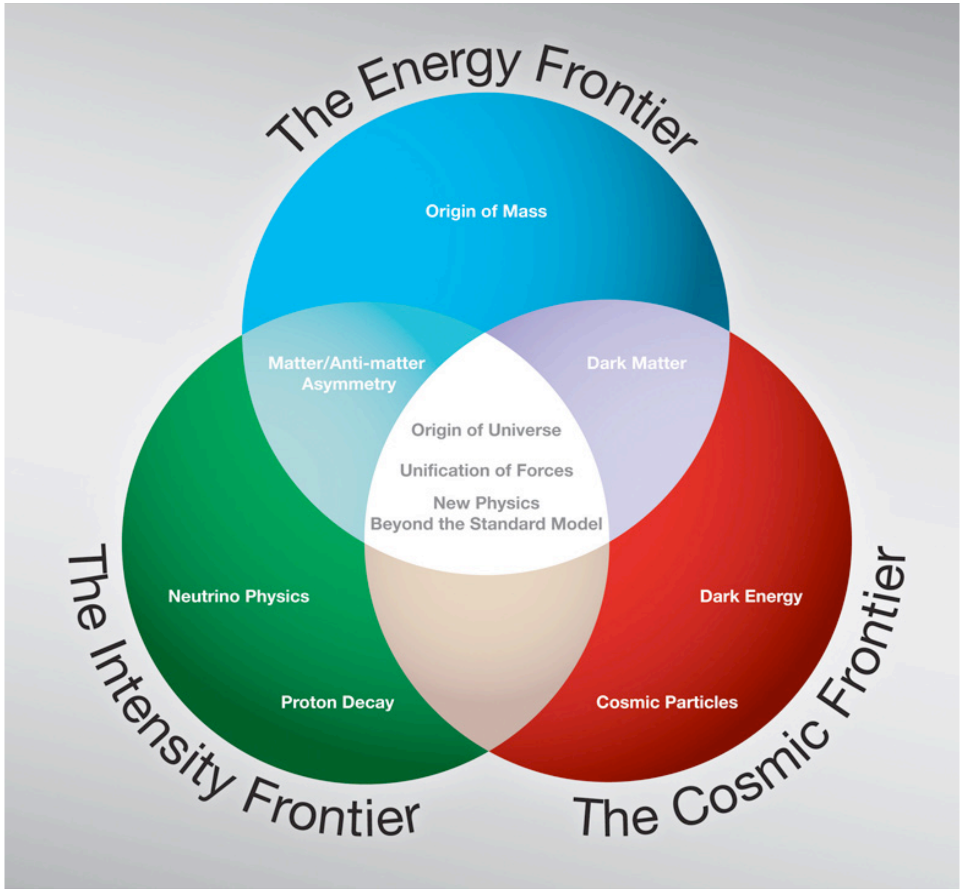
Overview of Currently Running Reactor and Accelerator Experiments

Sanjib Kumar Agarwalla

sanjib@iopb.res.in

Institute of Physics, Bhubaneswar, India

Big News in Neutrino Sector: Discovery of θ_{13}



Global Neutrino Meeting important

Exciting results from all the three frontiers

The Energy Frontier:
Discovery of Higgs at LHC

The Intensity Frontier:
Discovery of θ_{13}

The Cosmic Frontier:
High Precision Planck measurements

BICEP2 detected B-mode polarization
Smoking gun evidence for Inflation

Intensity Frontier: Neutrino properties: A window to our Universe and New Physics

Discovery of moderately large value of θ_{13} has crucial consequences for future theoretical and experimental efforts

Non-zero θ_{13} is the gateway to discover leptonic CP violation & to measure δ_{CP}

Neutrino Physics: An Exercise in Patience

Three most fundamental questions were being asked in the past century…

1. How small is the neutrino mass? (Pauli, Fermi, '30s)

Planck + BAO + WMAP polarization data: upper limit of 0.23 eV for the sum of ν masses!

Planck Collaboration, arXiv:1303.5076 [astro-ph.CO]

2. Can a neutrino be its own antiparticle? (Majorana, '30s)

Hunt for ν-less Double-β decay (Z,A → Z+2, A) is still on, demands lepton number violation!

Nice Review by Avignone, Elliott, Engel, Rev.Mod.Phys. 80 (2008) 481-516

3. Do different ν flavors 'oscillate' into one another? (Pontecorvo, Maki-Nakagawa-Sakata, '60s)

B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968) [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)]

Last question positively answered only in recent years. Now an established fact that **neutrinos are massive** and leptonic flavors are not **symmetries of Nature**!

Recent measurement of $\boldsymbol{\theta_{13}}$, a clear first order picture of the 3-flavor lepton mixing matrix has emerged, signifies a major breakthrough in ν physics!

This year marks the 60th anniversary since ν detector of Reines & Cowan was turned on

Neutrino Oscillations in 3 Flavors

It happens because flavor (weak) eigenstates do not coincide with mass eigenstates

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} : $P(\nu_\mu \to \nu_\mu)$ by Atoms. ν and ν beam

θ_{13}: $P(\nu_e \to \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \to \nu_e)$ by Reactor and solar ν

Three mixing angles: θ_{23} , θ_{13} , θ_{12} and one CP violating (Dirac) phase δ_{CP}

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \qquad \tan^2\theta_{23} \equiv \frac{|U_{\mu3}|^2}{|U_{\tau3}|^2}; \qquad U_{e3} \equiv \sin\theta_{13}e^{-i\delta}$$

3 mixing angles simply related to flavor components of 3 mass eigenstates

Over a distance L, changes in the relative phases of the mass states may induce flavor change!

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij},$$

$$\Delta_{ij} = \Delta m^2_{ij}L/4E_\nu$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

2 independent mass splittings Δm^2_{21} and Δm^2_{32}, for anti-neutrinos replace δ_{CP} by -δ_{CP}

Present Status of Neutrino Oscillation Parameters

	bfp $\pm 1\sigma$	3σ range	Relative 1σ Precision
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	4%
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$	
$\sin^2\theta_{23}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$	$0.366 \to 0.663$	11%
$\theta_{23}/^\circ$	$41.9^{+0.4}_{-0.4} \oplus 50.0^{+1.9}_{-2.2}$	$37.2 \to 54.5$	
$\sin^2\theta_{13}$	$0.0229^{+0.0020}_{-0.0019}$	$0.0170 \to 0.0288$	8.7%
$\theta_{13}/^\circ$	$8.71^{+0.37}_{-0.38}$	$7.50 \to 9.78$	
$\delta_{CP}/^\circ$	265^{+56}_{-61}	$0 \to 360$	(Not Known)
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	2.4%
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.013}_{-0.013}$	$+2.247 \to +2.623$	2.5%
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.062}$	$-2.602 \to -2.226$	

Non-maximal $> 1.4\sigma$

Non-zero $> 10\sigma$

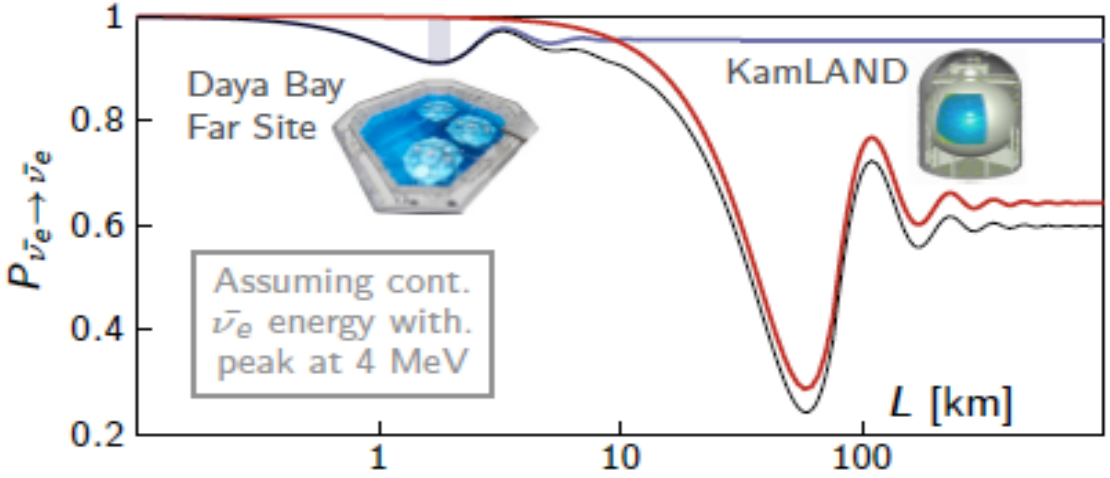
$\sin\delta_{CP} < 0$ at 90% C.L.

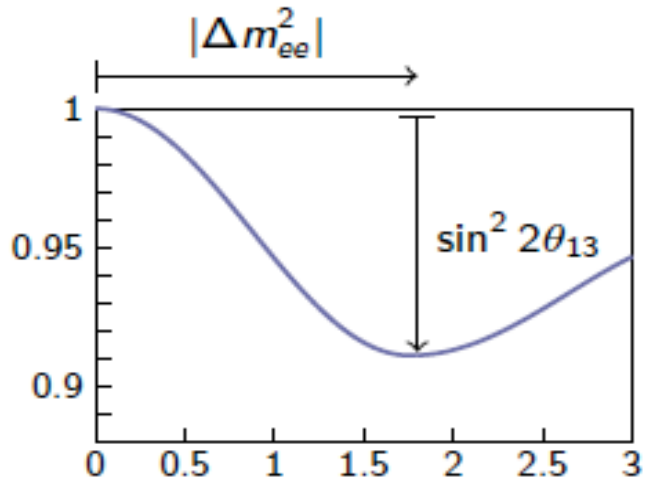
See the talk by E. Lisi

Based on the data available after TAUP 2013 conference

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

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

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

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

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

+: Normal Hierarchy
−: Inverted Hierarchy

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

Crucial Issues in Reactor Experiment and Possible Solutions

Problem: Statistics

Solution: Powerful Reactors (17.6 GW_{th}) and
Large Detectors (80 ton at Far Site)

Problem: Reactor-related uncertainty

Solution: Far/Near relative measurement

Problem: Detector-related uncertainty

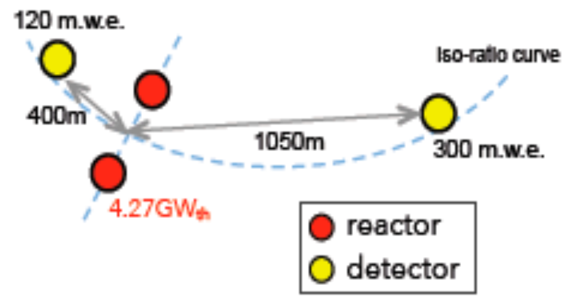
Solution: Multiple functional identical detectors (4 Near + 4 Far)

Problem: Background

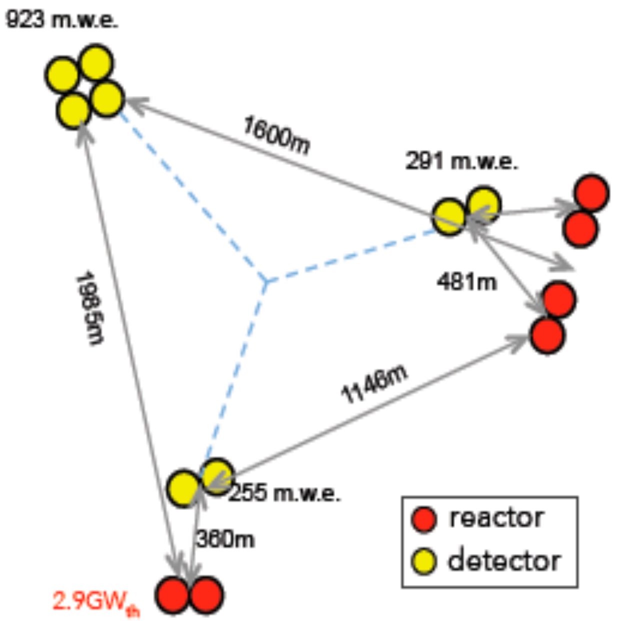
Solution: Deep underground (860 m.w.e at far site)

