Projected Sensitivity from ICAL + LBL Experiments

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This work has been done in collaboration with

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Tarak Thakore

Amol Dighe

Latest Results from

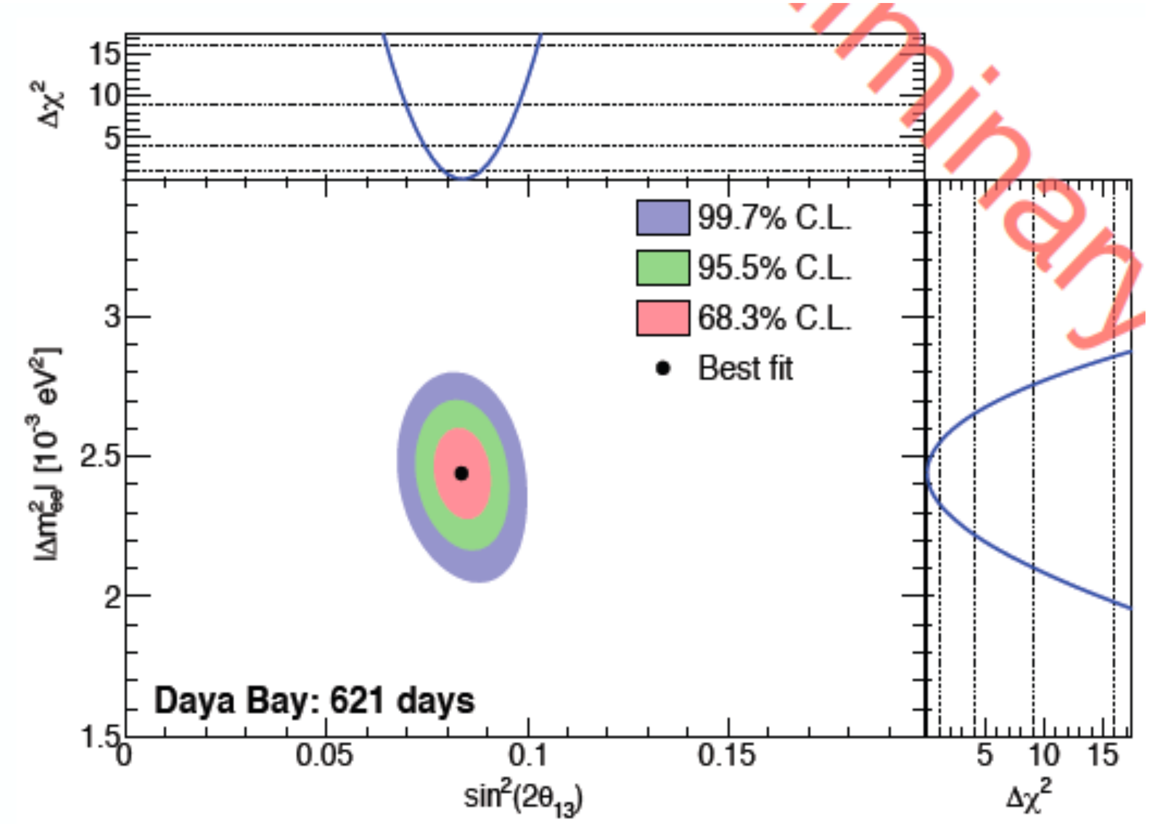
Reactor,

Long-baseline, and

Atmospheric Experiments

Latest Oscillation Results from Daya Bay

Rate + Shape Oscillation Results [Announced in Neutrino 2014]



$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

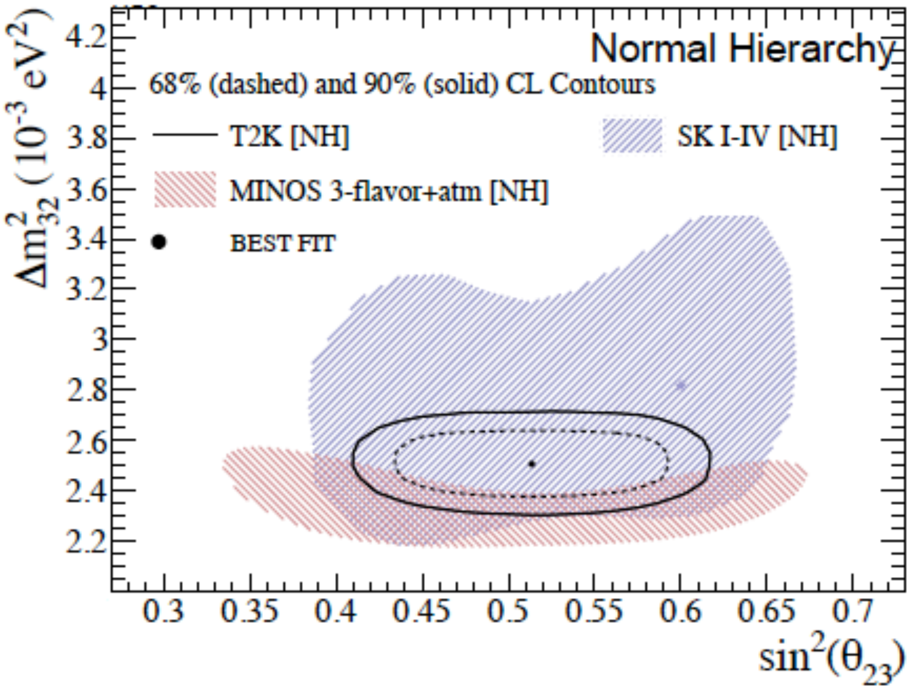
$$\chi^2/NDF = 134.7/146$$

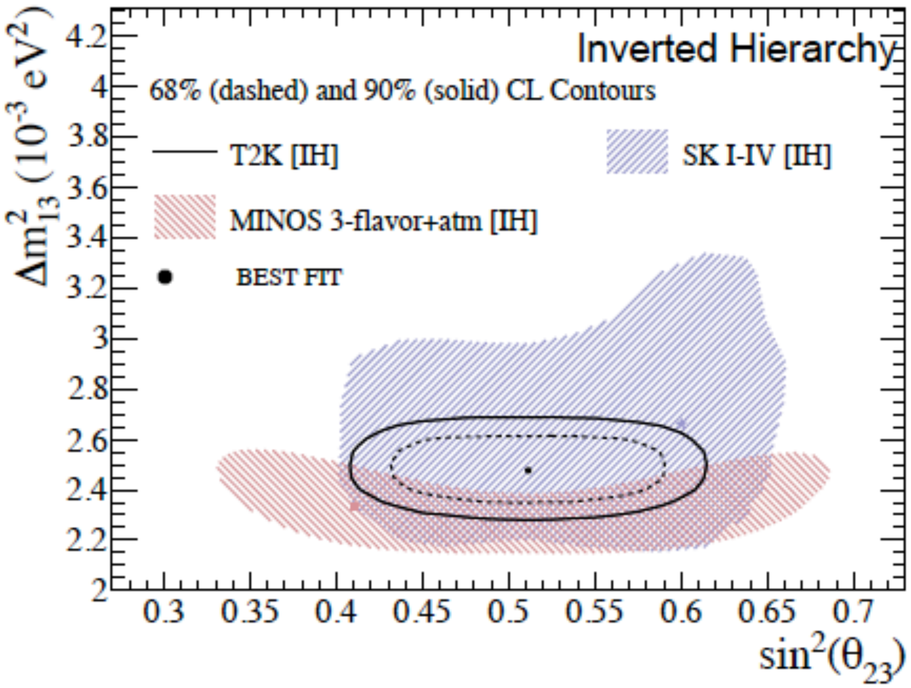
6% precision in $\sin^2 2\theta_{13}$ achieved

Strong confirmation of oscillation-interpretation of observed $\bar{\nu_e}$ deficit

	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.39^{+0.10}_{-0.11}$	$-2.49^{+0.10}_{-0.11}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

New Measurements of Atmospheric Parameters



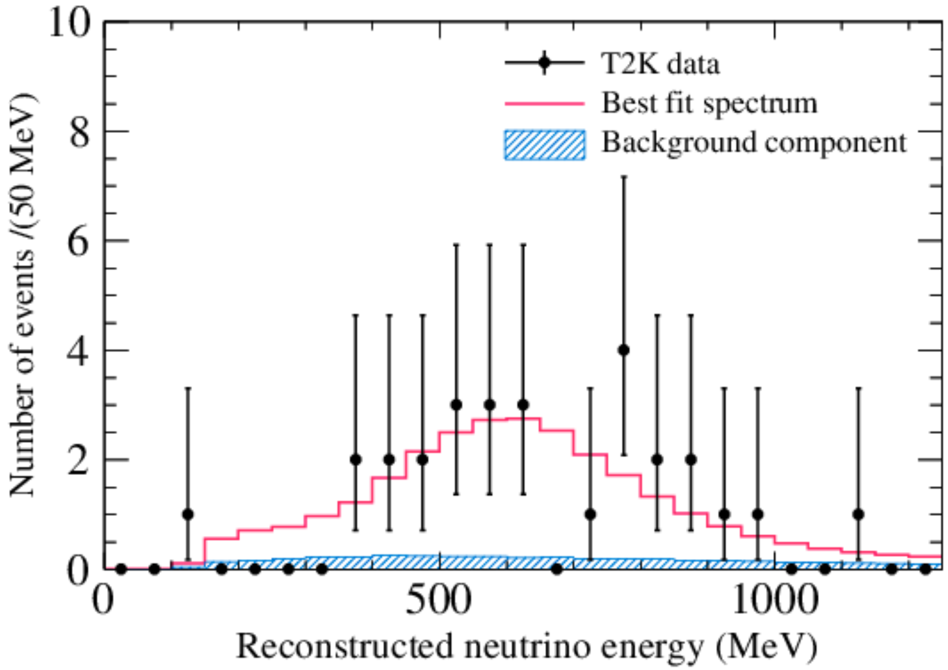


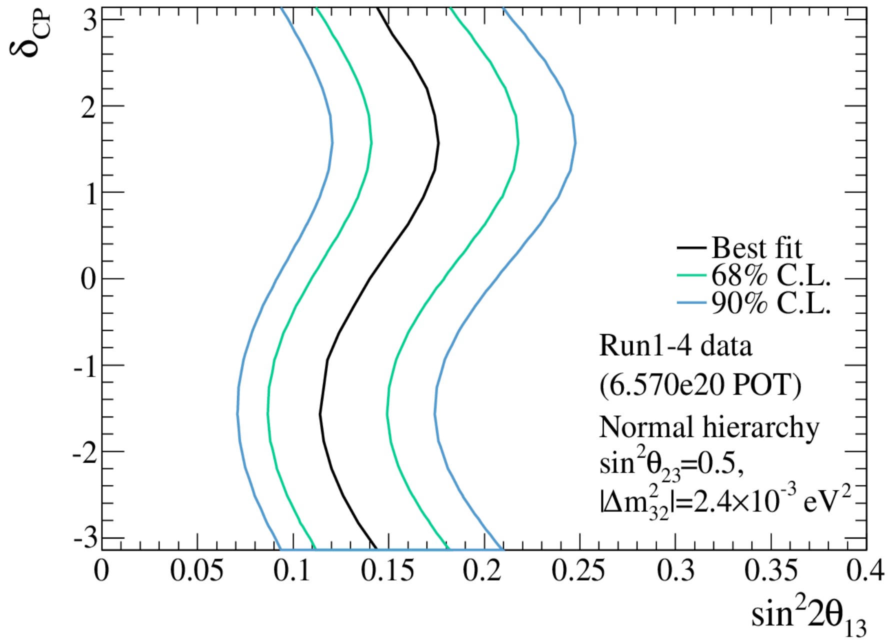
		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

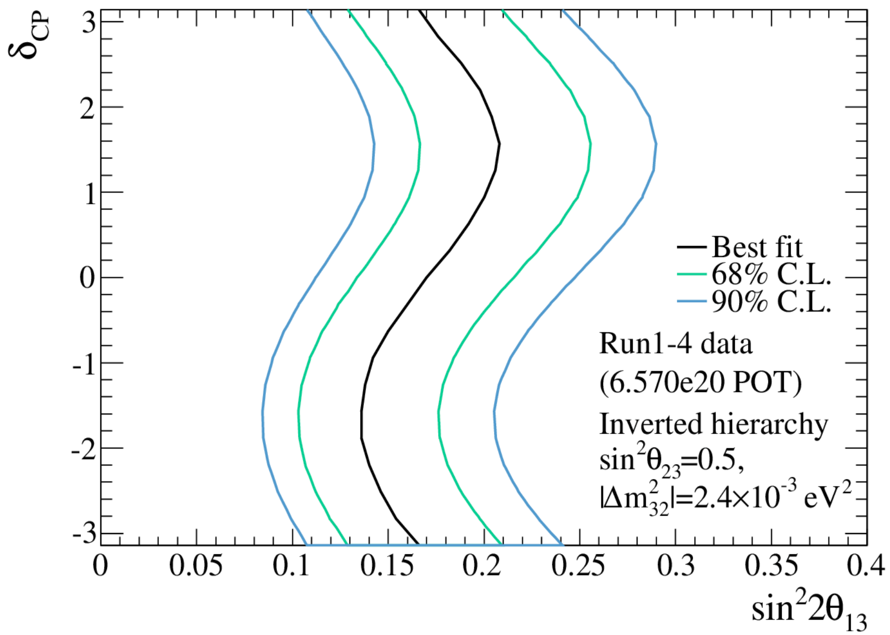
Already mixing angle is better constrained by T2K in comparison to SK and MINOS

