Phenomenology of θ_{13}

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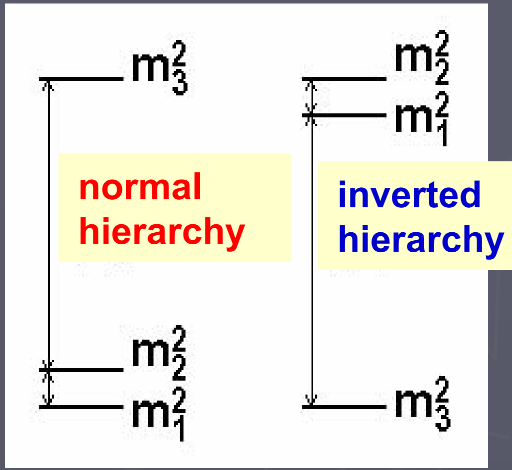
JPS meeting
11 September 2012@Kyoto Sangyo Univ.

Contents

1. Introduction

Framework of 3 flavor ν oscillation

Both hierarchy patterns are allowed



Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

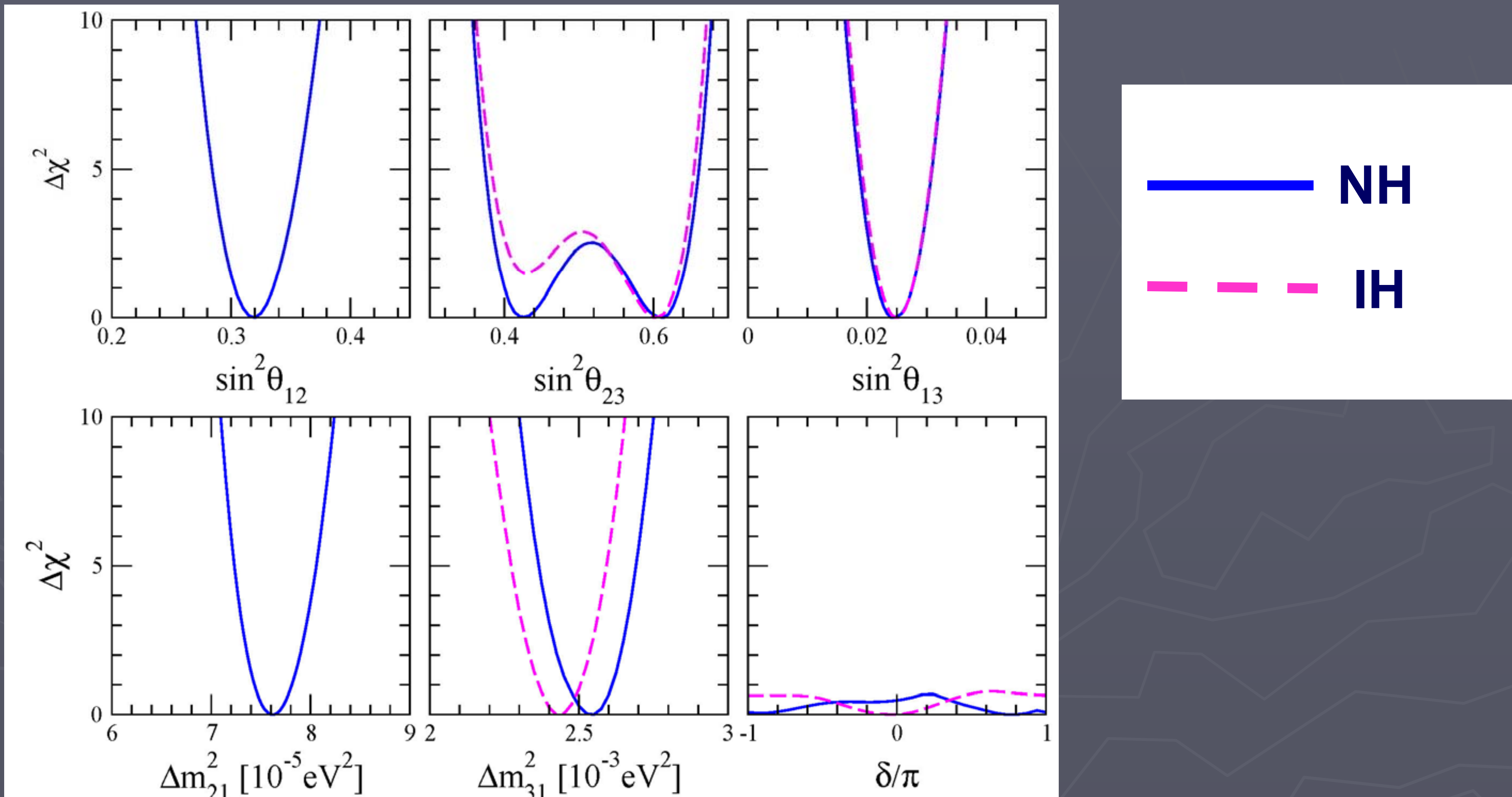
3 mixing angles have been measured :

ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m_{21}^2 \cong 8 \times 10^{-5} eV^2$

ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m_{32}^2| \cong 2.5 \times 10^{-3} eV^2$

DCHOOZ+Daya Bay+Reno (reactors), T2K+MINOS, others → $\theta_{13} \cong \frac{\pi}{20}$