Currently Running Reactor θ_{13} Experiments

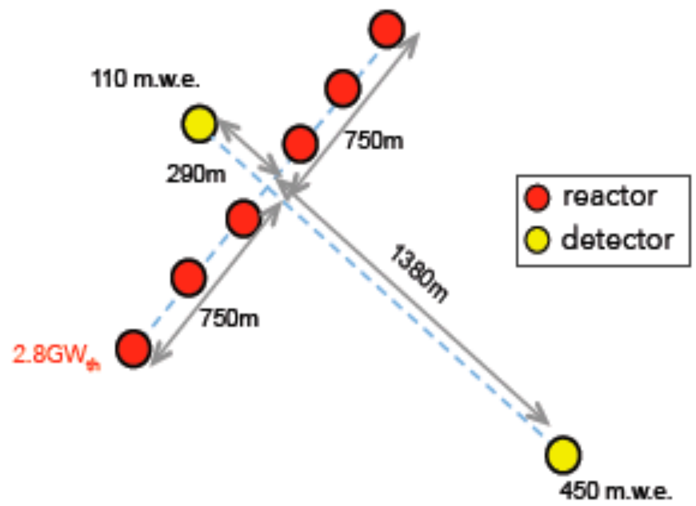
Double Chooz (France)



Daya Bay (China)



RENO (Korea)



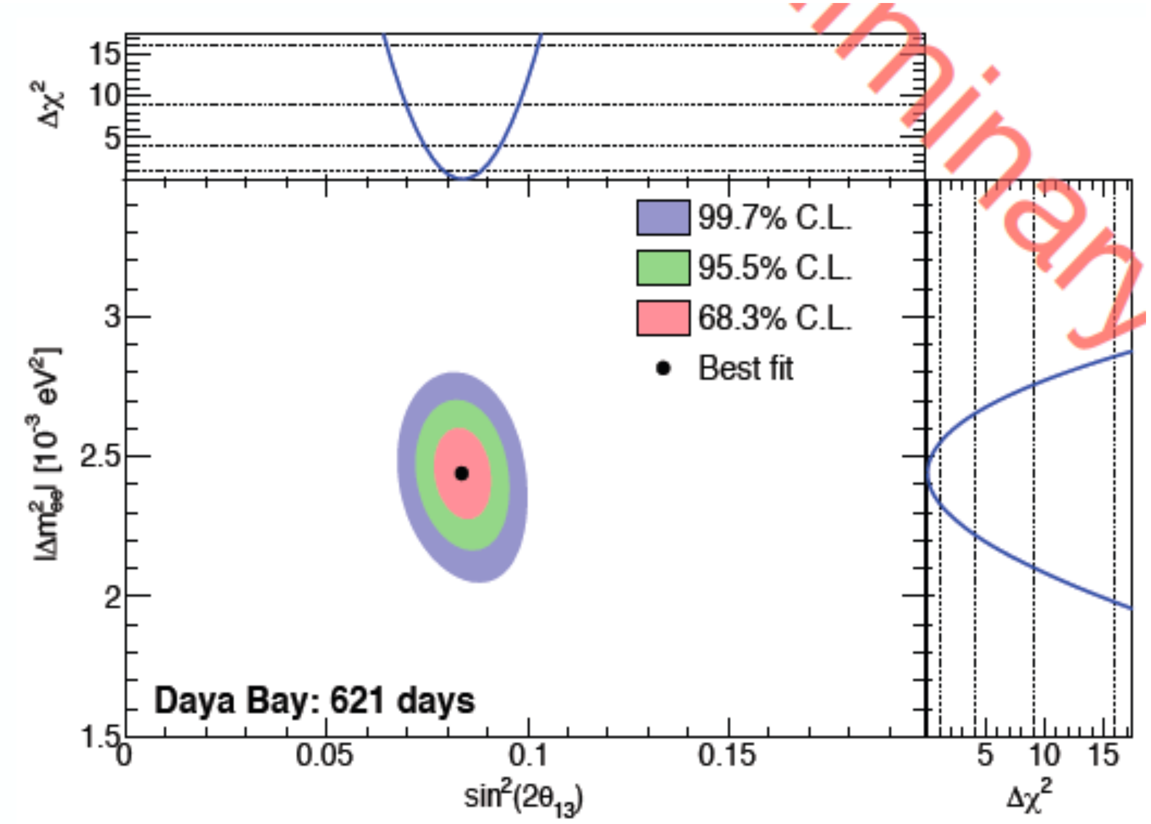
Key Features of three Reactor Experiments

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!

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 $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

Latest Oscillation Results from RENO & Double Chooz

Preliminary Rate-only Results from RENO based on ~ 800 days data set (Neutrino 2014)

$$\sin^2 2\theta_{13} = 0.101 \pm 0.008\ (\text{stat.}) \pm 0.010\ (\text{sys.})$$

7.8σ confirmation of non-zero θ_{13} and 13% precision achieved

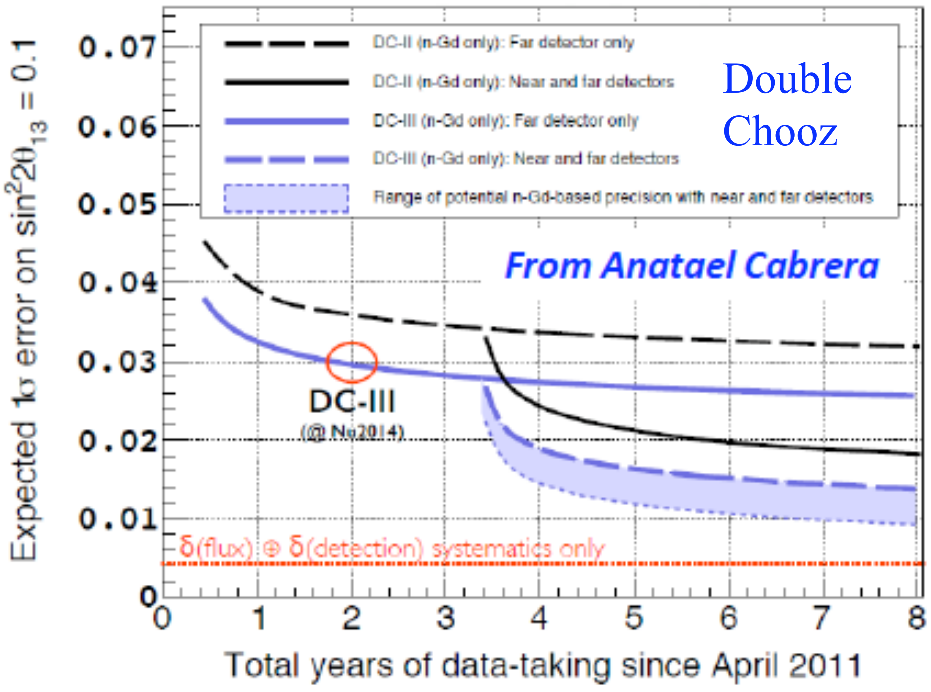
Improved Results from Double Chooz Gd-III with 2 times more statistics (Neutrino 2014)

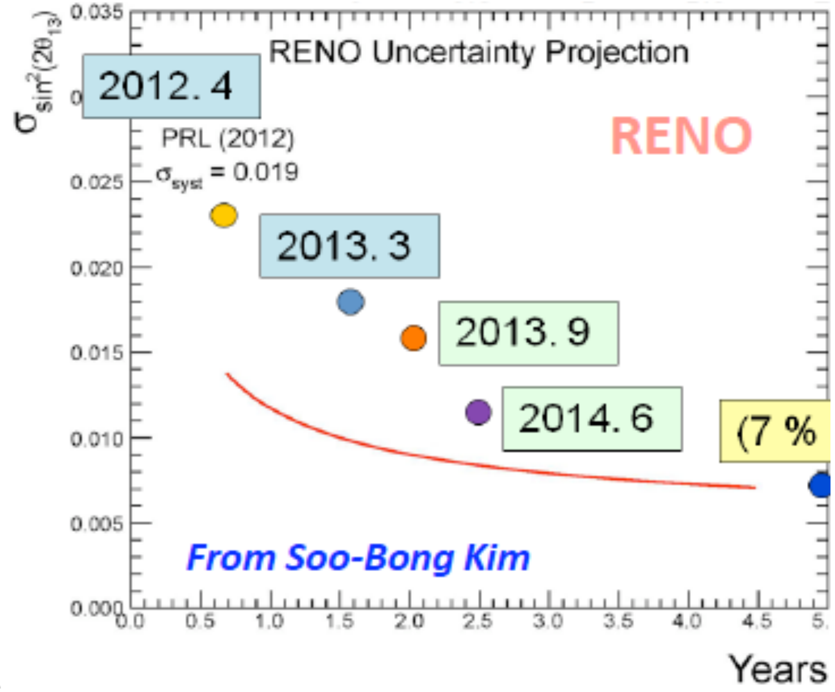
$$\sin^2 2\theta_{13} = 0.09 \pm 0.03\ (\text{Rate+Shape})$$

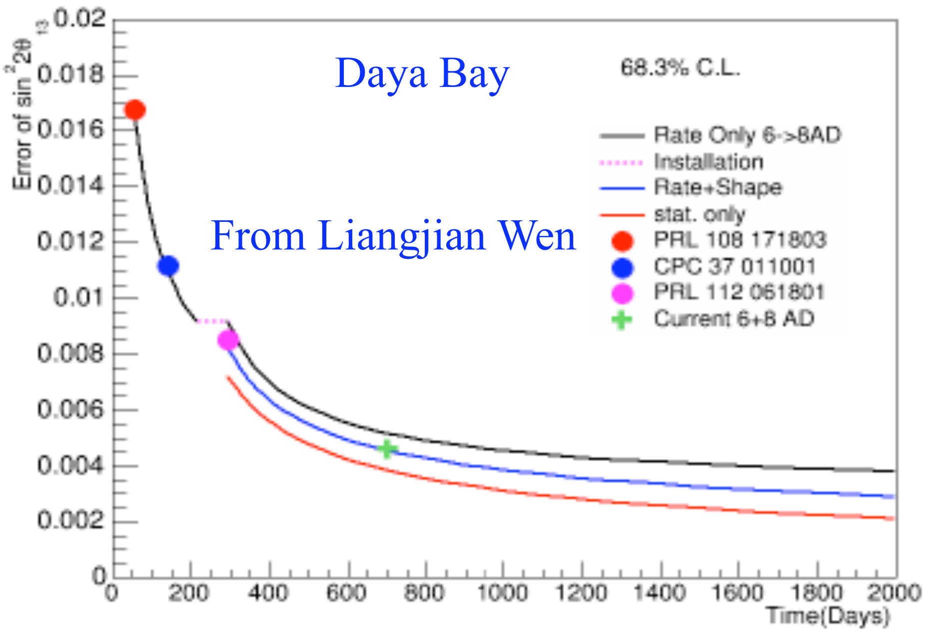
33% precision achieved

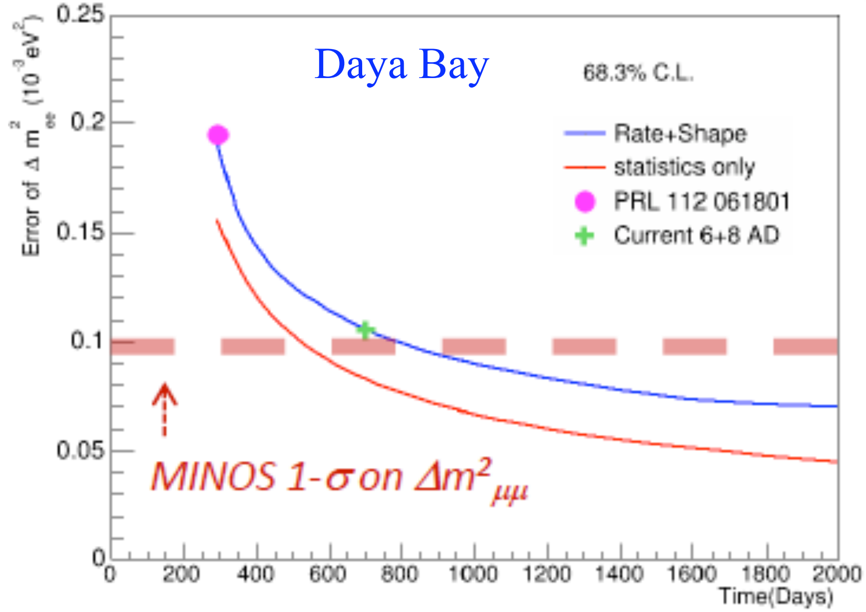
Independent confirmation from all the three reactor experiments is very crucial