Talk by C. Walter in Neutrino 2014

T2K ν_e Appearance Results







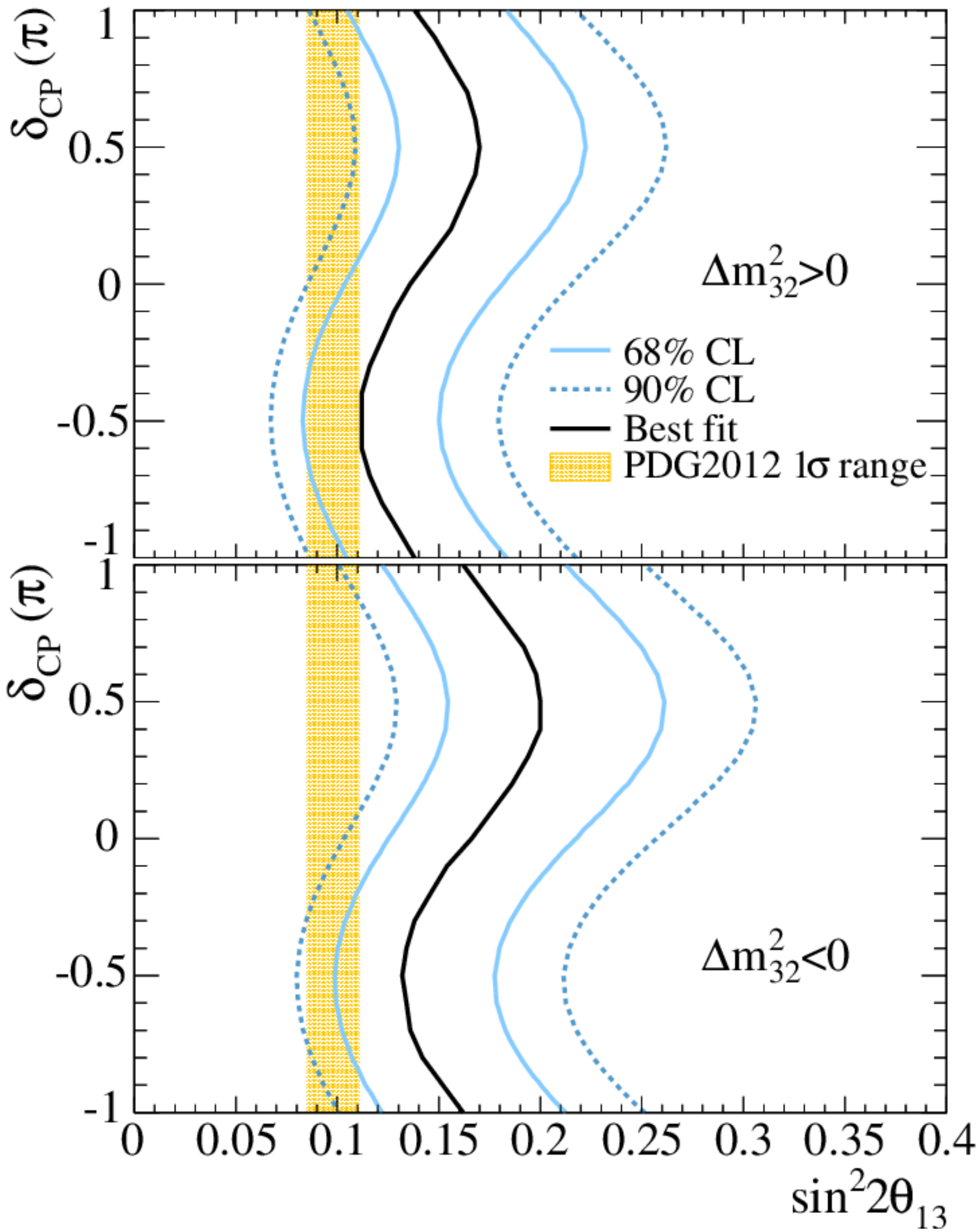
Observed events: 28
Expected background: 4.92 ± 0.55

If $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, and $\delta_{CP} = 0$
21.6 events expected

7.3σ confirmation for non-zero θ_{13}

Phys. Rev. Lett. 112, 061802 (2014)

Important Synergy between Reactor and Accelerator data



First hint of δ_{CP} combining Reactor and Accelerator data

Best overlap is for Normal hierarchy & $\delta_{CP} = -\pi/2$

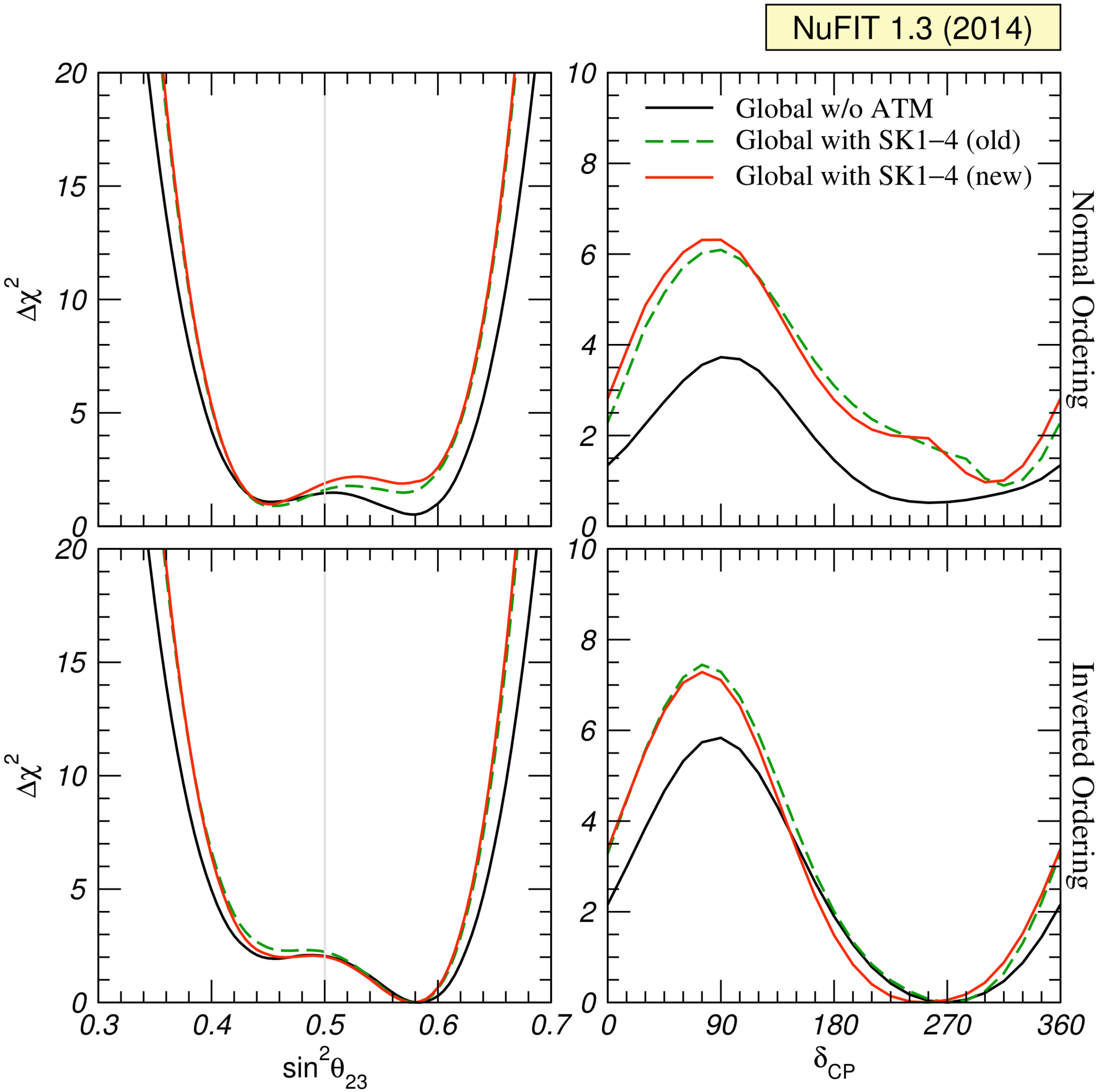
- ★ **Is Nature very kind to us?**
- ★ **Are we very lucky?**
- ★ **Is CP violated maximally?**

Strong motivation for anti-neutrino run in T2K

In these plots, atmospheric parameters are marginalized over

Courtesy C. Walter (T2K Collaboration) Talk at Neutrino 2014

Role of Atmospheric Neutrinos in Global Fit



Based on the data available after Neutrino 2014 conference

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

Oscillation Parameters After Neutrino 2014

	bfp $\pm 1\sigma$	3σ range	Relative 1σ Precision
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	4%
$\theta_{12}/^\circ$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	
$\sin^2\theta_{23}$	$[0.451^{+0.001}_{-0.001}] \oplus 0.577^{+0.027}_{-0.035}$	$0.385 \to 0.644$	9.6%
$\theta_{23}/^\circ$	$[42.2^{+0.1}_{-0.1}] \oplus 49.4^{+1.6}_{-2.0}$	$38.4 \to 53.3$	
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0011}$	$0.0188 \to 0.0251$	4.8%
$\theta_{13}/^\circ$	$8.52^{+0.20}_{-0.21}$	$7.87 \to 9.11$	
$\delta_{CP}/^\circ$	251^{+67}_{-59}	$0 \to 360$	(Not Known)
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	2.4%
$\frac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$[+2.458^{+0.002}_{-0.002}]$	$+2.325 \to +2.599$	1.9%
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.448^{+0.047}_{-0.047}$	$-2.590 \to -2.307$	

Non-maximal $> 1.4\sigma$

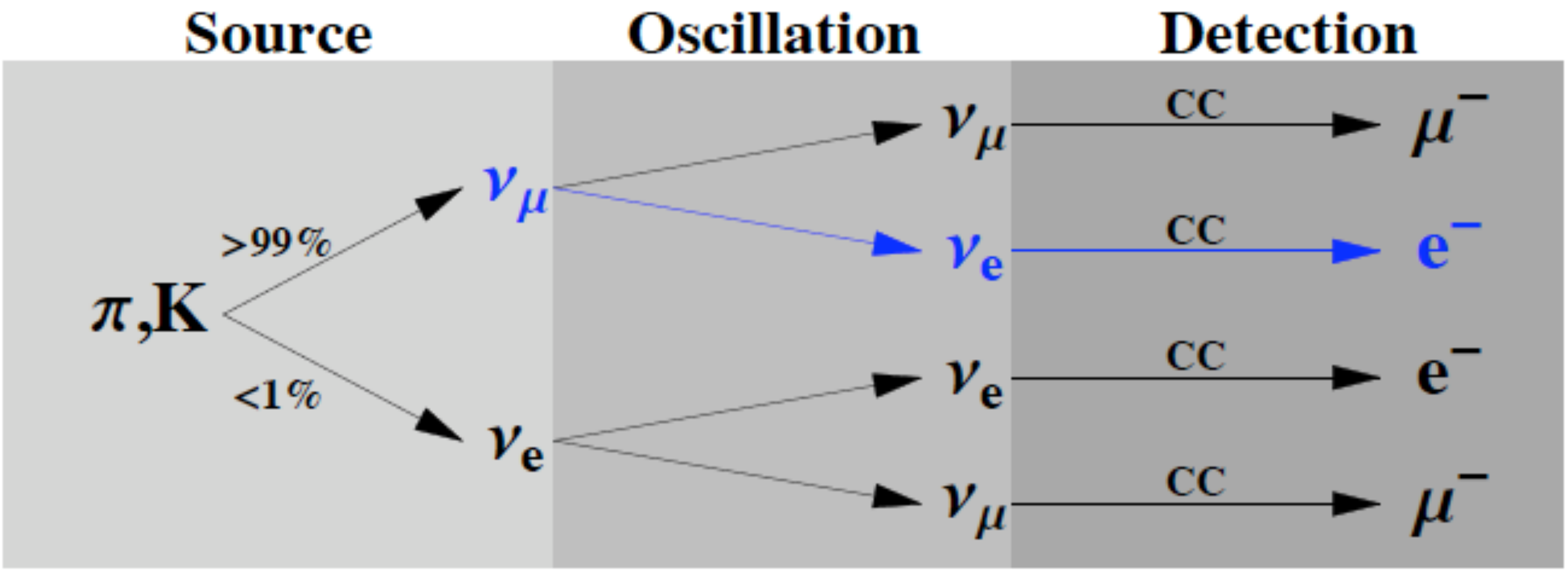
Non-zero $> 10\sigma$

$\sin\delta_{CP} < 0$ at 90% C.L.

Based on the data available after Neutrino 2014 conference

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

Superbeams



Traditional approach: Neutrino beam from pion decay

Current Generation Experiments:

Tokai to Kamioka (T2K) : 295 km (2.5° off-axis, 1st Osc. Max = 0.6 GeV)
J-PARC Beam: 0.75 MW, Total 7.8×10^{21} protons on target, 5 years ν run
Detector: Super-Kamiokande (22.5 kton fiducial volume)

FNAL to Ash River (NOvA) : 810 km (0.8° off-axis, 1st Osc. Max = 1.7 GeV)
NuMI Beam: 0.7 MW, Total 3.6×10^{21} protons on target, 3 yrs ν + 3 yrs anti-ν
Detector: 14 kton Totally Active Scintillator Detector (TASD)

Three Flavor Effects in $\nu_\mu \rightarrow \nu_e$ oscillation probability

The appearance probability $(\nu_\mu \to \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ (0.03) and $\sin 2\theta_{13}$ (0.3),

$$P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

→ θ_{13} Driven

$$- \alpha \sin 2\theta_{13} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ CP odd

$$+ \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ CP even

$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$

→ Solar Term

$\sin^2 2\theta_{13}$: 0.09; $\alpha \sin 2\theta_{13}$: 0.009; α^2: 0.0009

$\sin^2\theta_{23}$ → Resolves octant

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2}G_F n_e E)/\Delta m^2_{31}$

changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!

changes sign with polarity causes fake CP asymmetry!

Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracy! How can we break them?

Physics Potential of T2K & NOvA in light of large θ_{13}

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Potential of optimized NOνA for large θ_{13} & combined performance with a LArTPC & T2K

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Abstract: NOνA experiment has reoptimized its event selection criteria in light of the recently measured moderately large value of θ_{13}. We study the improvement in the sensitivity to the neutrino mass hierarchy and to leptonic CP violation due to these new features. For favourable values of δ_{CP}, NOνA sensitivity to mass hierarchy and leptonic CP violation is

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Resolving the octant of θ_{23} with T2K and NOνA

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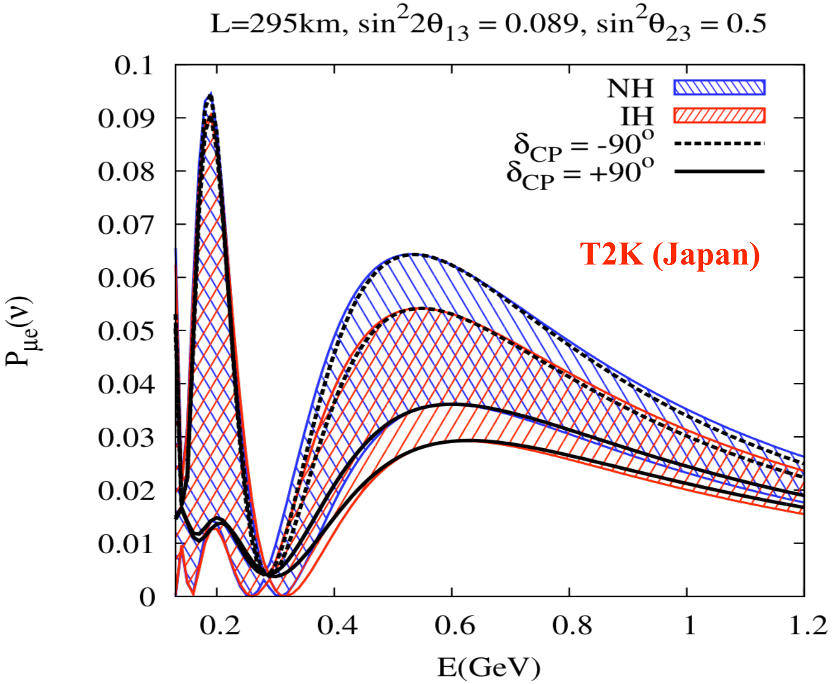
Abstract: Preliminary results of MINOS experiment indicate that θ_{23} is not maximal. Global fits to world neutrino data suggest two nearly degenerate solutions for θ_{23}: one in the lower octant (LO: $\theta_{23} < 45°$) and the other in the higher octant (HO: $\theta_{23} > 45°$). $\nu_\mu \to \nu_e$ oscillations in superbeam experiments are sensitive to the octant and are capable of resolving this degeneracy. We study the prospects of this resolution by the current T2K and upcoming NOνA experiments. Because of the hierarchy-δ_{CP} degeneracy and the octant-δ_{CP} degeneracy, the impact of hierarchy on octant resolution has to be taken into account.

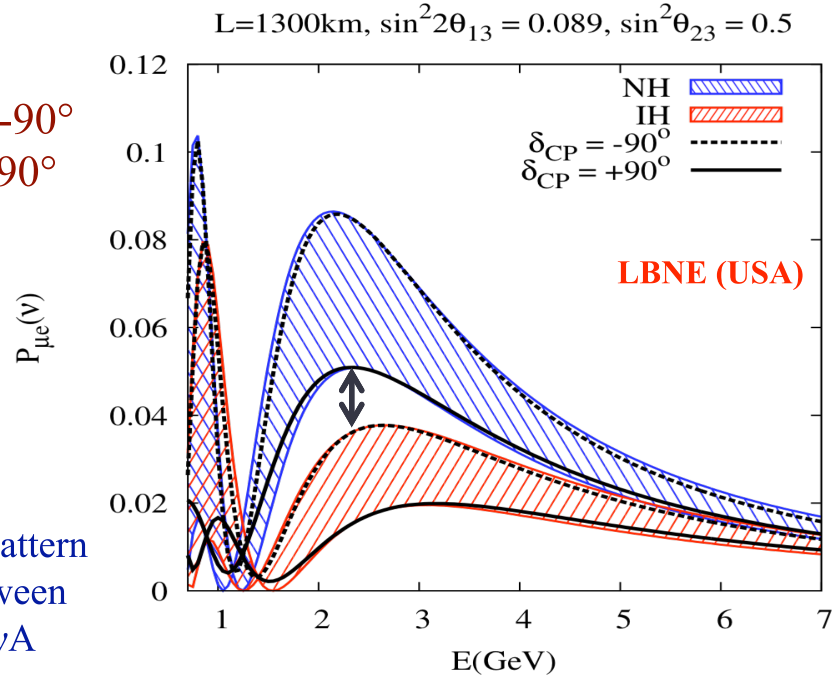
JHEP07(2013)131

Combined data from T2K and NOvA are expected to provide
the first hint for neutrino mass hierarchy, leptonic CP violation, and octant of θ_{23}

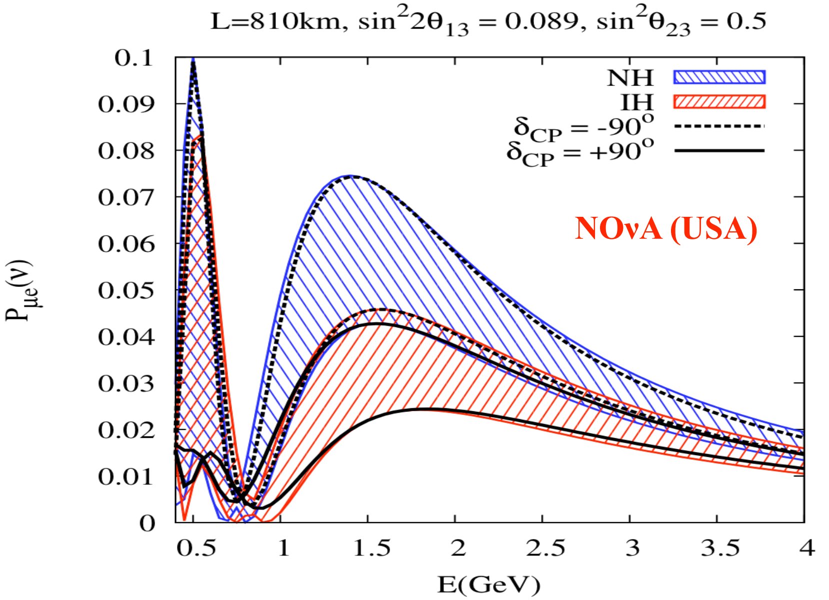
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



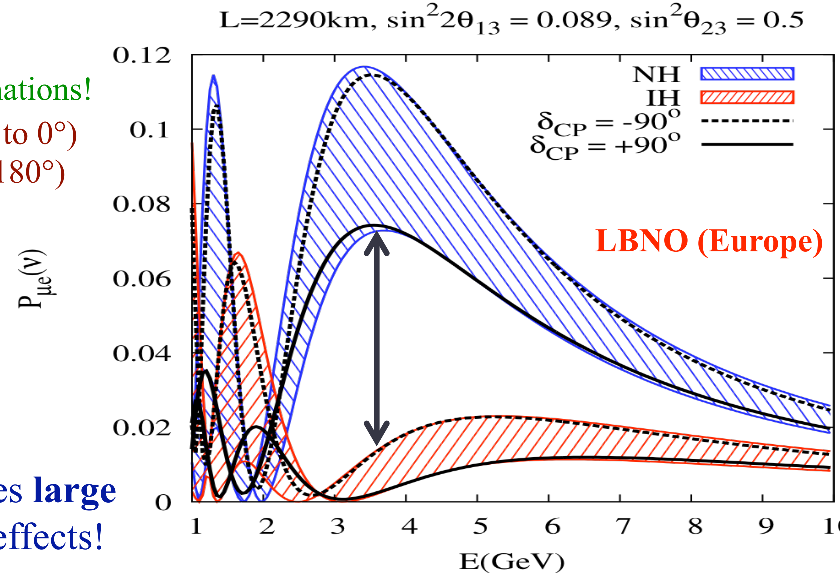
For ν:
Max: NH, -90°
Min: IH, 90°



Degeneracy pattern different between T2K & NOνA



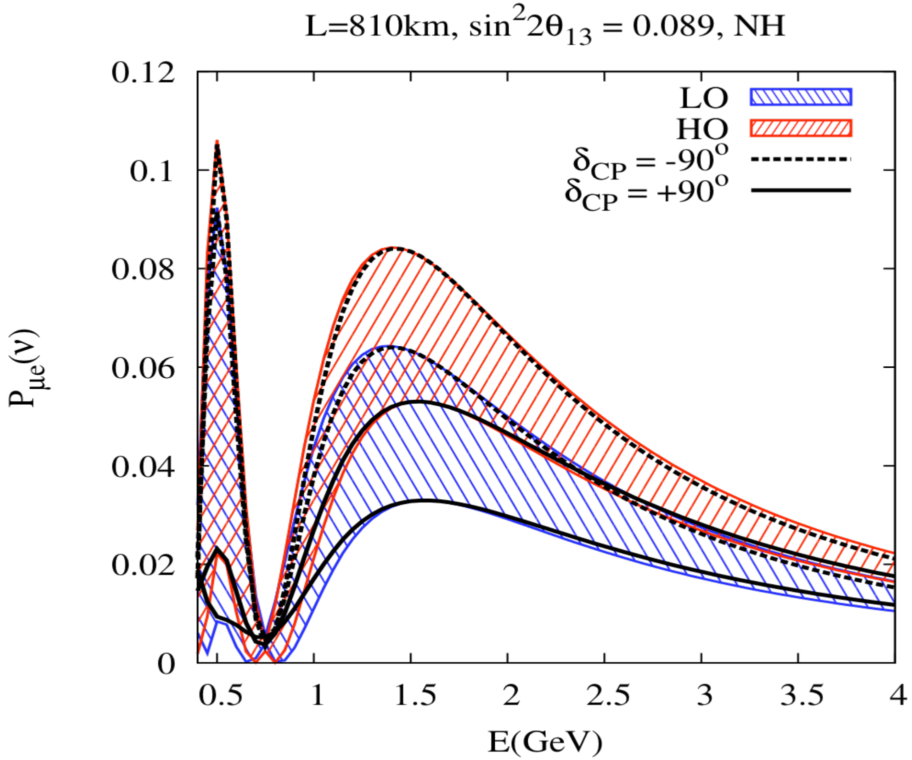
Favorable combinations!
NH, LHP (-180° to 0°)
IH, UHP (0° to 180°)

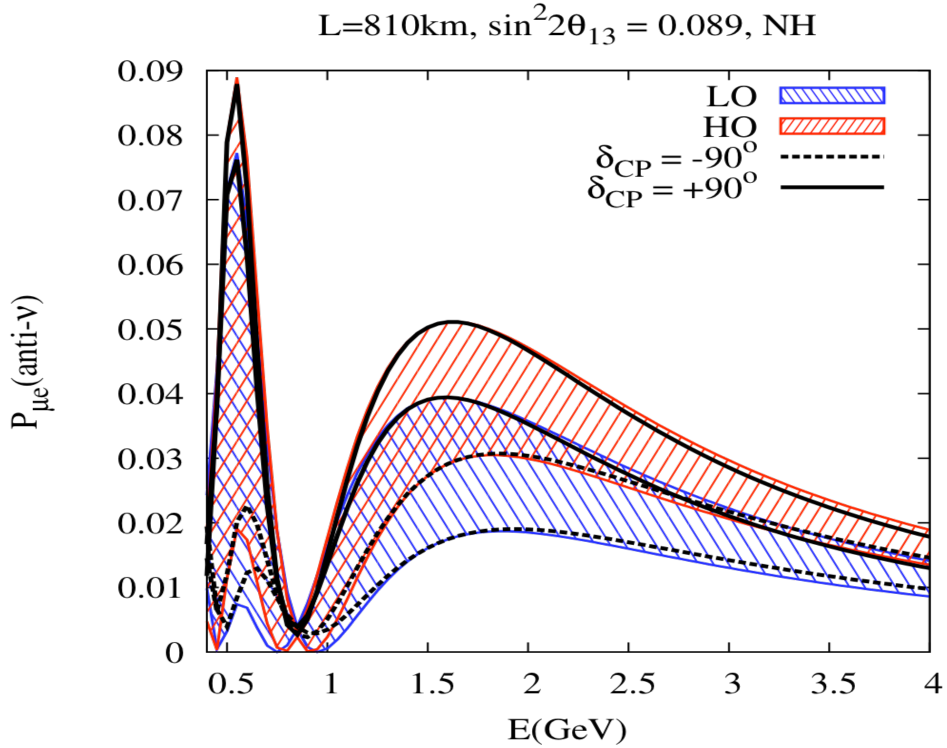


Large θ_{13} causes **large** Earth matter effects!