One hint at nu2012: θ_{23} appears to be nonmaximal

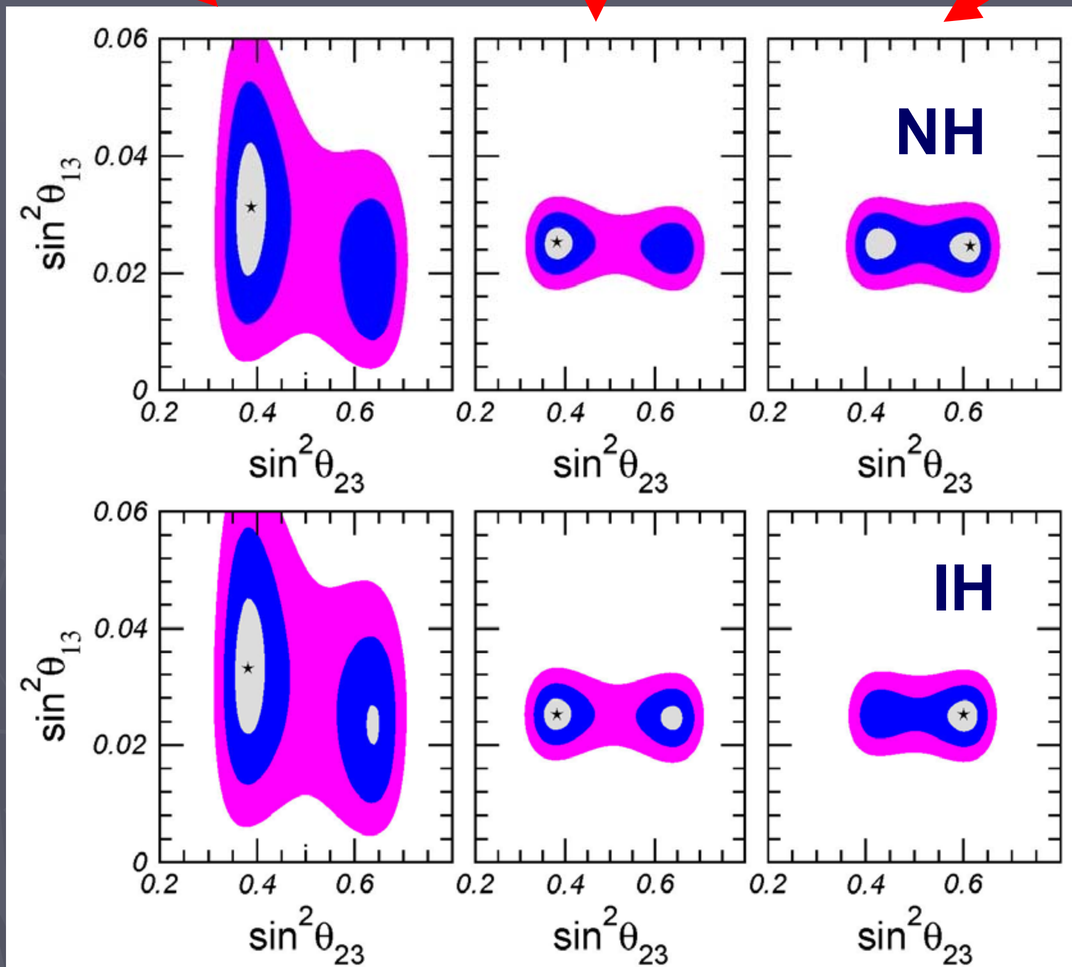


Forero, Tortola, Valle arXiv:1205.4018 (nu2012 data included)

