FUTURE OF ATMOSPHERIC NEUTRINO MEASUREMENTS

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Harish-Chandra Research Institute, India

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WHAT IS KNOWN

- $\Delta m^2_{21} \sim 7.6 \times 10^{-5}\ eV^2$, $\sin^2\theta_{12} \sim 0.31$ *Fogli et. al.,1205.5254* *Valle, et. al.,1205.4018*
- $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}\ eV^2$, $\sin^2 2\theta_{23}$ almost maximal

- ***θ_{13} is large*** *T2K, Double Chooz, Daya Bay, Reno*
- *Mass Hierarchy (MH) determination will be easier*
- *Possibility of CPV determination is now opened up*

WHAT IS UNKNOWN

- *Neutrino mass ordering is completely unknown* - ***Probe it!!***
- *Some hints of θ_{23} being non-maximal* - ***Probe it!!***
- *If θ_{23} is non-maximal, then what's correct octant*-***Probe it!!***
- *Whether CPV exists in the lepton sector* - ***Probe it!!***

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Atm nus

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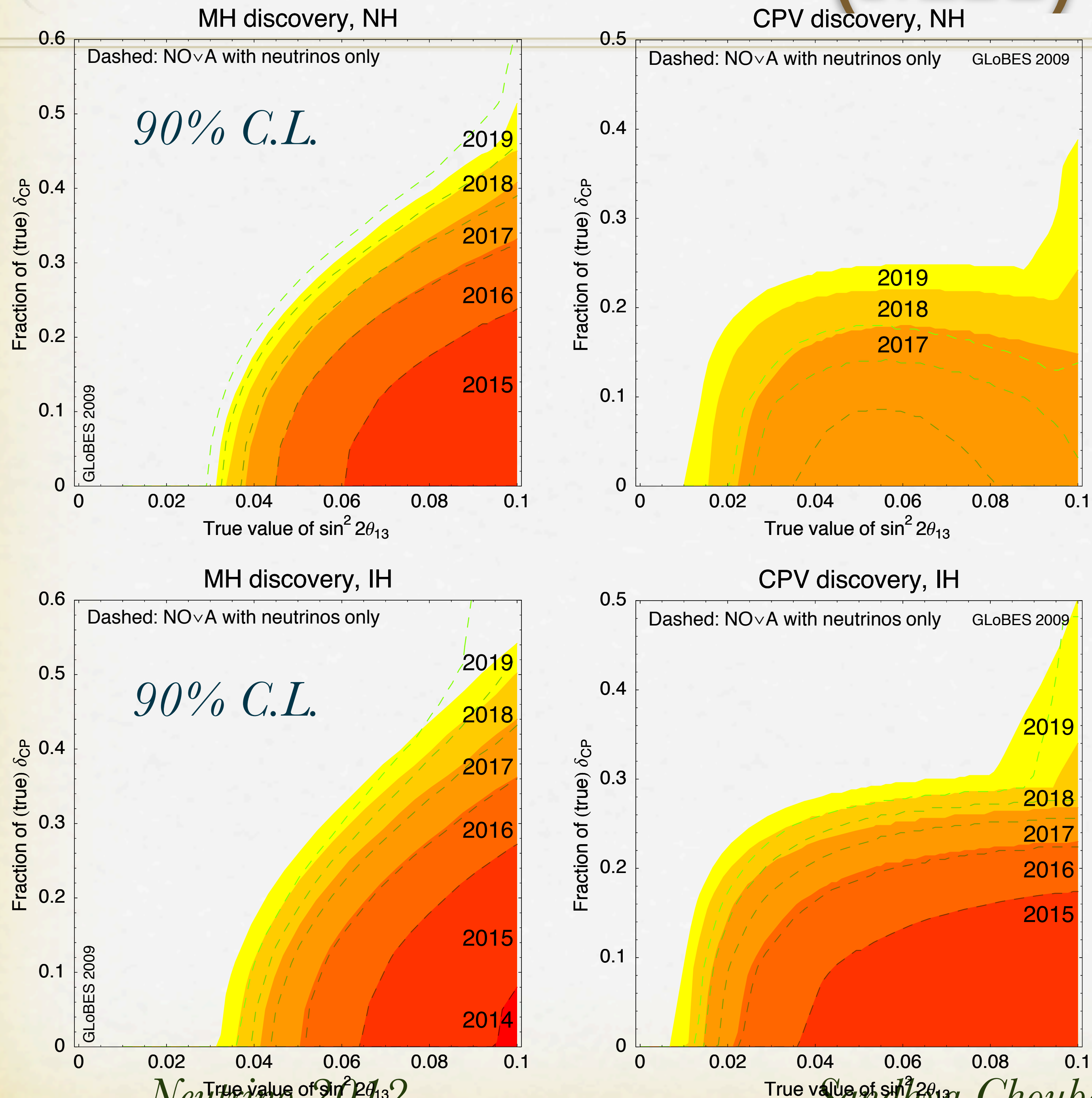
- *Some hints of θ_{23} being non-maximal -* ***Probe it!!***
- *If θ_{23} is non-maximal, then what's correct octant-****Probe it!!***
- *Whether CPV exists in the lepton sector -* ***Probe it!!***

ROLE OF THE LBL/REACTOR EXPERIMENTS

REACH OF T2K+NOvA+Reactors (MH)



- *Projected sensitivity curve with expts specifications and timeline taken from LOI*
- *MH can be discovered only at 90% C.L. for only about 50% of the δ_{cp} values*
- *At 3σ these plots are almost empty and there is no MH sensitivity :(*

Huber, Lindner, Schwetz, Winter, 0907.1896

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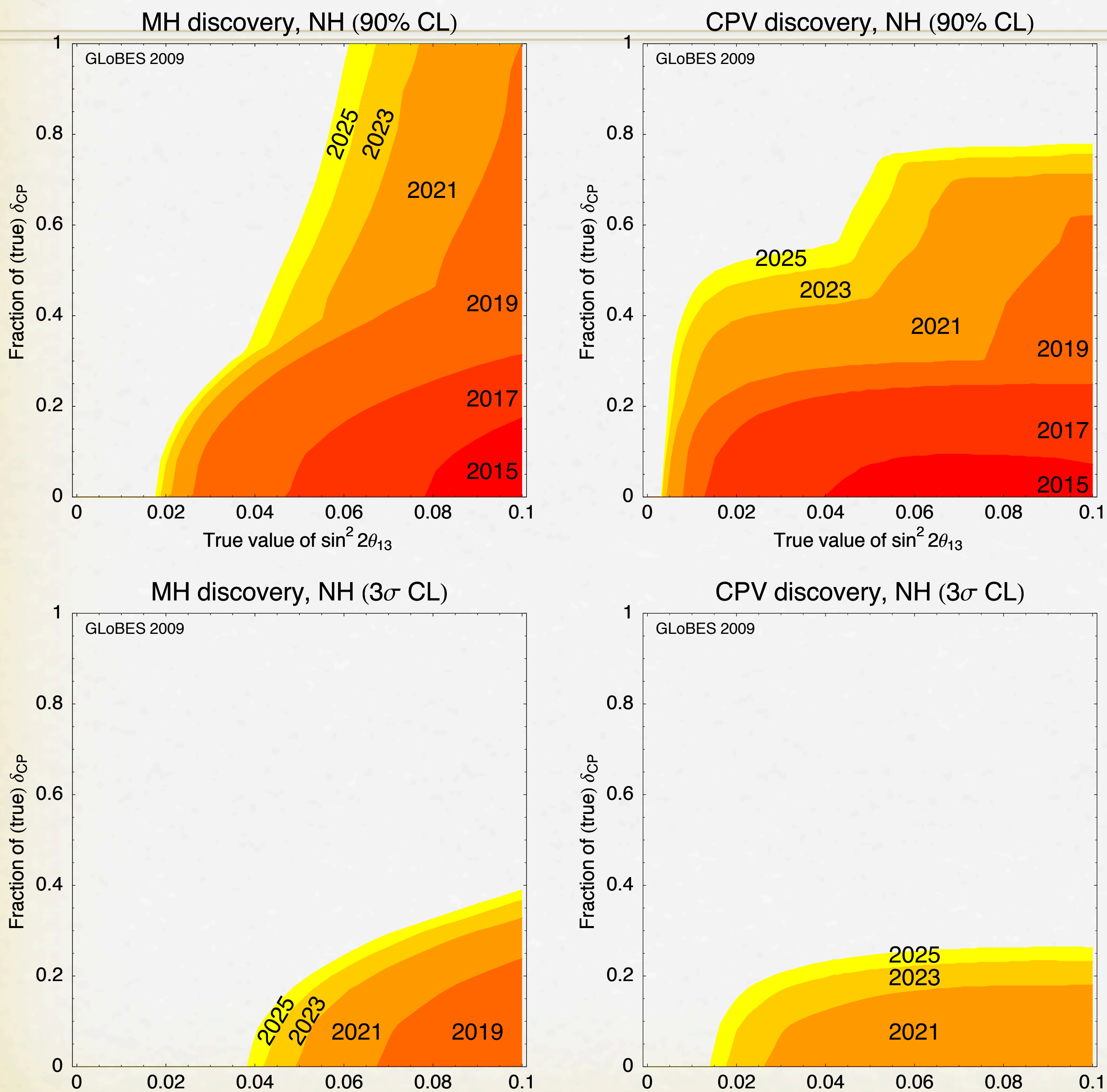


- *T2K power increased to 1.66 MW*
- *NOvA power increased to 2.3 MW*
- *MH sensitivity at 3σ in 2025 for 40% of δ_{cp} values*

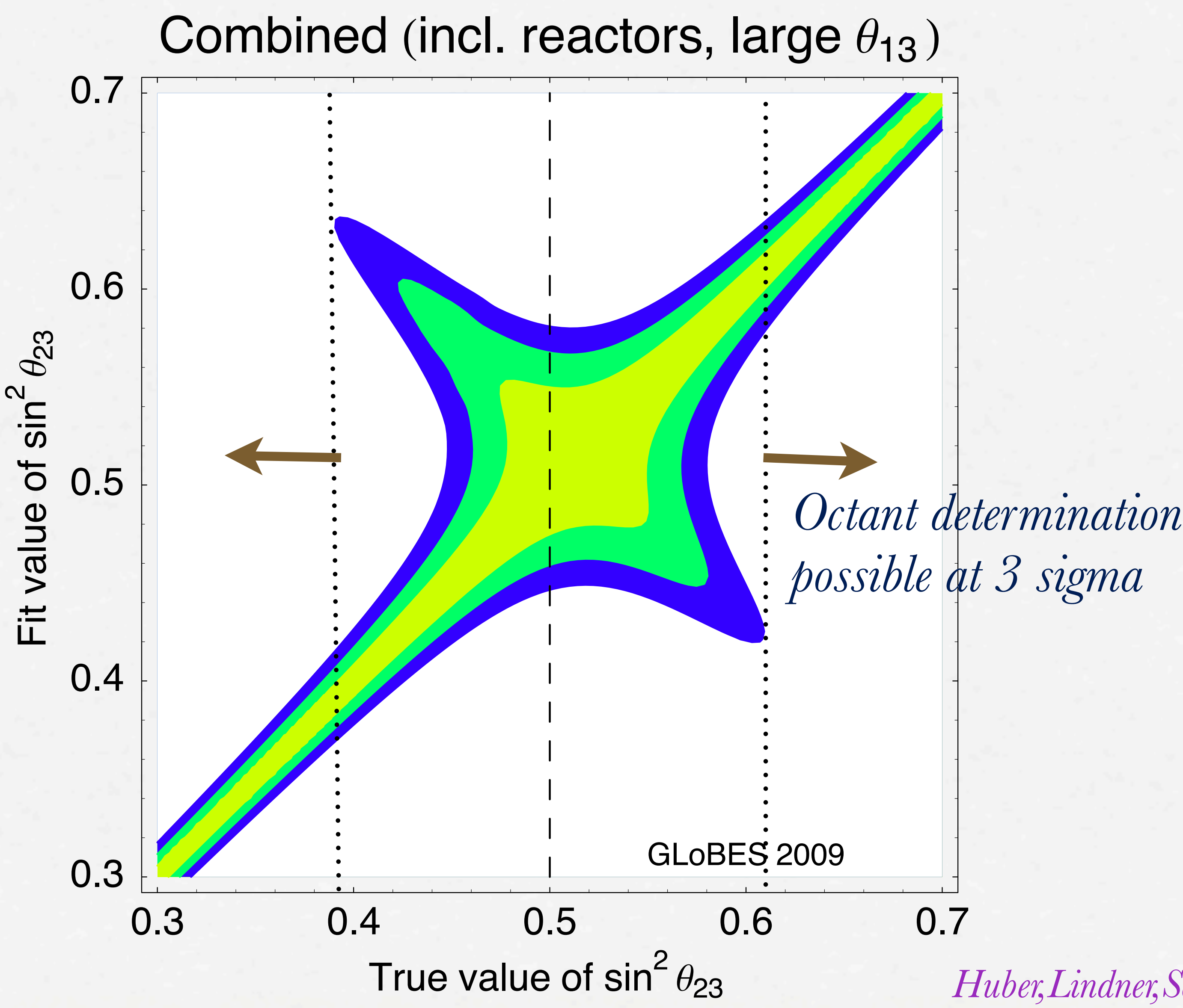
Huber, Lindner, Schwetz, Winter, 0907.1896

REACH OF T2K+NOvA+Reactors (θ_{23})

$$P_{e\mu} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$
$$\pm\,\alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta_{CP}\sin(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$
$$+\,\alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\delta_{CP}\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$
$$+\,\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

- *T2K and NOvA measure this combination of* $\sin^2\theta_{23}\sin^2 2\theta_{13}$
- *Reactor experiments measure only* $\sin^2 2\theta_{13}$
- *Combination of the two data sets brings in some octant sensitivity*

REACH OF T2K+NOvA+Reactors (θ_{23})



Huber,Lindner,Schwetz,Winter, 0907.1896

See talk by H. Minakata for LBL+Reactor prospects

ROLE OF FUTURE ATMOSPHERIC NEUTRINO EXPERIMENTS

THREE-FLAVOR EFFECTS IN ATMOSPHERIC NEUTRINOS

- *Incomplete list of the literature:*

Petcov (1998), Chizov, Maris, Petcov (1998), Akhmedov (1999),Akhmedov,Dighe,Lipari,Smirnov (1999),Kim (1998),Peres,Smirnov(1999),Bernabeu, Palomares-Ruiz, Perez, Petcov, (2002), Gonzalez-Garcia, Maltoni (2003), Bernabeu, Palomares-Ruiz, Petcov (2003), Peres, Smirnov (2004), Indumathi, Murthy (2004), Gandhi, Ghoshal, Goswami, Mehta, Sankar (2004), Gonzalez-Garcia, Maltoni, Smirnov (2004), Palomares-Ruiz, Petcov (2005), Choubey, Roy (2005), Fogli, Lisi, Marrone, Palazzo (2005); Huber, Maltoni, Schwetz (2005), T. Kajita (2005); E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2005), Petcov, Schwetz (2006), S. Choubey (2006); Indumathi, Murthy, Rajasekaran, Sinha (2006), E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2007), R. Gandhi, P. Ghoshal, S. Goswami, P. Mehta, S. U. Sankar and S. Shalgar (2007), E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2008), Gandhi, Ghoshal, Goswami, Sankar (2008), Mena, Mocioiu, Razzaque (2008), Peres, Smirnov (2009), Gandhi, Ghoshal, Goswami, Sankar (2009), Samanta (2006 - 10), Samanta, Smirnov (2010), Conrad, de Gouvea, Shalgar (2010), Gonzalez-Garcia, Maltoni, Salvado (2011), Barger, Gandhi, Ghoshal, Goswami, Marfatia, Prakash, Raut, Sankar (2012), Blennow, Schwetz (2012), Akhmedov, Razzaque, Smirnov (2012), ...