Agarwalla, Prakash, Raut, Sankar, 2012-2013

Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel





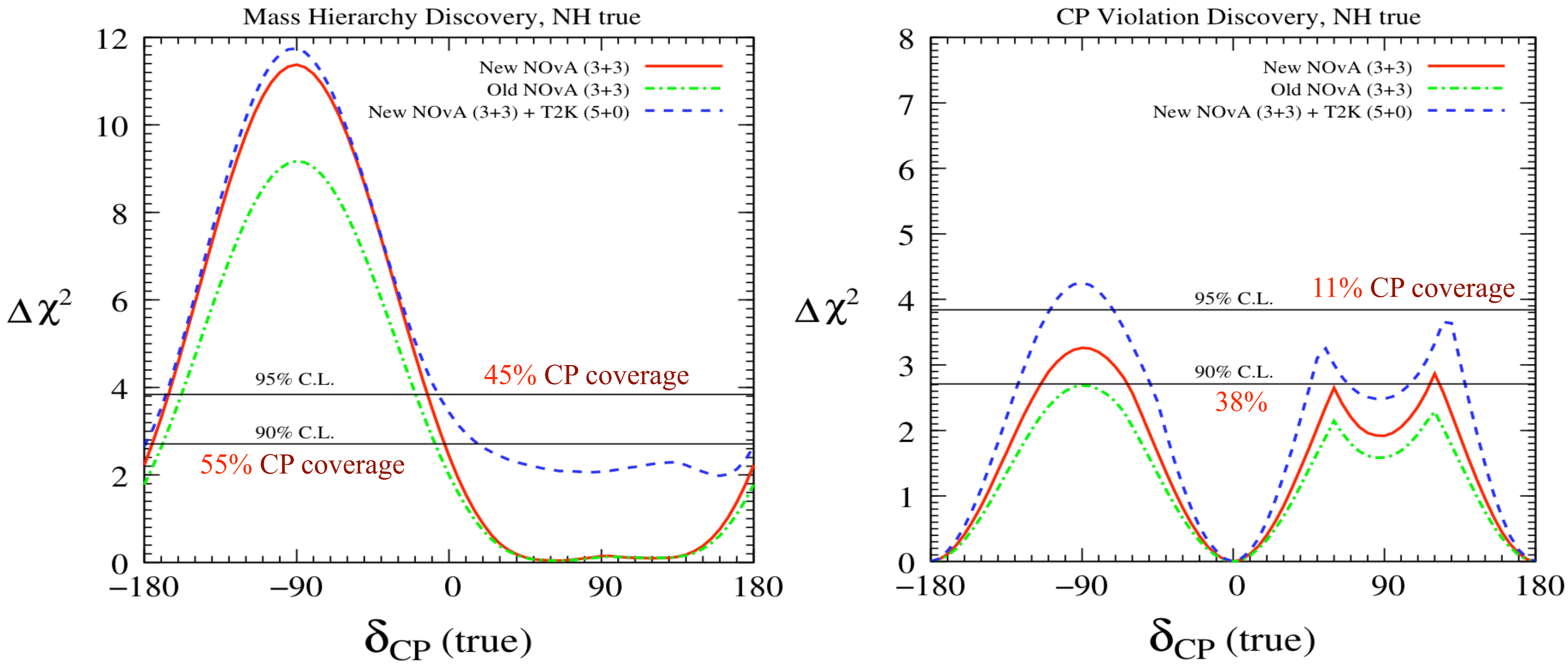
For neutrino:
Maximum: HO, -90°
Minimum: LO, 90°

For anti-neutrino:
Maximum: HO, 90°
Minimum: LO, -90°

Unfavorable CP values for neutrino are favorable for anti-neutrino & vice-versa

Agarwalla, Prakash, Sankar, arXiv: 1301.2574

Mass Hierarchy & CP Violation Discovery with T2K and NOvA

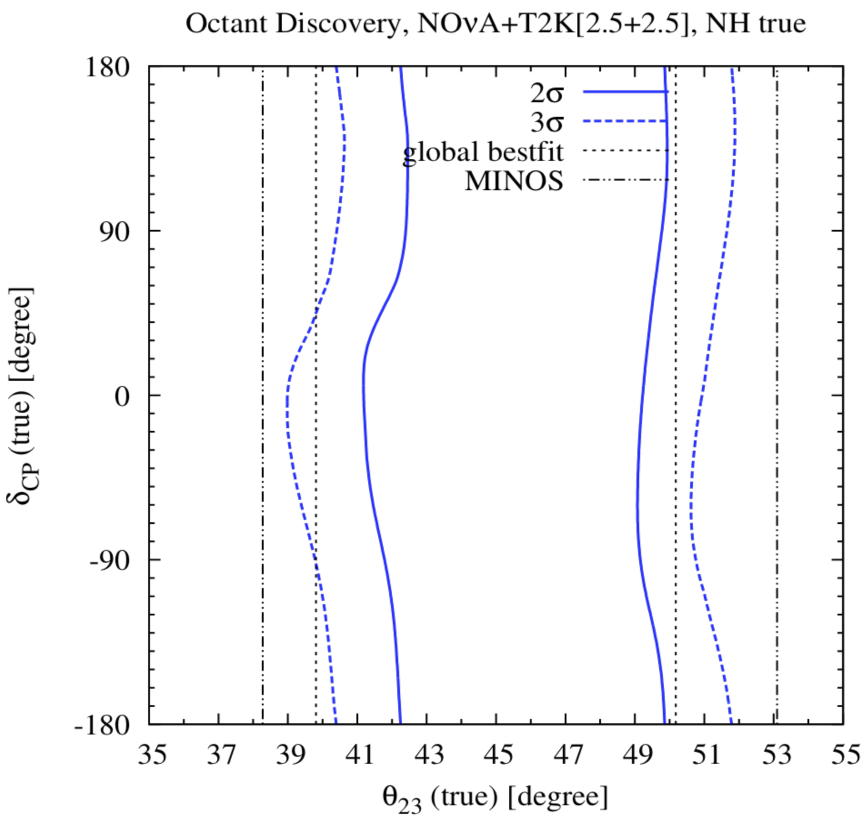


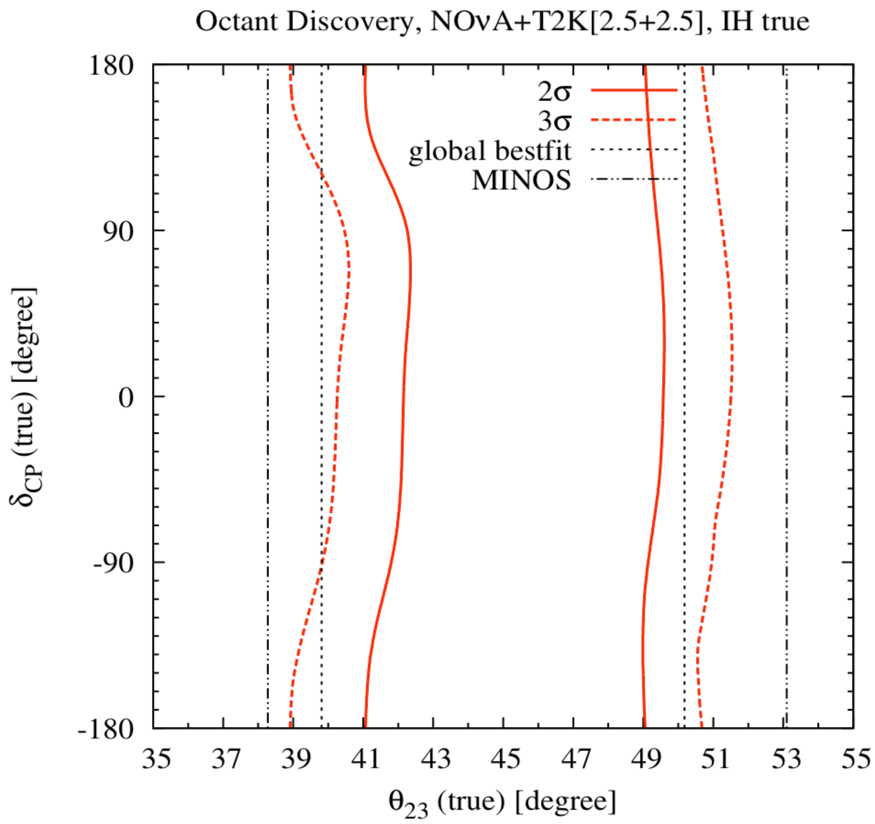
Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644
See also, Huber, Lindner, Schwetz, Winter, arXiv: 0907.1896;
Machado, Minakata, Nunokawa, Funchal, arXiv: 1307.3248;
Ghosh, Ghosal, Goswami, Raut, arXiv: 1401.7243

Adding data from T2K and NOvA is useful to kill the intrinsic degeneracies

CP asymmetry $\propto 1/\sin 2\theta_{13}$, large θ_{13} increases statistics but reduces asymmetry, Systematics are important

Resolving Octant of θ_{23} with T2K and NOvA





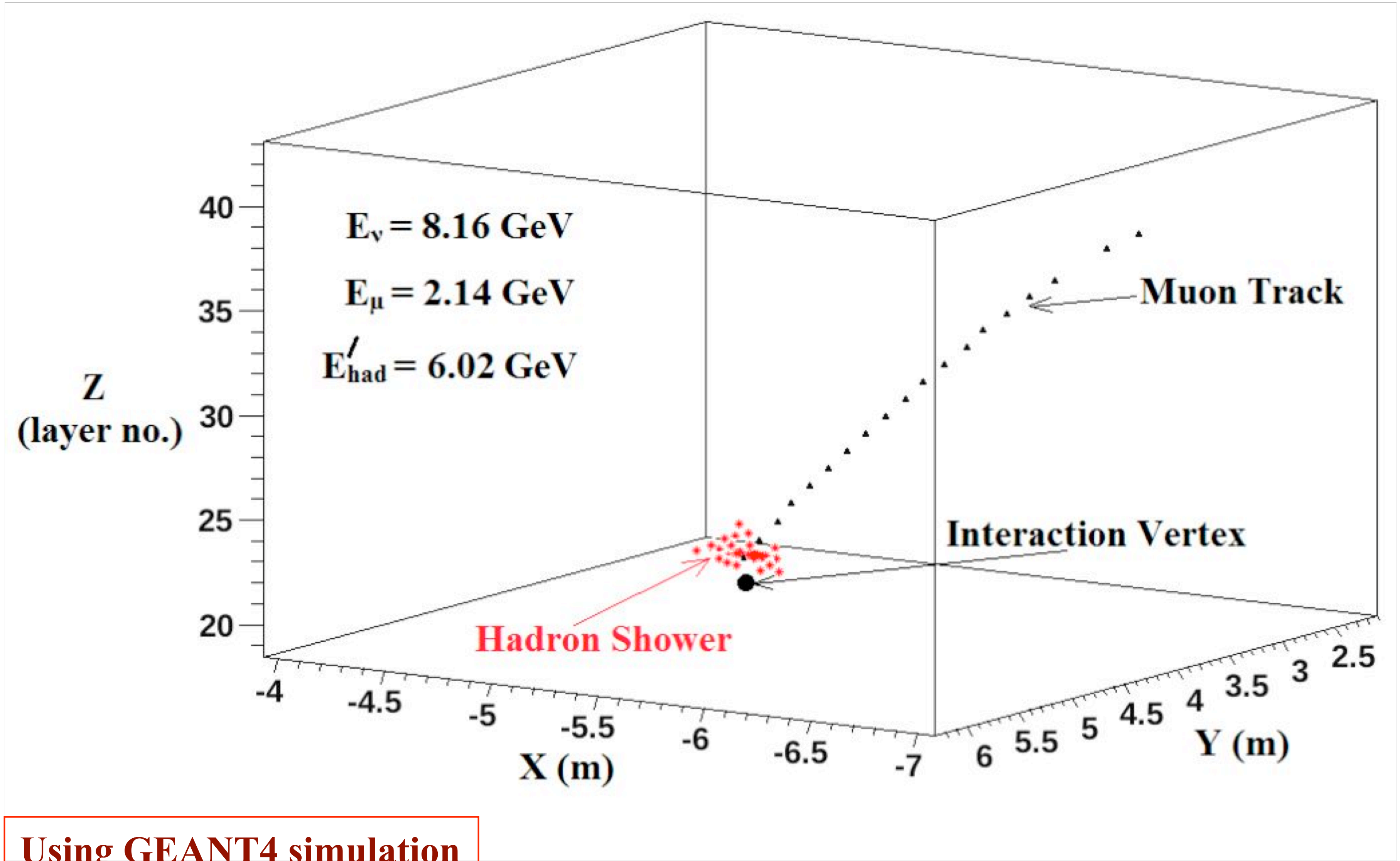
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]
See also, Chatterjee, Ghoshal, Goswami, Raut, arXiv:1302.1370 [hep-ph]

If $\theta_{23} < 41°$ or $\theta_{23} > 50°$, we can resolve the octant issue at 2σ irrespective of δ_{CP}

If $\theta_{23} < 39°$ or $\theta_{23} > 52°$, we can resolve the octant issue at 3σ irrespective of δ_{CP}