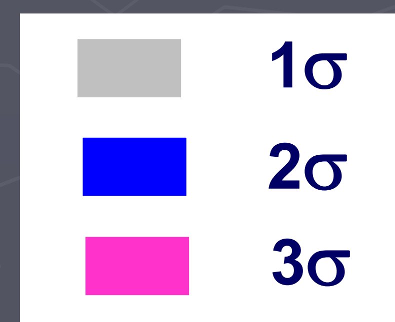
MINOS+T2K +sol+ KL

MINOS+T2K+sol+ KL+DC+DB+RENO

MINOS+T2K+sol+ KL+DC+DB+RENO+atm

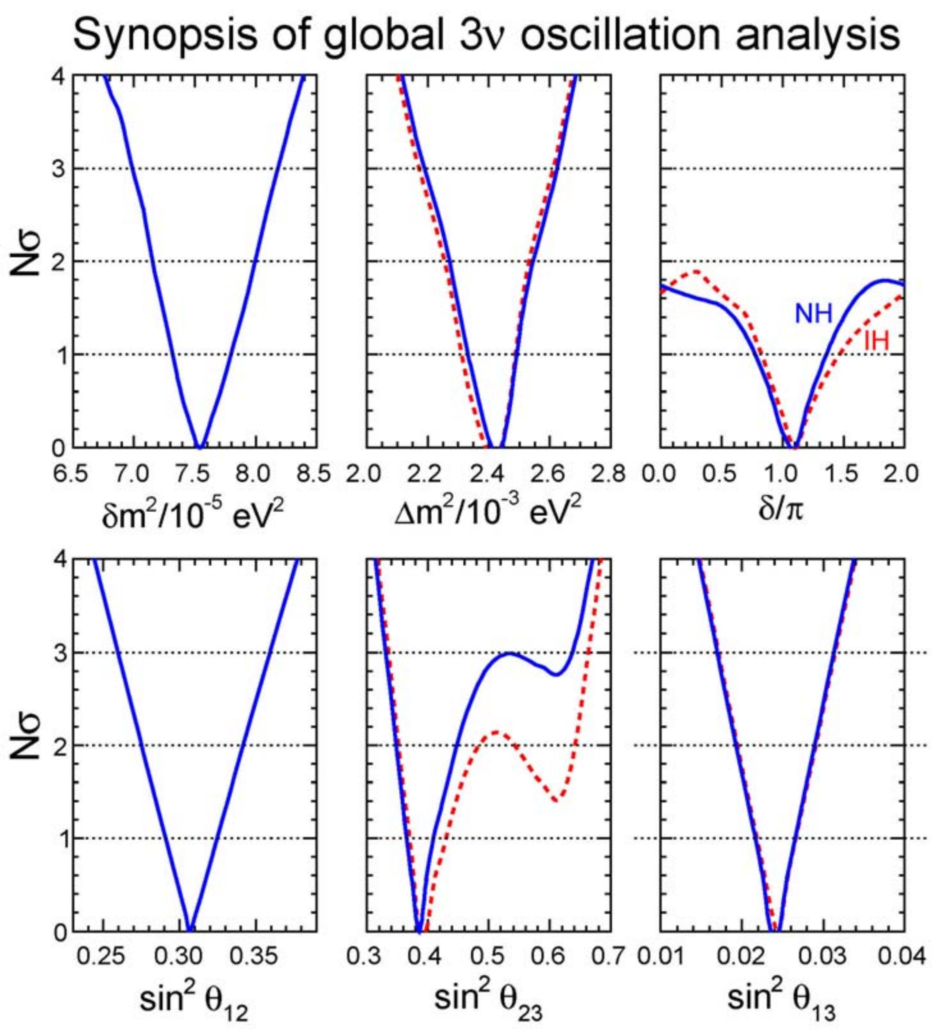


$\pi/4 - \theta_{23} < 0$ is preferred



Forero, Tortola, Valle arXiv:1205.4018

Octant of θ_{23} ($\pi/4 - \theta_{23} > 0$?) appears to be subtle



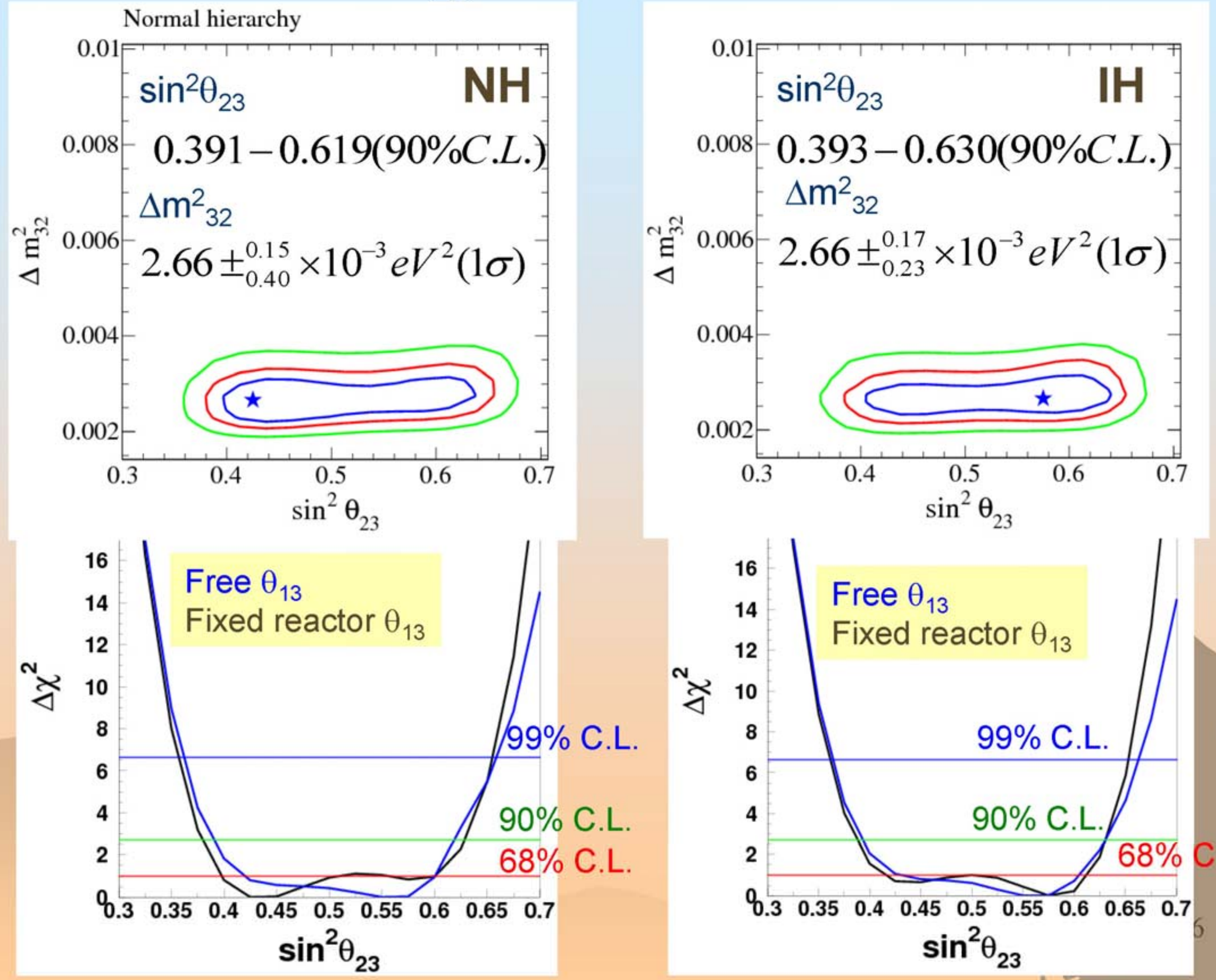
$\pi/4 - \theta_{23} > 0$ is preferred

Fogli, Lisi, Marrone, Montanino , Palazzo, Rotunno
Phys.Rev. D86 (2012) 013012 arXiv:1205.5254

Info on MH seems necessary

Itow@ν2012

Δm^2 and $\sin^2\theta_{23}$ with reactor constraint



A word on theory: Simple theoretical ansatz to predict θ_{13} successfully

◆ **Anarchy**

Hall, Murayama, Weiner, PRL 84 (2000) 2572

$\sin^2 2\theta_{13} \sim 0.1$ $\sin^2 2\theta_{23} \sim 1$

◆ **Quark-lepton complementarity**

Minakata, Smirnov, PR D70 (2004) 073009

$\theta_{12} + \theta_C = 45$ deg

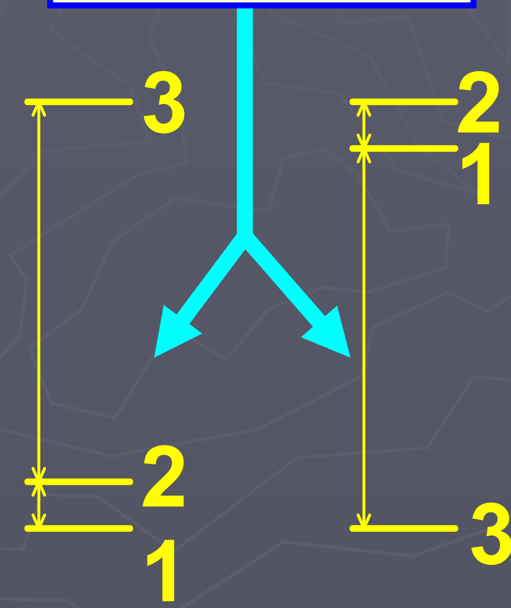
$\Rightarrow$
- $\theta_{13} = 8.9$ deg
- $\theta_{12} = 35.4$ deg
- $\theta_{23} = 42.1$ deg

Dighe, Goswami, Roy
PR D76 (2007) 096005

2. Parameter degeneracy

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & \varepsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

- **Both mass hierarchies are allowed**



normal hierarchy	inverted hierarchy
$\Delta m^2_{32} > 0$	$\Delta m^2_{32} < 0$

Next task is to measure
sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ.

To determine δ, accelerator long baseline experiments with $\nu_\mu \to \nu_e$ and $\overline{\nu_\mu} \to \overline{\nu_e}$ are necessary.

Parameter degeneracy

Even if we know $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu_\mu} \to \overline{\nu_e})$ in a long baseline accelerator experiments with approximately monoenergetic neutrino beam, precise determination of θ_{13} , θ_{23} , sign(Δm^2_{31}) and δ is difficult because of the 8-fold parameter degeneracy.

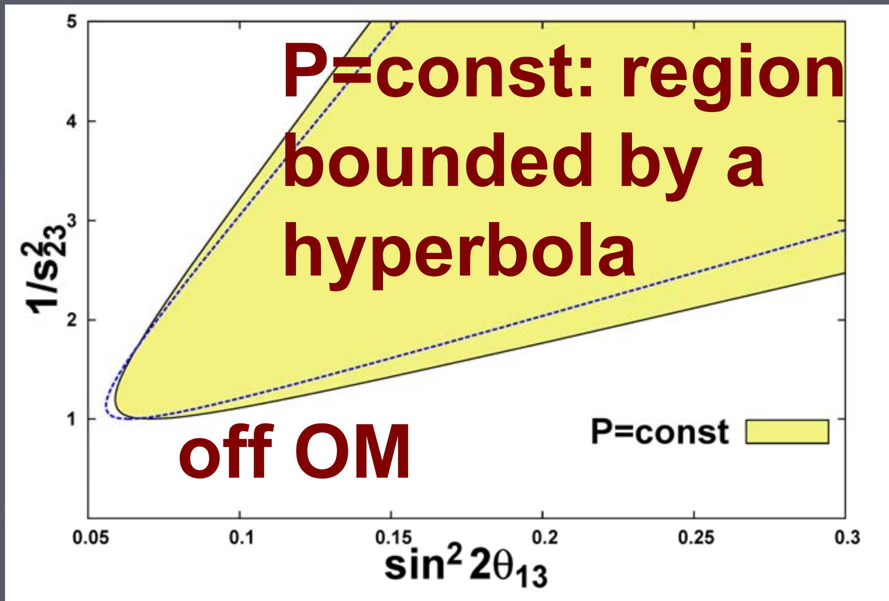
Plots in ($\sin^2 2\theta_{13}$, $1/s^2_{23}$) plane

