals
  - Producing a complete working environment will take time
  - Some members of this WG are also participating

- Up until now HK studies have been done using SK/T2K tools
- We are currently discussing the possibility of making software developed by Super-K and T2K available to Hyper-K members
  - Similar agreements exist between Super-K and T2K for example
  - In order to make a realistic proposal we need to know if there is a real need exists
  - If you aren't part of SK or T2K but would like to use some software for your studies please let me (or Yokoyama-san, or Shiozawa-san) know
    - What you need and why?
    - What is the timescale for your study?

Update 20130909

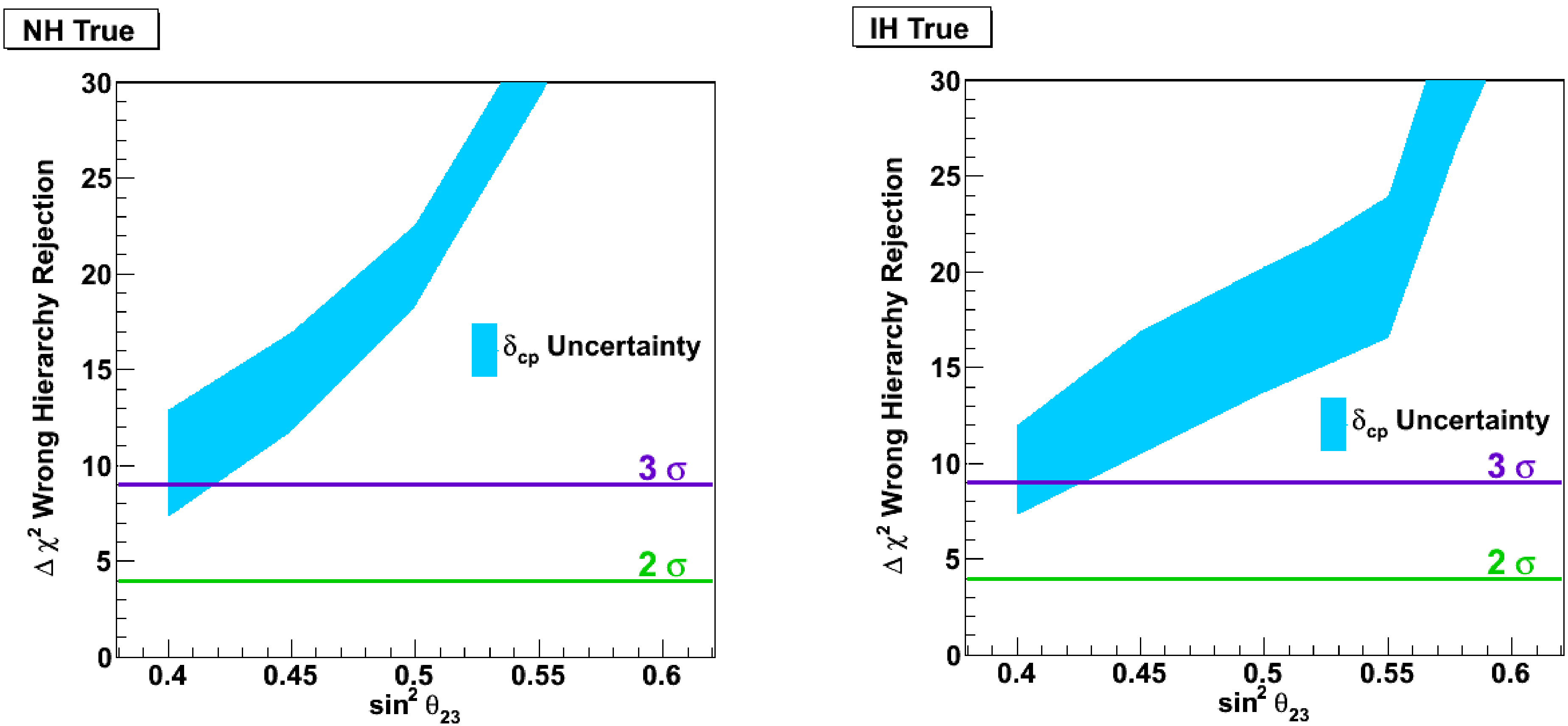
- The 10year HK Sensitivity plots were updated for the Snowmass process and reported here
- The result is unchanged, only annotation has been added to the plots for clarity