- *My apologies if your name is missing here -*

CATALOGUE OF ATMOSPHERIC NEUTRINO EXPERIMENTS

- *Magnetized Iron Calorimeters:* ➽ *ICAL@INO*
- *Water Cherenkov Detectors:* ➽ *Hyper-Kamiokande*
- *(Magnetized) Liquid Argon:* ➽ *Glacier*
- *Multi-Mton Ice Detectors:* ➽ *ICDC, PINGU*

CATALOGUE OF ATMOSPHERIC NEUTRINO EXPERIMENTS

- *Magnetized Iron Calorimeters:* ➽ *ICAL@INO*
  - ✔ *Charge identification capability*
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  - ✘ *Relatively high threshold*
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  - ✔ *Huge size*
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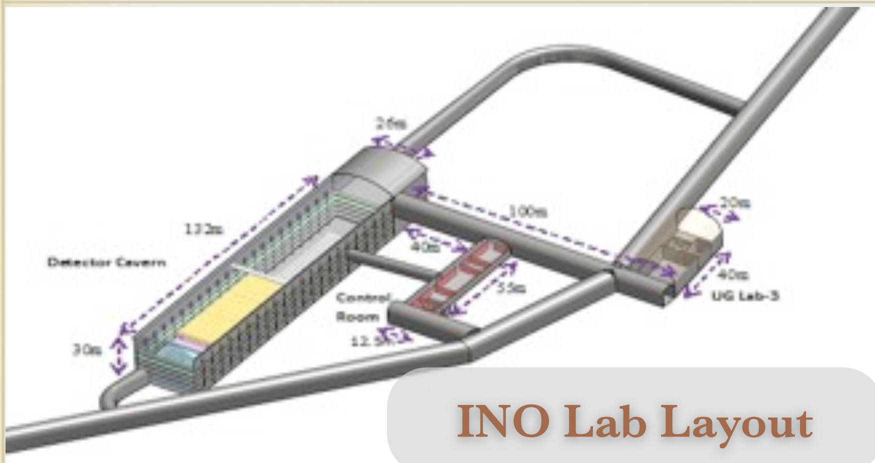
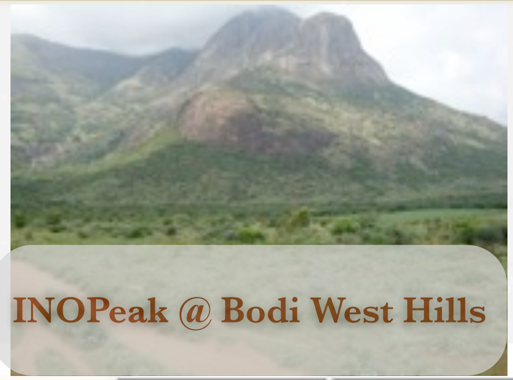
- *Multi-Mton Ice Detectors:* ➽ *ICDC, PINGU*
  - ✔ *HUGE* ✘ *poor e,* ✘ *no charge id,* ✘ *bad E resoln,* ✘ *threshold?*

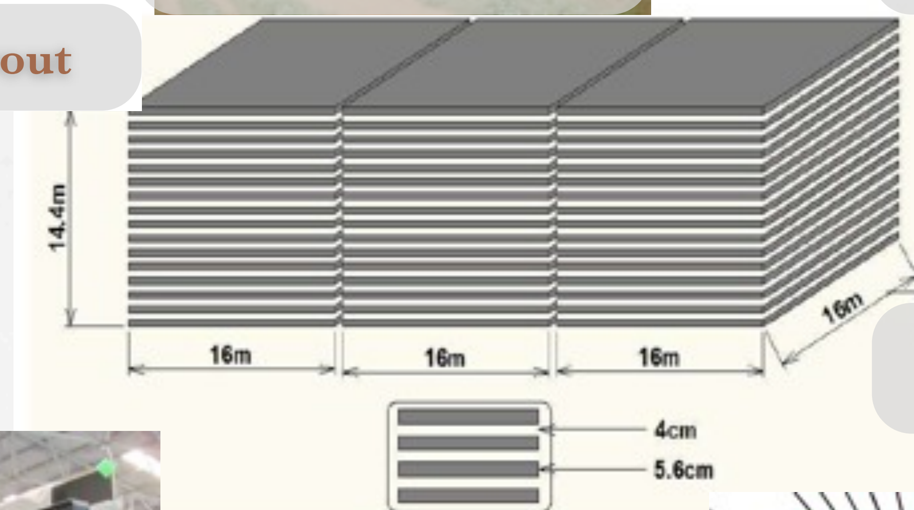
INDIA-BASED NEUTRINO OBSERVATORY (INO)



INO Lab Layout


INOPeak @ Bodi West Hills

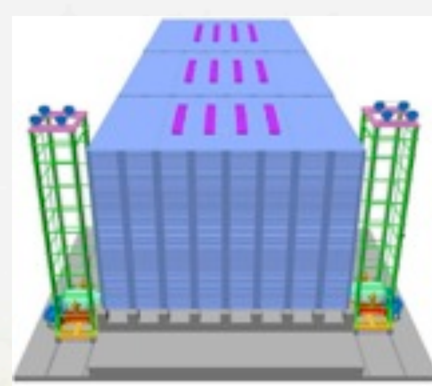

RPC Test stand at TIFR

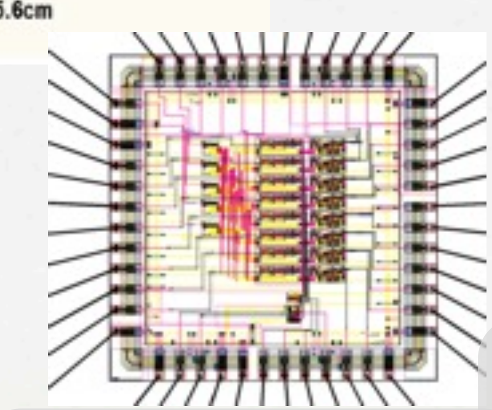



Prototype ICAL at VECC


RPC fabrication at TIFR


RPC fabrication at Asahi Glass Co.




ASIC for RPC designed at BARC


2mx2m RPC stand at TIFR

INO : THE LABORATORY (SALIENT FEATURES)

- *Underground lab at Theni ($9^o 58'$ N, $77^o 16'$ E), with ~1 km all-round rock cover accessed through a 2 km long tunnel. One large and several small caverns to facilitate many experimental programs.*
- *In addition to ICAL, it will support several other expts such as neutrinoless double beta decay expts, dark matter search expts in the immediate future.*
- *INO facility will be available to the international community for setting up experiments.*

INO : THE LABORATORY (SALIENT FEATURES)

- *Frontline neutrino issues will be explored in a manner complementary to the on-going efforts world-wide*
- *Will be close to the magic baseline with respect to **all** major existing accelerator facilities -*

CERN-INO: ~7300 km
JPARC-INO: ~6500 km
RAL-INO:~7600
magic baseline ~ 7500 km
FNAL-INO: second magic

APPROVALS FROM INDIAN FUNDING AGENCIES FOR

- *Construction of an underground laboratory and surface facilities at Pottipuram village in Theni district of Tamil Nadu, India*
- *Construction of 50 kton magnetized iron calorimeter (ICAL) detector to study neutrino properties*
- *Construction of INO center - The National Center for High Energy Physics (NCHEP) at Madurai*
- *Human Resource Development (INO Graduate Training Prog)*
- *Detector R&D*

CURRENT STATUS IN A NUTSHELL

- ***RPC development***
  - ✔ *Full size RPCs (2mx2m) are being fabricated not just in the INO labs but also by the industry*
- ***Electronics***
  - ✔ *First batch of ASIC front end designed by the INO electronics team and fabricated by Euro Practice IC Services being tested in the RPC lab*
- ***Magnet:***
  - ✔ *Prototype magnet at VECC/SINP, Kolkata running. 2^{nd} engineering module will be fabricated in the next two years*
- ***Human Resource:***
  - ✔ *Graduate Training Program since 2008*
- ***INO Site:***
  - ✔ *Environment and Forest Clearances obtained*
  - ✔ *26 hectares of land at Pottipuram provided by the TN Govt free!*

PERT CHART

SN	Description of work	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
	Civil work at Pottipuram						
1	Land acquisition and pre-project work	↔					
2	Architectural and Engineering consultancy	↔					
3	Tendering and award of contracts	↔					
4	Mining of access portal		↔				
5	Excavation of tunnel		↔	↔			
6	Excavation of caverns				↔	↔	
7	Installation of services, cranes, lifts etc.					↔	
8	Civil work for magnet support bed					↔	
9	Surface facilities		↔	↔	↔		
	Magnet						
10	Procurement of steel plates			↔	↔		
11	Machining job for steel plates				↔	↔	
12	Transportation of machined plates at site					↔	
13	Procurement of copper coils				↔	↔	
14	Assembly/erection of magnet (3 modules)					↔	↔
	RPC						
15	Finalization of all design details, tendering	↔					
16	Procurement of components	↔	↔				
17	Fabrication and assembly of 30000 pcs		↔	↔	↔	↔	
18	Transportation to site and tests				↔	↔	↔
19	Procurement of electronics, gas handling		↔	↔	↔		
20	Installation and commissioning						↔

PHYSICS WITH ATMOSPHERIC NEUTRINOS

- *Reconfirm neutrino oscillations from distortion in L/E*
- *Measure* $|\Delta m^2_{31}|$ *and* $\sin^2 2\theta_{23}$
- *Determine the neutrino mass hierarchy*
- *Determine the deviation of* θ_{23} *from* 45^o *and its octant*
- *Other (new) physics (sterile neutrinos, NSI, CPTV, LIV, Long range forces….)*
- *Very high energy neutrinos and muons*

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SIMULATION FRAMEWORK

Simulation Framework

NUANCE

Neutrino Event Generation

$\nu_a + X \rightarrow A + B + \ldots$

Generates particles that result from a random interaction of a neutrino with matter using theoretical models .

Output:
i) Reaction Channel
ii) Vertex Information
Iii) Energy & Momentum of all Particles

GEANT4

Event Simulation

A + B + ... through RPCs + Mag.Field

Simulate propagation of particles through the detector (RPCs + Magnetic Field)

Output:
i) x,y,z,t of the particles at their interaction point in detector
ii) Energy deposited
iii) Momentum information

Event Digitisation

(x,y,z,t) of A + B + ... + noise + detector efficiency

Add detector efficiency and noise to the hits

Output:
i) Digitised output of the previous stage (simulation)

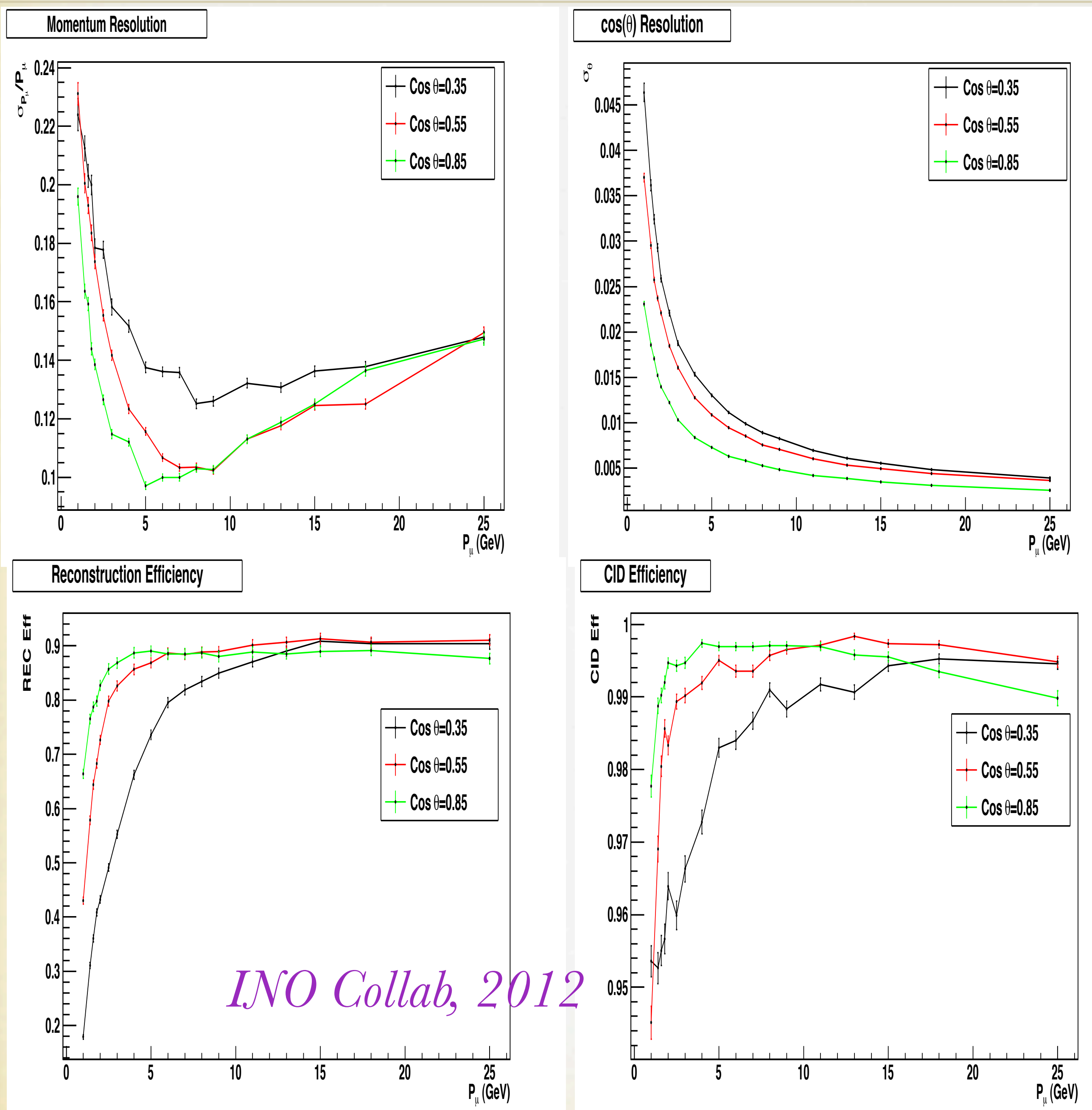
Event Reconstruction

(E,p) of ν + X = (E,p) of A + B + ...

Fit the tracks of A + B + ... to get their energy and momentum.