Ultimate Precision in Reactor Experiments

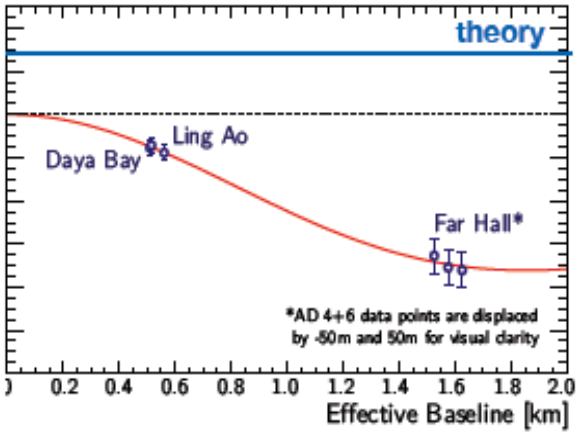


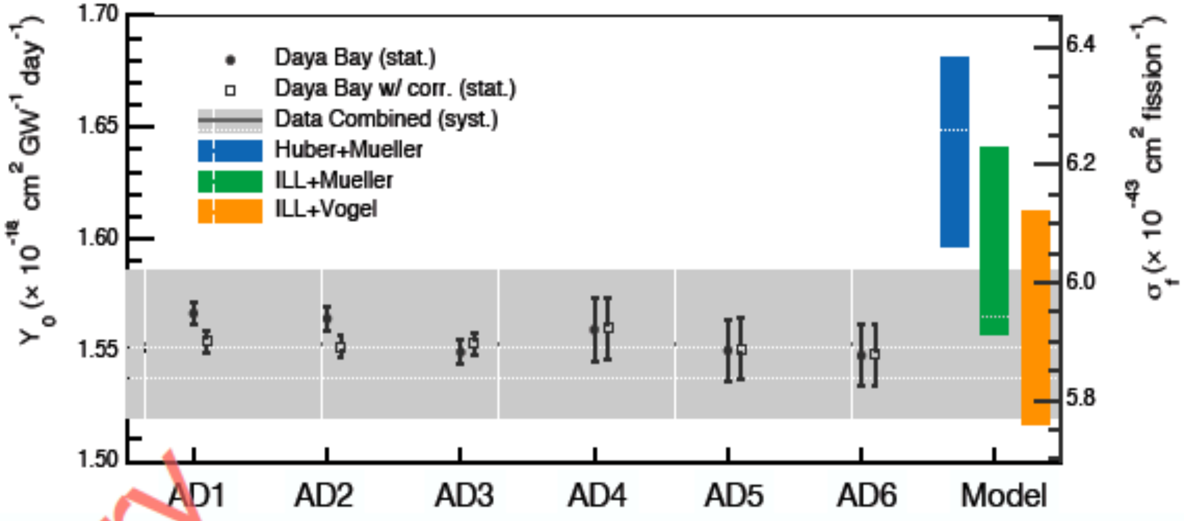






Absolute Reactor Anti-neutrino Flux





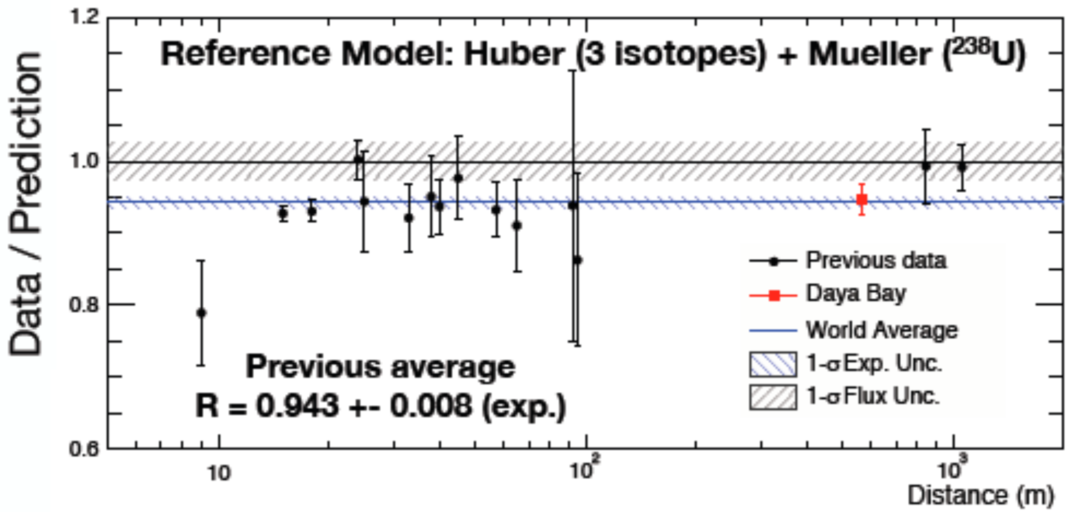
Flux Measurement Uncertainty

	Uncertainty
statistics	0.2%
θ_{13}	0.2%
reactor	0.9%
detector efficiency	2.1%
Total	2.3%

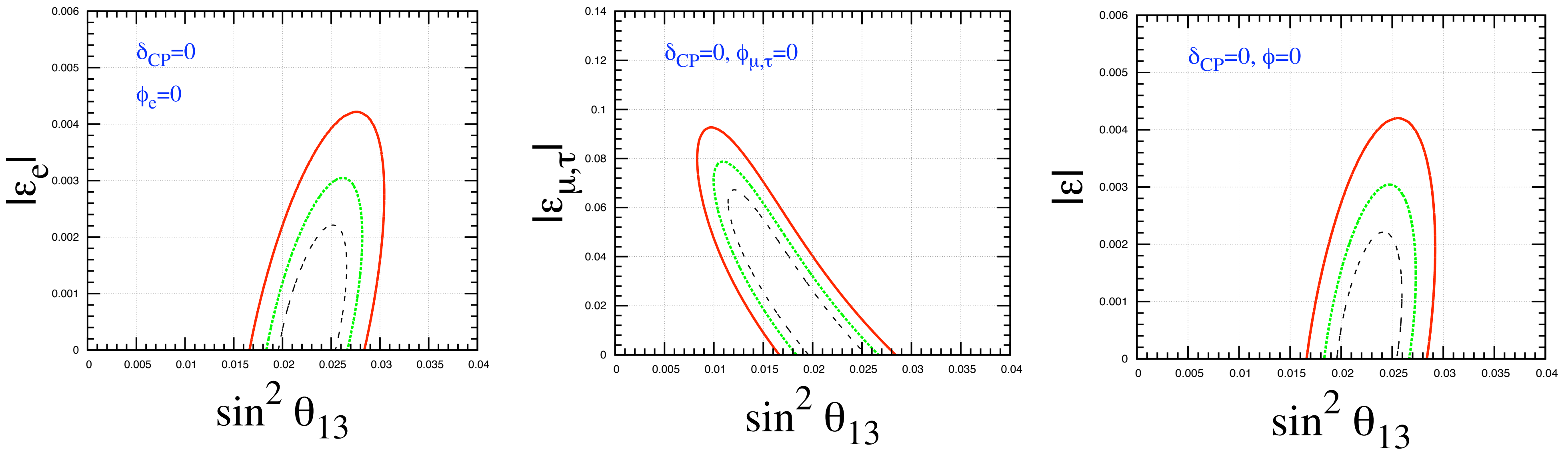
^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu	0.586 : 0.076 : 0.288 : 0.050
Y_0 (cm^2 GW^{-1} day^{-1})	1.553×10^{-18}
σ_f (cm^2 fission^{-1})	5.934×10^{-43}
Data / Prediction (Huber+Mueller)	0.947 ± 0.022
Data / Prediction (ILL+Vogel)	0.992 ± 0.023

preliminary

Daya Bay's reactor flux measurement is consistent with previous short baseline experiments



Probing Non-Standard Interactions at Daya Bay



$$P^{\text{NSI-e}}_{\bar\nu_e^s\to\bar\nu_e^d} \simeq P^{SM}_{\bar\nu_e\to\bar\nu_e} + 4|\varepsilon_e|\cos\phi_e + 4|\varepsilon_e|^2 + 2|\varepsilon_e|^2\cos 2\phi_e$$

$$P^{\text{NSI-}\mu}_{\bar\nu_e^s\to\bar\nu_e^d} \simeq P^{SM}_{\bar\nu_e\to\bar\nu_e} + 2|\varepsilon_\mu|^2 - 4\{s_{23}^2|\varepsilon_\mu|^2 + 2s_{13}s_{23}|\varepsilon_\mu|\cos(\delta-\phi_\mu)\}\sin^2\Delta_{31}$$

$$P^{\text{NSI-}\alpha}_{\bar\nu_e^s\to\bar\nu_e^d} \simeq P^{SM}_{\bar\nu_e\to\bar\nu_e} + 4|\varepsilon|\cos\phi + 2|\varepsilon|^2(4+\cos 2\phi)$$
$$- 4\{|\varepsilon|^2 + 2s_{23}c_{23}|\varepsilon|^2 + 2s_{13}|\varepsilon|\cos(\delta-\phi)(s_{23}+c_{23})\}\sin^2\Delta_{31}$$

NSI at production and detection

Agarwalla, Bagchi, Forero, Tortola, in preparation

See also, Girardi, Meloni, arXiv: 1403.5507v1

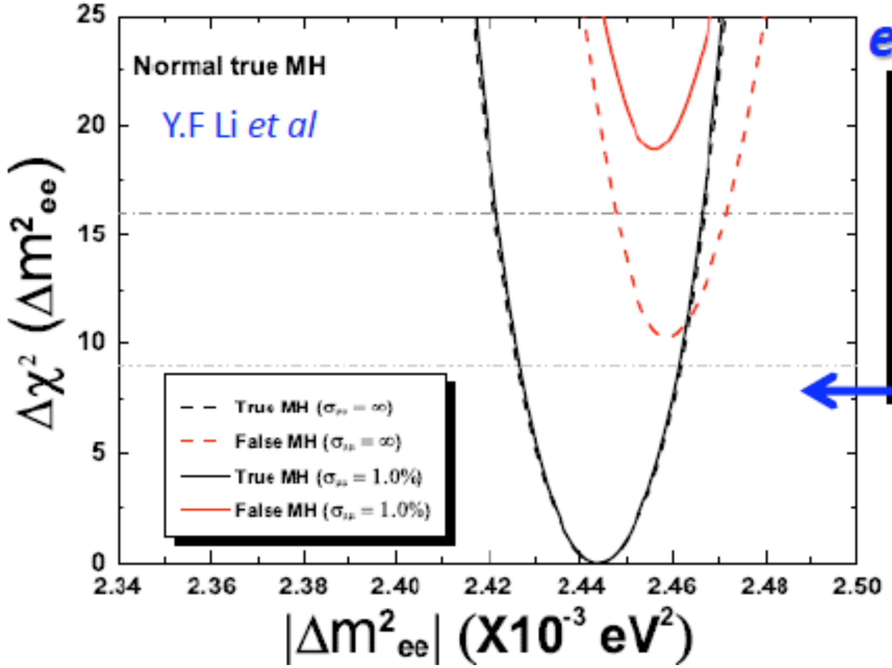
New Constraints on NSI from Daya Bay

phases	$\sin^2\theta_{13}$	ε
electron-type NSI coupling		
$\delta = \phi_e = 0$	$0.019 \leq \sin^2\theta_{13} \leq 0.027$	$\lvert\varepsilon_e\rvert \leq 0.0024$
$\delta = 0,\ \phi_e$ free	$0.019 \leq \sin^2\theta_{13} \leq 0.027$	$\lvert\varepsilon_e\rvert$ unbound
muon-tau type NSI couplings		
$\delta = \phi_{\mu,\tau} = 0$	$0.011 \leq \sin^2\theta_{13} \leq 0.026$	$\lvert\varepsilon_{\mu,\tau}\rvert \leq 0.070$
$(\delta - \phi_{\mu,\tau})$ free	$0.011 \leq \sin^2\theta_{13} \leq 0.045$	$\lvert\varepsilon_{\mu,\tau}\rvert \leq 0.069$
universal NSI couplings		
$\delta = \phi_\alpha = 0$	$0.019 \leq \sin^2\theta_{13} \leq 0.026$	$\lvert\varepsilon\rvert \leq 0.0024$
δ free, $\phi_\alpha = 0$	$0.019 \leq \sin^2\theta_{13} \leq 0.028$	$\lvert\varepsilon\rvert \leq 0.0023$
$\delta = 0,\ \phi_\alpha$ free	$\sin^2\theta_{13} \leq 0.026$	$\lvert\varepsilon\rvert \leq 0.116$
δ and ϕ_α free	$\sin^2\theta_{13} \leq - - -$	$\lvert\varepsilon\rvert \leq - - -$