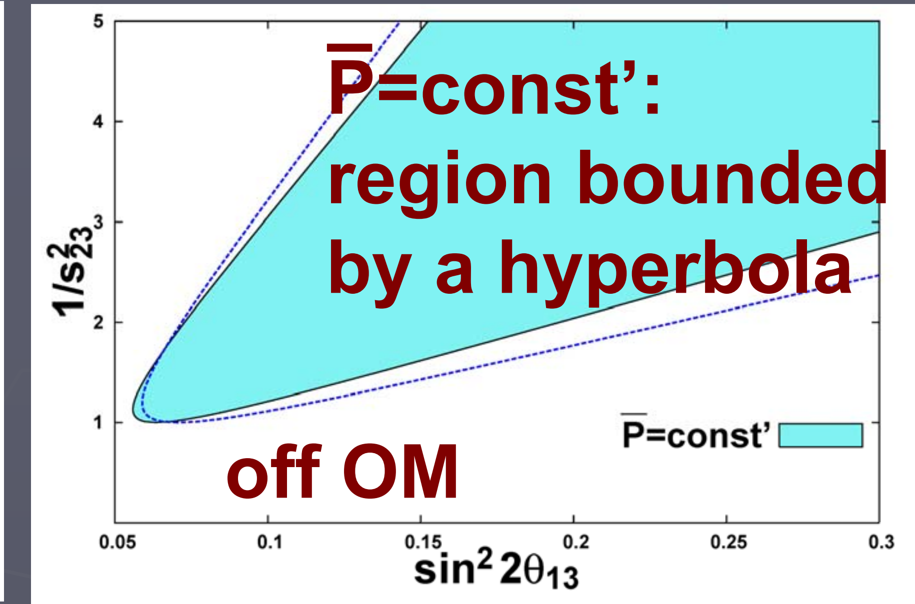
$$P \equiv P\left(\nu_\mu \to \nu_e\right)$$

$$\bar{P} \equiv P\left(\overline{\nu_\mu} \to \overline{\nu_e}\right)$$

OY, New J.Phys. 6 (2004) 83

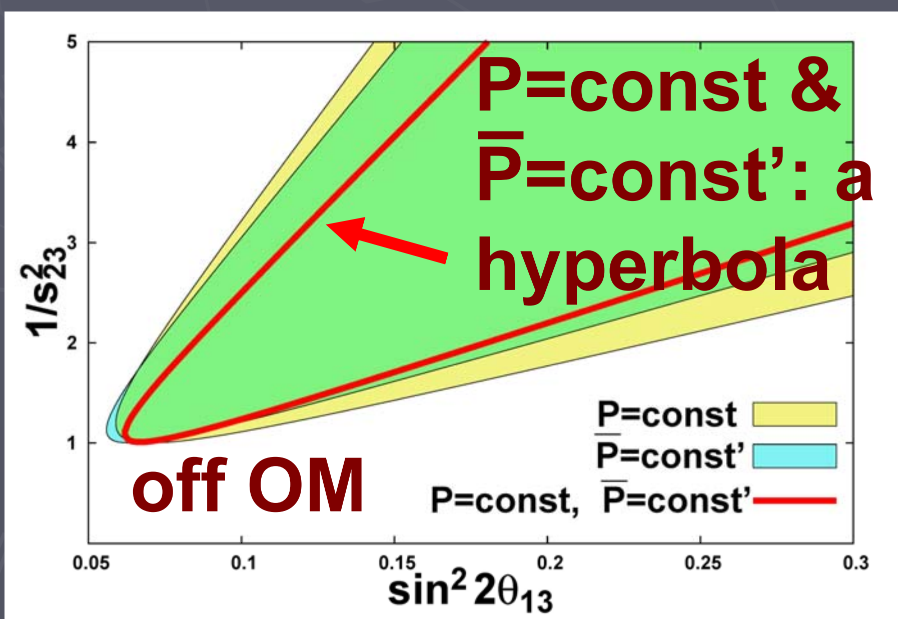
In this plot, the region of P=const or $\bar{P}$=const is described by quadratic curves (hyperbolic or elliptic).

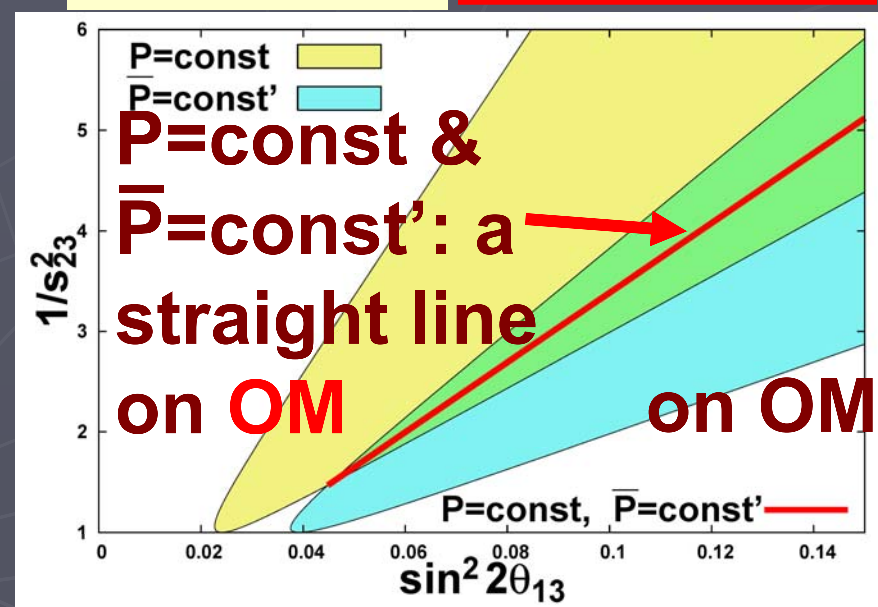




Oscillation Maximum:

$$\Delta \equiv \frac{|\Delta m^2_{31}|L}{4E} = \frac{\pi}{2}$$

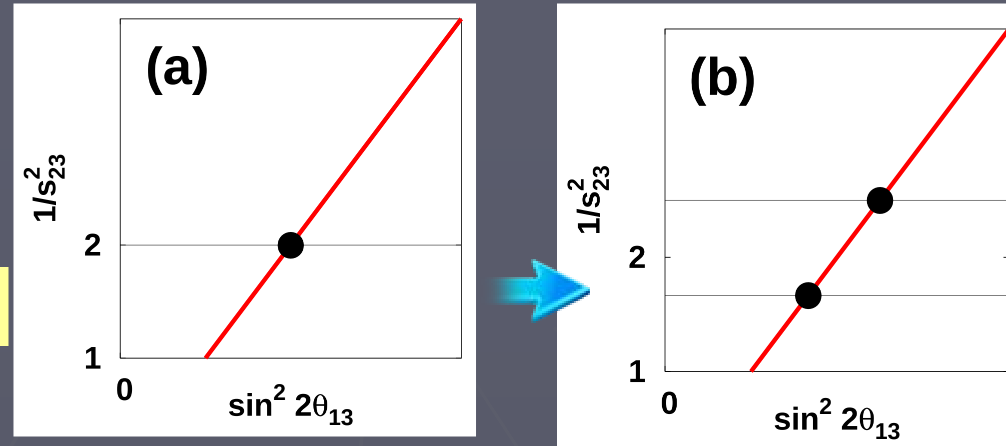




octant degeneracy

$\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$

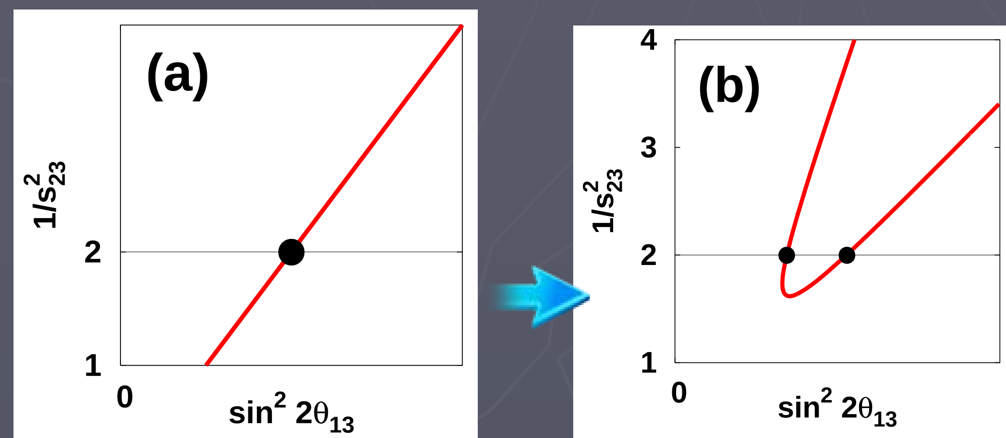
$$(a)\cos 2\theta_{23} = 0 \rightarrow (b)\cos 2\theta_{23} \neq 0$$



intrinsic degeneracy

(δ, θ_{13})

$$(a)\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} = 0 \rightarrow (b)\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \cong \frac{1}{35} \neq 0$$