Important message: T2K must run in anti-neutrino mode in future

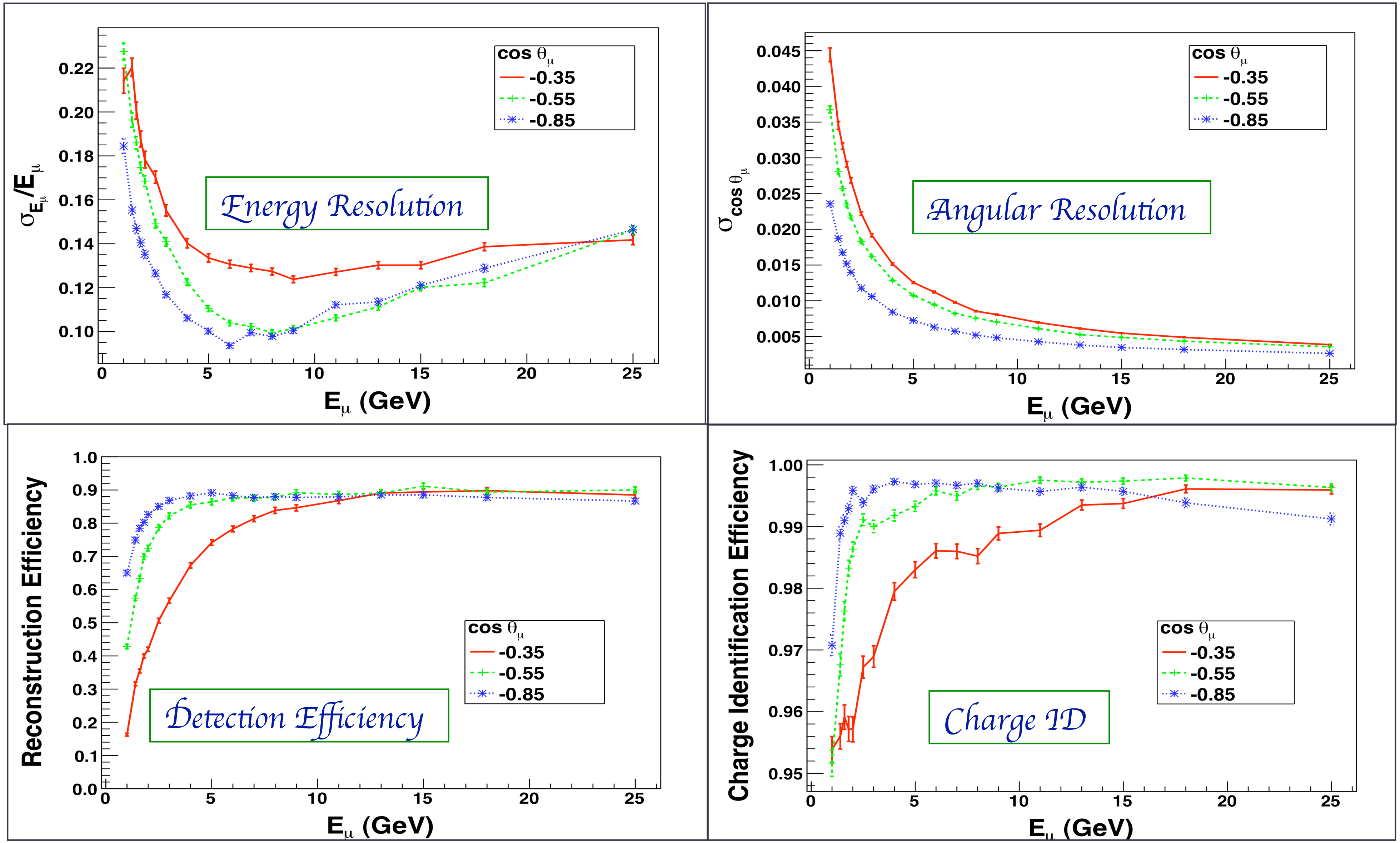
Event Display Inside the ICAL Detector



Using GEANT4 simulation

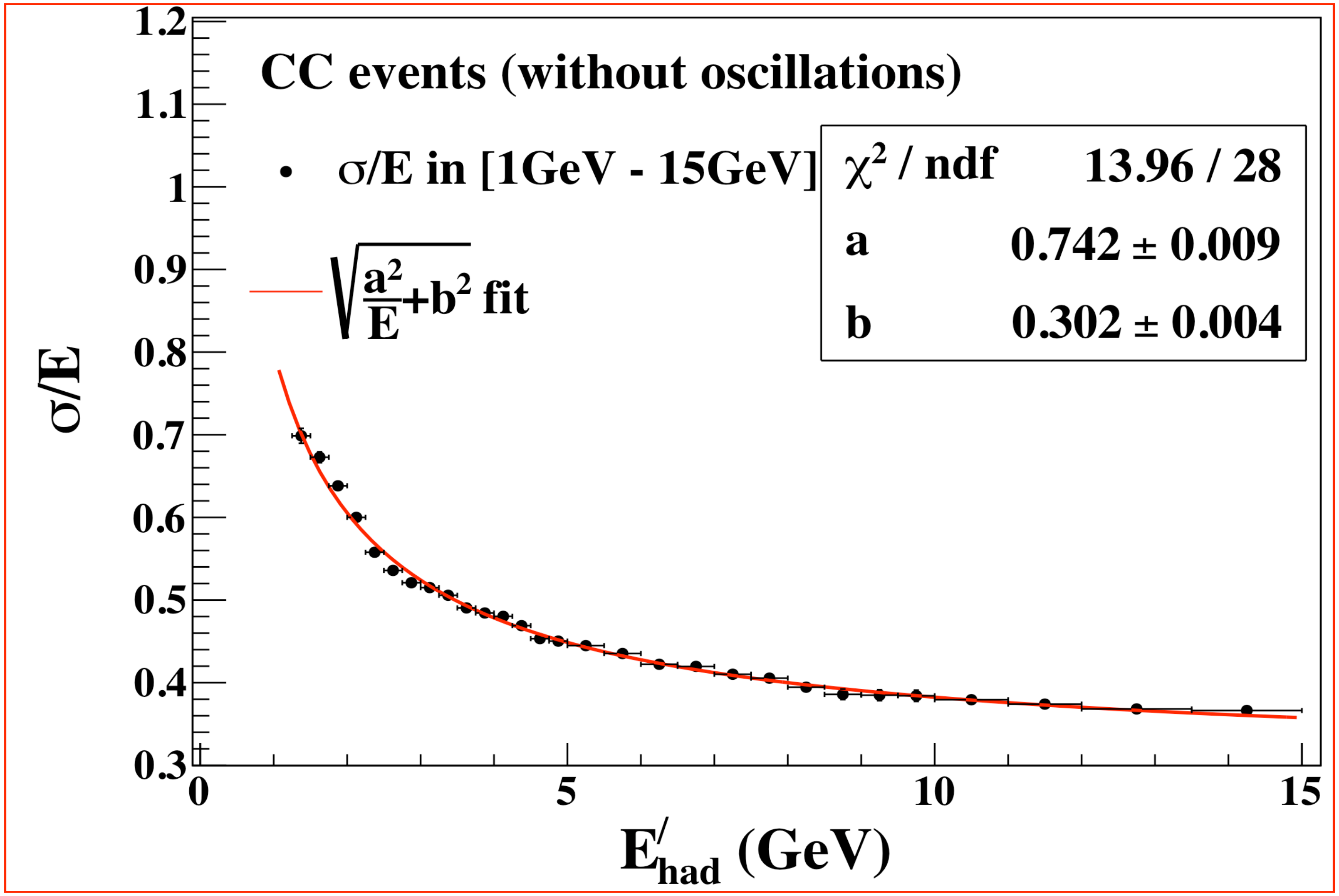
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Muon Efficiencies and Resolutions



Animesh Chatterjee, Meghna K.K., Kanishka Rawat, Tarak Thakore etal., arXiv:1405.7243 [physics.ins-det]

Hadron Energy Response of ICAL



$E'_h = E_\nu - E_\mu$ (from hadron hit calibration)

Hadron energy resolution: 85% at 1 GeV and 36% at 15 GeV

Moon Moon Devi, Anushree Ghosh, Daljeet Kaur, Lakshmi S. Mohan etal., JINST 8 (2013) P11003

The χ^2 Analysis

We define the Poissonian χ^2_- for μ^- events as :

$$\chi^2_- = \min_{\xi_l} \sum_{i=1}^{N_{E'_{\rm had}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos\theta_\mu}} \left[2(N_{ijk}^{\rm theory} - N_{ijk}^{\rm data}) - 2N_{ijk}^{\rm data} \ln\left(\frac{N_{ijk}^{\rm theory}}{N_{ijk}^{\rm data}}\right)\right] + \sum_{l=1}^{5} \xi_l^2 \,,$$

where

$$N_{ijk}^{\rm theory} = N_{ijk}^0 \left(1 + \sum_{l=1}^{5} \pi_{ijk}^l \xi_l\right) .$$

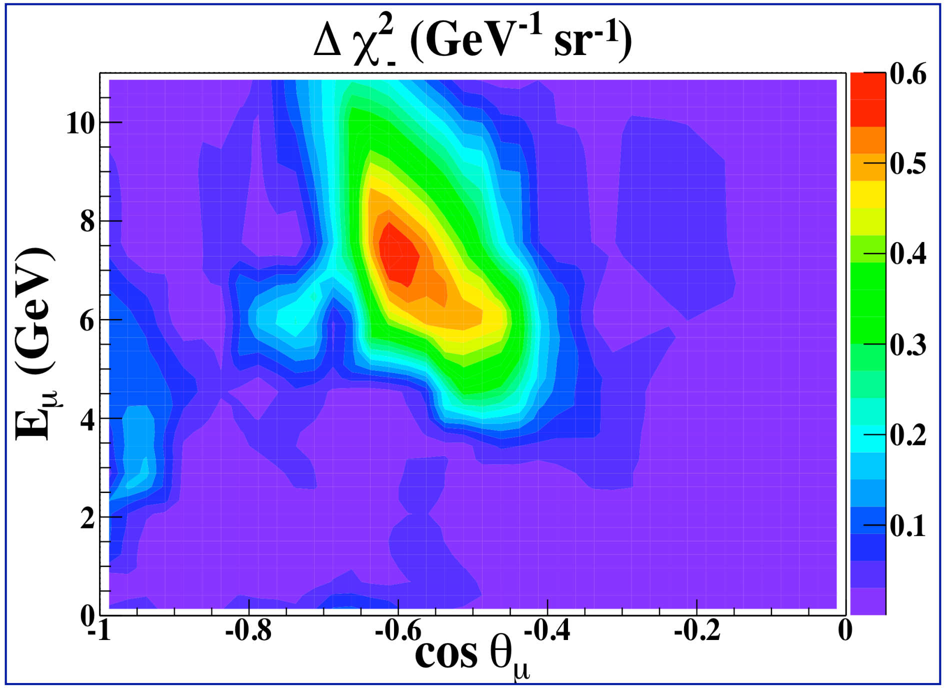
Observable	Range	Bin width	Total bins	
E_μ (GeV)	$[1,4)$	0.5	6	10
	$[4,7)$	1	3	
	$[7,11)$	4	1	
$\cos\theta_\mu$	$[-1.0,-0.4)$	0.05	12	21
	$[-0.4,0.0)$	0.1	4	
	$[0.0,1.0]$	0.2	5	
$E'_{\rm had}$ (GeV)	$[0,2)$	1	2	4
	$[2,4)$	2	1	
	$[4,15)$	11	1	

1) Overall 5% systematic uncertainty
2) Overall flux normalization: 20%
3) Overall cross-section normalization: 10%

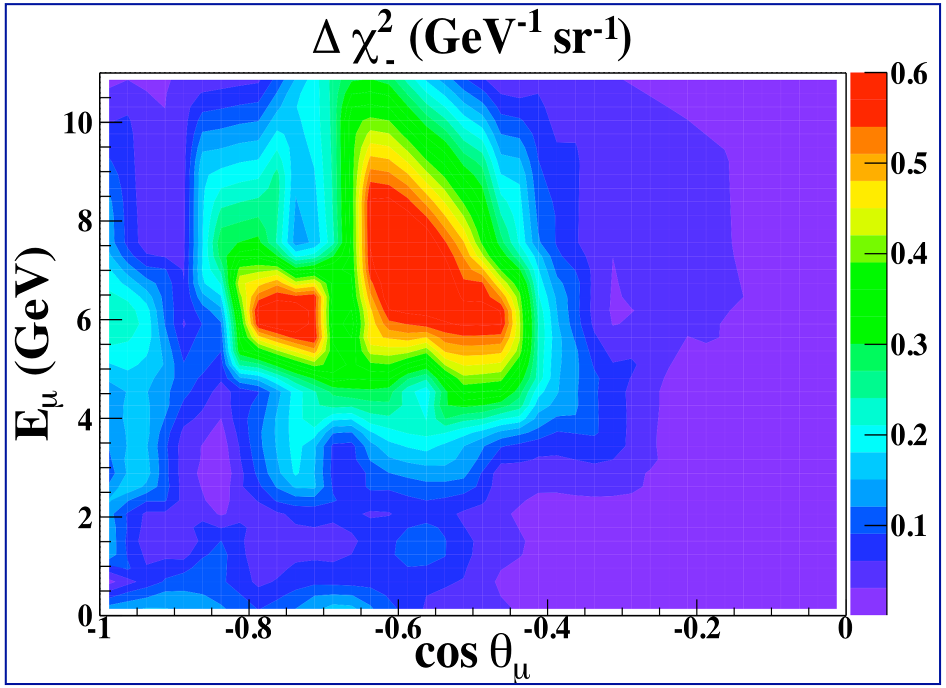
4) 5% uncertainty on the zenith angle dependence of the fluxes
5) Energy dependent tilt factor:
$\Phi_\delta(E) = \Phi_0(E)\,[E/E_0]^\delta \approx \Phi_0(E)\,[1+\delta \ln E/E_0]$
where $E_0 = 2$ GeV and
δ is the 1σ systematic error of 5%

Neutrino Mass Hierarchy Discrimination

Distribution of $\Delta\chi^2$ [χ^2 (IH) - χ^2 (NH)] for mass hierarchy discrimination considering μ^- events