Output:
i) Energy & Momentum of the initial neutrino

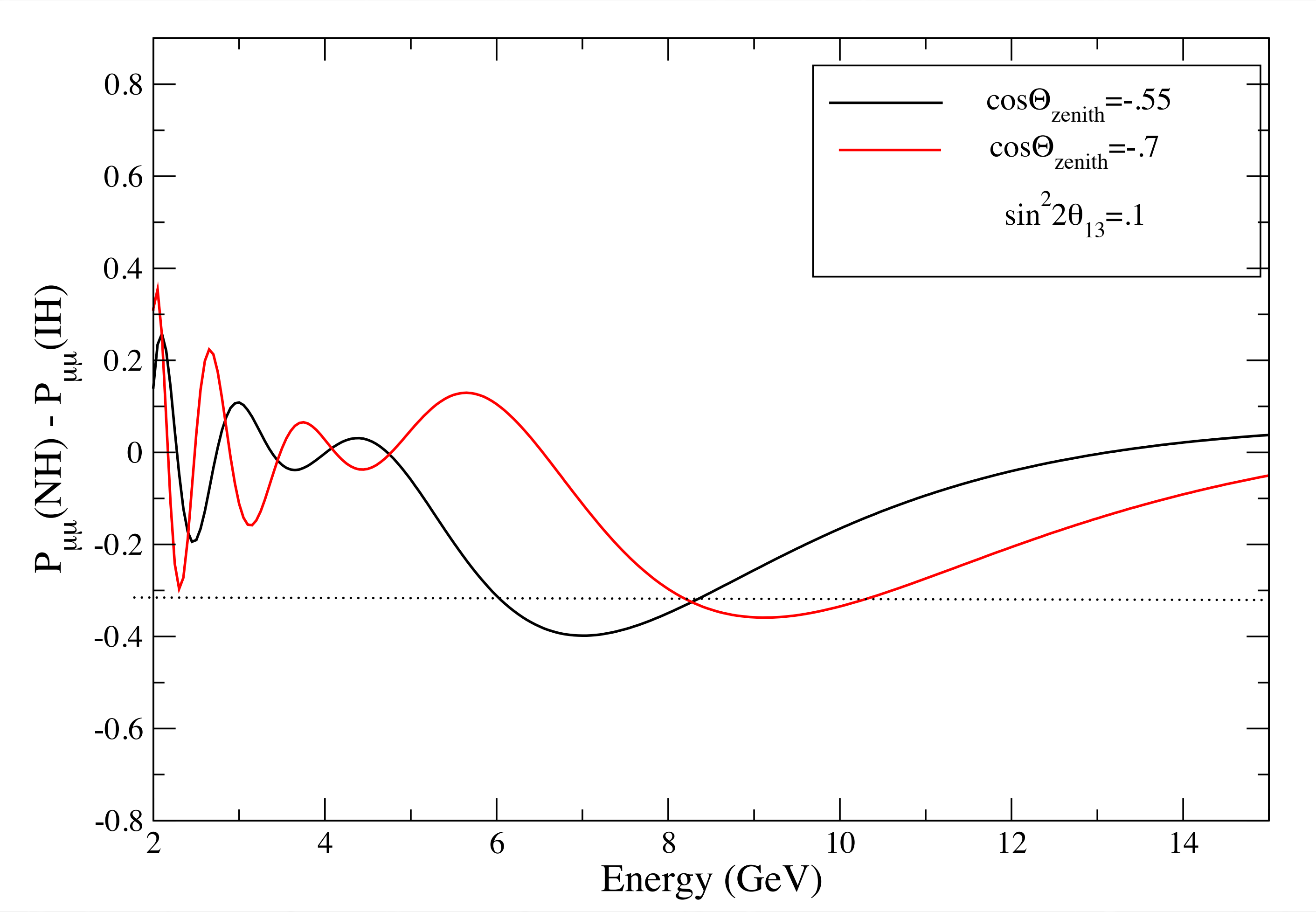
DETECTOR PERFORMANCE



INO Collab, 2012

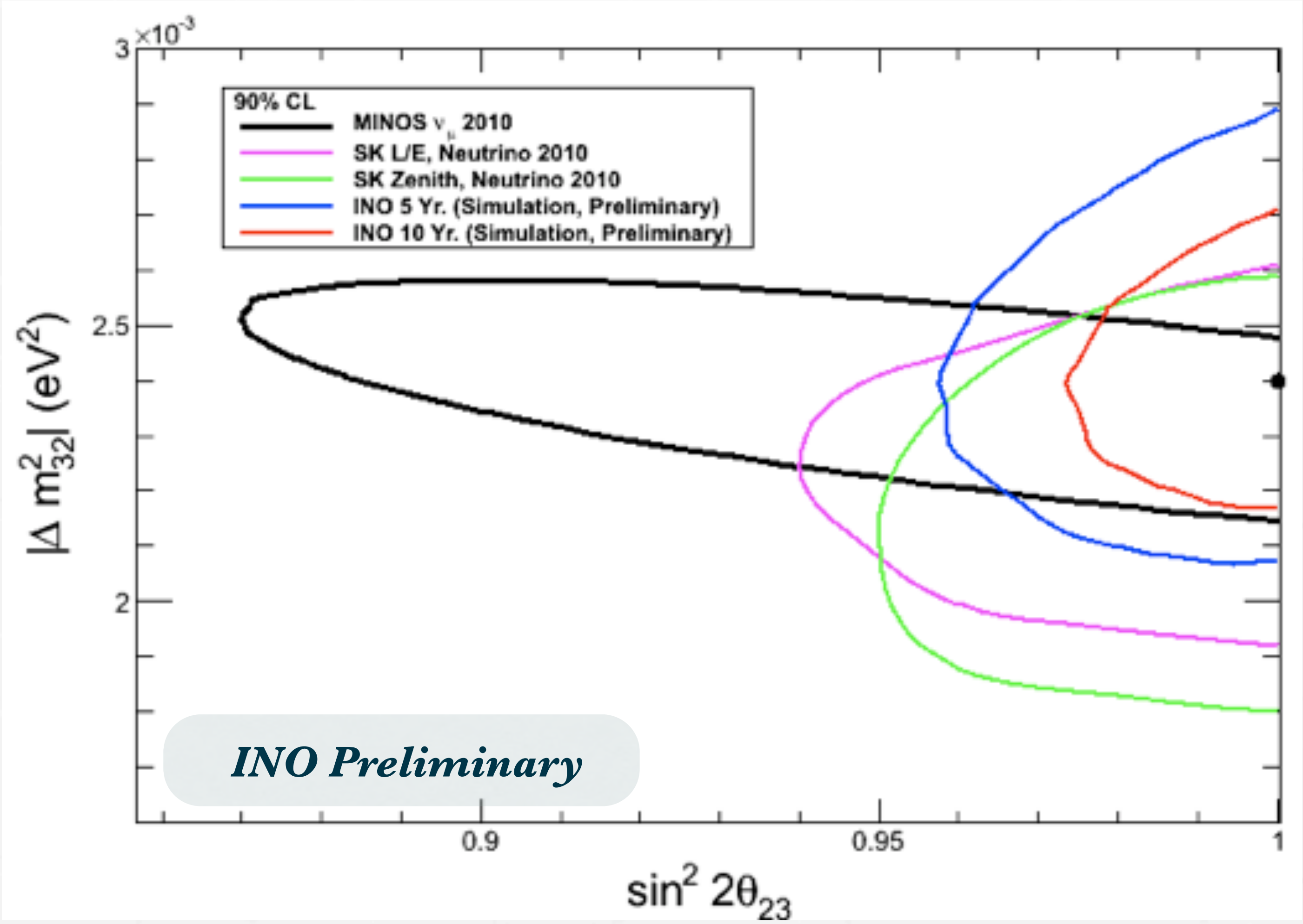
- *Inhomogeneous magnetic field mapping implemented in the ICAL code*
- *Effect of iron thickness on efficiencies and charge id under study*
- *Resolution functions for hadrons also obtained but not used in results shown here*

PHYSICS REACH OF ICAL@INO



- *Matter effects fluctuate rapidly with E and $\cos\theta_{zenith}$*
- *ICAL has good E and $\cos\theta_{zenith}$ resolution*
- *Effect will also be opp for nu and anti-nu...ICAL has charge id!*

LEADING ATMOSPHERIC PARAMERTERS @ INO

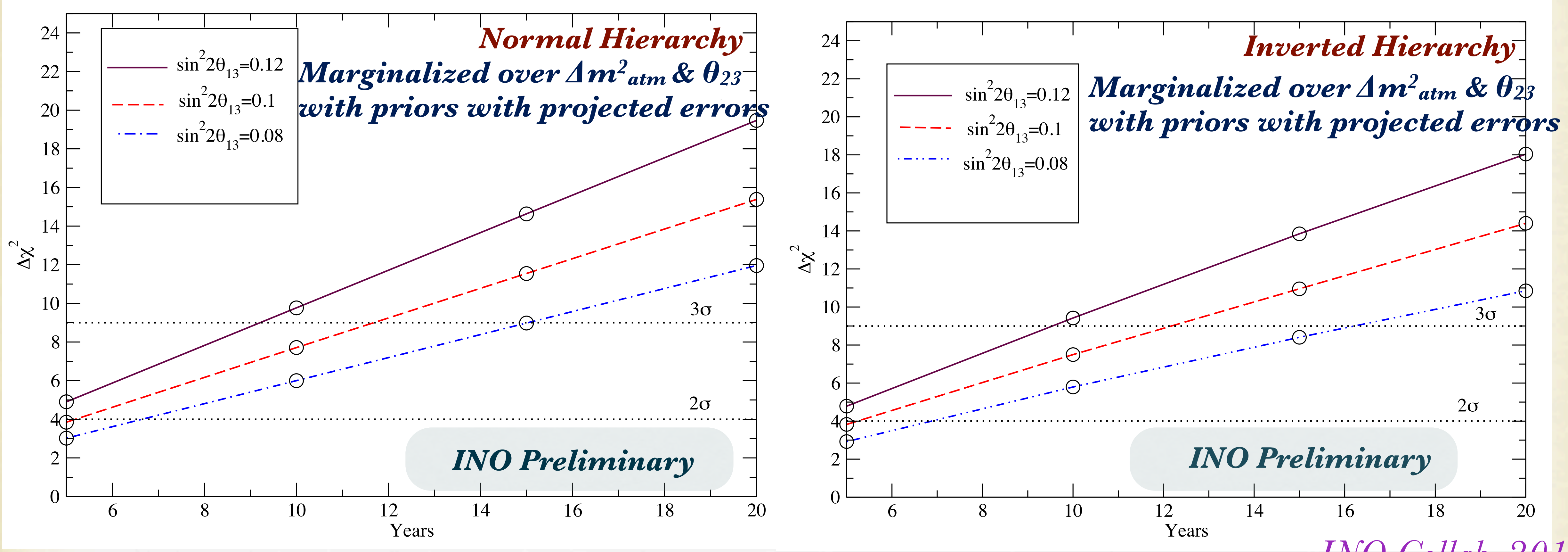


INO Collab, 2012

- *Precision not competitive with LBL expts, but complementary*
- *Use priors on* $|\Delta m^2_{atm}|$, θ_{23}, θ_{13} *from LBL+reactors projected reach*

MASS HIERARCHY @ INO

- Events generated using Nuance and ICAL resoln in E and $\cos\theta_{zenith}$

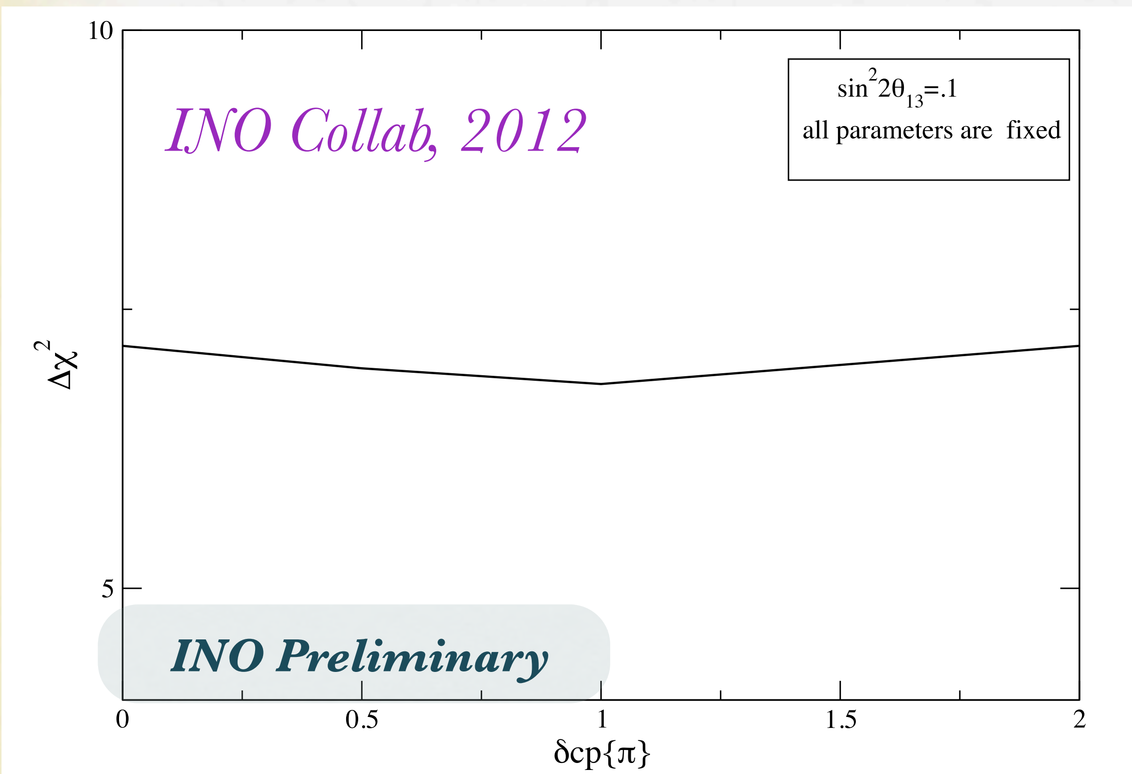


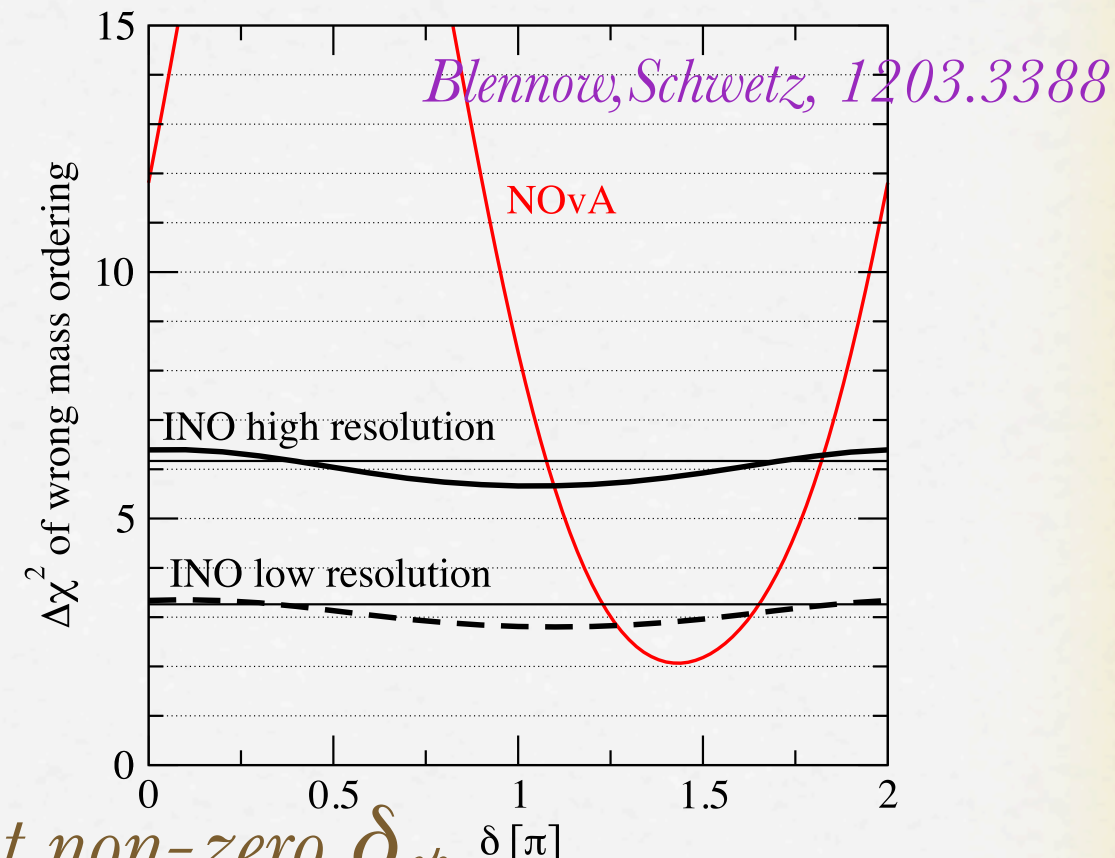
INO Collab, 2012

- ~2σ sensitivity for $\sin^2\theta_{23}=0.5$, $\sin^2 2\theta_{13}=0.1$ by 2022 (5 yrs)
- ~2.7σ sensitivity for $\sin^2\theta_{23}=0.5$, $\sin^2 2\theta_{13}=0.1$ by 2027 (10 yrs)