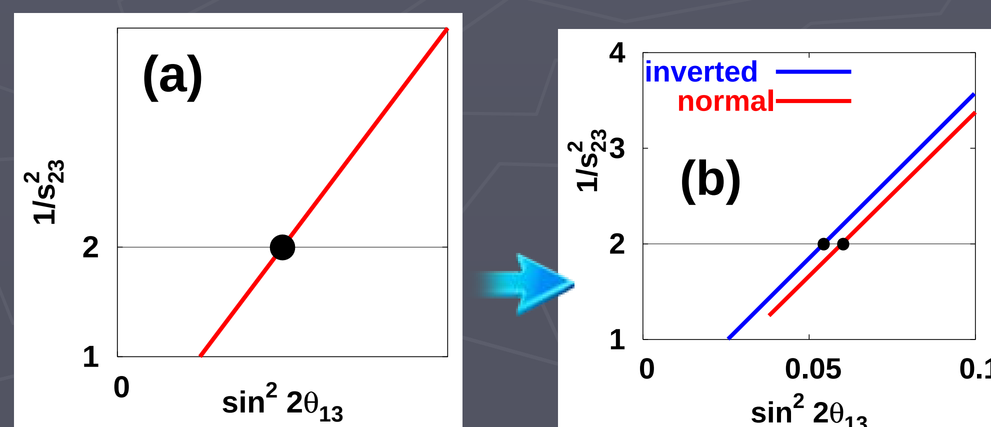


sign degeneracy

$\Delta m^2_{31} \Leftrightarrow -\Delta m^2_{31}$

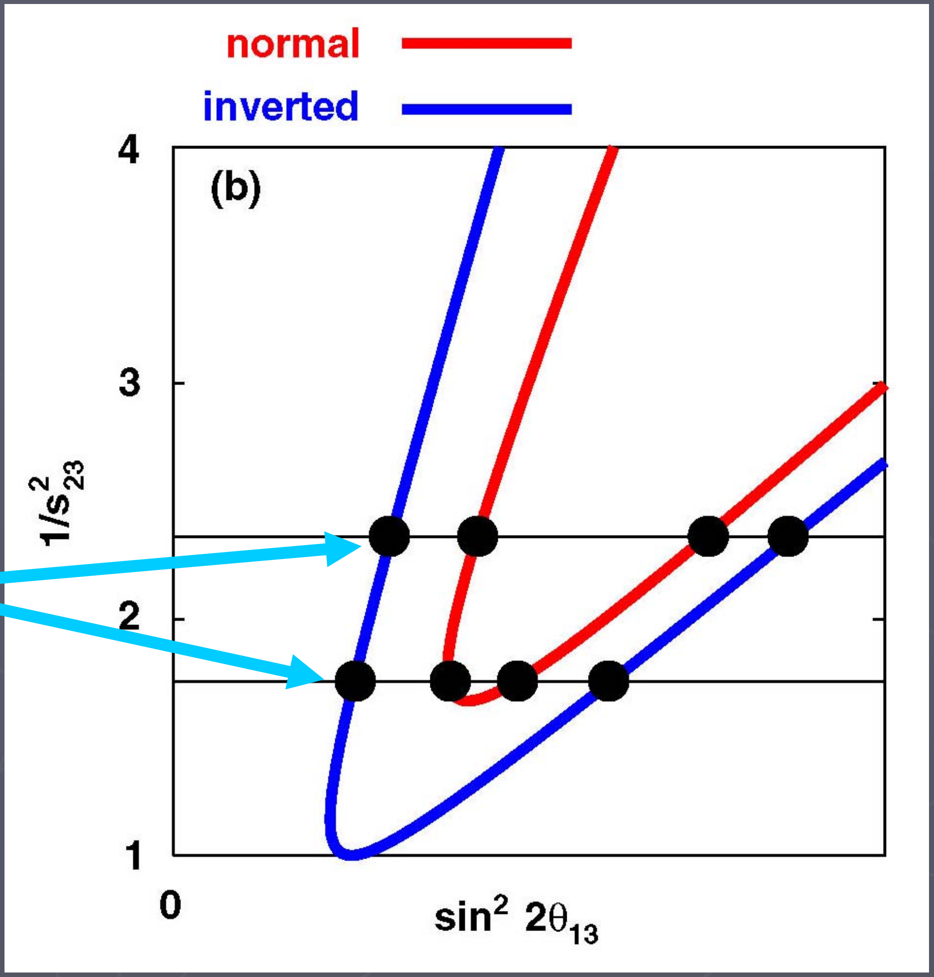
$$(a)AL/2 = 0 \rightarrow (b)AL/2 \neq 0$$

$$A \equiv \sqrt{2} G_F N_e \cong 1/2000\text{km}$$



In total we have 8-fold parameter degeneracy

Each point has different value of δ.



For precise measurements of δ, one has to resolve parameter degeneracy.

Differences in values of CP phases

θ_{13}:= θ_{13}(true), θ_{13}':= θ_{13}(false)

δ:= δ(true), δ':= δ(false)

sign degeneracy

$$\sin^2 2\theta'_{13} = \sin^2 2\theta_{13} \tan^2\theta_{23} + \frac{\alpha^2 g^2 \sin^2 2\theta_{12}}{f\bar{f}}(1-\tan^2\theta_{23}),$$

$$\sin 2\theta'_{13}\sin\delta' = \sin 2\theta_{13}\sin\delta + \frac{\alpha g(f-\bar{f})\sin 2\theta_{12}}{f\bar{f}}\frac{\cot 2\theta_{23}}{\sin\Delta},$$