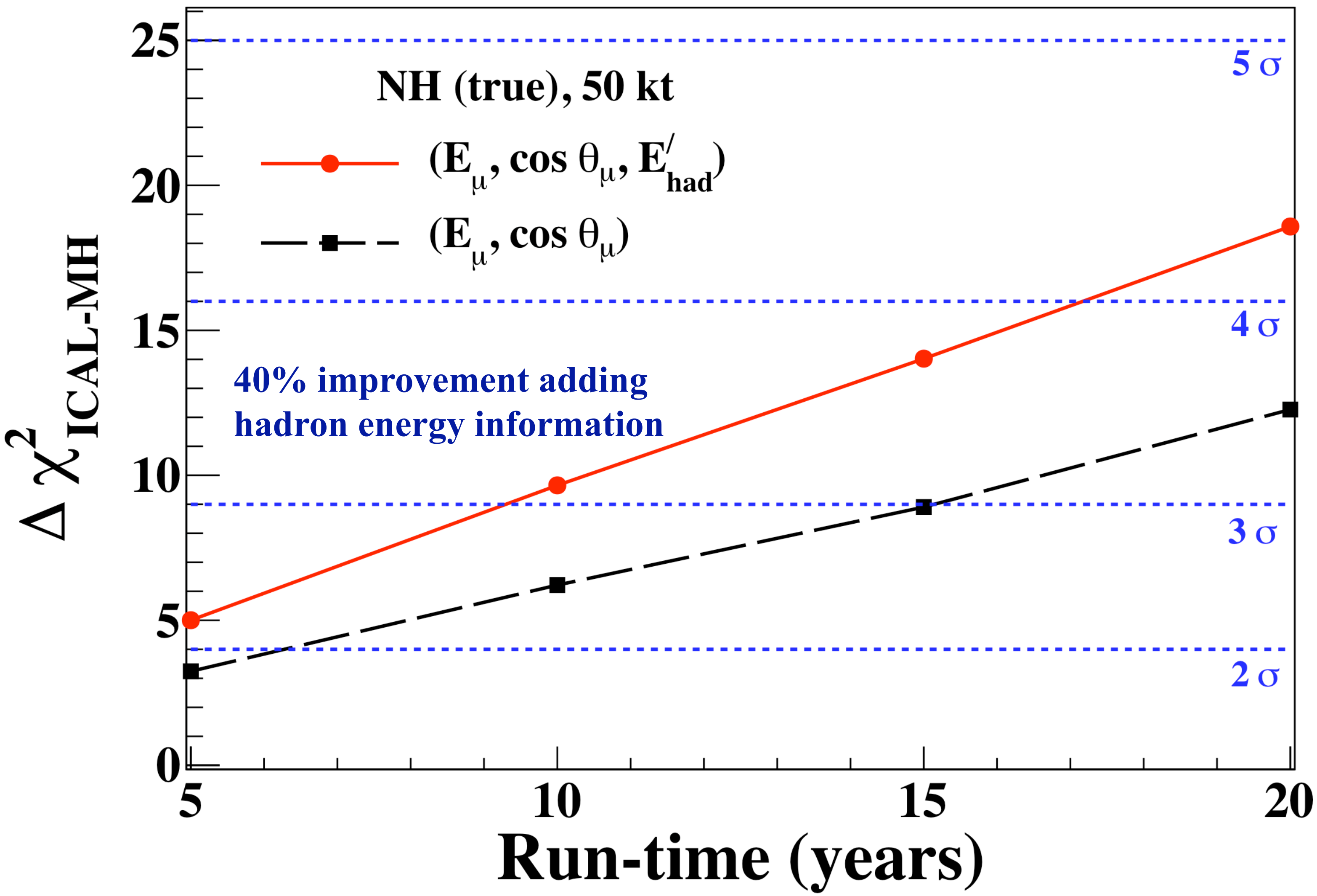
Hadron energy information not used



Hadron energy information used

- Further subdivide the events into four hadron energy bins
- Hadron energy carries crucial information
- Correlation between hadron energy and muon momentum is very important

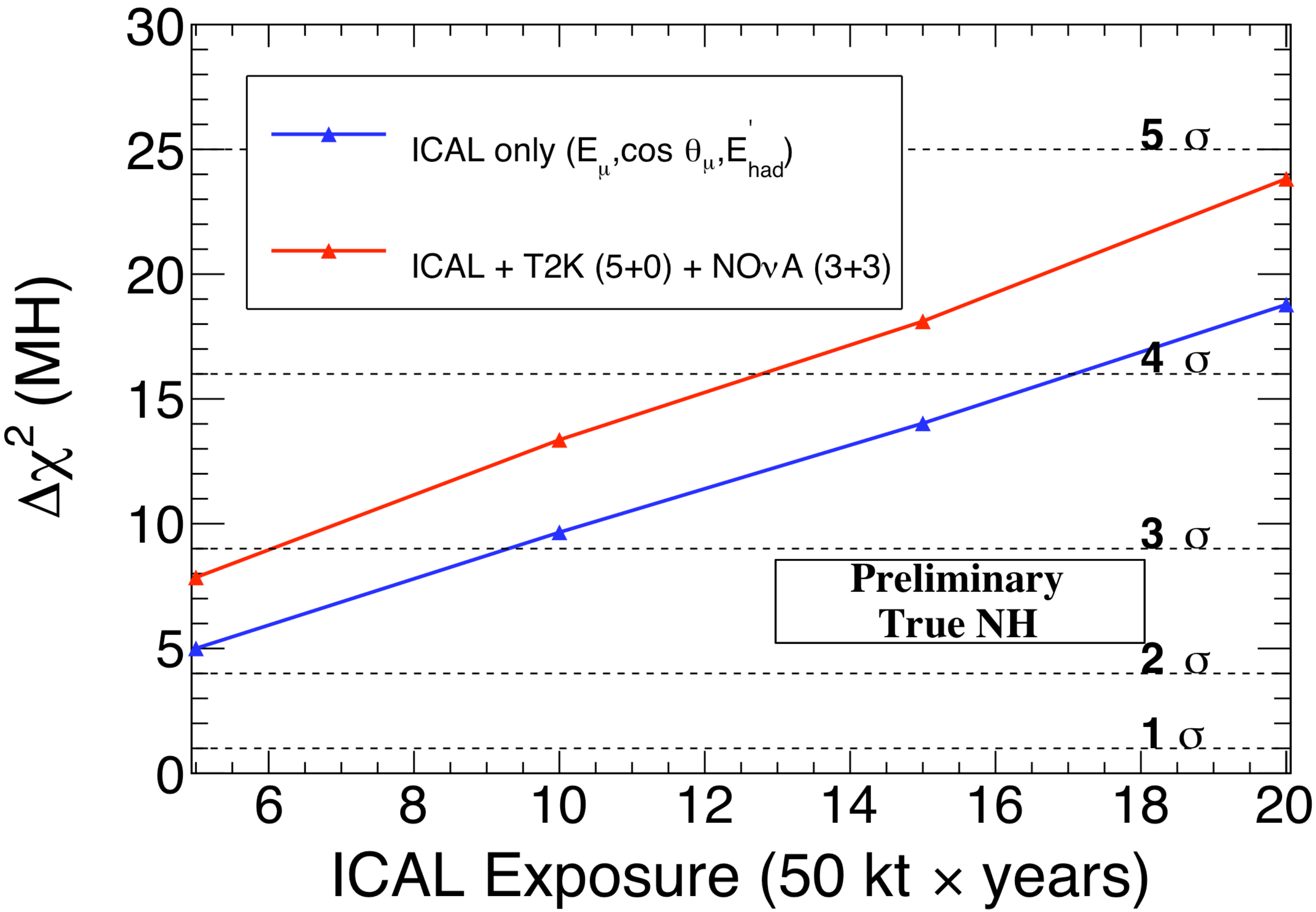
Identifying Neutrino Mass Hierarchy with ICAL



Median Sensitivity

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

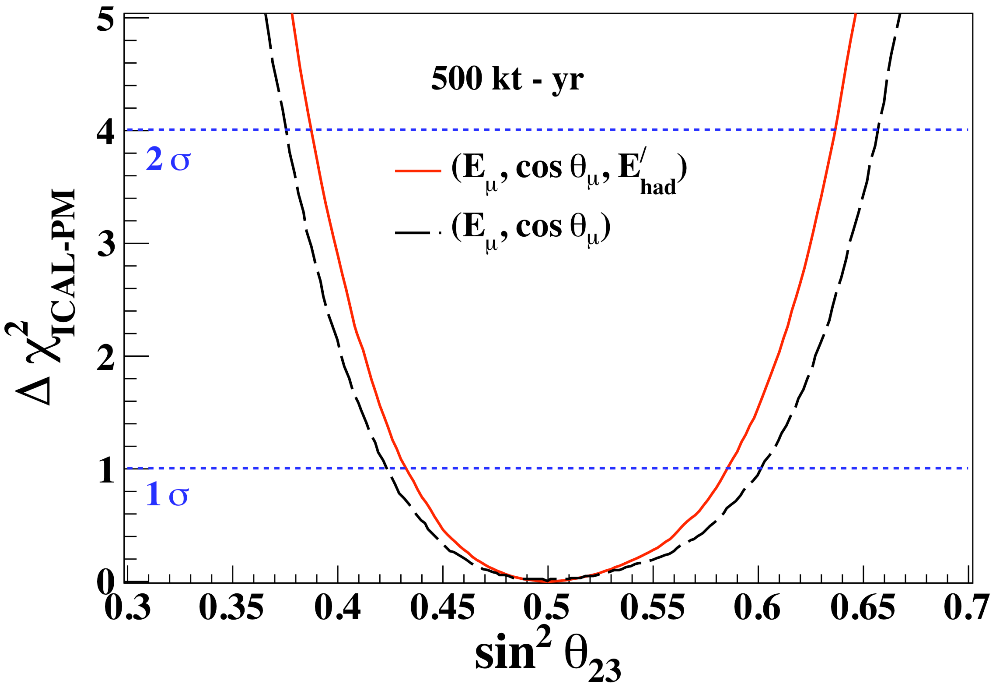
50 kt ICAL can rule out the wrong hierarchy with $\Delta\chi^2 \approx 9.5$ in 10 years

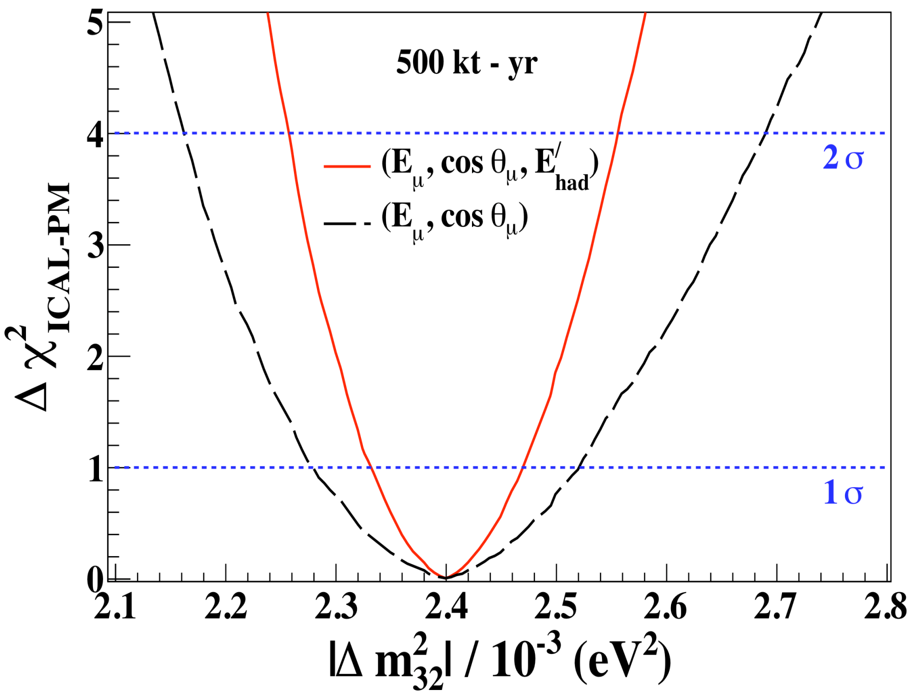


Devi, Thakore, Agarwalla, work in progress (INO Collaboration)