MASS HIERARCHY @ INO

- *What is the impact of δ_{cp} on the MH sensitivity of ICAL@INO*

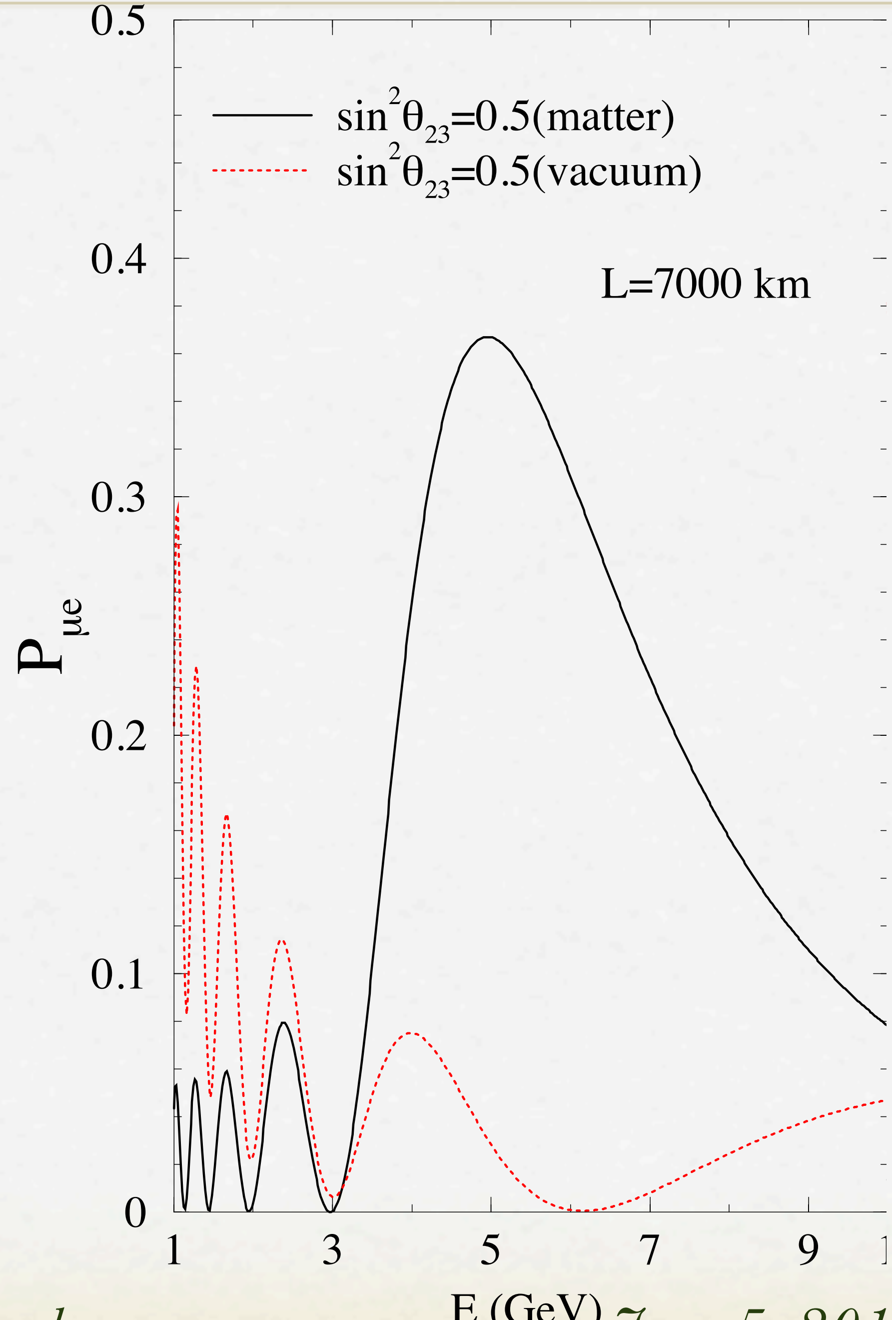




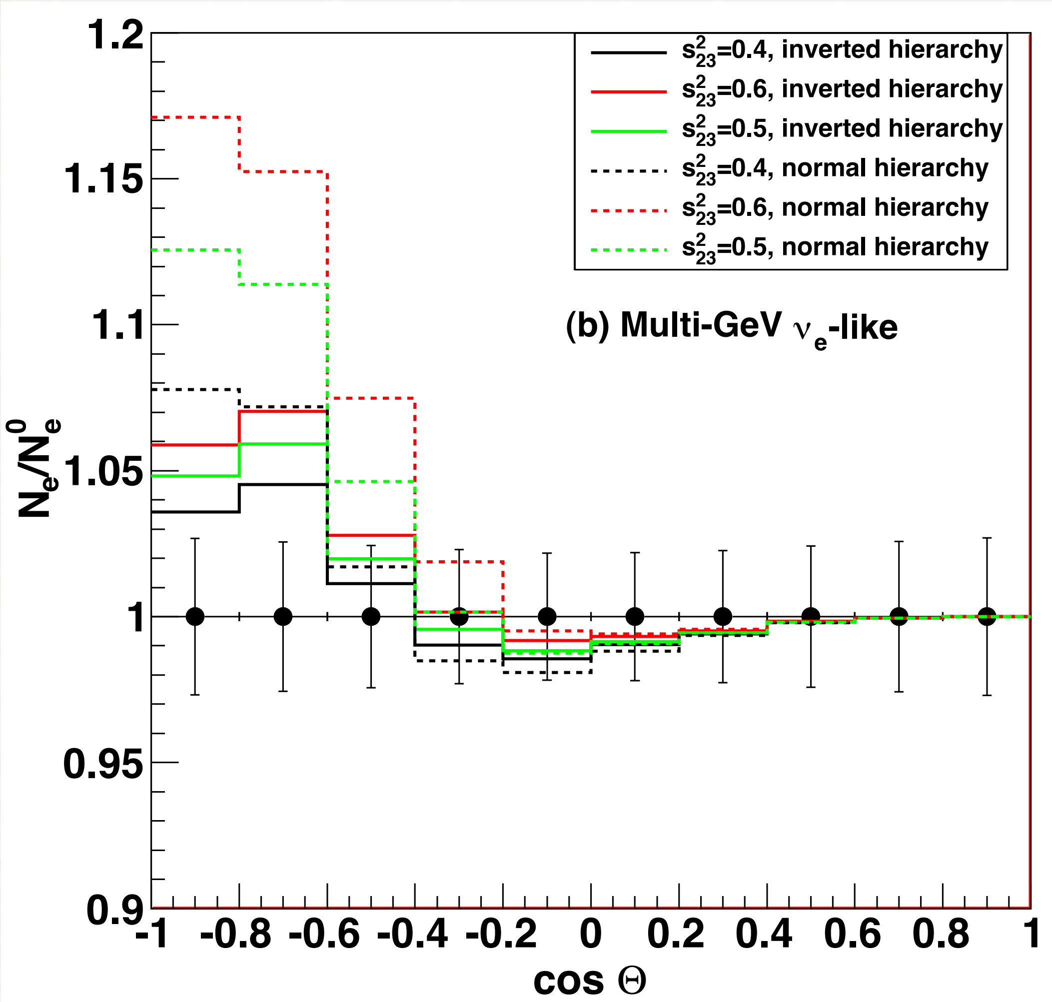
- *Data generated at δ_{cp}=0 and fitted at non-zero δ_{cp}*
- *INO will give MH sensitivity almost indep of δ_{cp}*
- *For more details of the ICAL@INO see poster by T. Thakore*

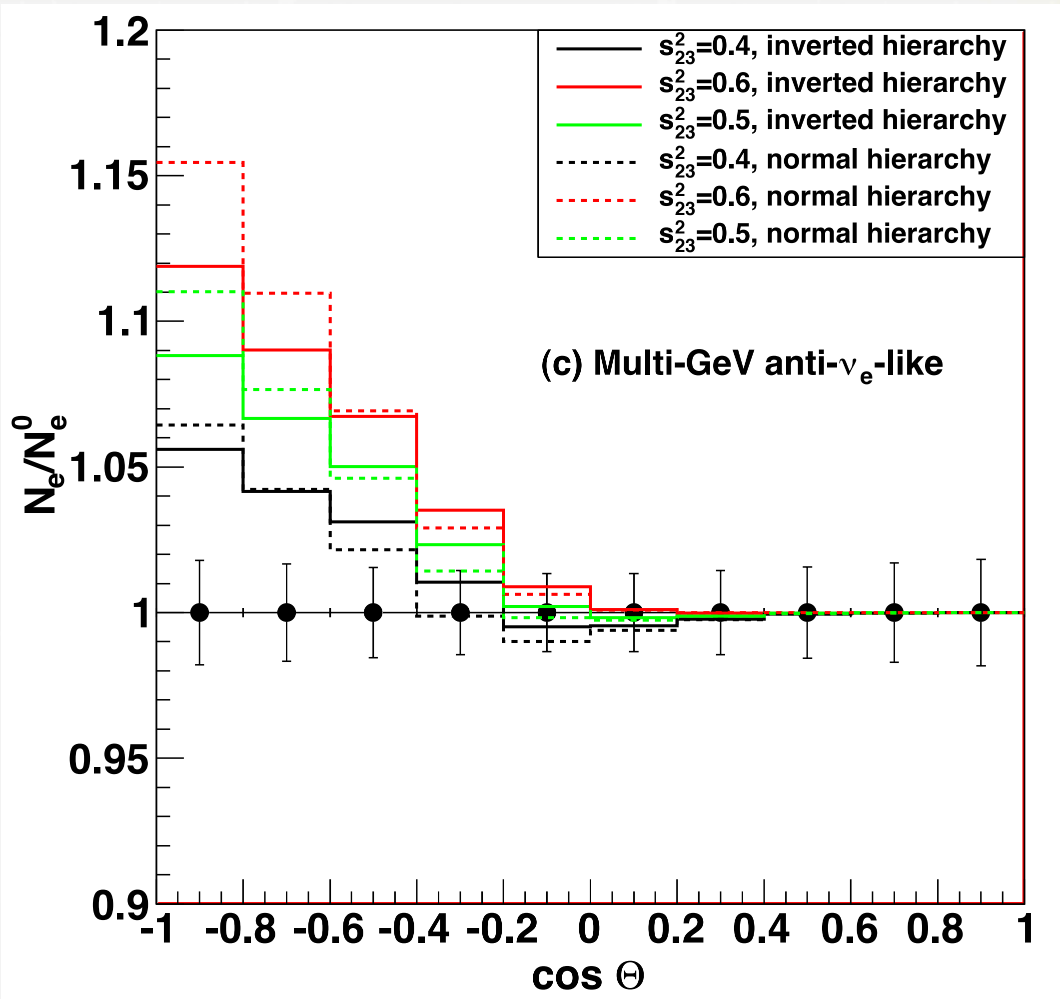
ATMOSPHERIC NEUTRINOS IN HYPER-KAMIOKANDE

- *Matter effects in muons demands good resoln in both E and L*
- *Matter effects in electrons does not vary so fast with E and L*
- *In WC detectors subdominant effects mainly in electron events*