90% C.L. bounds (1 d.o.f) taking fixed normalization of reactor flux

Agarwalla, Bagchi, Forero, Tortola, in preparation

Medium-baseline Reactor Oscillation Experiments

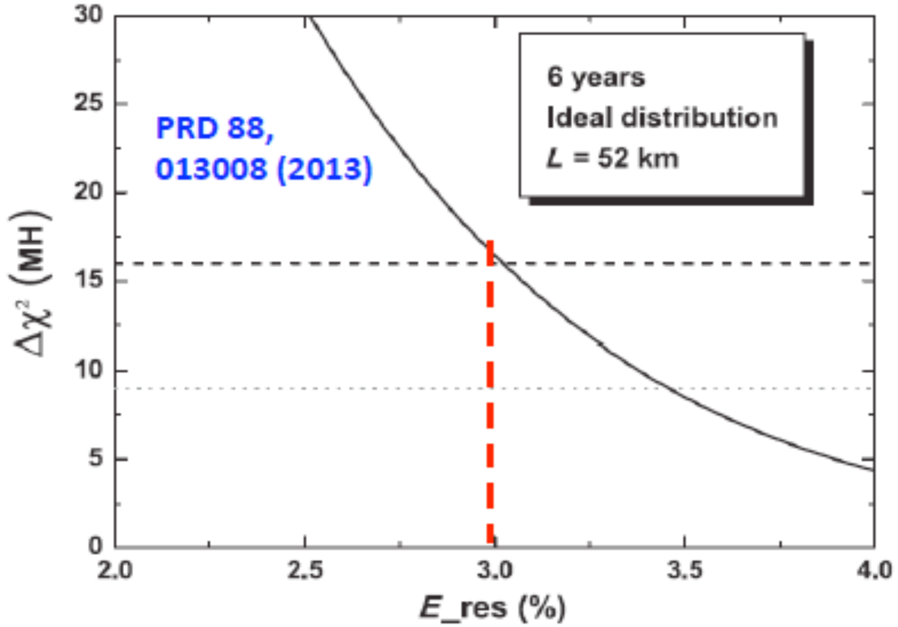


e.g JUNO MH sensitivity with 6 years' data:

Ref: Y.F Li et al, PRD 88, 013008 (2013)	Relative Meas.	[a]Use absolute Δm^2
Ideal case	4σ	5σ
[b]Realistic case	3σ	4σ

[a] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M^2_{\mu\mu}$ to ~1% level

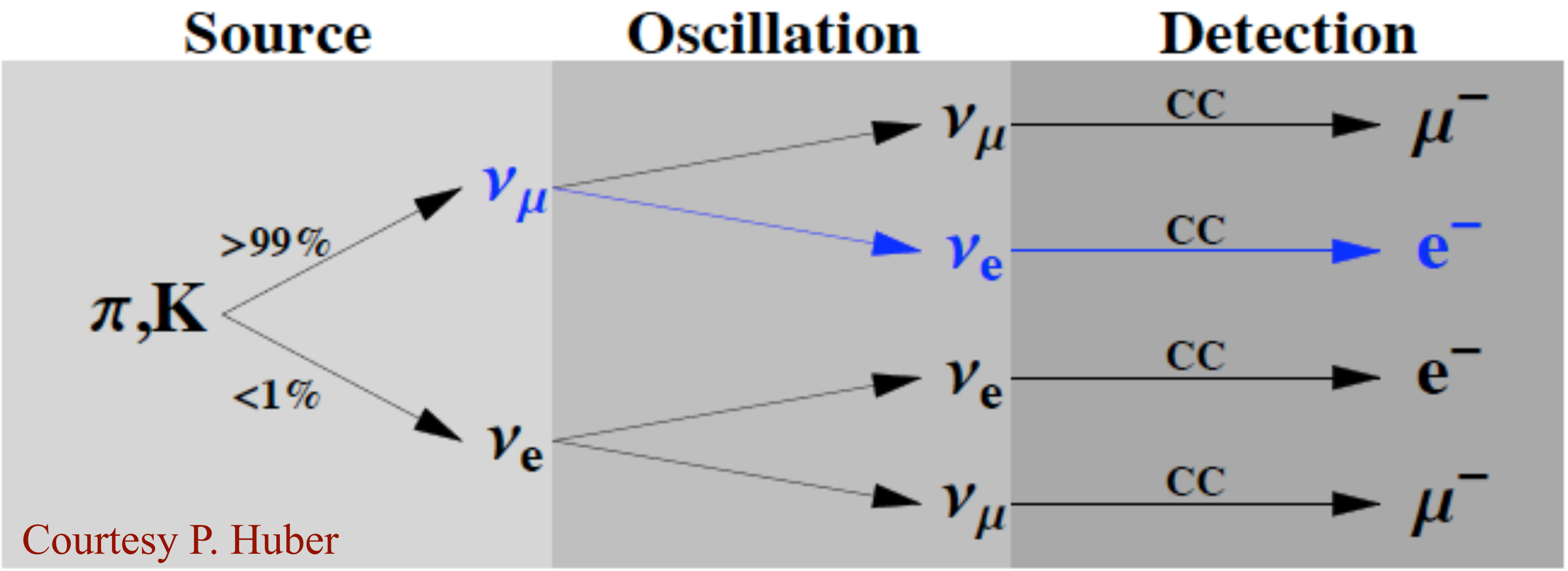
[b] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc



	Current	e.g JUNO
Δm^2_{12}	~3%	~0.5%
Δm^2_{23}	~4%	~0.6%
$\sin^2\theta_{12}$	~7%	~0.7%
$\sin^2\theta_{23}$	~15%	N/A
$\sin^2\theta_{13}$	~6% → ~4%	~ 15%

Courtesy Liangjian Wen, talk at Neutrino 2014

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

0.03 0.3

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

0.09

θ13 Driven

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

Resolves octant

0.009

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

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

0.0009

Solar Term

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

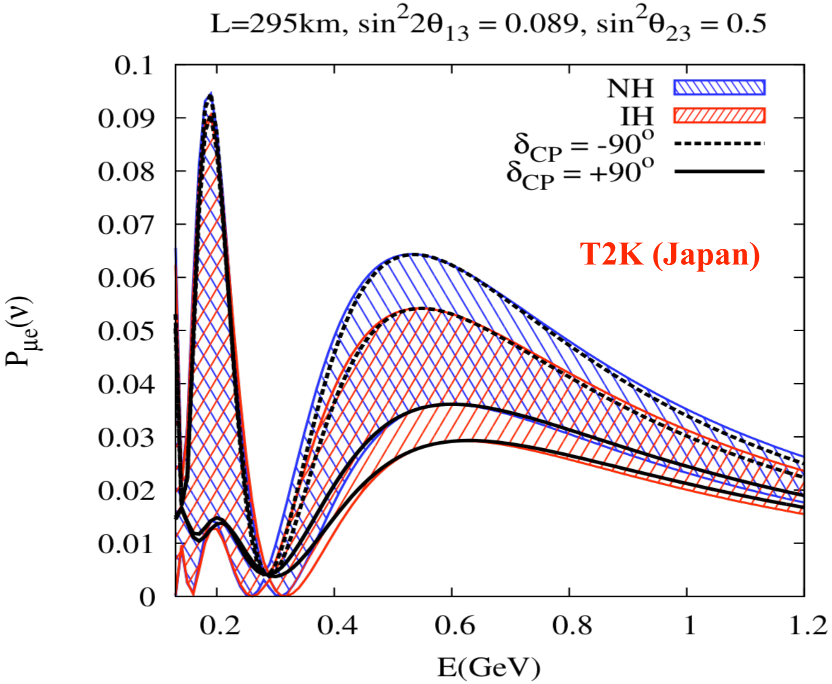
changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!

changes sign with polarity causes fake CP asymmetry!

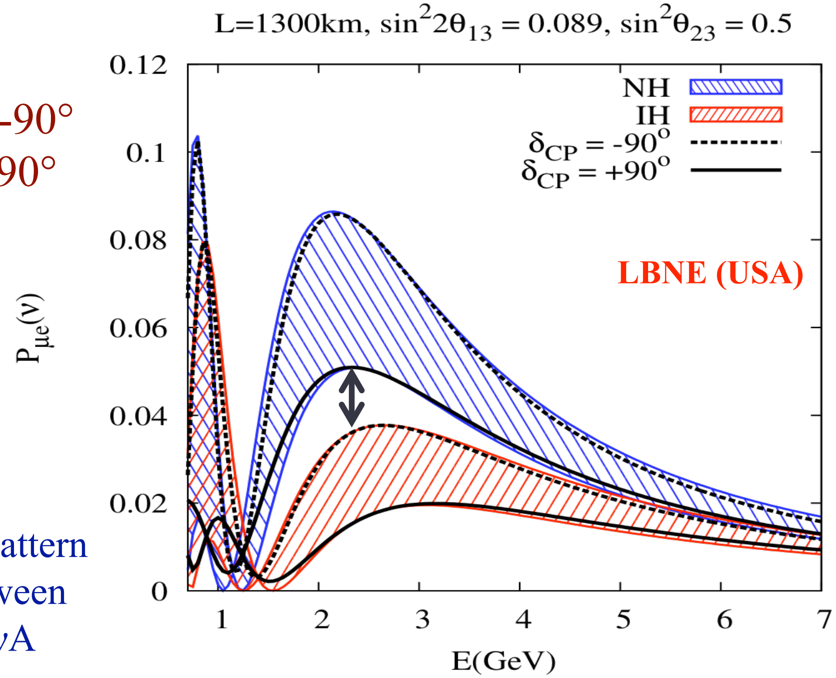
Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

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

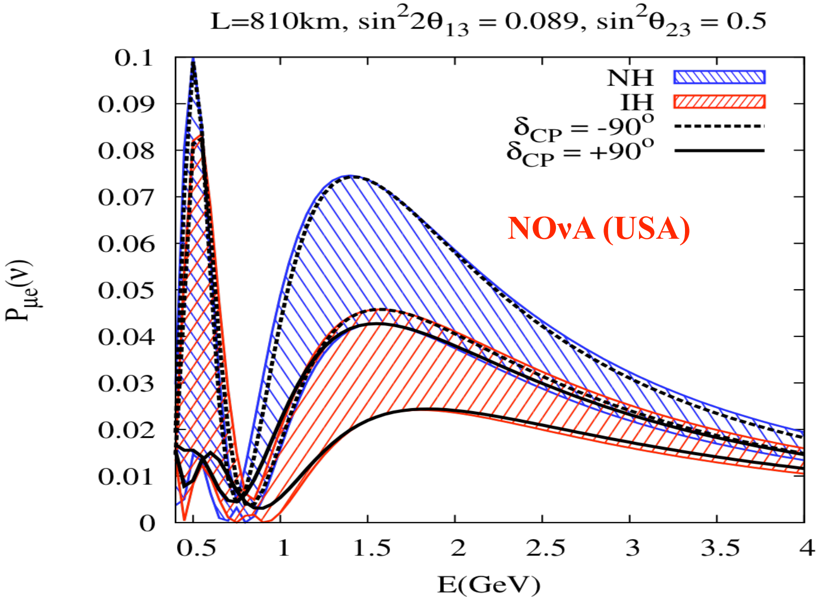
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