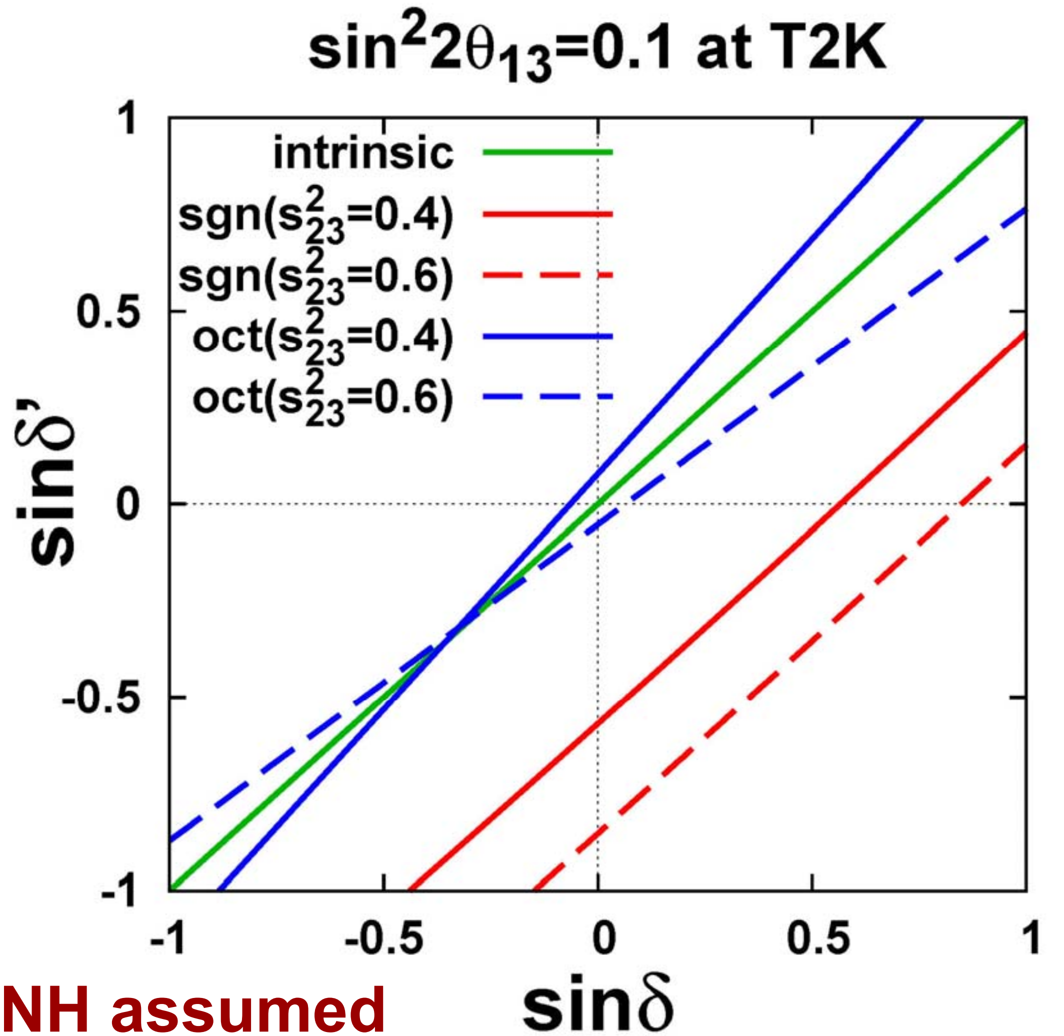
octant degeneracy

$$x'^2 = \frac{x^2(f^2+\bar{f}^2-f\bar{f}) - 2yg(f-\bar{f})x\sin\delta\sin\Delta}{f\bar{f}},$$

$$x'\sin\delta' = x\sin\delta\frac{f^2+\bar{f}^2-f\bar{f}}{f\bar{f}} - \frac{x^2}{\sin\Delta}\frac{f^2+\bar{f}^2}{f\bar{f}}\frac{f-\bar{f}}{2yg}.$$

Barger Marfatia Whisnant Phys.Rev.D65:073023,2002

Sign degeneracy is more serious than octant one, because $\sin\delta(\text{sign})=0 \Rightarrow \sin\delta'(\text{sign})=O(1)\neq 0$



NH assumed

NB: At T2K $|\Delta m^2_{31}|L/4E=\pi/2 \Rightarrow \sin\delta(\text{intrinsic}) =\sin\delta'(\text{intrinsic})$

⇓

Resolution of sign degeneracy is important for CP measurement

To solve parameter degeneracy, various combinations have been proposed:

(A) LBL measurement at $|\Delta m^2_{31}| L/4E = \pi/2$

→ hyperbola shrinks to a straight line

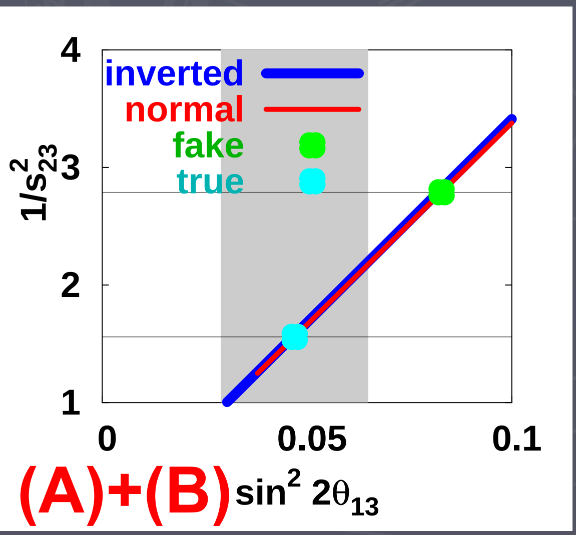
(B) reactor measurement of θ_{13} $\bar{\nu}_e \to \bar{\nu}_e$

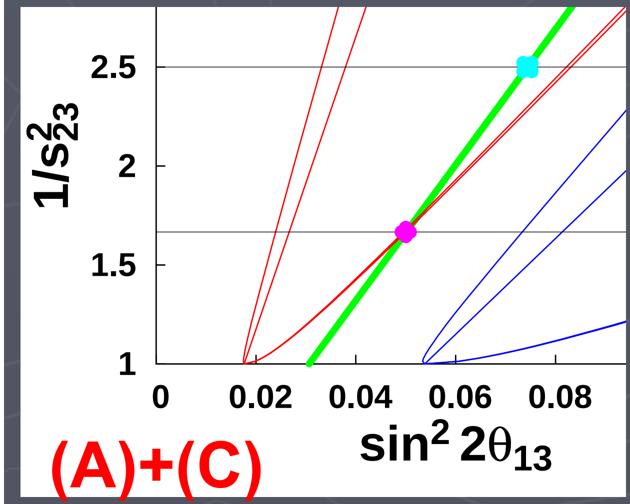
→ depends only on θ_{13}

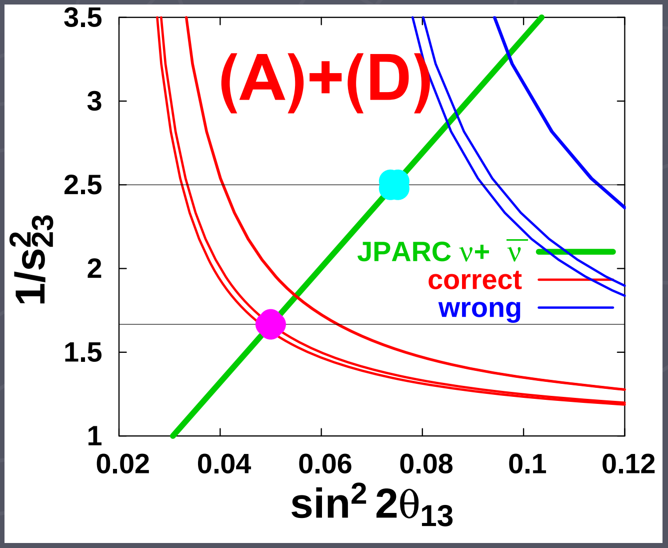
(C) LBL measurement of $\nu_\mu \to \nu_e$ (or $\nu_e \to \nu_\mu$)