ATMOSPHERIC NEUTRINO EVENTS IN HYPER-KAMIOKANDE



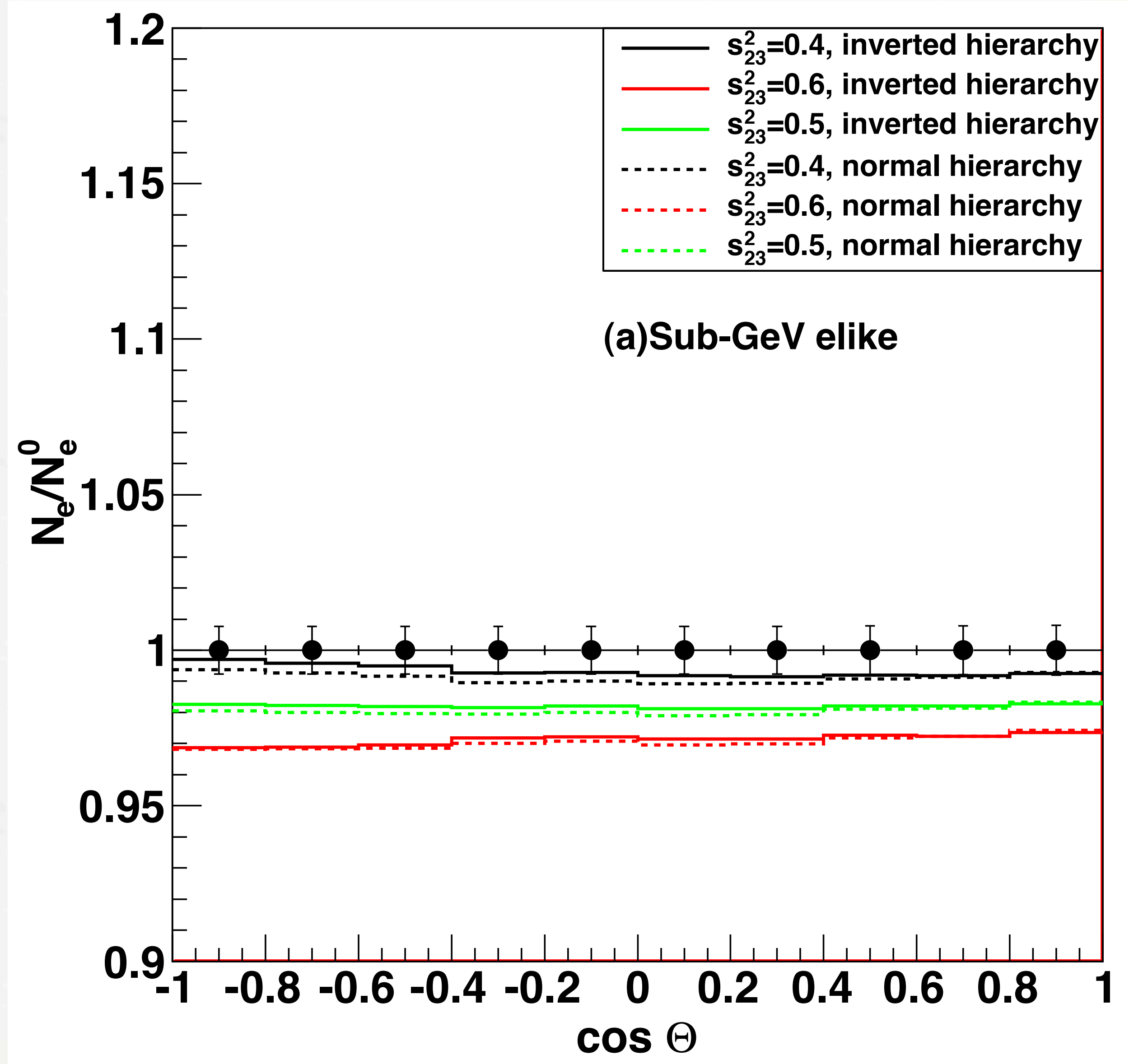


HK LOI, 1109.3262

- *Statistical separation of multi-GeV ν_e and anti-ν_e events*
- *Matter effects clearly visible in the multi-GeV ν_e-like sample*

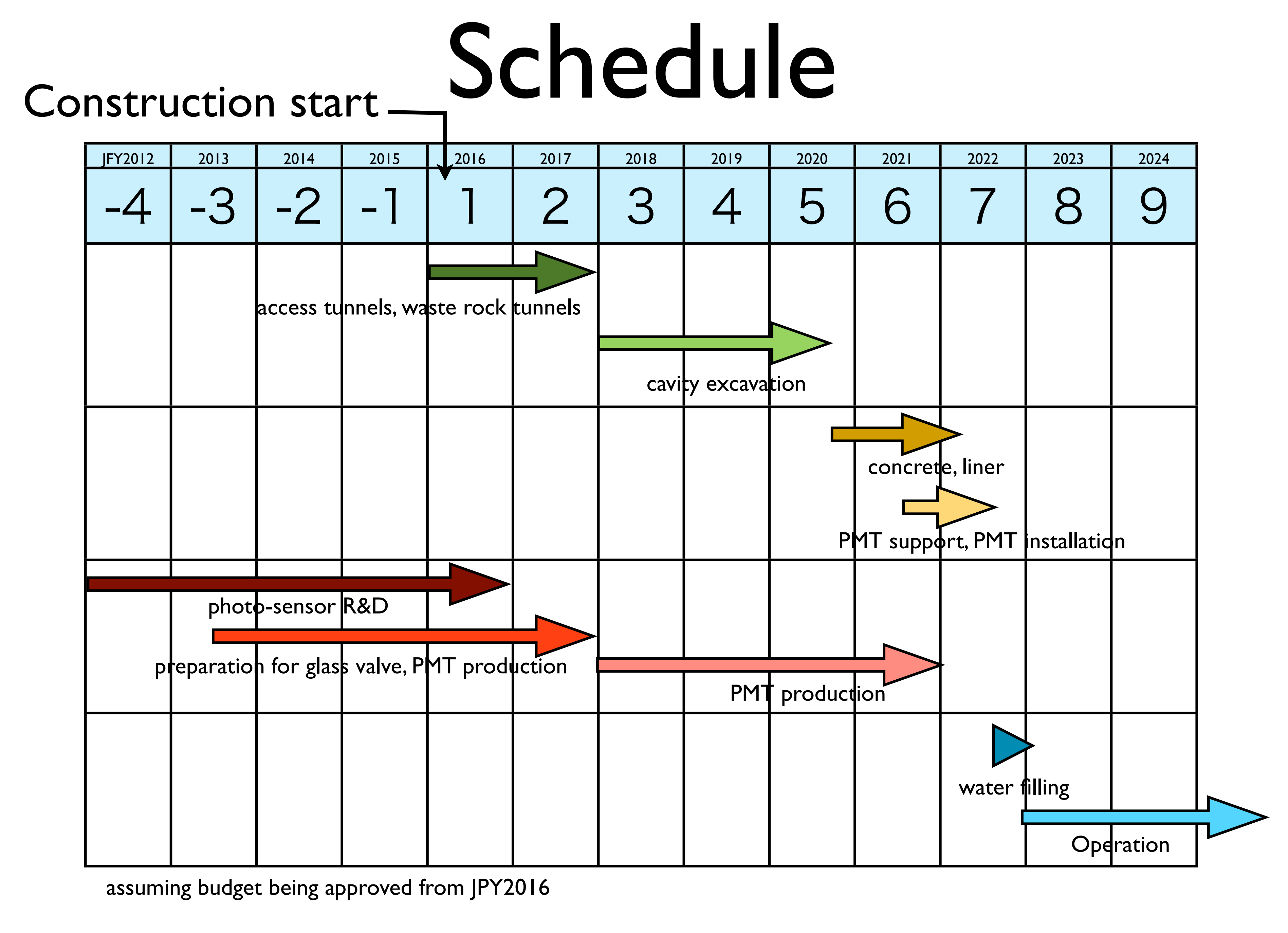
ATMOSPHERIC NEUTRINO EVENTS IN HYPER-KAMIOKANDE

- *Δm^2_{21} - driven osc in the sub-GeV e-like events*
- *Excess for $\sin^2\theta_{23}=0.4$ wrt $\sin^2\theta_{23}=0.5$*
- *Deficit for $\sin^2\theta_{23}=0.6$ wrt $\sin^2\theta_{23}=0.5$*
- *Leads to octant sensitivity*

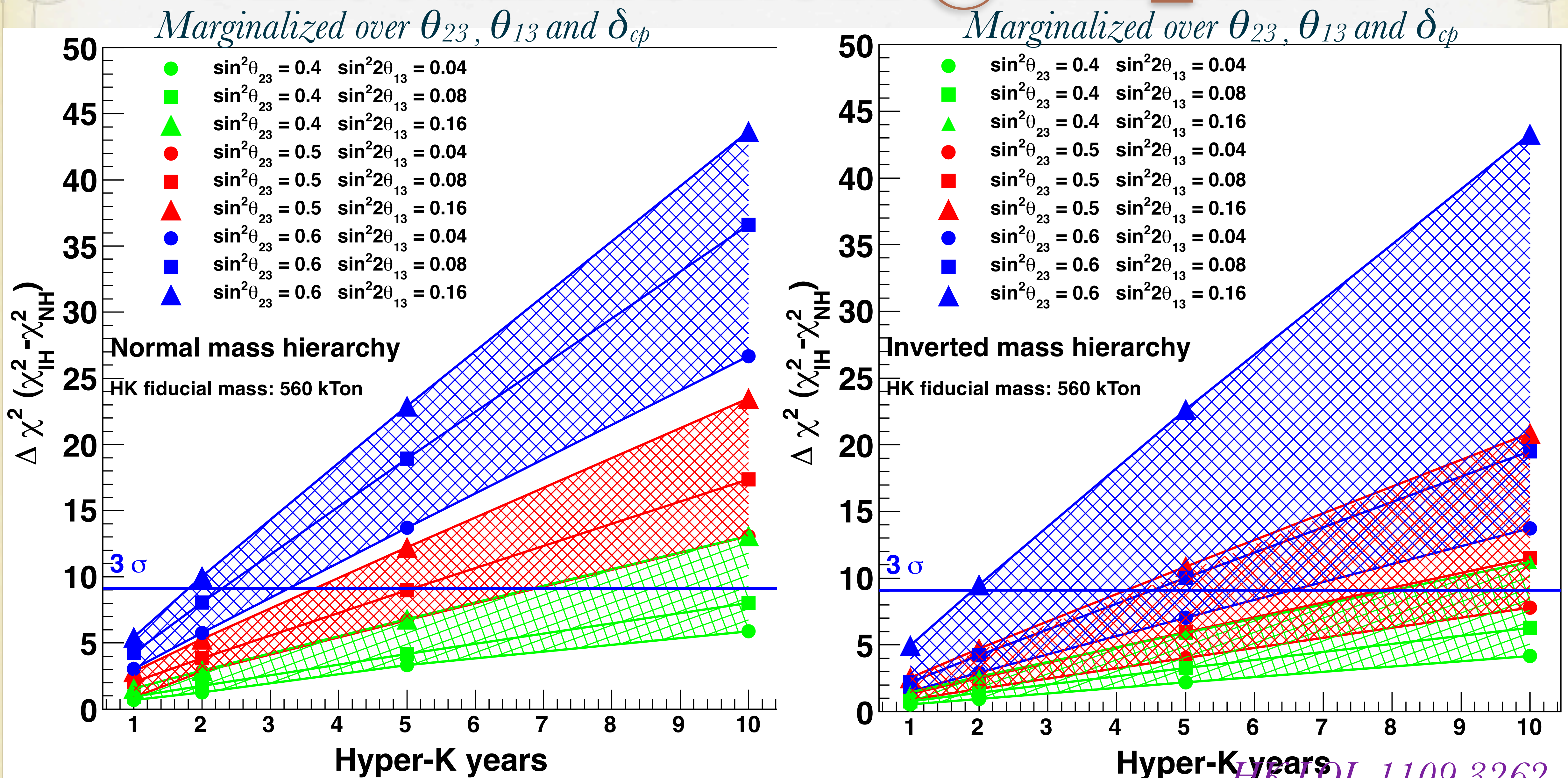


HK LOI, 1109.3262

HK TIMELINE


Schedule
Construction start
JFY2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
-4
-3
-2
-1
1
2
3
4
5
6
7
8
9
access tunnels, waste rock tunnels
cavity excavation
concrete, liner
PMT support, PMT installation
photo-sensor R&D
preparation for glass valve, PMT production
PMT production
water filling
Operation
assuming budget being approved from JPY2016