Hierarchy sensitivity, 10 years of Atmospheric neutrino data

NH, unknown

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.10$

IH, Unknown



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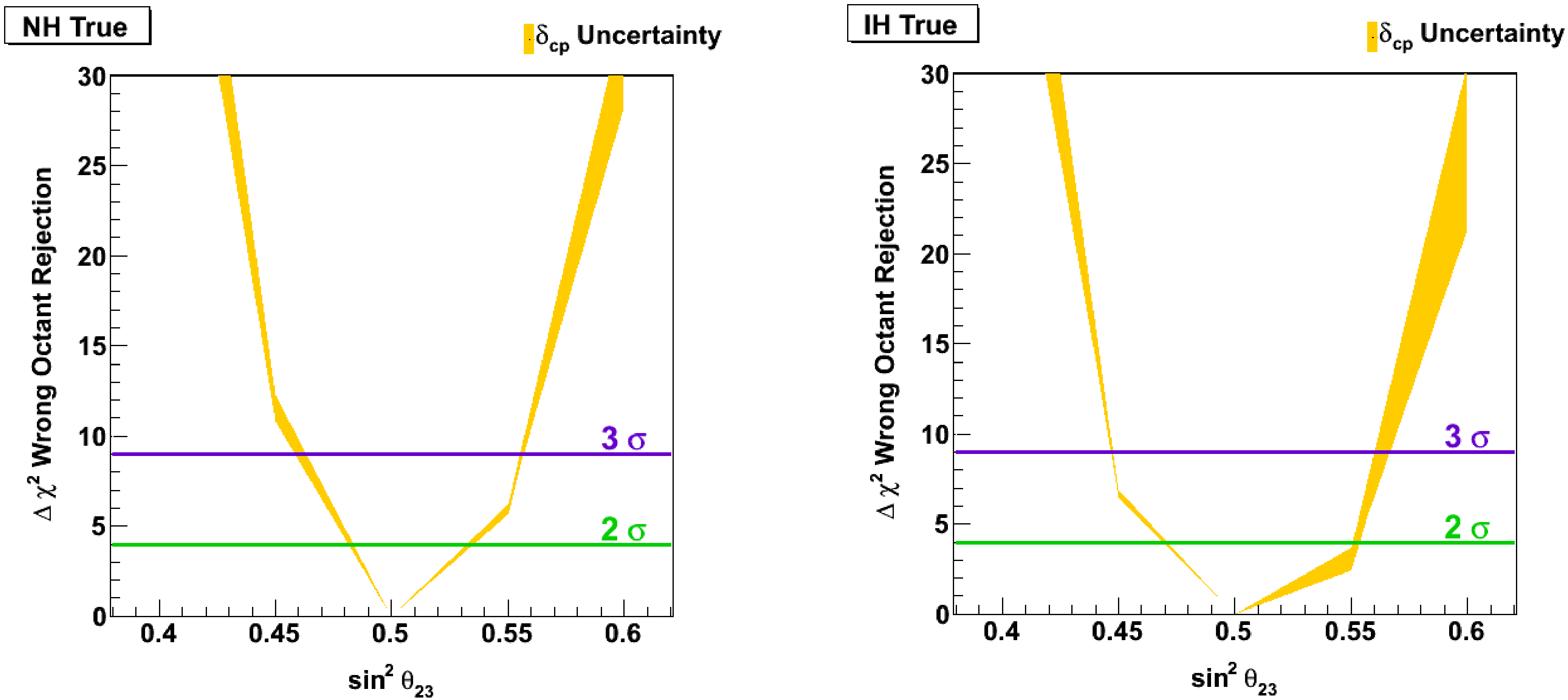
Octant sensitivity, 10 years of Atmospheric data

NH, θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.098$ IH



- Thickness of the band corresponds to the uncertainty from δ_{cp}
- Best value of δ_{cp} = 40 degrees
- Worst value of δ_{cp} = 140 (260) degrees, for 1st (2nd) octant