For ν:
Max: NH, -90°
Min: IH, 90°

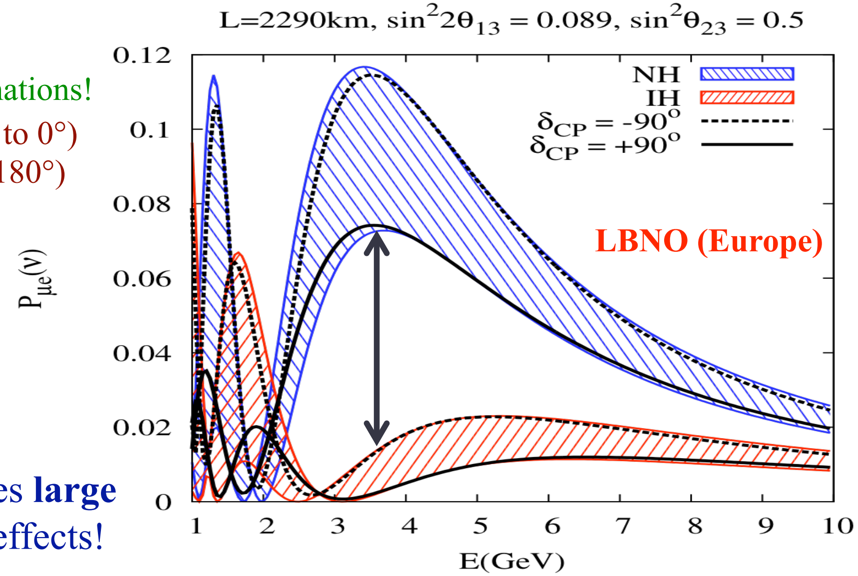


Degeneracy pattern different between T2K & NOνA



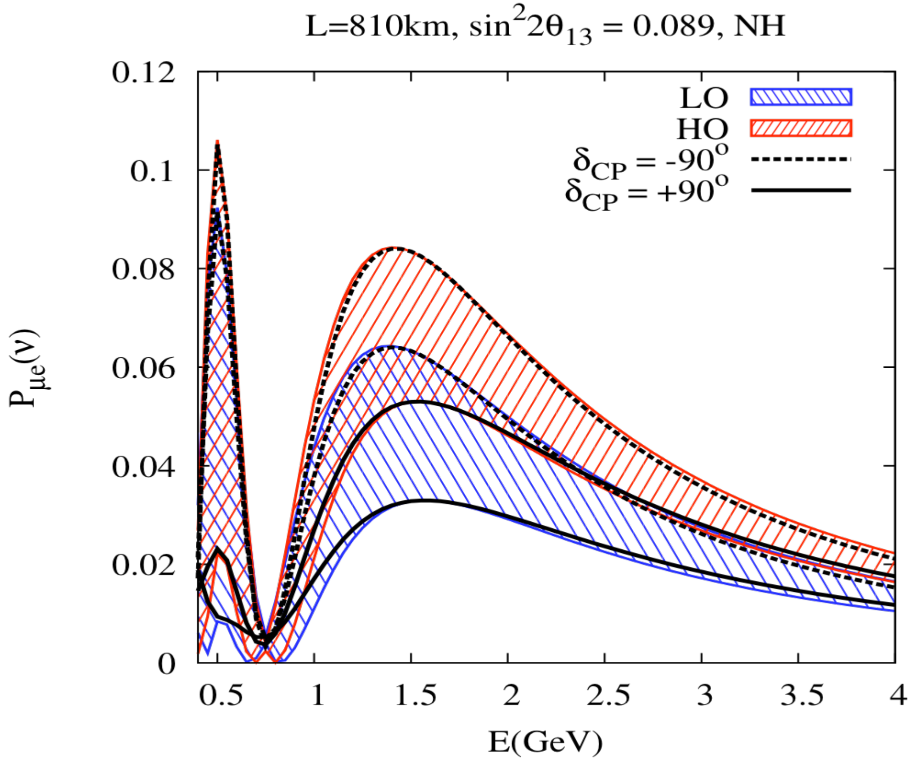
Favorable combinations!
NH, LHP (-180° to 0°)
IH, UHP (0° to 180°)

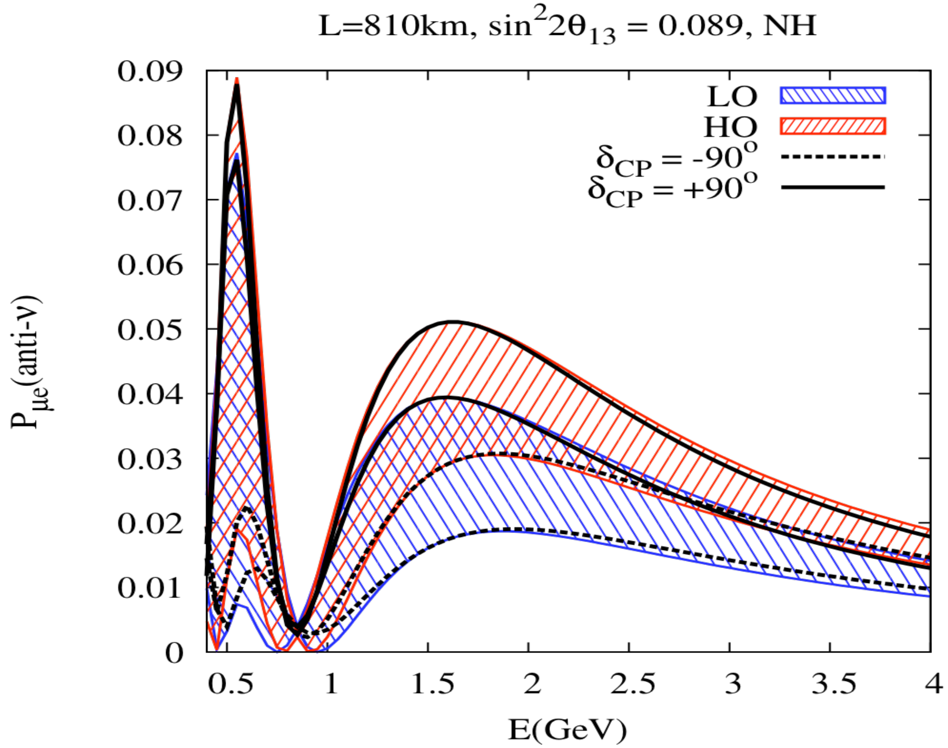
Large θ_{13} causes **large** Earth matter effects!



Agarwalla, Prakash, Raut, Sankar, 2012-2013

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





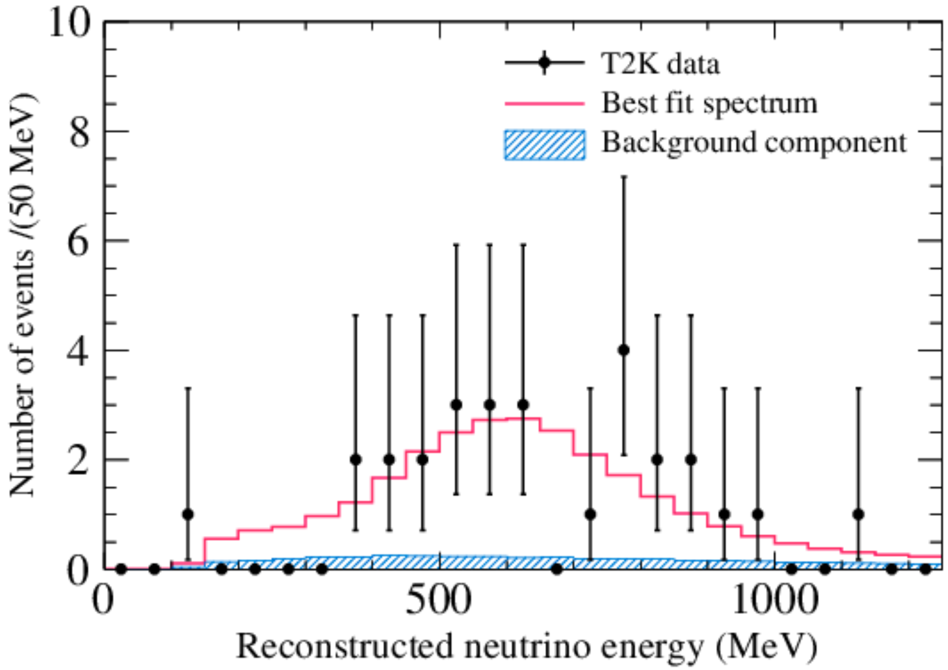
For neutrino:
Maximum: HO, -90°
Minimum: LO, 90°

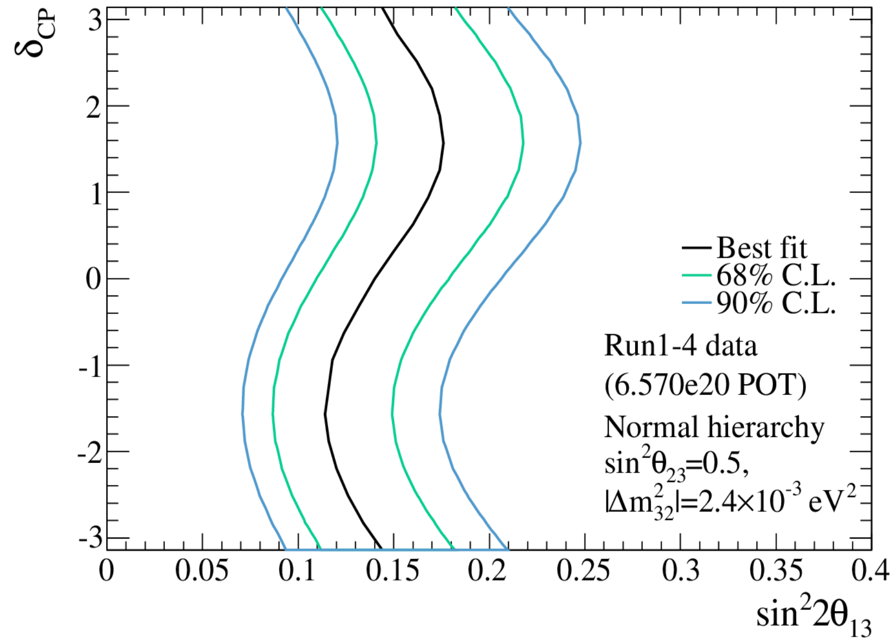
For anti-neutrino:
Maximum: HO, 90°
Minimum: LO, -90°

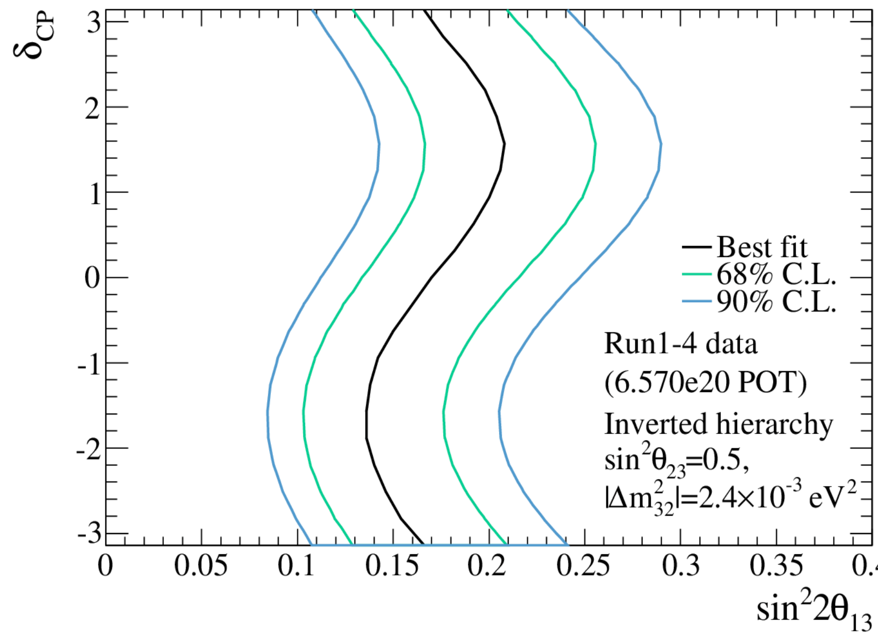
Unfavorable CP values for neutrino are favorable for anti-neutrino & vice-versa

Agarwalla, Prakash, Sankar, arXiv: 1301.2574

T2K ν_e Appearance Results







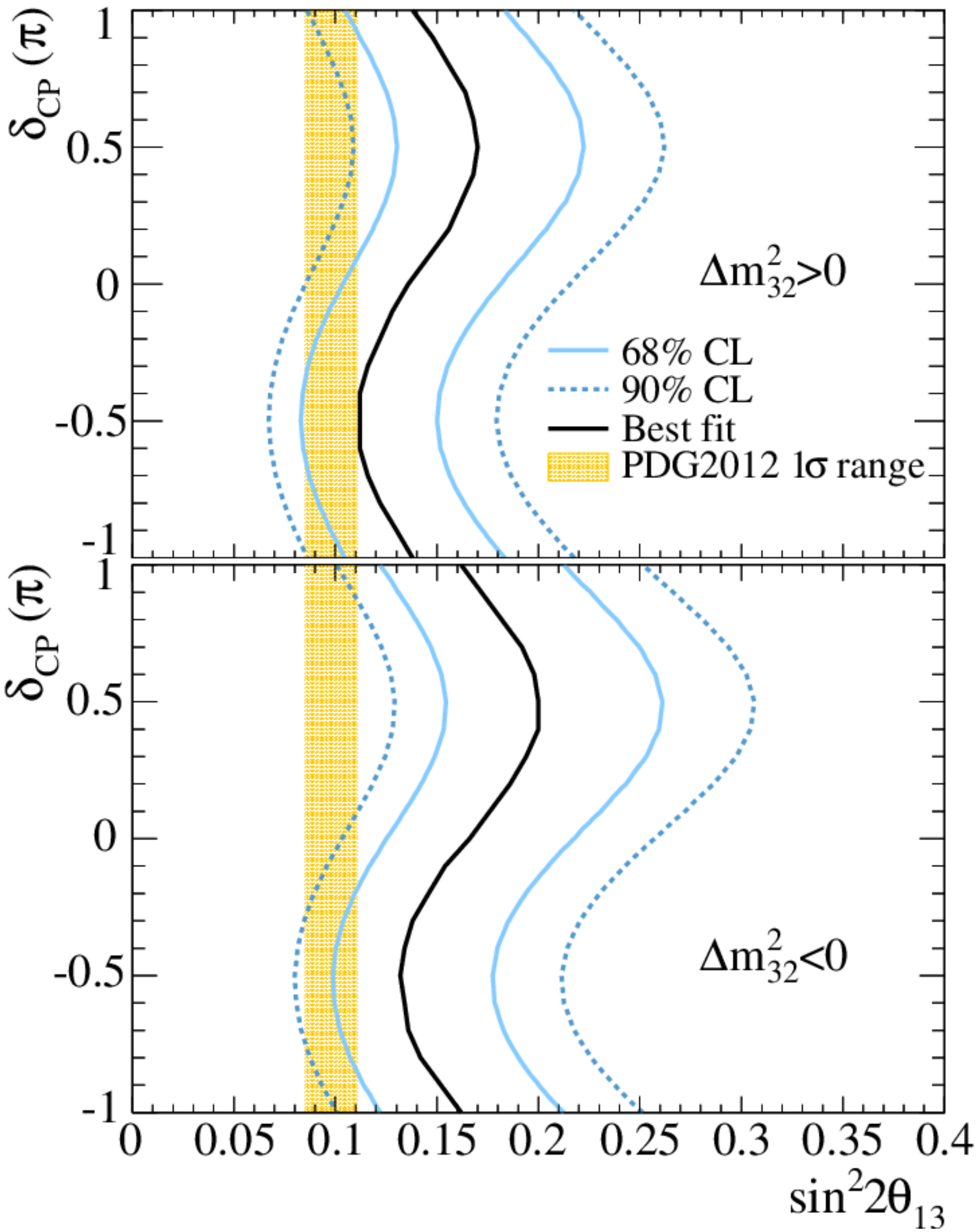
Observed events: 28
Expected background: 4.92 ± 0.55