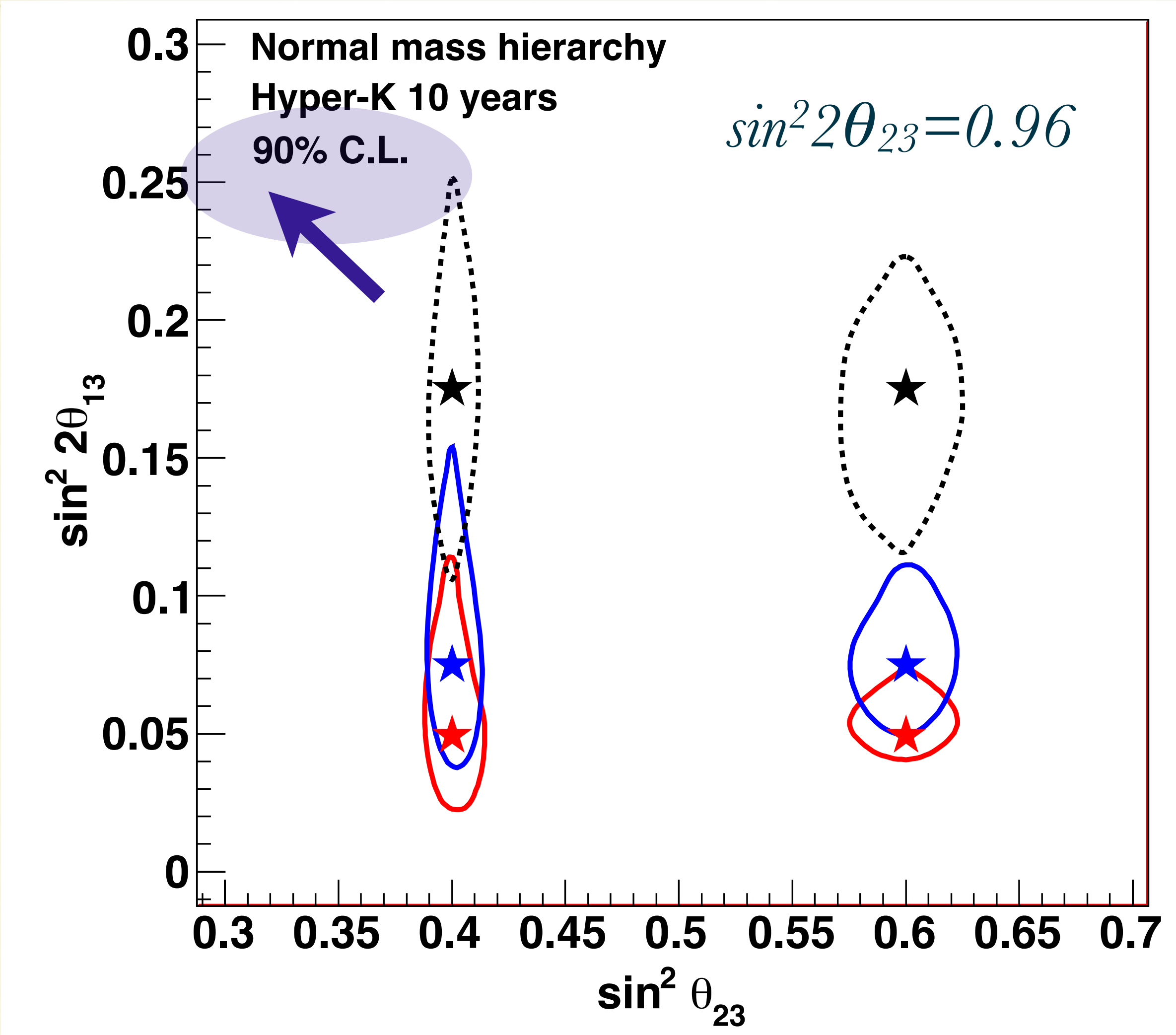
MASS HIERARCH @ HK_ATM

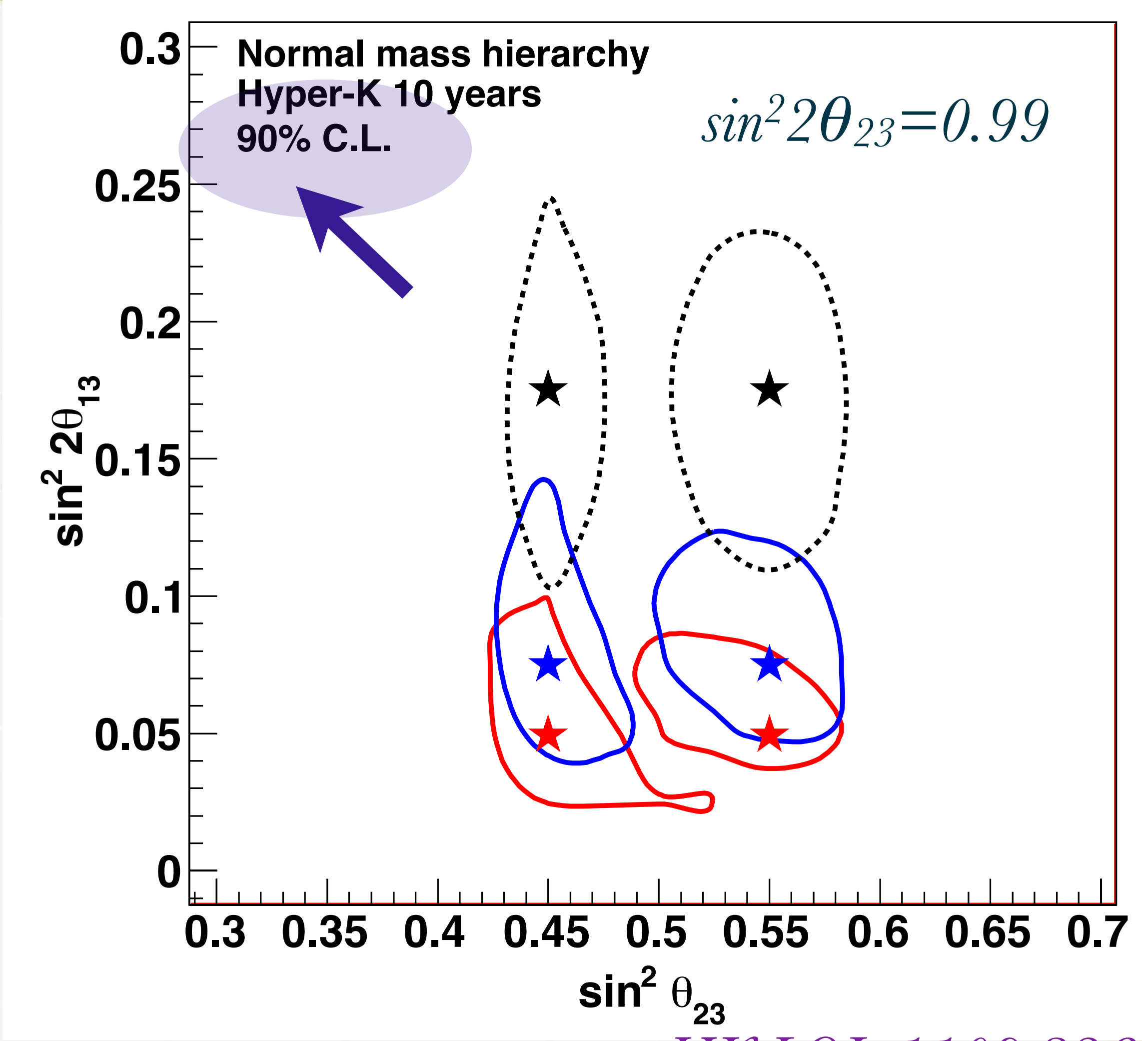


HK LOI, 1109.3262

- $\sim 3\sigma$ sensitivity for $\sin^2\theta_{23}=0.5$, $\sin^2 2\theta_{13}=0.1$ by 2027-28 (5 yrs)
- $\sim 4\sigma$ sensitivity for $\sin^2\theta_{23}=0.5$, $\sin^2 2\theta_{13}=0.1$ by 2033-34 (10 yrs)

OCTANT @ HK_ATM





HK LOI, 1109.3262

- *Sensitivity to octant at 90%C.L. up to $sin^2 2\theta_{23}=0.99$ (right plot)*

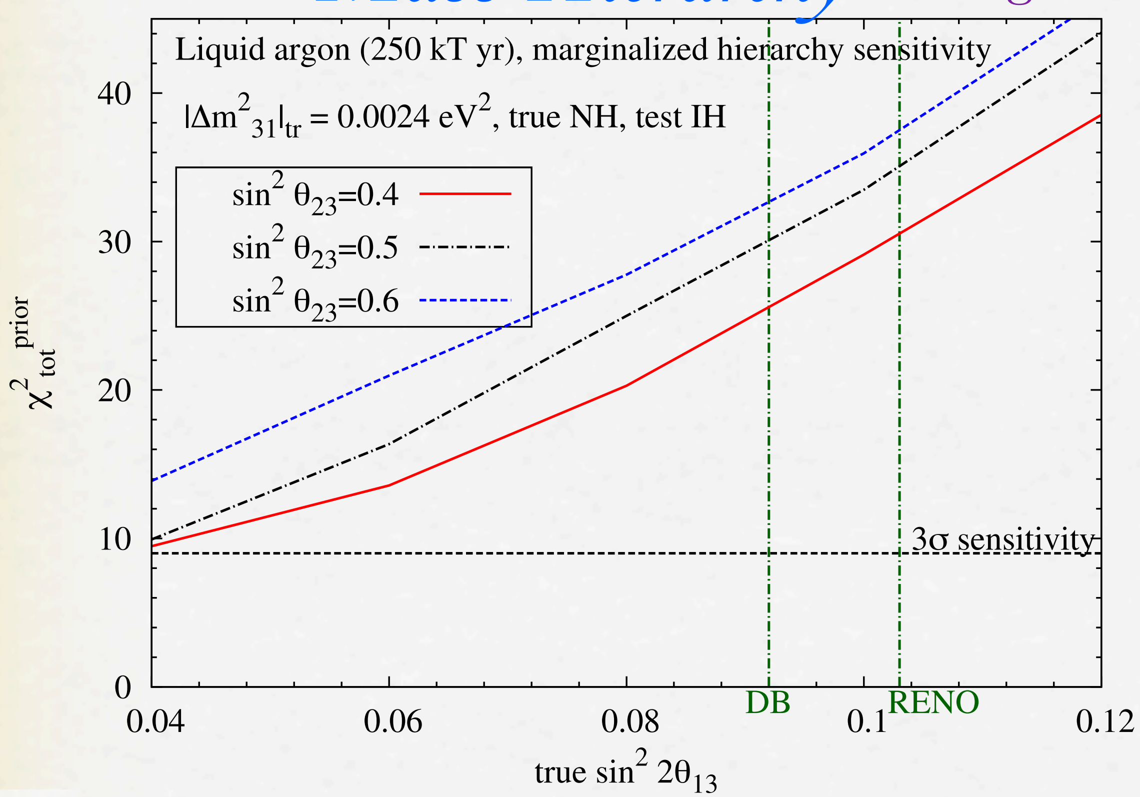
ATMOS NUS IN (MAGNETIZED) LIQUID ARGON

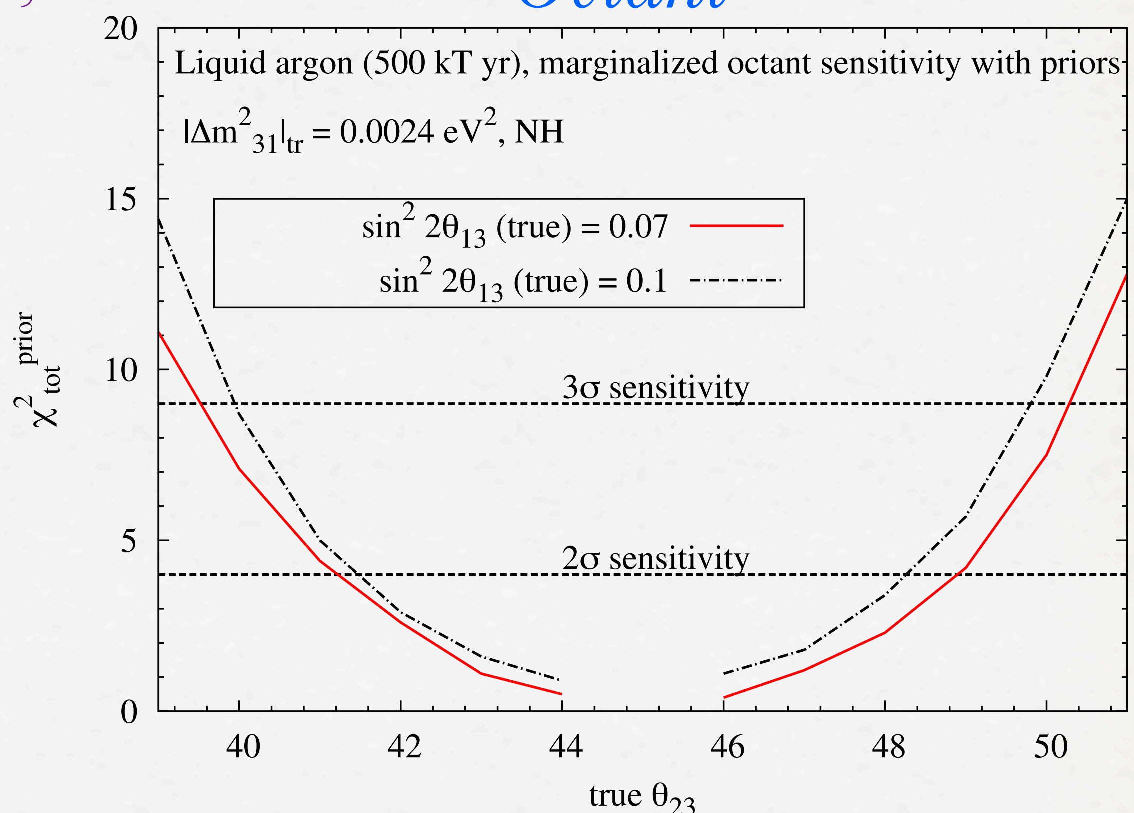
- *Change in gear...from full MC analysis using final leptons to analysis using neutrino energy and direction by phenomenologists*
- ***Assuming:***
- *50-100 kton , 100% cid for μ and 20% for e in 1-5 GeV*
- $$\sigma_\nu/E_\nu = \sqrt{(1-y)^2(\sigma_l/E_l) + y^2(\sigma_h/E_h)}$$
  $$\sigma_{E_\nu} = \sqrt{(0.01)^2 + (0.015)^2/yE_\nu + (0.03)^2}$$
  $$\sigma_h = \sqrt{(0.15)^2/E_h + (0.03)^2}$$
- $$\sigma_{\theta_{\nu_e}} = 2.8^\circ \qquad \sigma_{\theta_{\nu_\mu}} = 3.2^\circ$$
  $$\sigma_l = 0.01$$

Barger et. al., 1203.6012

ATMOS NUS IN (MAGNETIZED) LIQUID ARGON

Mass Hierarchy *Barger et. al., 1203.6012* *Octant*





- *With 250 kton-yr ~5σ sens to MH with these specs!*
- *With 250 kton-yr ~3σ sens to MH with toned down specs*

Poster by Gallagher

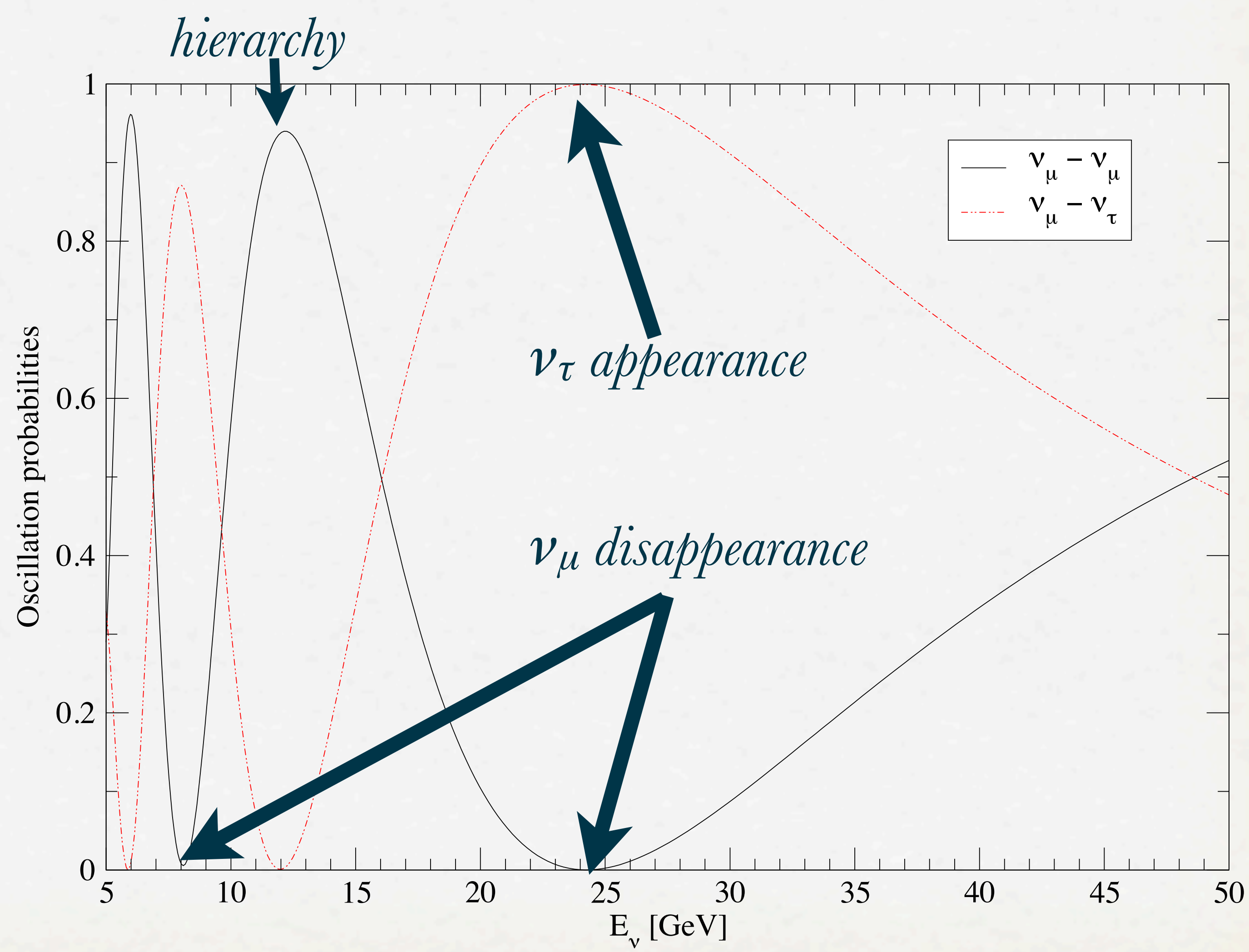
- *With 500 kton-yr 3σ sensitivity to octant for about $0.4 > \sin^2\theta_{23} > 0.6$*