3σ median sensitivity can be achieved in 6 years

Precision of Atmospheric Oscillation Parameters





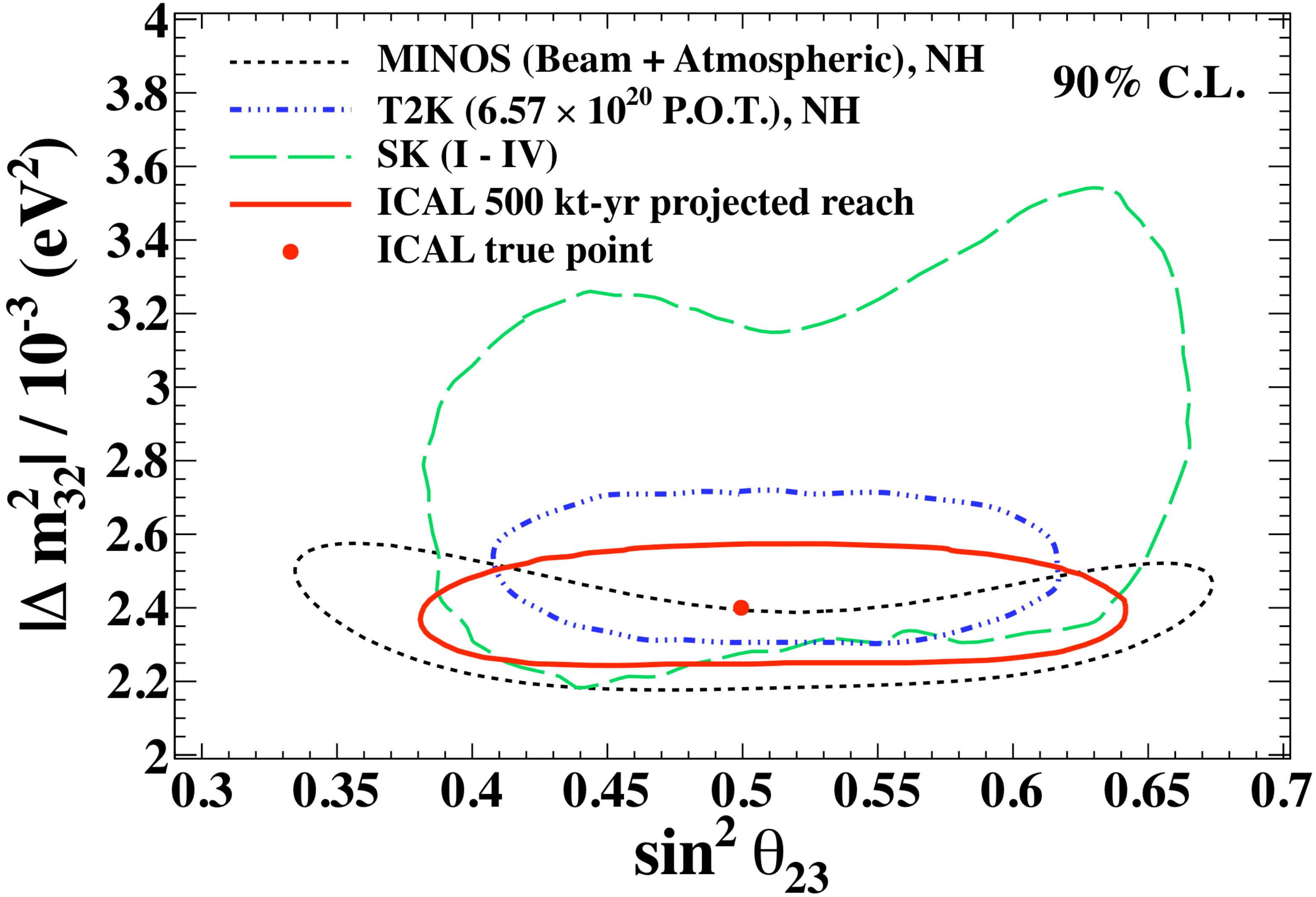
Relative 1σ precision: 12%

Relative 1σ precision: 2.9%

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Significant improvement in the precision measurement of atmospheric mass splitting by adding hadron energy information with muon momentum

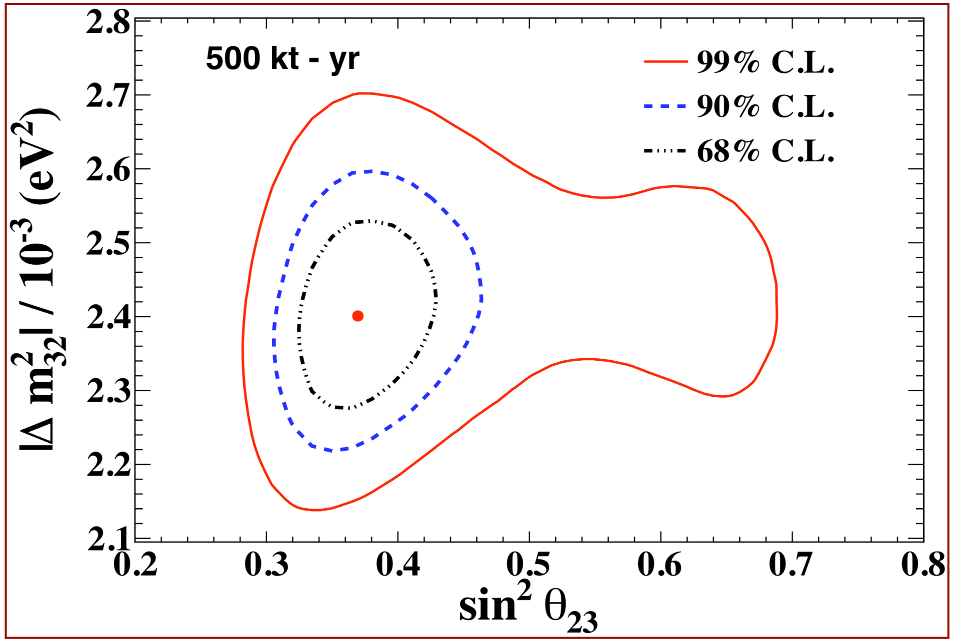
Precision Measurement of Atmospheric Parameters

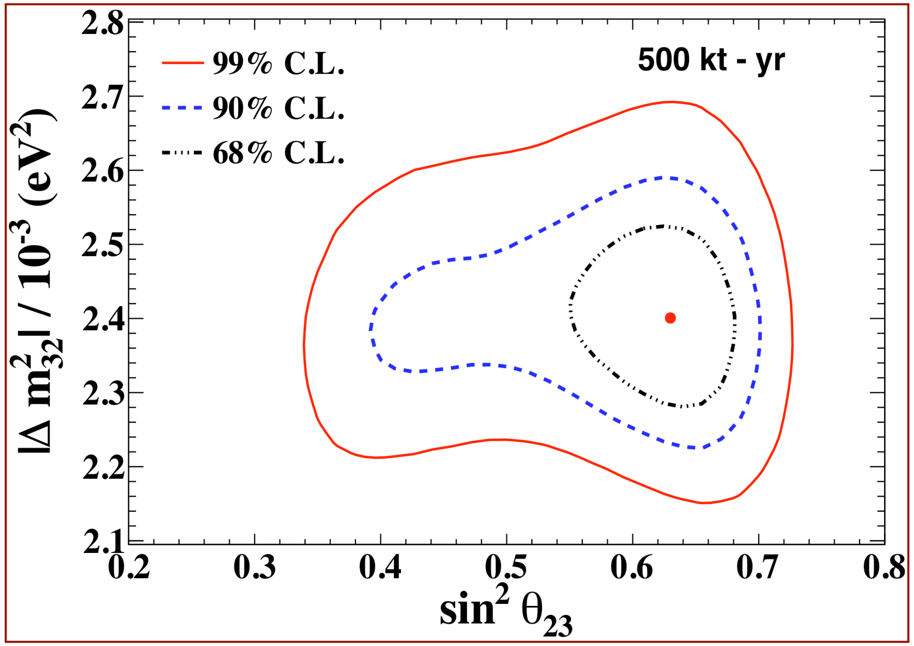


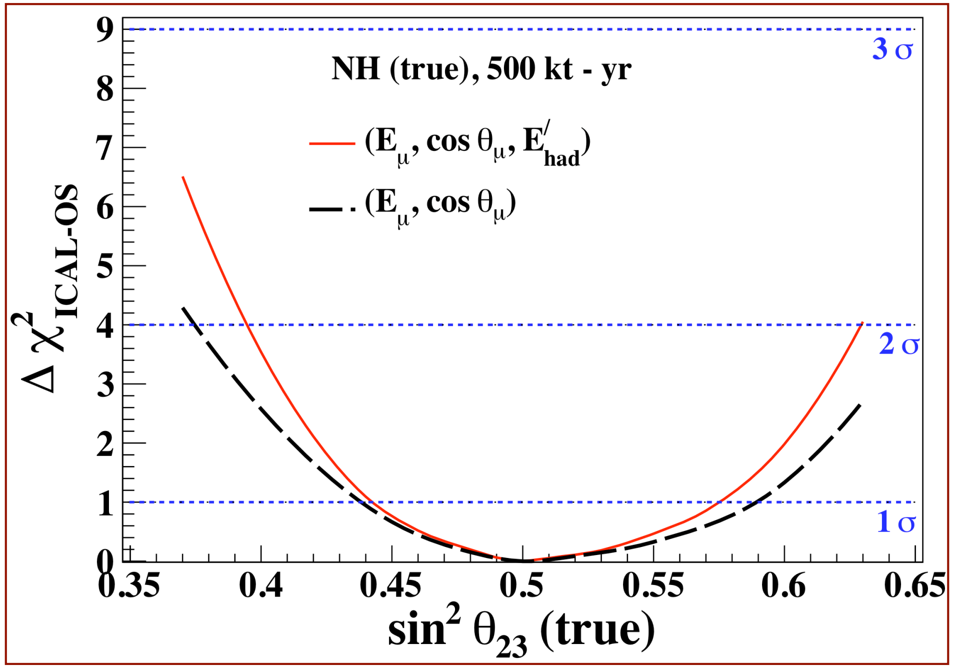
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

ICAL's expected precision on atmospheric mass splitting is far superior than SK

Octant of θ_{23} with ICAL-INO



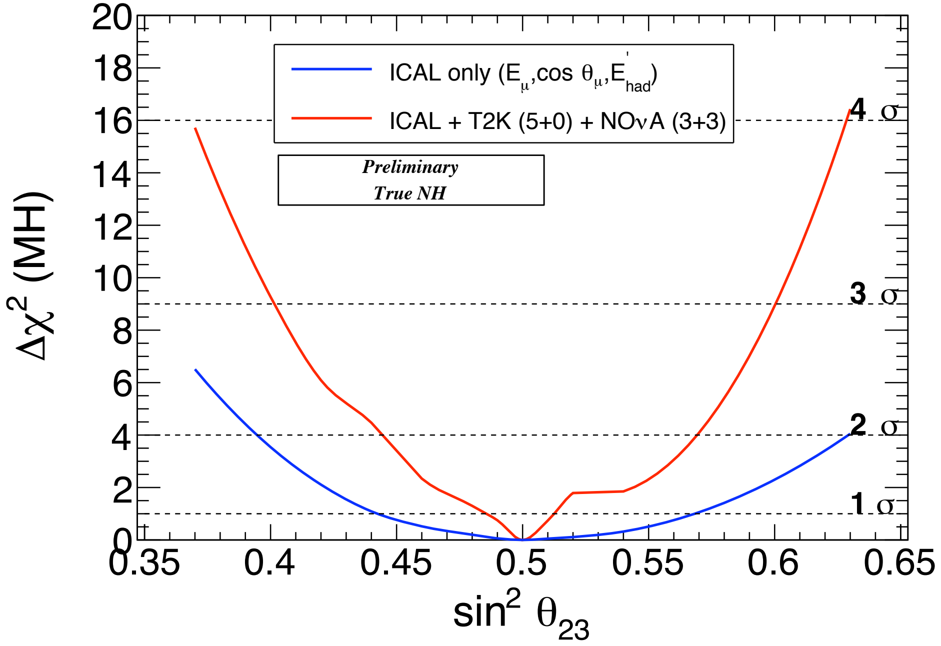


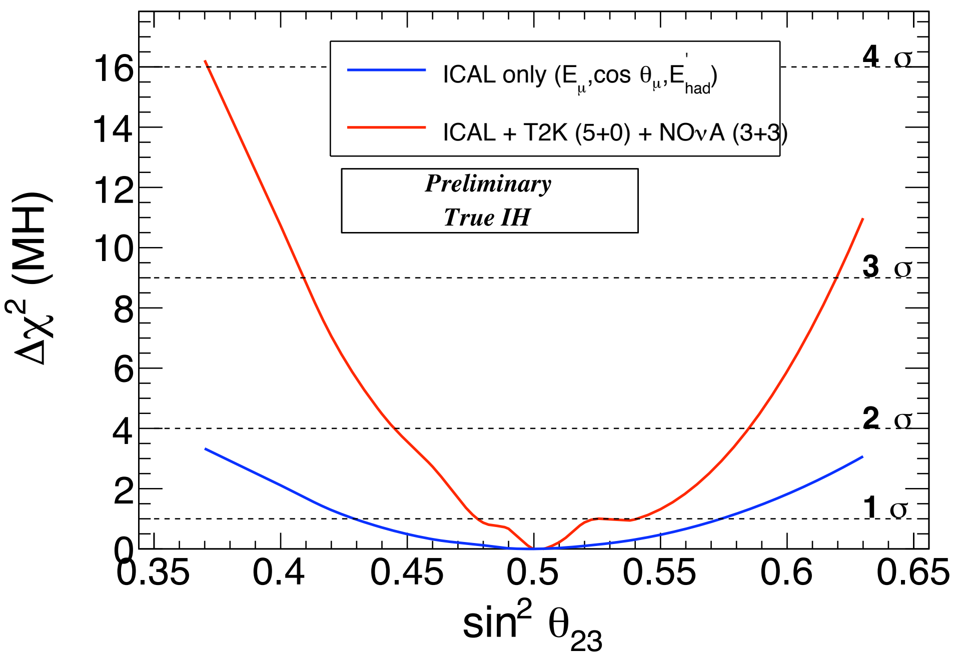


Median 2σ discovery of θ_{23} octant is possible if θ_{23} is sufficiently away from maximal value

Devi, Thakore, Agarwalla, Dighe, arXiv: 1406.3689
(INO Collaboration)

Octant of θ_{23} with ICAL+T2K+NOvA





Devi, Thakore, Agarwalla, work in progress (INO Collaboration)

Concluding Remarks

Present generation long-baseline experiments T2K and NOvA will play a crucial role in projecting the physics sensitivity of ICAL atmospheric experiment

ICAL's MH discovery reach can be enhanced significantly adding the data from projected data T2K and NOvA

Important synergy exists between atmospheric and long-baseline data

3σ median discovery reach for MH with ICAL + T2K + NOvA in 6 years

Can we increase the detector mass of ICAL to achieve the goal faster?

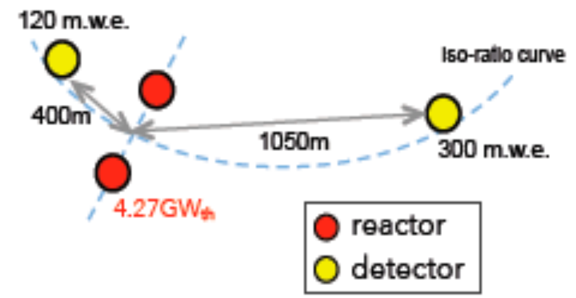
Can we go for 100 kt detector mass?