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 & δ_{CP} = - π/2

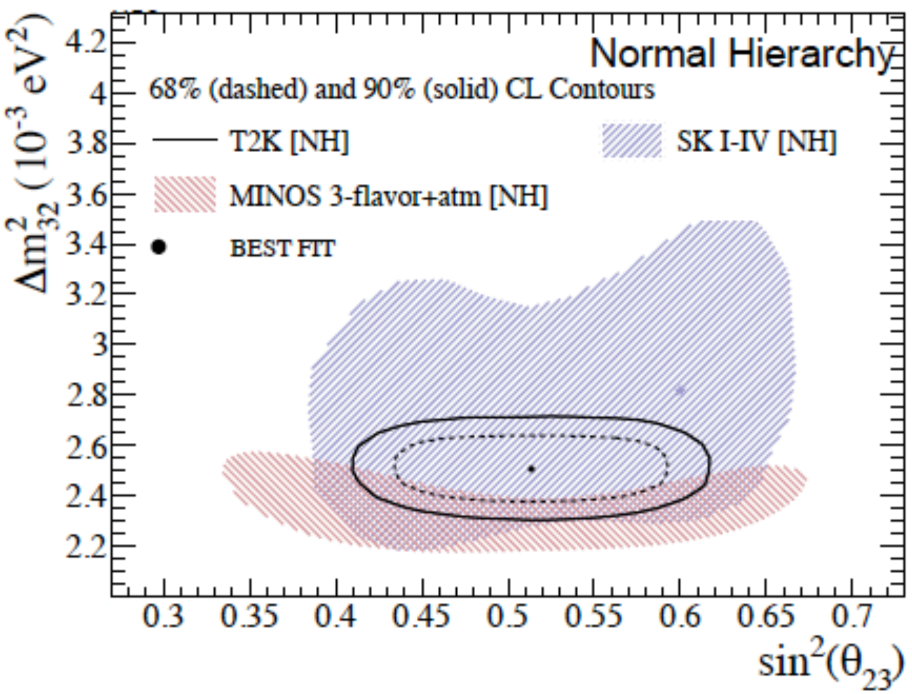
Is Nature very kind to us?
Are we very lucky?
Is CP violated maximally?

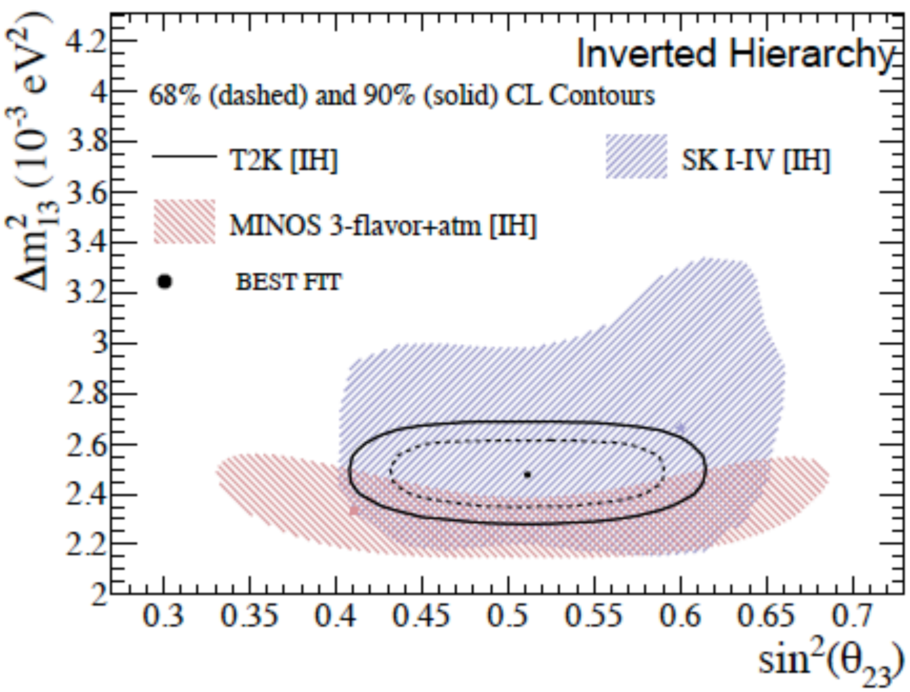
Strong motivation for anti-neutrino run

In these plots, atmospheric parameters are marginalized over

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

T2K Disappearance Results



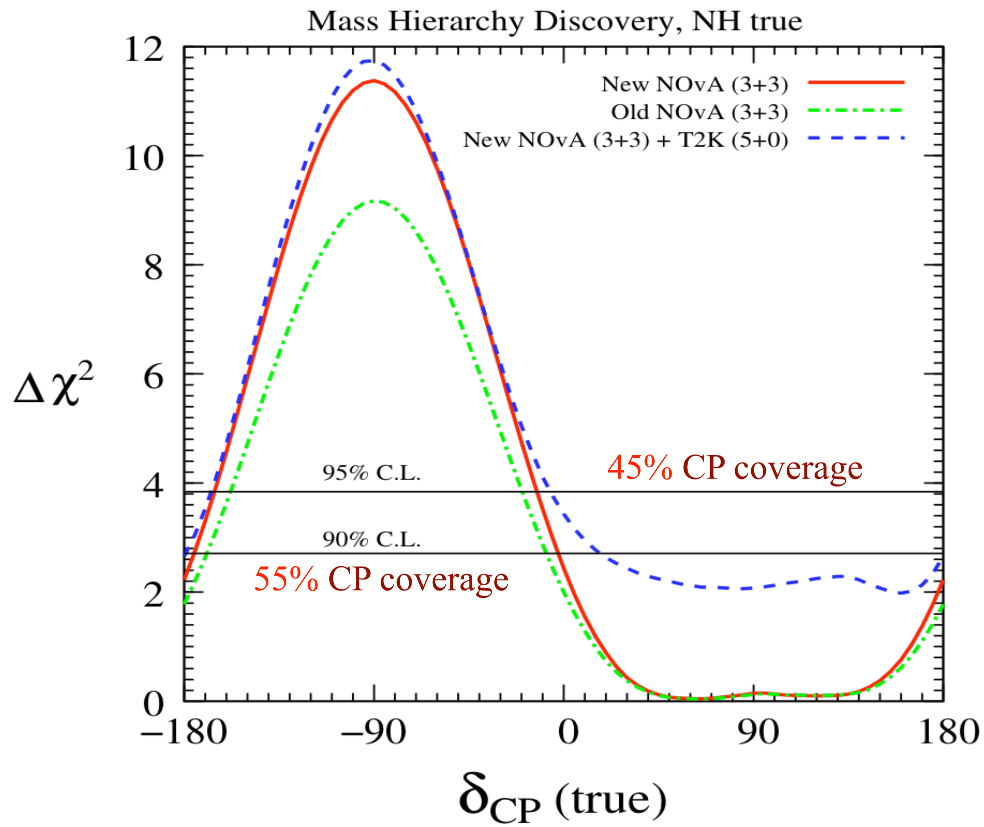


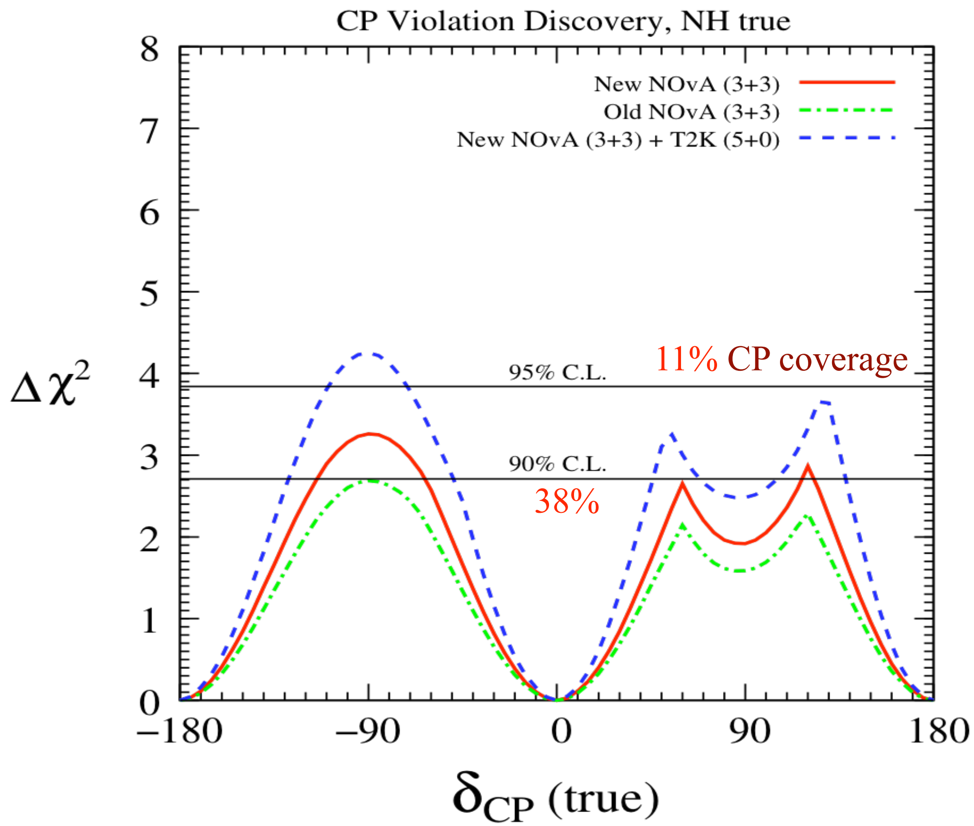
		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