ATMOSPHERIC NEUTRINOS IN DEEP CORE

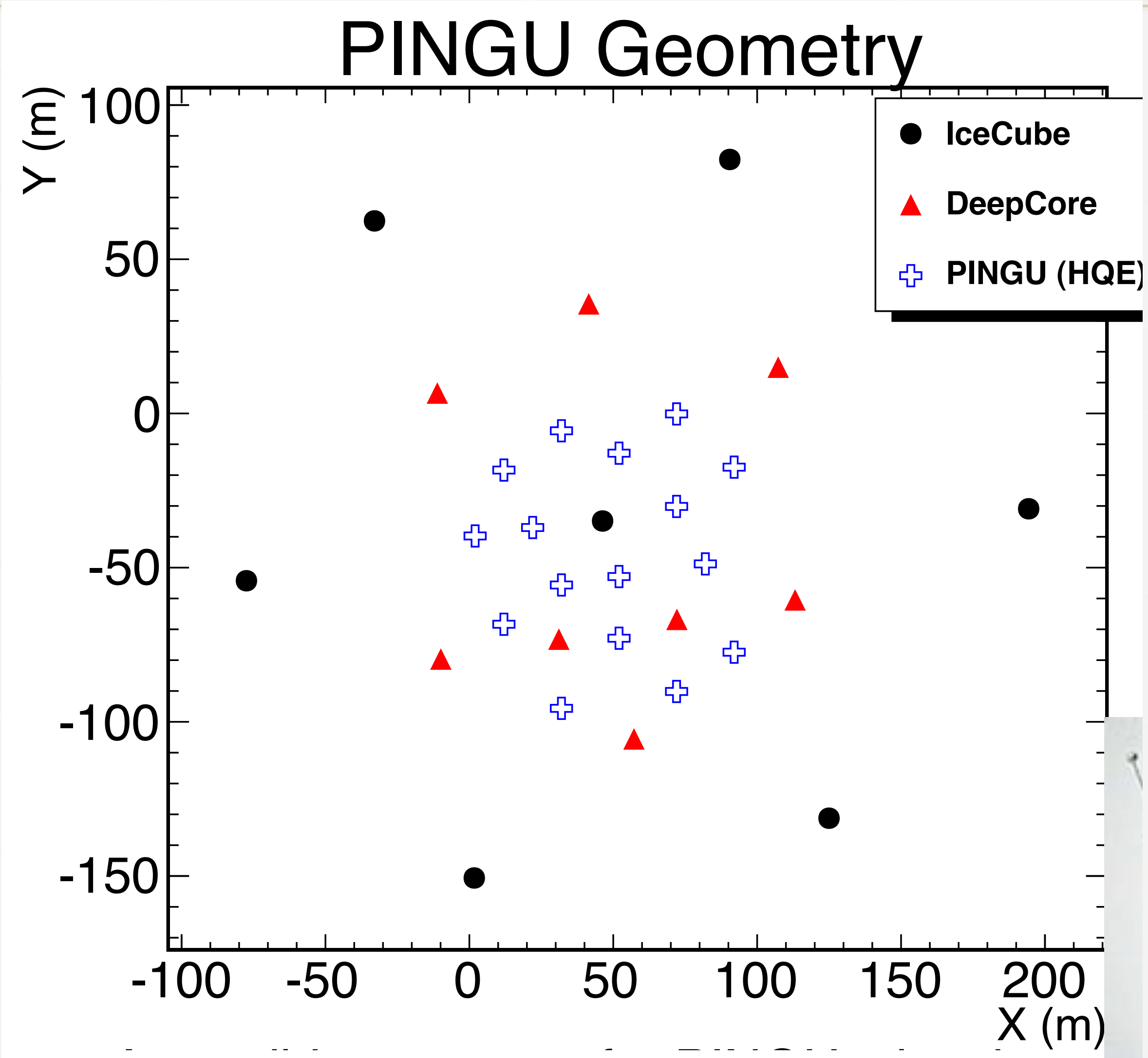
Mena,Mocioiu,Razzaque,0803.3044

- *8 additional string + 7 IceCube strings*
- *Threshold ~ 10 GeV*

Poster by A. Gross

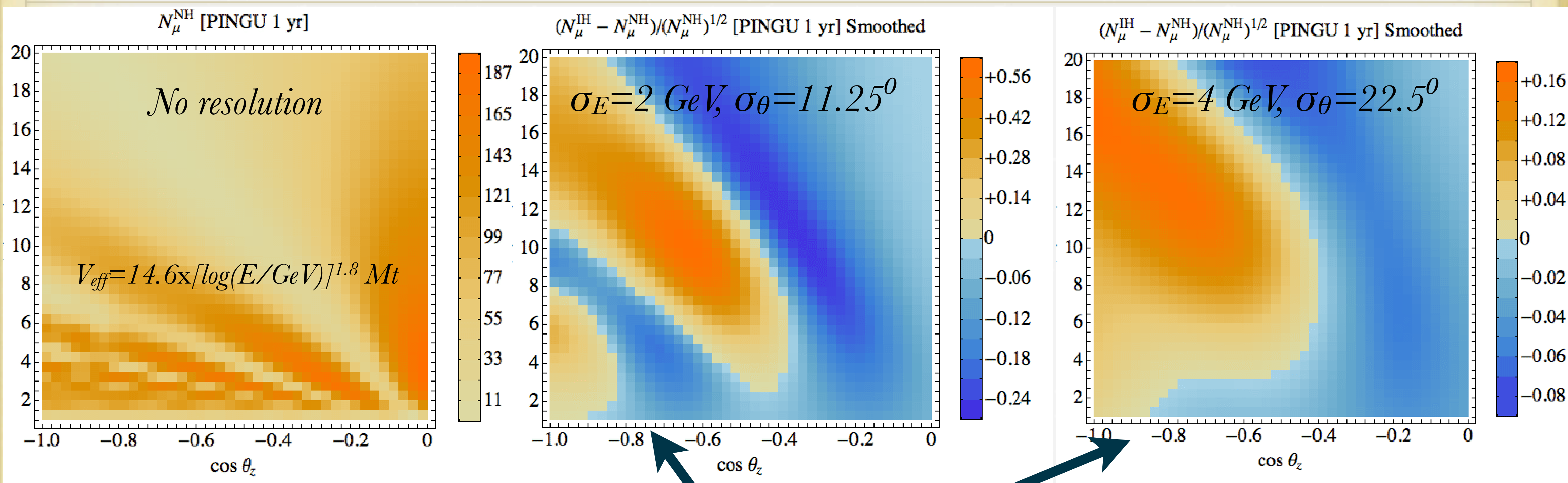


ATMOSPHERIC NEUTRINOS IN PINGU



- *20 additional strings in the Deep Core, threshold reduced to ~ 1 GeV*

ATMOSPHERIC NEUTRINOS IN PINGU



Akhmedov, Smirnov, Razzaque, 1206.7071

- 20 additional strings in the Deep Core, threshold reduced to ~ 1 GeV
- Multi-mton vol allows for 3σ to 11σ hierarchy sensitivity in 5 yrs for 10% and 5% bin-to-bin uncorr systematic errors respectively

TEV ATMOSPHERIC NEUTRINOS IN ICECUBE

- *Can be used to look for the (LSND) sterile neutrinos*

  Nunokawa, Peres, Zukanovic Funchal, 0302039
  SC, 0709.1937
  Smirnov, Razzaque, 1203.5406

- *Can be used to look for NSI and other exotic physics*

  Gonzalez-Garcia, Halzen, Maltoni, 0502223

- *Can be used for Earth tomography by neutrino absorption*

  Gonzalez-Garcia, Halzen, Tanaka, 0711.0745

Can be done is any km^3 neutrino telescope

SUMMARY

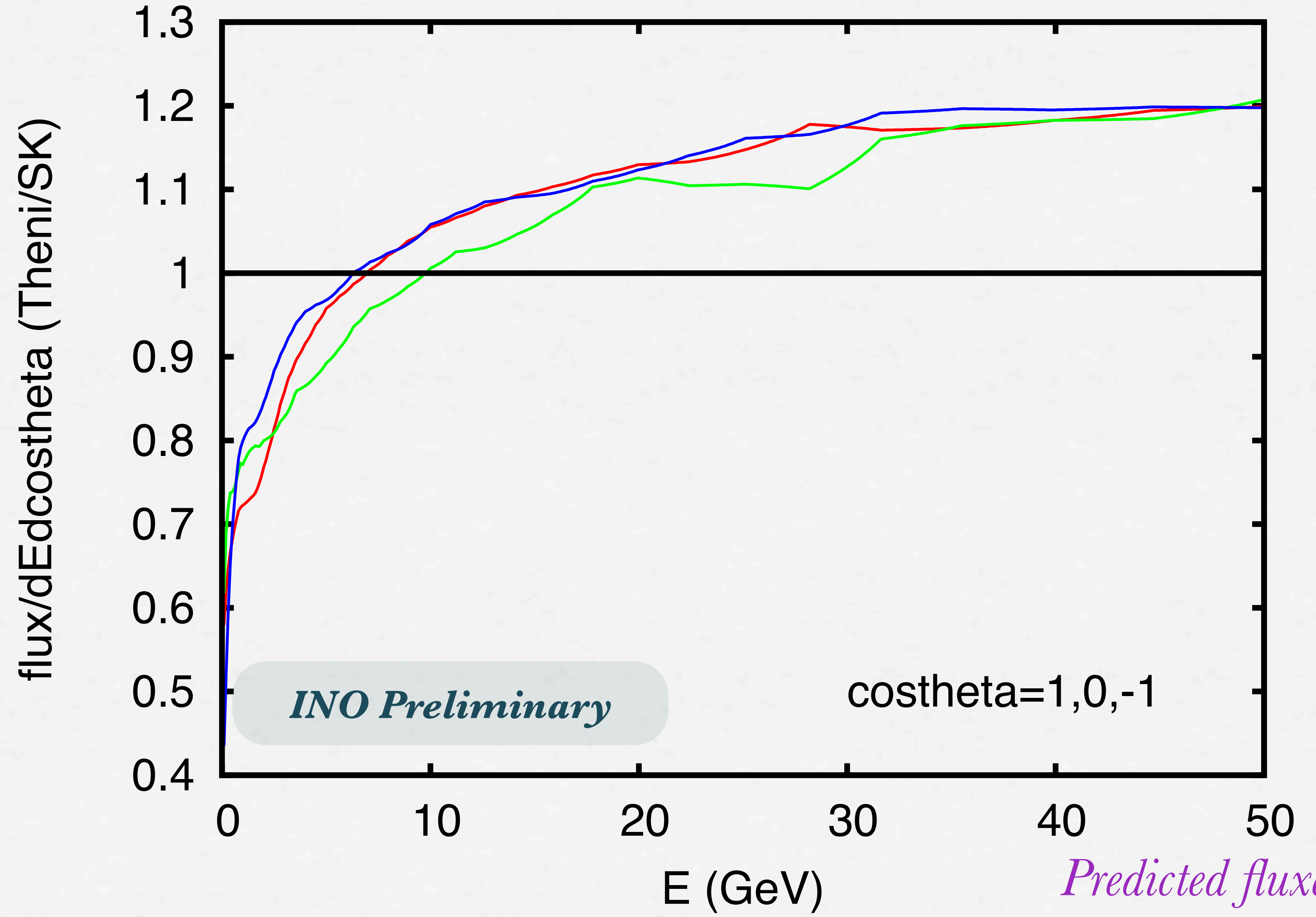
- *Large θ_{13} has opened up the searches for MH and CPV*
- *MH can be discovered in current LBL+Reactor experiments at 90% C.L. only for 50% of δ_{cp} values by 2019*
- *Atmospheric neutrinos will play a crucial role for MH discovery*
- *MH will be measured at INO at ~2σ by 2022 (250 kton-yr) and at ~2.7σ by 2027 (500 kton-yr data)*
- *MH will be measured at HK at ~3σ by 2028 (2.8 Mton-yr) and at >4σ by 2033 (5.6 Mton-yr data)*

SUMMARY

- *MH sensitivity will go up with $\sin^2\theta_{23}$*
- *Very good prospects for measuring MH with atmospheric neutrino detection in large liquid argon detectors*
- *Very good prospects for measuring MH with atmospheric neutrino detection at IceCube (PINGU)*
- *Variety of other (new) physics searches (sterile neutrinos, NSI, CPTV, LIV, Long range forces….) can be performed using atmospheric neutrino detection in the range 1 GeV to 10 TeV*