International participation can be quite helpful

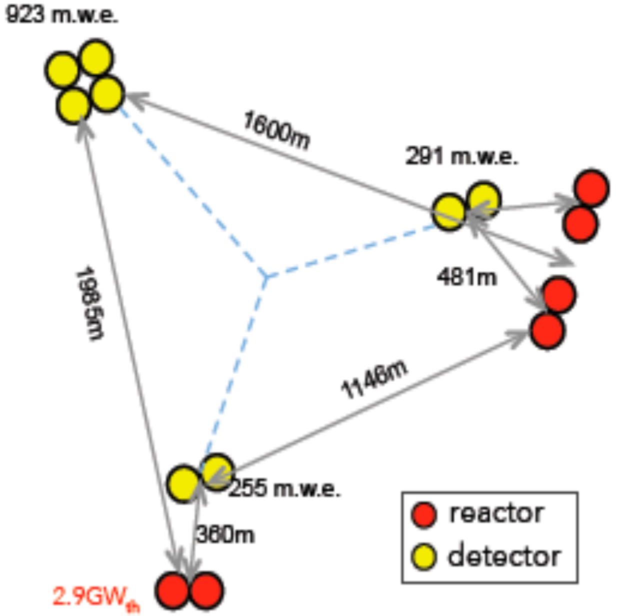
Now, we need to think on this seriously

Backup Slides: Currently Running Reactor θ_{13} Experiments

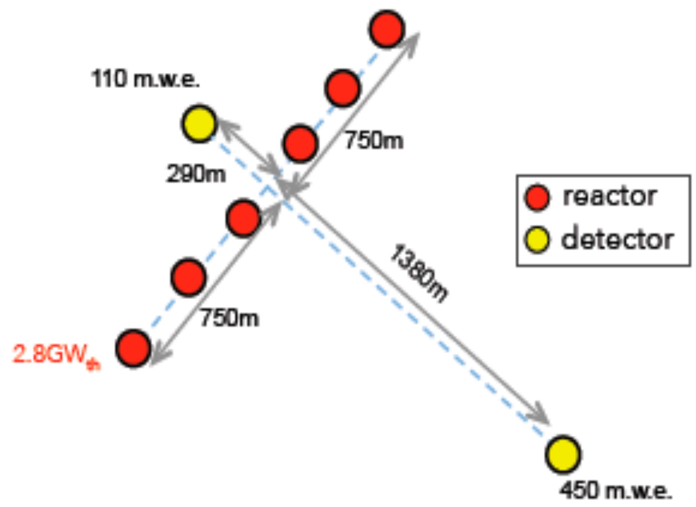
Double Chooz (France)



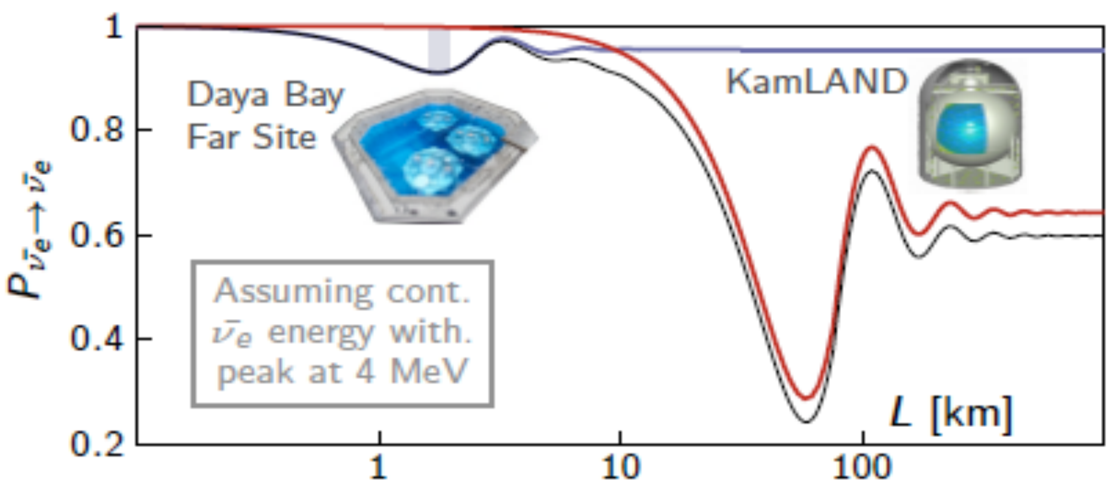
Daya Bay (China)

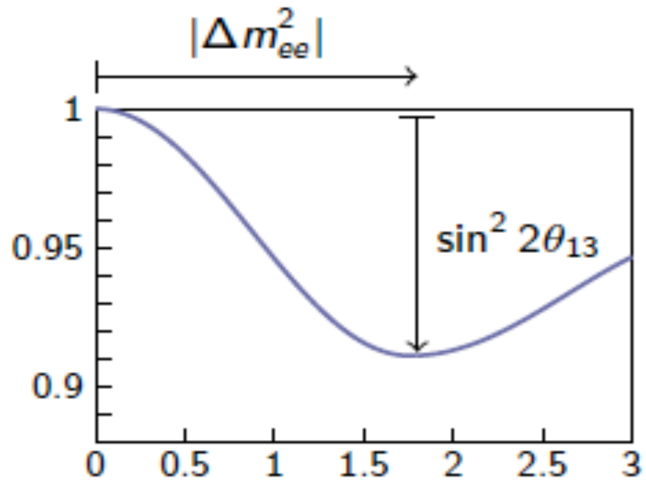


RENO (Korea)



Backup Slides: Short Baseline Reactor Neutrino Oscillation





θ_{13} measured by seeing the deficit of reactor anti-neutrinos at ~ 2 km

θ_{13} governs overall size of electron anti-neutrino deficit

Effective mass-squared difference $|\Delta m^2_{ee}|$ determines deficit dependence on L/E

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

Short Baseline   Long Baseline

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \mathrm{eV}^2$$

+: Normal Hierarchy
−: Inverted Hierarchy

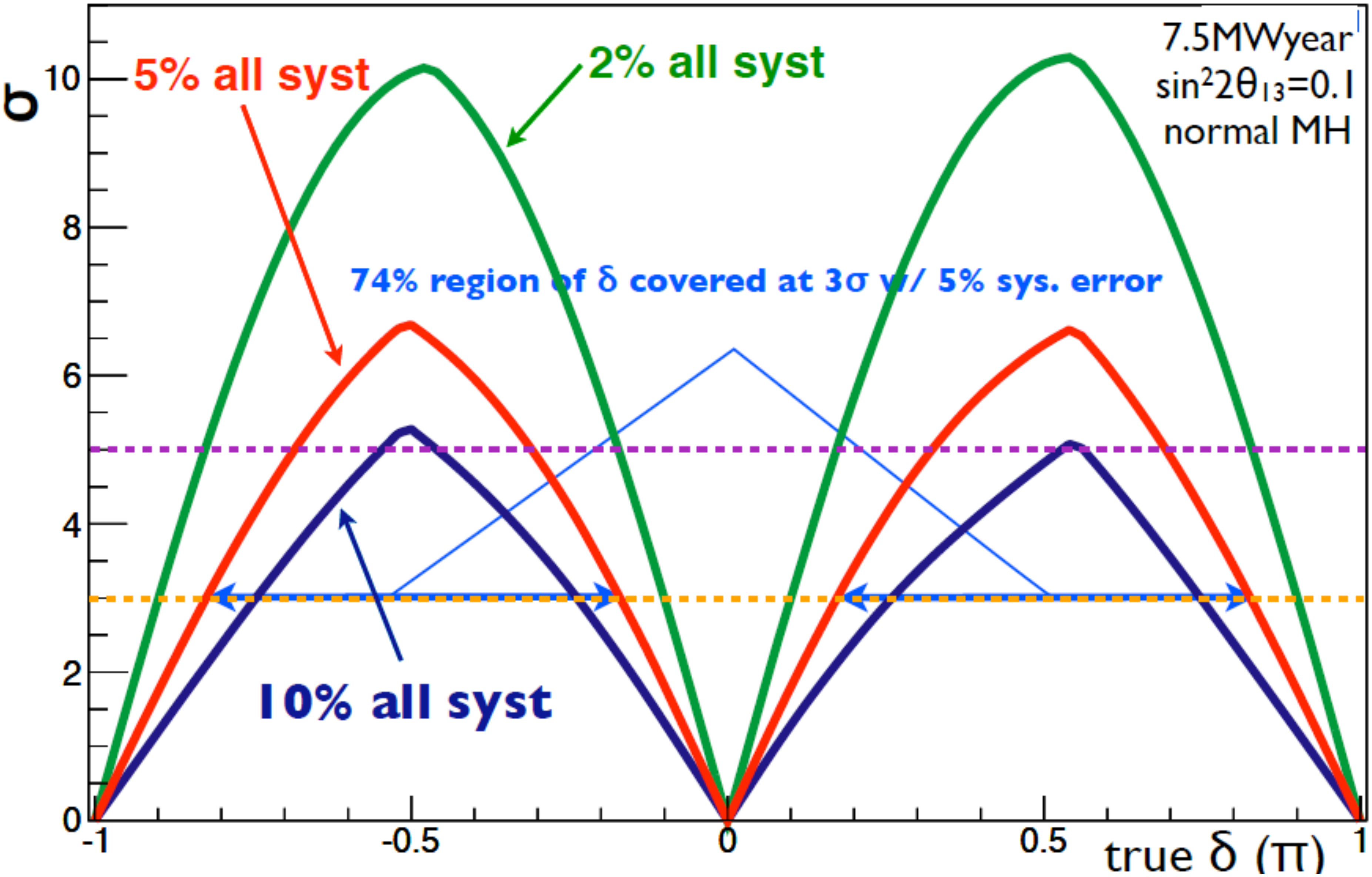
Hierarchy discrimination requires ~ 2% precision on both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$

Backup Slides: Key Features of three Reactor Experiments

Experiment	Double Chooz	Daya Bay	RENO
# of reactors (total power)	2 (9.4 GW)	3 (17.4 GW)	6 (16.8 GW)
Reactor configuration	2	3	6 inline
Detector configuration	1 near + 1 far	2 near + 1 far	1 near + 1 far
Baseline [m]	(400, 1050)	(364, 480, 1912)	(290, 1380)
Overburden [m.w.e.]	(120, 300)	(280, 300, 880)	(120, 450)
Target mass [ton]	(8.3, 8.3)	(40, 40, 80)	(16, 16)
Detector geometry	Cylindrical detector (Gd-LS, γ-catcher, buffer)		
Outer shield	0.5m of LS & 0.15 m of steel	2.5m water	1.5m of water
Muon veto system	LS & Scinti-Strip	Water Cerenkov & RPC	Water Cerenkov
Designed sensitivity (90% C.L.)	~0.03	~0.01	~0.02

Daya Bay Strategy: Go strong, big and deep!

Backup Slides: CPV Discovery in T2HK Setup (w/ MH known)



Hyper-Kamiokande, Letter of Intent, arXiv:1109.3262 [hep-ex]

Present Understanding of the 2-3 Mixing Angle

Information on θ_{23} comes from: a) atmospheric neutrinos and b) accelerator neutrinos

In two-flavor scenario: $$P_{\mu\mu} = 1 - \sin^2 2\theta_{\text{eff}} \sin^2\left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right)$$

For accelerator neutrinos: relate effective 2-flavor parameters with 3-flavor parameters:

$$\Delta m^2_{\text{eff}} = \Delta m^2_{31} - \Delta m^2_{21}(\cos^2\theta_{12} - \cos\delta_{\text{CP}}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23})$$

$$\sin^2 2\theta_{\text{eff}} = 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)$$ where $$\frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} = \tan^2\theta_{23}$$

Nunokawa etal, hep-ph/0503283; A. de Gouvea etal, hep-ph/0503079

Combining beam and atmospheric data in MINOS, we have:

MINOS Collaboration: arXiv:1304.6335v2 [hep-ex]

$$\sin^2 2\theta_{\text{eff}} = 0.95^{+0.035}_{-0.036}\ (10.71 \times 10^{21}\ \text{p.o.t})$$

$$\sin^2 2\bar{\theta}_{\text{eff}} = 0.97^{+0.03}_{-0.08}\ (3.36 \times 10^{21}\ \text{p.o.t})$$

Atmospheric data, dominated by Super-Kamiokande, still prefers maximal value of $\sin^2 2\theta_{\text{eff}} = 1$ (≥ 0.94 (90% C.L.))

Talk by Y. Itow in Neutrino 2012 conference, Kyoto, Japan

Bounds on θ_{23} from the global fits

In ν_μ survival probability, the dominant term mainly sensitive to $\sin^2 2\theta_{23}$

If $\sin^2 2\theta_{23}$ differs from 1 (as indicated by recent data), we get two solutions for θ_{23}:

one in lower octant (LO: $\theta_{23} < 45$ degree), other in higher octant (HO: $\theta_{23} > 45$ degree)

In other words, if ($0.5 - \sin^2\theta_{23}$) is +ve (-ve) then θ_{23} belongs to LO (HO)

This is known as the octant ambiguity of θ_{23}

Fogli and Lisi, hep-ph/9604415

Conferences	After Neutrino 2012	After NeuTel 2013	After TAUP 2013
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.437^{+0.061}_{-0.031}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$
3σ range	$0.34 \to 0.67$	$0.357 \to 0.654$	$0.366 \to 0.663$
1σ precision (relative)	13.4%	11.3%	11.1%

Based on Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

Global fit disfavors maximal 2-3 mixing at 1.4σ confidence level (mostly driven by MINOS)

ν_μ to ν_e oscillation data can break this degeneracy

The preferred value would depend on the choice of the neutrino mass hierarchy