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

Talk by C. Walter in Neutrino 2014

Mass Hierarchy & CP Violation Discovery with T2K and NOvA



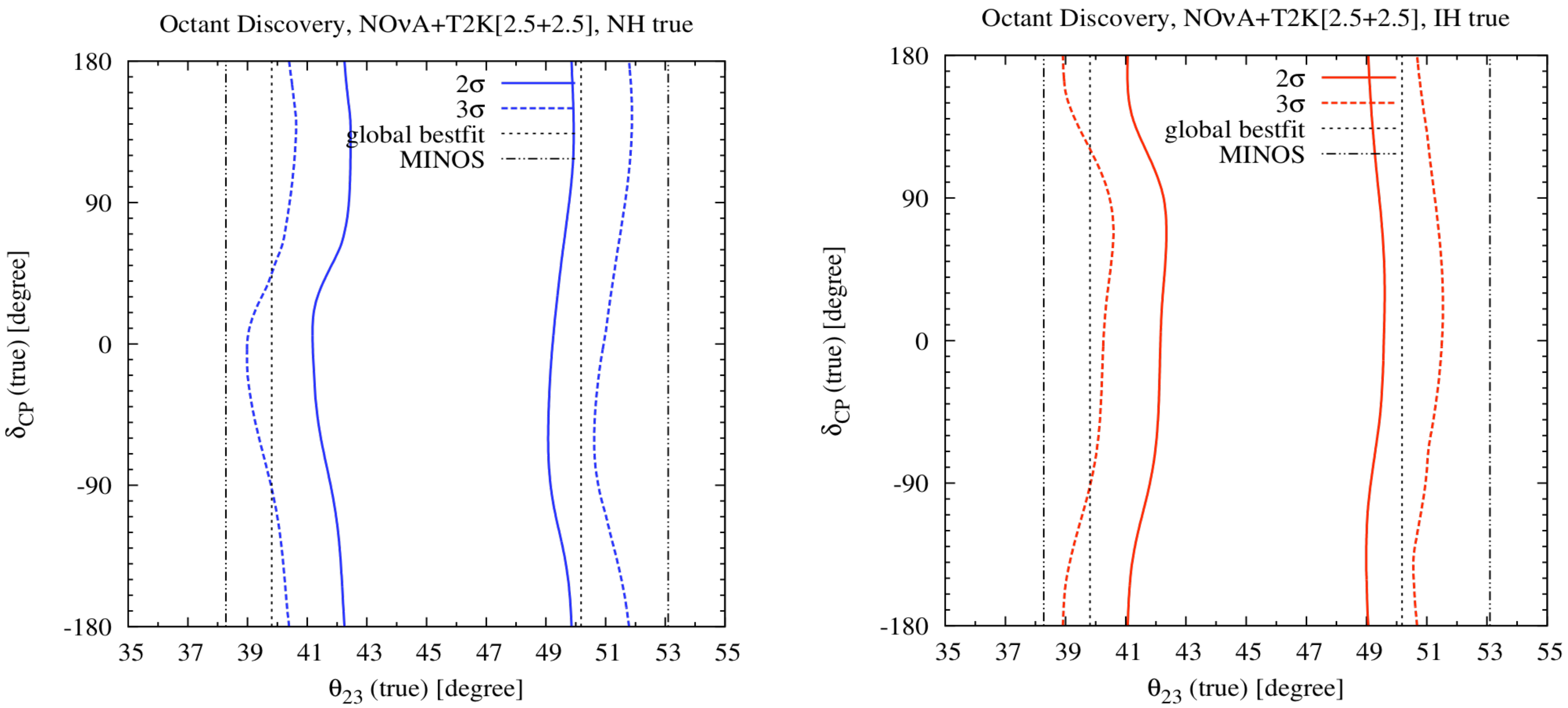


Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644
See also, Huber, Lindner, Schwetz, Winter, arXiv: 0907.1896;
Machado, Minakata, Nunokawa, Funchal, arXiv: 1307.3248;
Ghosh, Ghosal, Goswami, Raut, arXiv: 1401.7243

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



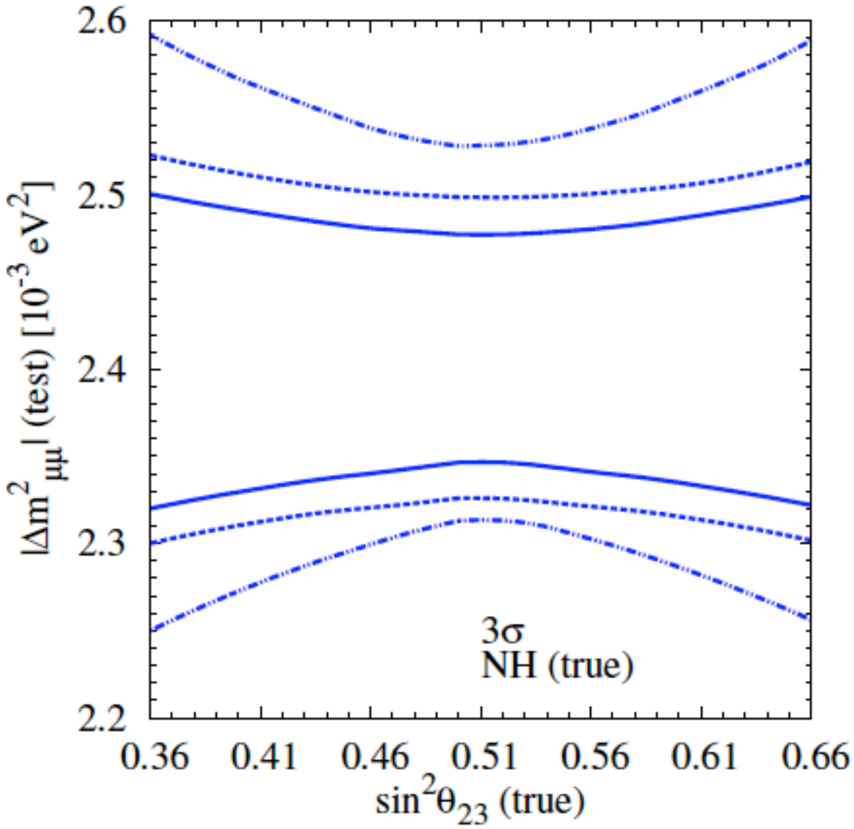
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]
See also, Chatterjee, Ghoshal, Goswami, Raut, arXiv:1302.1370 [hep-ph]

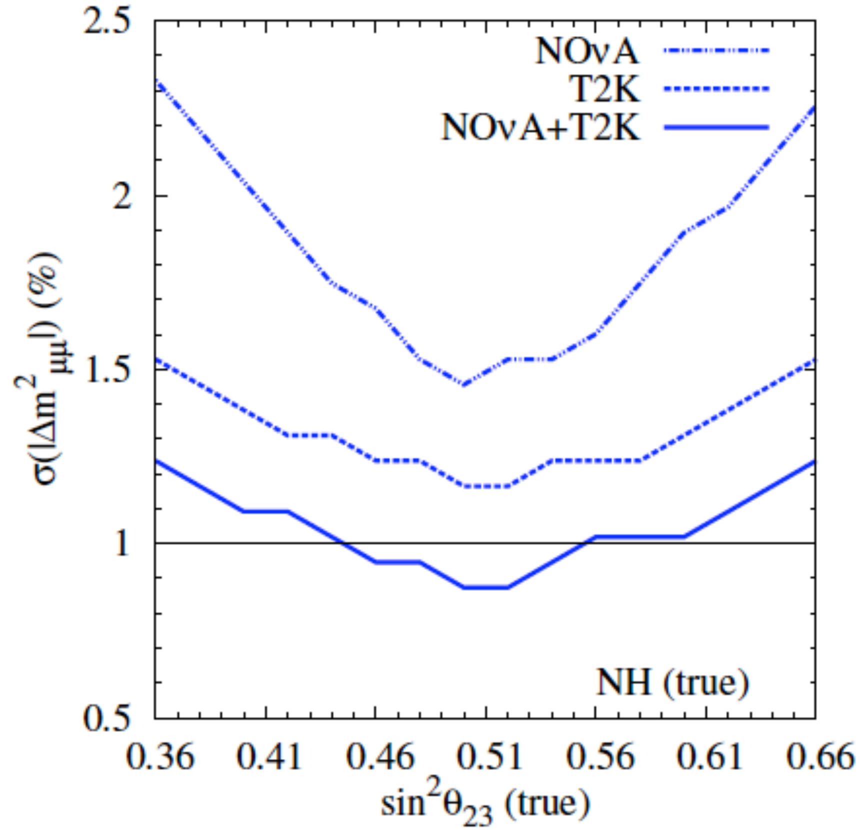
If $\theta_{23} < 41°$ or $\theta_{23} > 50°$, we can resolve the octant issue at 2σ irrespective of δ_{CP}

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!

Atmospheric Mass Splitting with T2K and NOνA

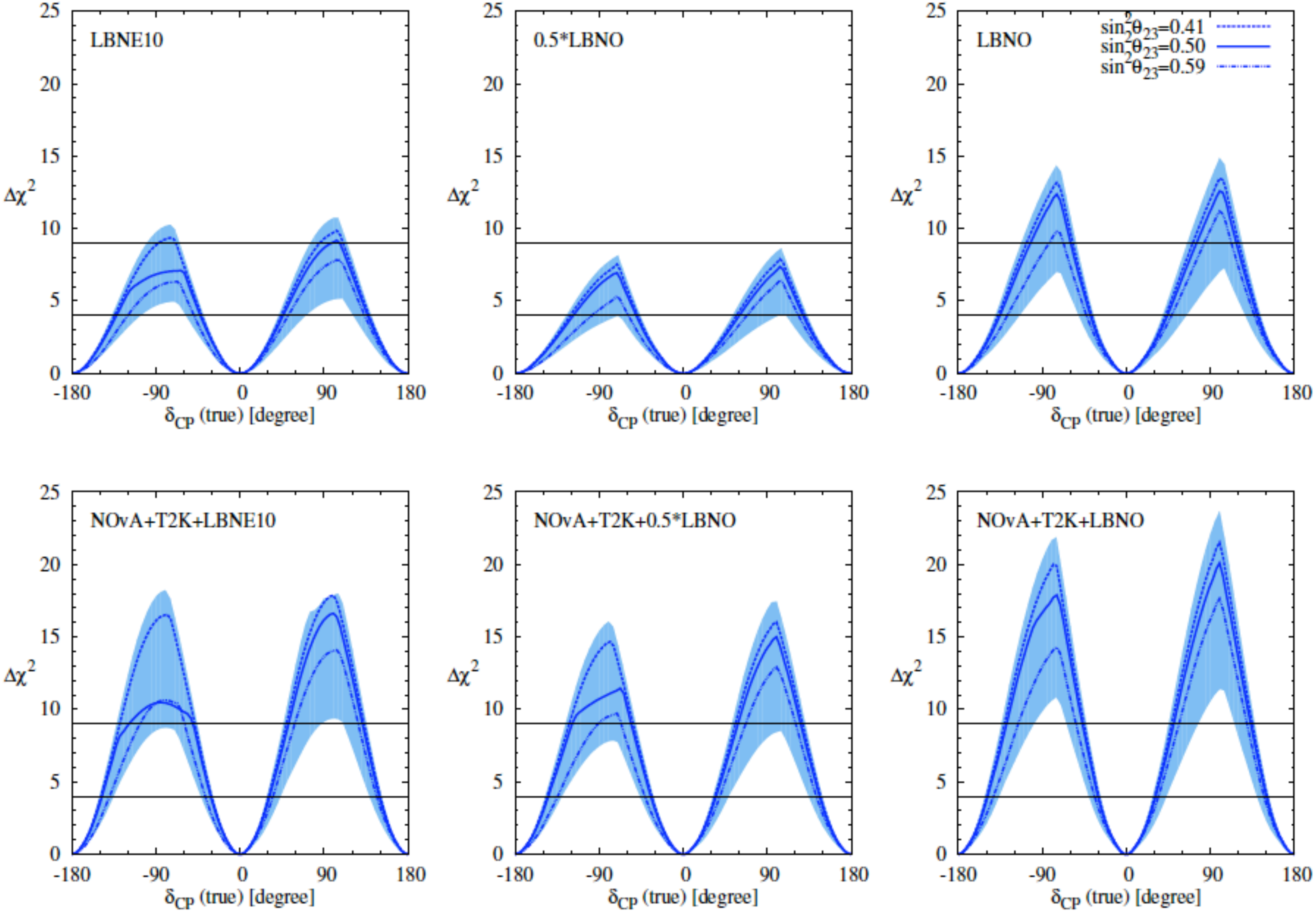




True $\sin^2\theta_{23}$	T2K (5ν)	NOνA ($3\nu + 3\bar{\nu}$)	T2K + NOνA
0.36	1.53%	2.33%	1.24% ($2.41^{+0.09}_{-0.09}$)
0.50	1.16%	1.45%	**0.87%** ($2.41^{+0.07}_{-0.06}$)
0.66	1.53%	2.26%	1.24% ($2.41^{+0.09}_{-0.09}$)

Agarwalla, Prakash, Wang, arXiv:1312.1477 [hep-ph]

T2K and NOvA help Next Generation Experiments



Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

T2K and NOvA will play crucial role in the first phase of LBNE and LBNO

T2K and NOvA help Next Generation Experiments

Setups	Fraction of δ_{CP}(true)	
	2σ confidence level	3σ confidence level
LBNE10 (10 kt)	0.51	0.03
LBNE10 + T2K + NOνA	0.63	0.43
0.5*LBNO (10 kt)	0.40	0.0
0.5*LBNO + T2K + NOνA	0.63	0.37
LBNO (20 kt)	0.51	0.23
LBNO + T2K + NOνA	0.69	0.46

Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

T2K and NOvA will play crucial role in the first phase of LBNE and LBNO

Concluding Remarks

Recent discovery of θ_{13} signifies an important breakthrough in establishing the standard three flavor oscillation picture of neutrinos

It has opened up exciting possibilities for current & future oscillation experiments

At present, we have:

$$|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.799 \to 0.844 & 0.515 \to 0.581 & 0.129 \to 0.173 \\ 0.212 \to 0.527 & 0.426 \to 0.707 & 0.598 \to 0.805 \\ 0.233 \to 0.538 & 0.450 \to 0.722 & 0.573 \to 0.787 \end{pmatrix}$$

Satisfactory progress in last 15 years but still very far from the 'dream' precision:

$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

!! Let us work together and achieve it !!