BACK-UP

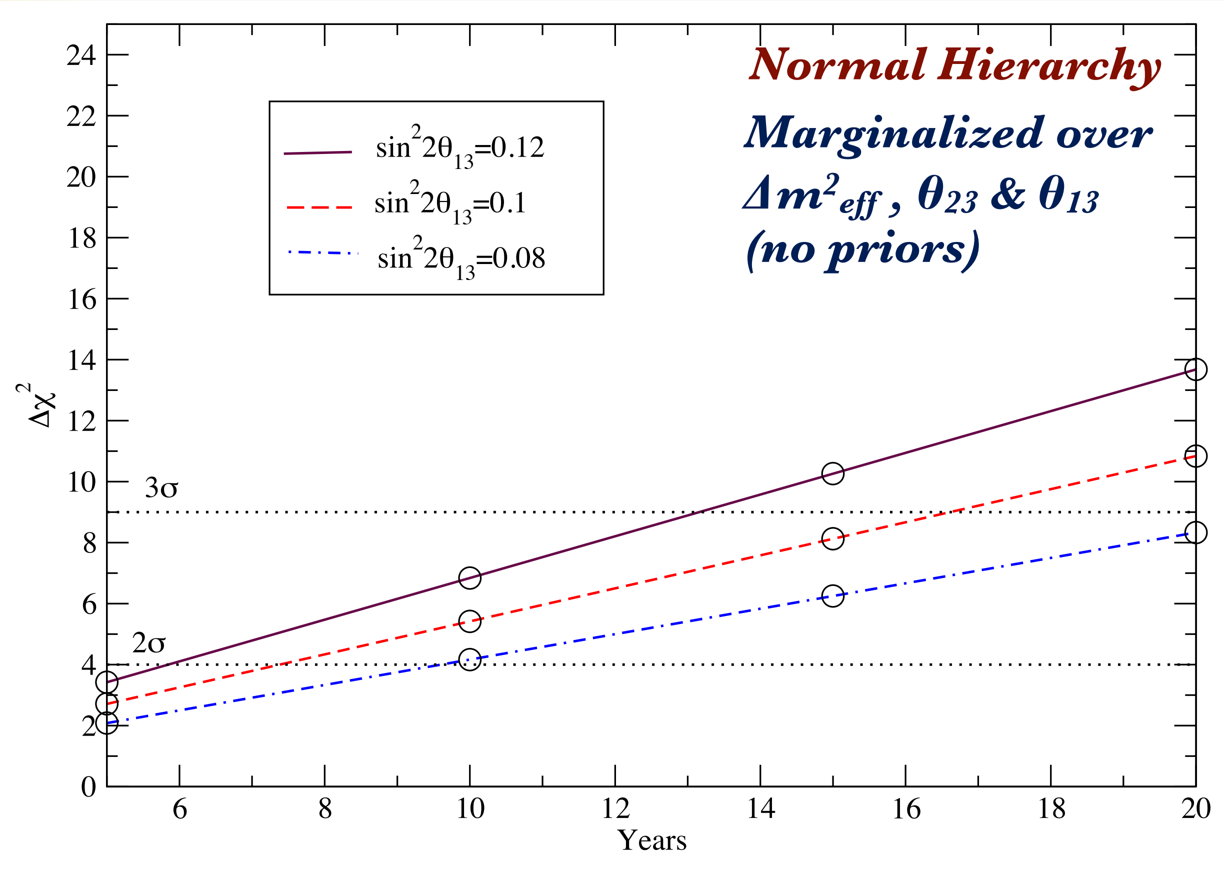
ATMOSPHERIC NEUTRINO FLUX AT THENI

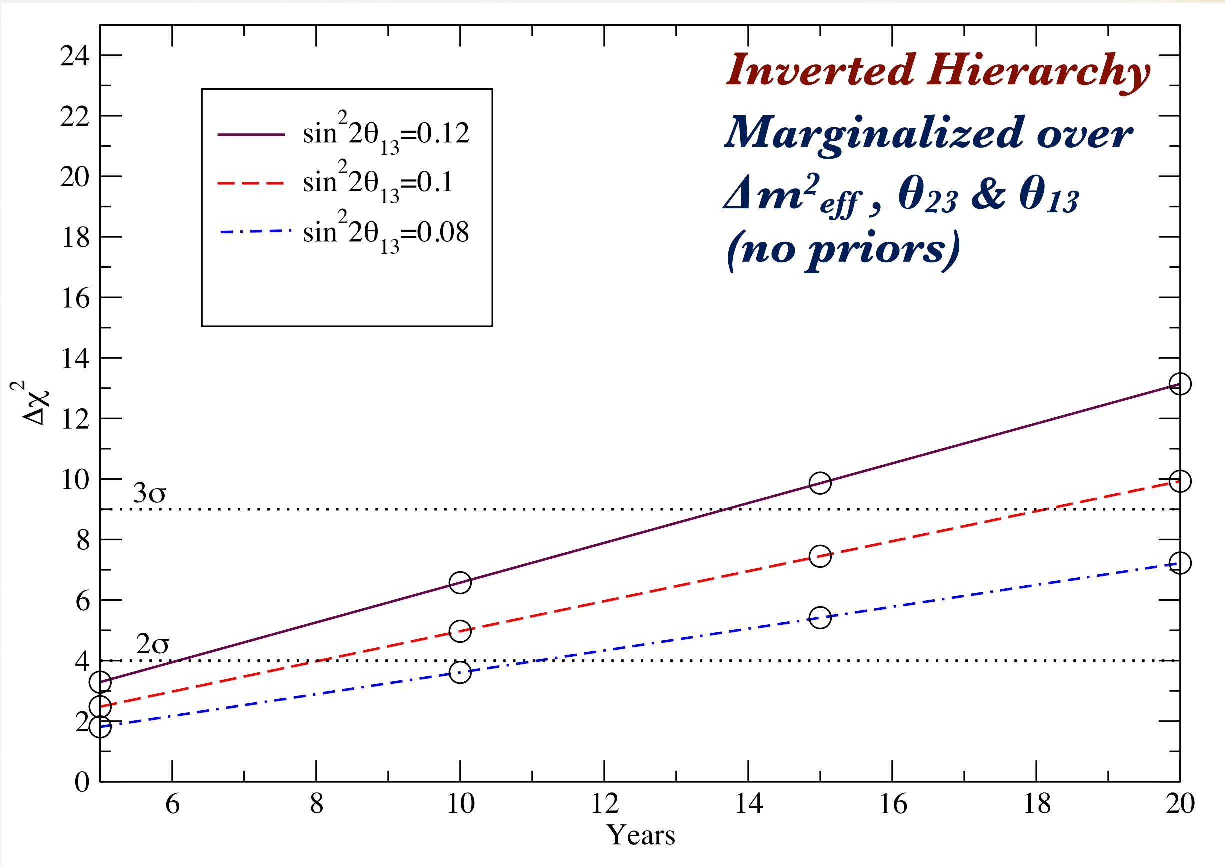


Predicted fluxes by Honda et. al.

MASS HIERARCHY @ INO

- *Events generated using Nuance and ICAL resoln in E and $\cos\theta_{zenith}$*

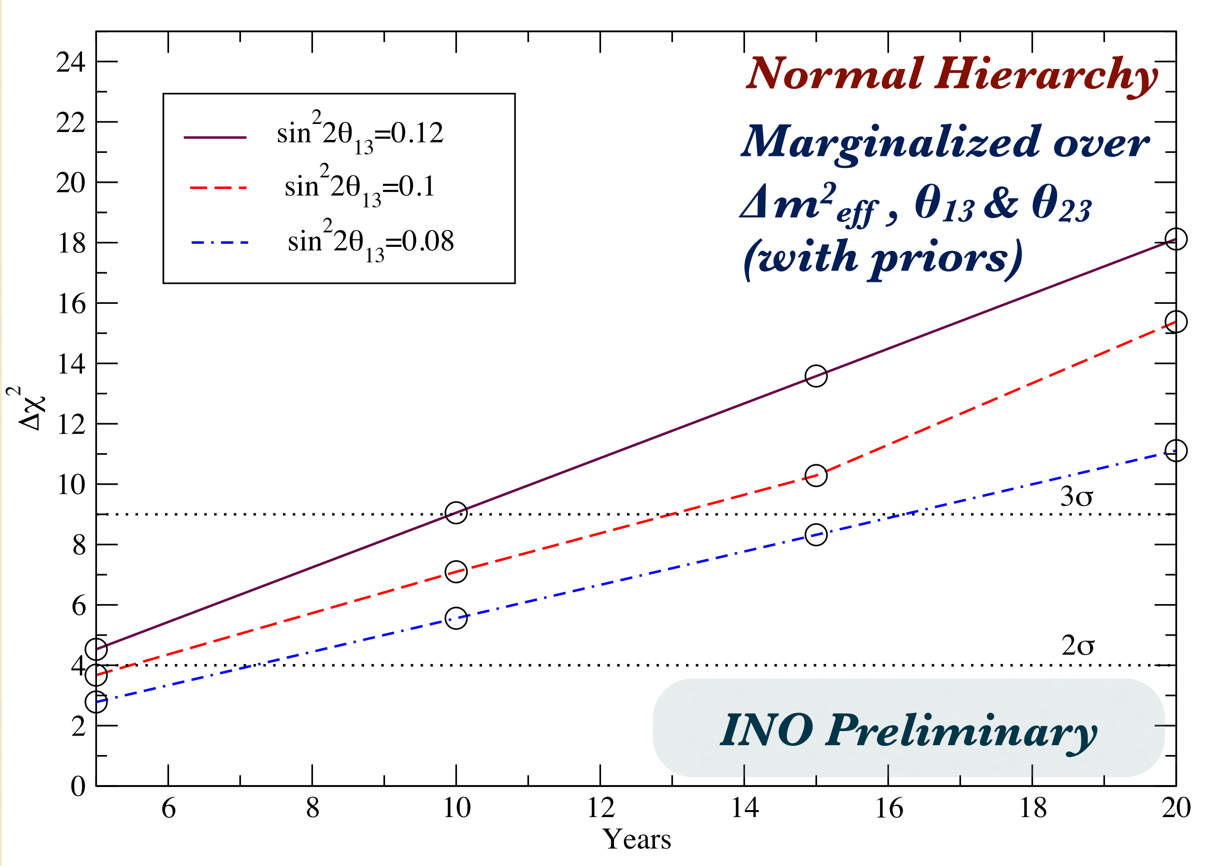


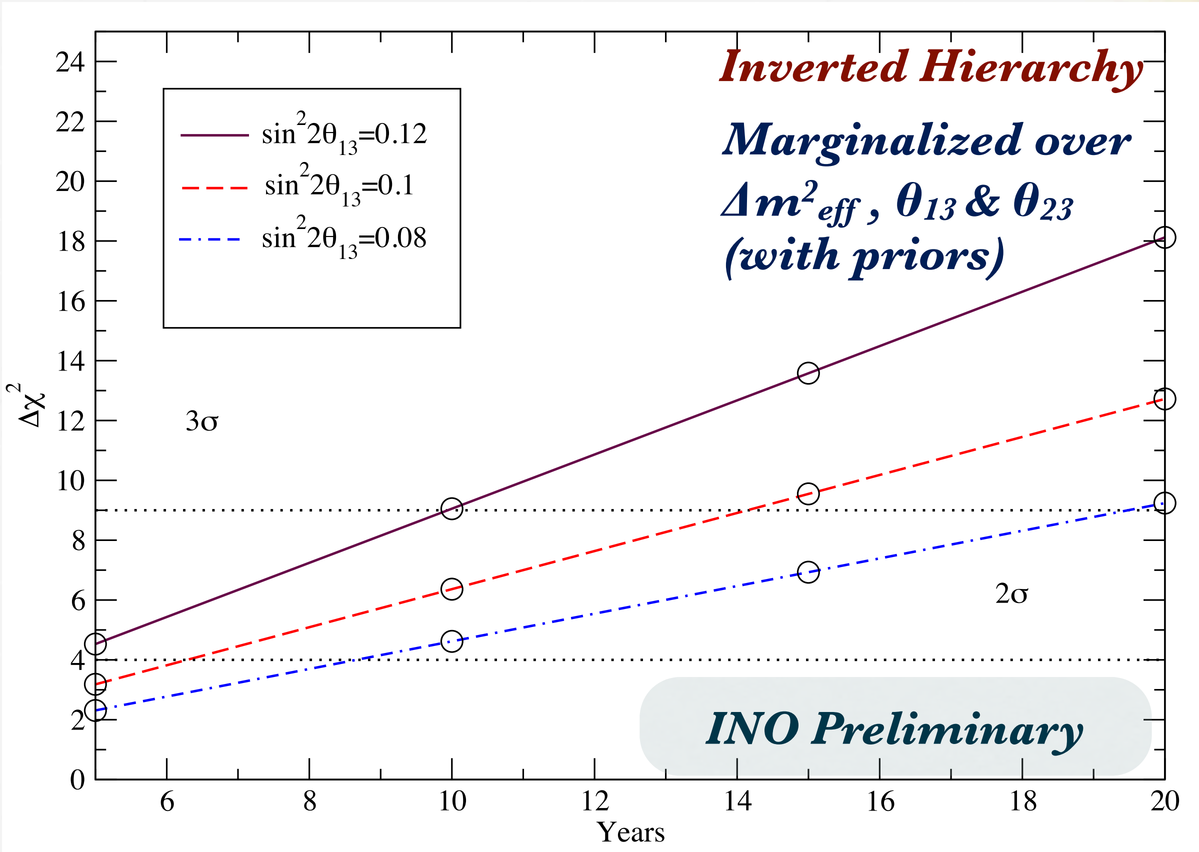


INO Collab, 2012

MASS HIERARCHY @ INNO

- *Events generated using Nuance and ICAL resoln in E and cosθ_{zenith}*





INO Collab, 2012

$\sigma(|\Delta m^2_{eff}|)=5\%, \sigma(\sin^2 2\theta_{23})=2\%, \sigma(\sin^2 2\theta_{23})=0.01$

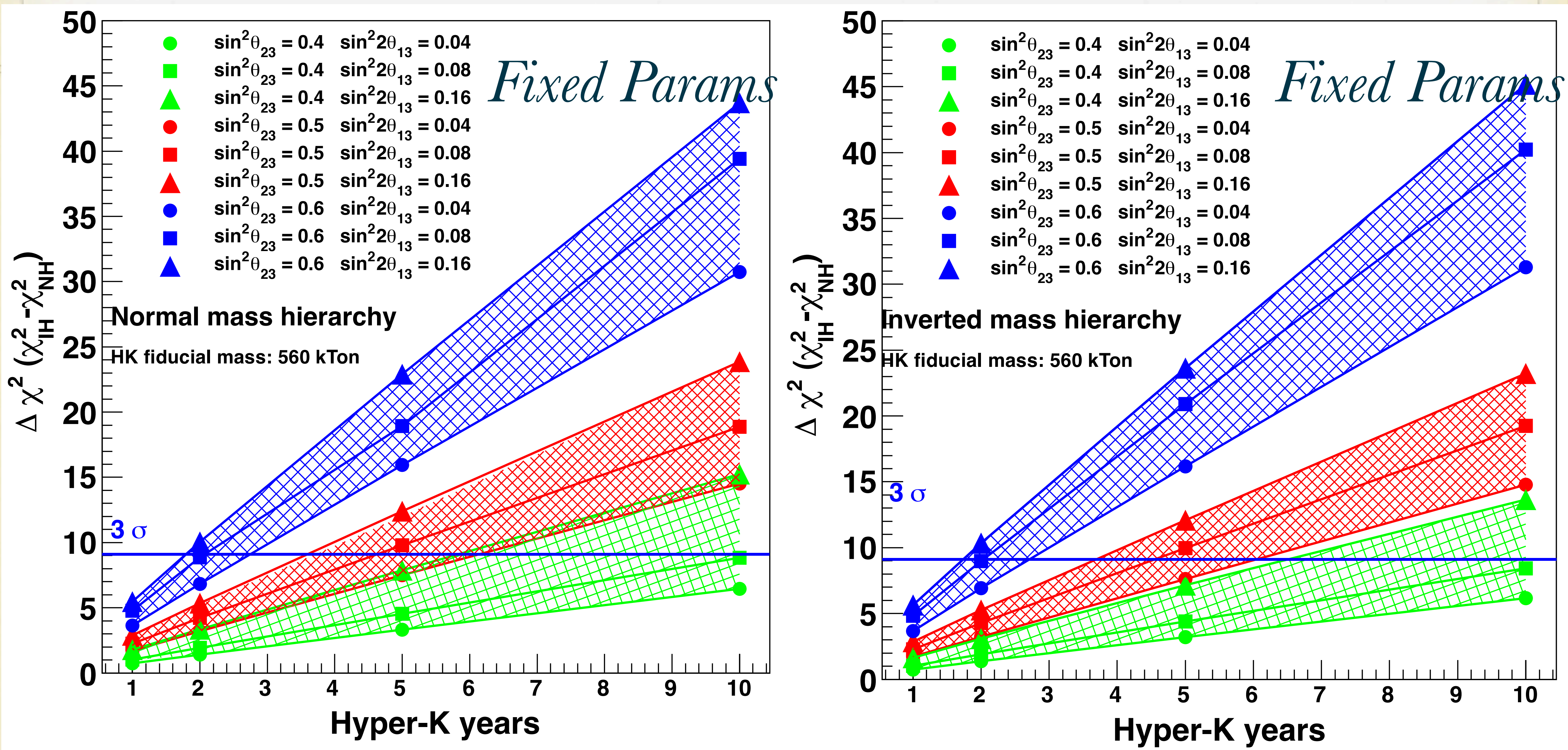
ATMOSPHERIC NEUTRINO EVENTS IN HK

TABLE XII. Expected number of ν_e-like and $\bar{\nu}_e$-like events in 10 Hyper-K years for each interaction component.

	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	NC	Total
ν_e-like sample	15247	2831	3731	4792	26601
- single-ring	6356	1086	1682	1740	10864
- multi-ring	8891	1745	2049	3052	15737
Percentage (%)	57.3	10.6	14.0	18.0	100.0
$\bar{\nu}_e$-like sample	28309	17255	1232	4559	51355
- single-ring	20470	13401	444	2496	36811
- multi-ring	7839	3854	788	2063	14544
Percentage (%)	55.1	33.6	2.4	8.9	100.0

HK LOI, 1109.3262

MASS HIERARCH @ HK_ATM



- *IH case improves significantly, NH changes slightly*

HK LOI, 1109.3262