Thank you!

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: $$\mathrm{P}_{\mu\mu} = 1 - \sin^2 2\theta_{\text{eff}} \sin^2\left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right)$$

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

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

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

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]

$$\boxed{\sin^2 2\theta_{\text{eff}} = 0.95^{+0.035}_{-0.036}\ (10.71 \times 10^{21}\ \text{p.o.t})}$$ $$\boxed{\sin^2 2\bar{\theta}_{\text{eff}} = 0.97^{+0.03}_{-0.08}\ (3.36 \times 10^{21}\ \text{p.o.t})}$$

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

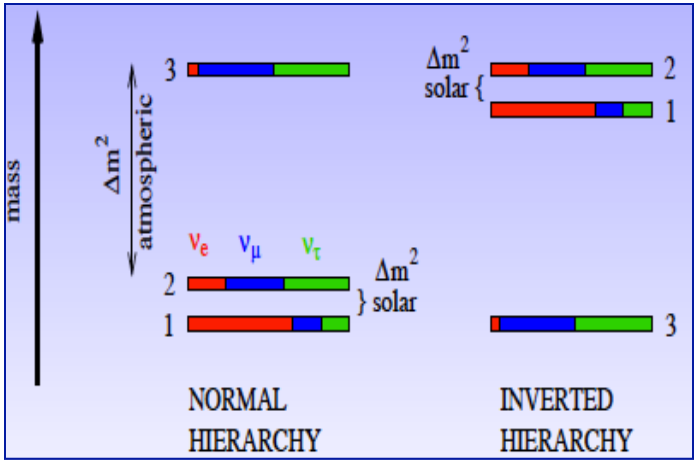
Global fit disfavors maximal 2-3 mixing at 1.4σ confidence level (mostly driven by MINOS)

ν_μ to ν_e oscillation data can break this degeneracy!

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

Fundamental Unknowns in Neutrino Sector

1. What is the hierarchy of the neutrino mass spectrum, normal or inverted?



- *The sign of* $\Delta m^2_{31} = m^2_3 - m^2_1$ *is not known!*
- *Currently do not know which neutrino is the heaviest?*
- *Only have a lower bound on the mass of the heaviest ν!*

$$\boxed{\sqrt{2.5 \cdot 10^{-3} \mathrm{eV}^2} \sim 0.05 \text{ eV}}$$

2. What is the octant of the 2-3 mixing angle, lower ($\theta_{23} < 45°$) or higher ($\theta_{23} > 45°$)?

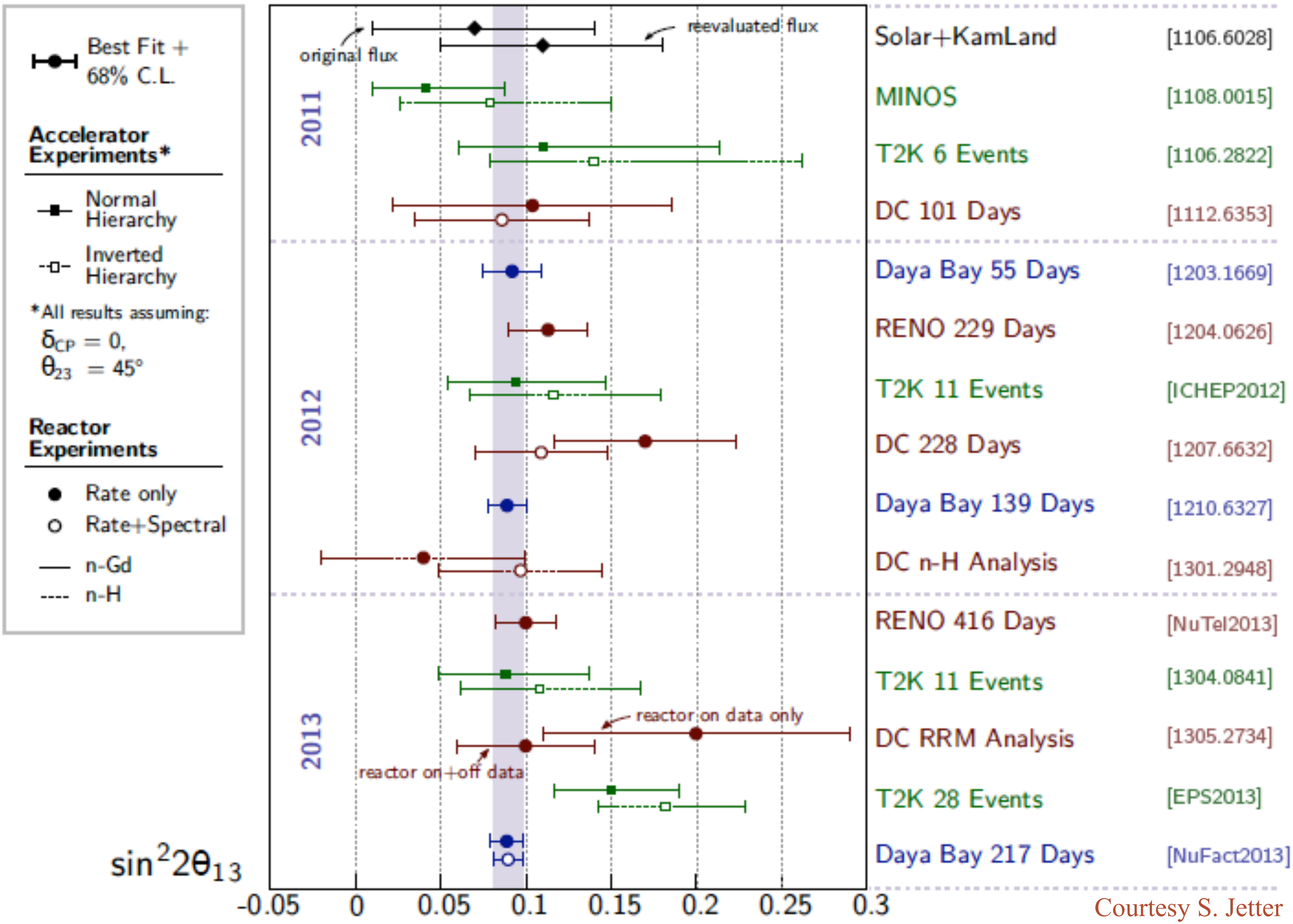
Measure θ_{23} precisely, Establish deviation from maximality at higher C.L. Then look for Octant

2. Is there CP violation in the leptonic sector, as in the quark sector?

Mixing can cause CP violation in the leptonic sector (if δ_{CP} differs from 0° and 180°)!
Need to measure the CP-odd asymmetries: $\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta; L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta; L)$ $(\alpha \neq \beta)$

With current knowledge of θ_{13}, resolving these unknowns fall within our reach!
Sub-leading 3 flavor effects are extremely crucial in current & future oscillation expts!

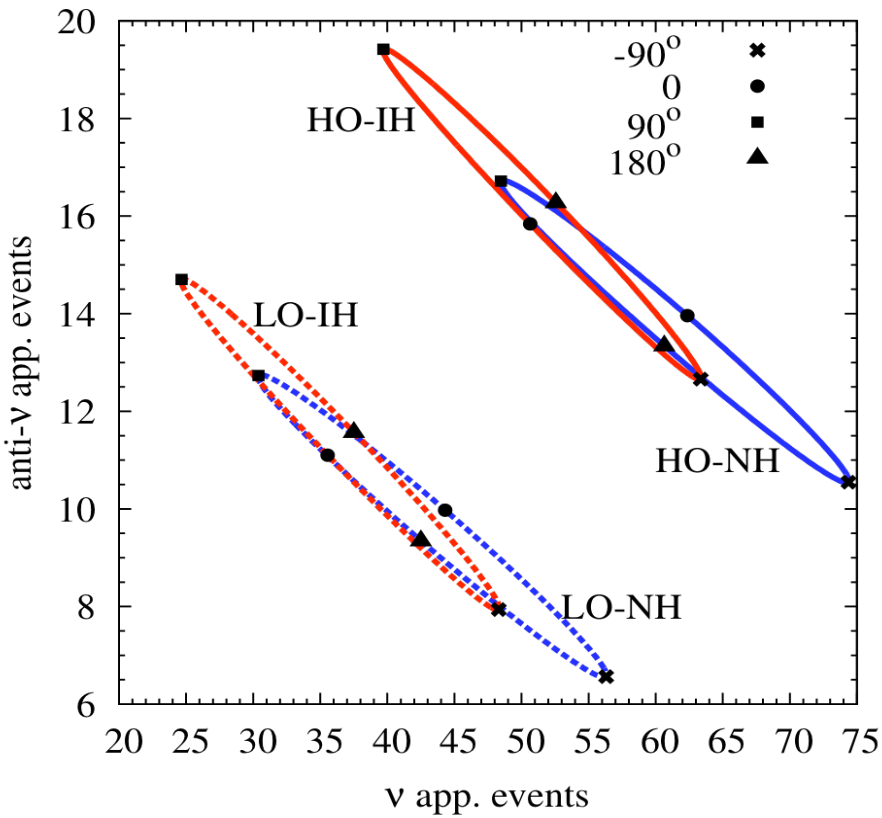
The θ_{13} Revolution

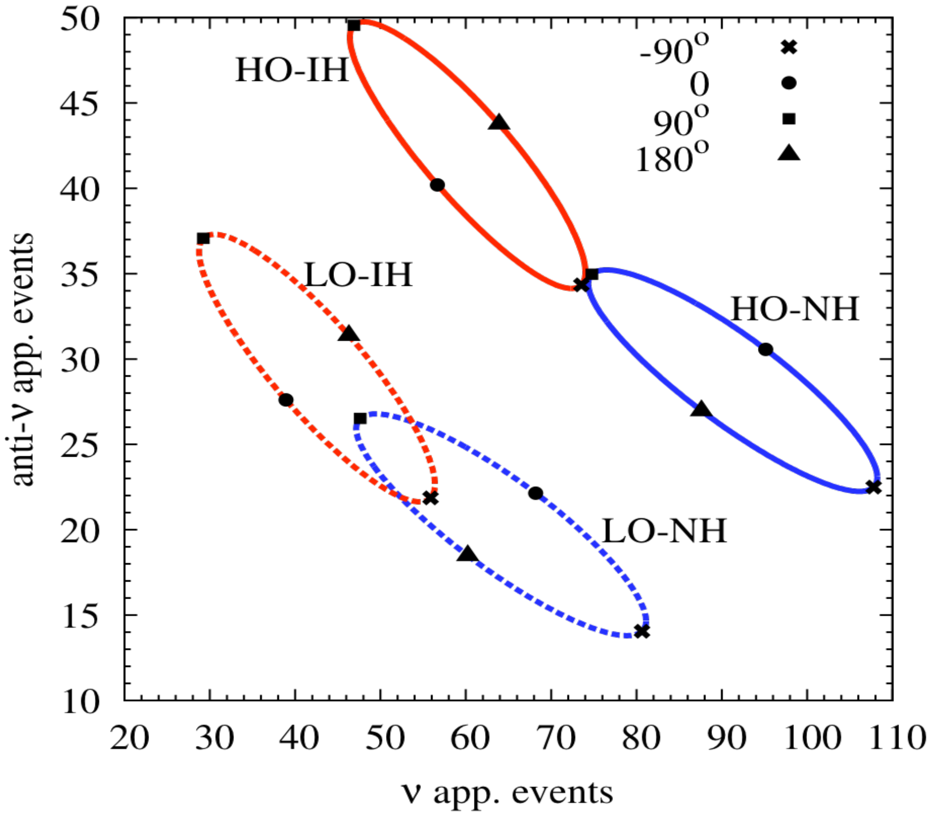


Courtesy S. Jetter

Bi-Event Plots for T2K and NOνA

T2K[2.5+2.5] T2K & NOνA: both off-axis experiments NOνA[3+3]





Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

ν vs. anti-ν events for various octant-hierarchy combinations, ellipses due to varying δ_{CP}!

If δ_{CP} = -90° (90°), the asymmetry between ν and anti-ν events is largest for NH (IH)

Hierarchy discovery: data from two experiments with widely different baselines mandatory!

Octant discovery: balanced ν & anti-ν runs needed in each experiment!