with different L/E

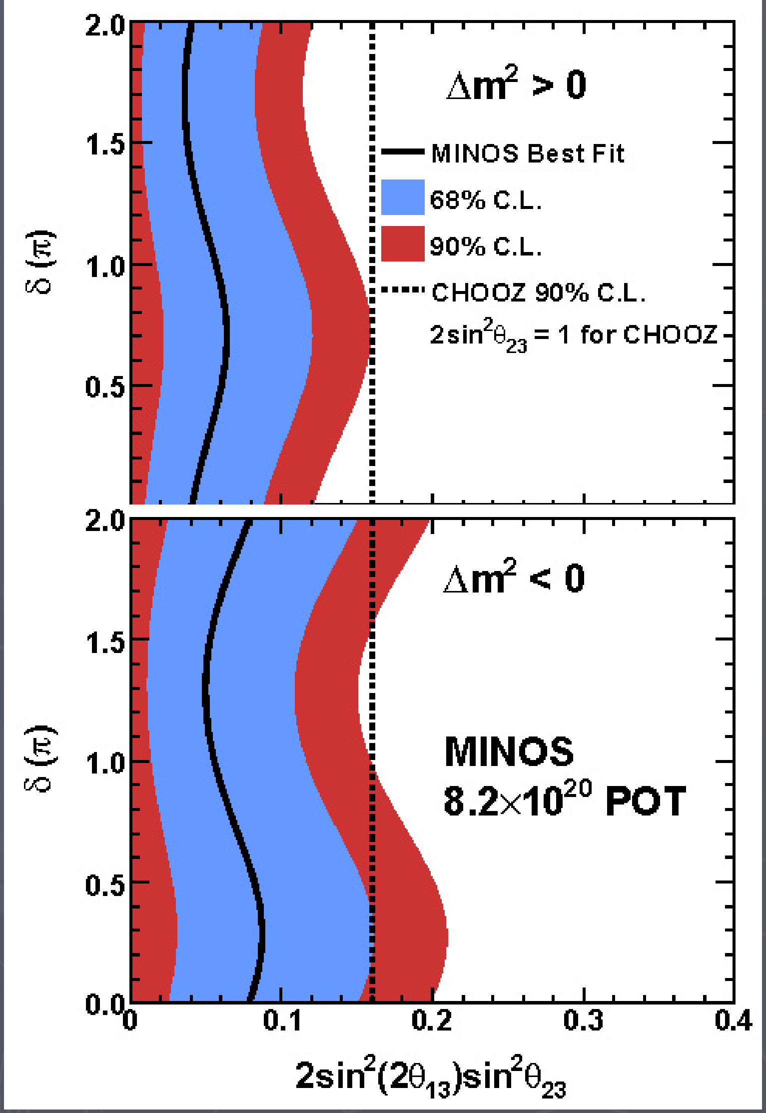
(D) measurement of $\nu_e \to \nu_\tau$



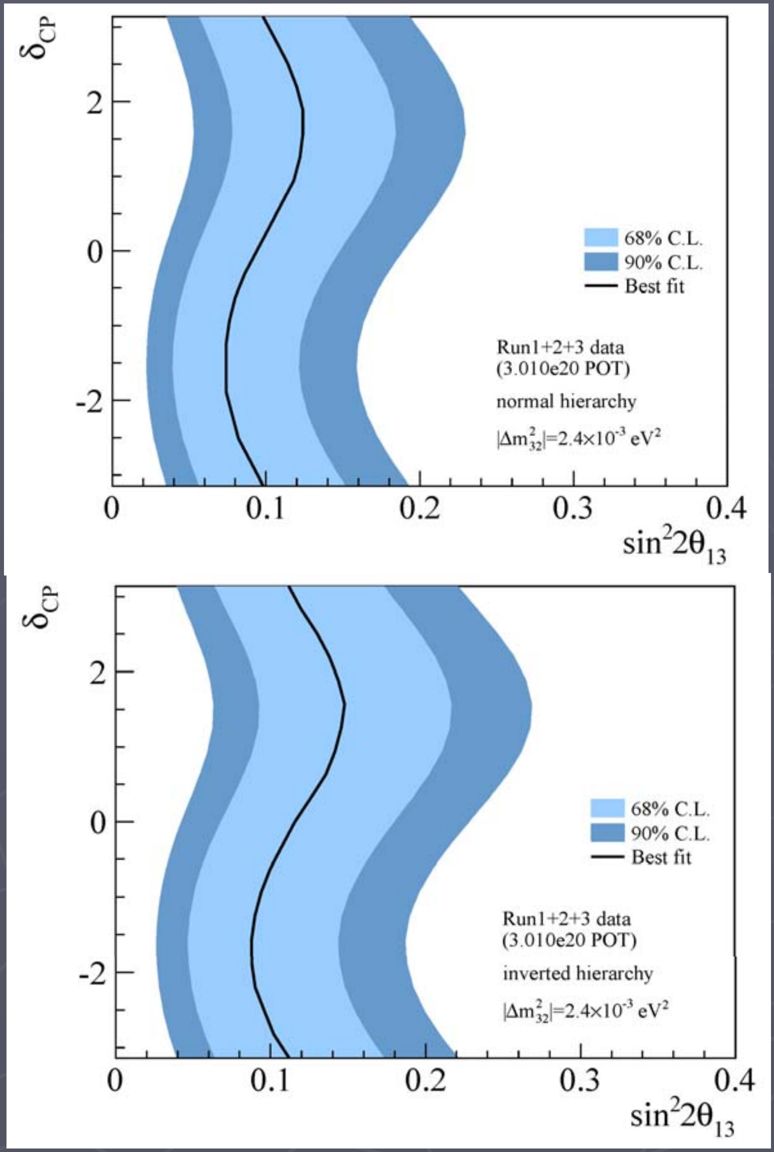




Current status of appearance experiments

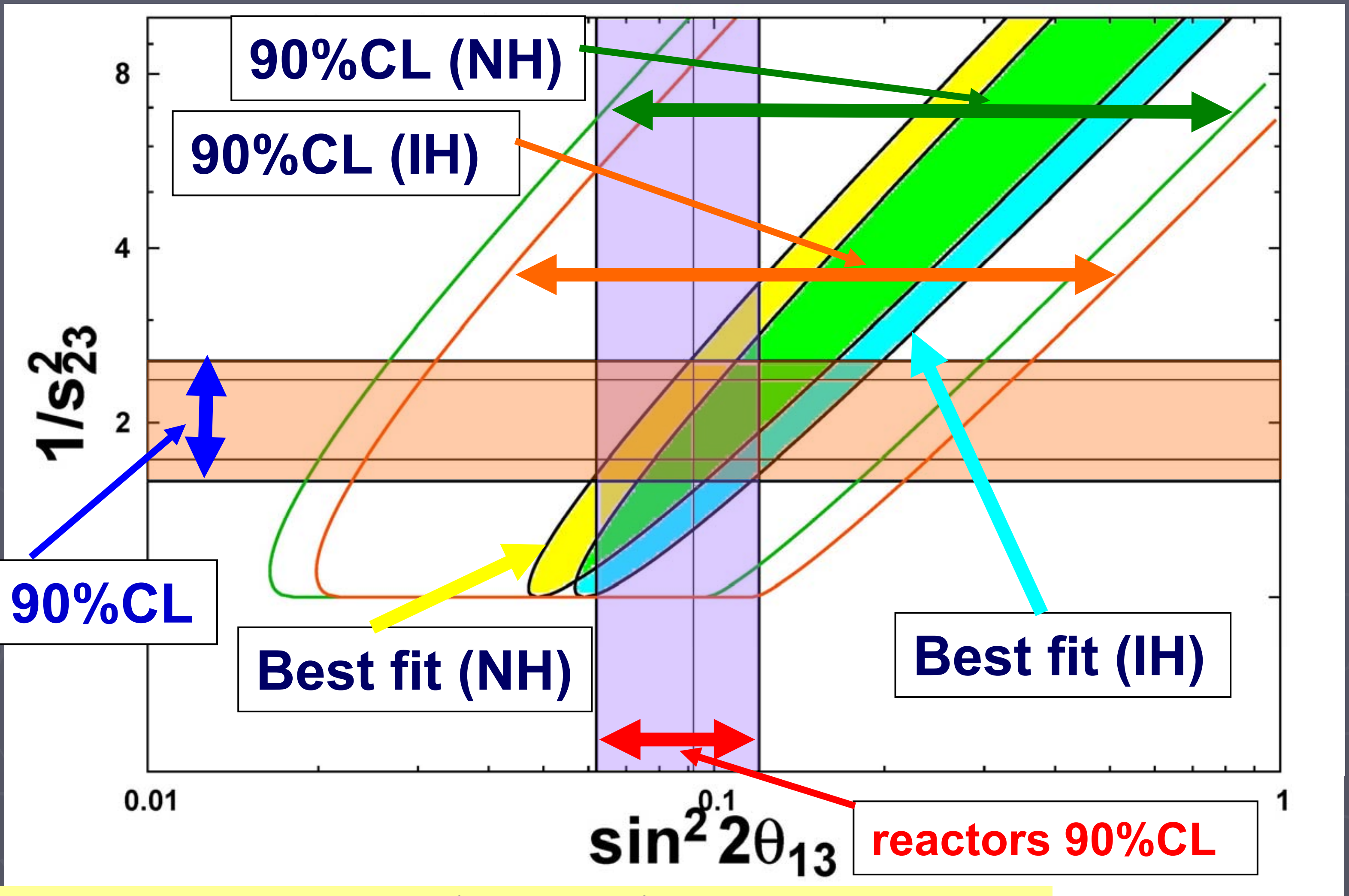


arXiv:1108.0015



Sakashita@ICHEP2012

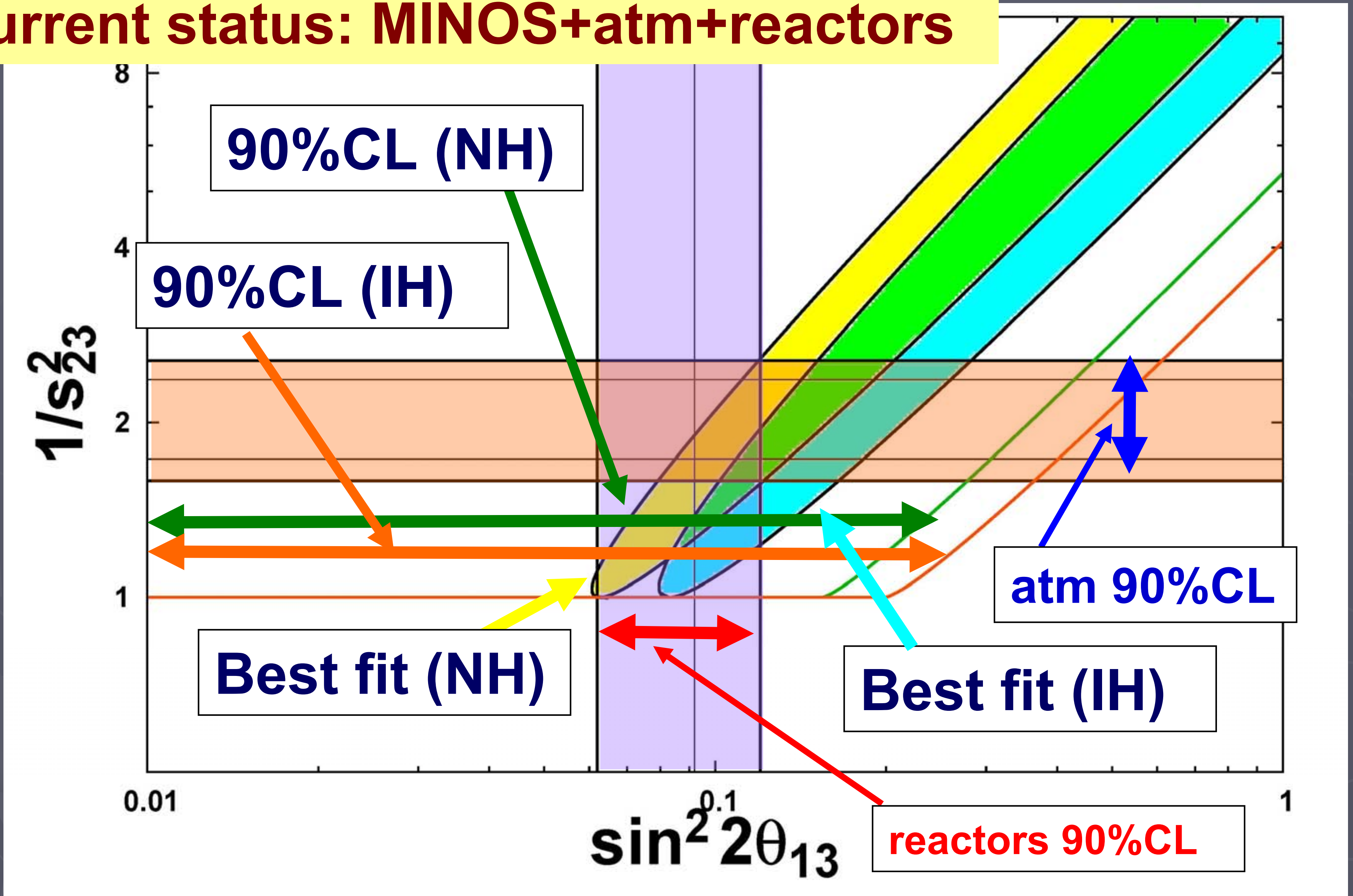
Current status: T2K+atm+reactors



Allowed region from $P(\nu_\mu \to \nu_e)$ of T2K at best-fit & 90%CL (w/ Sakashita@ICHEP2012)

Error is large→needs more statistics & $P(\overline{\nu_\mu} \to \overline{\nu_e})$ to improve

Current status: MINOS+atm+reactors



Allowed region from $P(\nu_\mu \to \nu_e)$ of MINOS at best-fit & 90%CL (w/ arXiv:1108.0015 data)

3. Future LBL experiments

To perform precise measurements of θ_{13} and δ, one has to have a lot of numbers of events to improve statistical errors.

→We need **high intensity** beam

Candidates for high intensity beam in the future:

- (conventional) superbeam

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \nu_\mu \to \nu_e$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

- neutrino factory

  μ in a storage ring

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \qquad \nu_e \to \nu_\mu$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \qquad \bar{\nu}_e \to \bar{\nu}_\mu$$

- beta beam

  RI in a storage ring

$${}^6_2\mathrm{He} \to {}^6_3\mathrm{Li} + e^- + \bar{\nu}_e \qquad \bar{\nu}_e \to \bar{\nu}_\mu$$
$${}^{18}_{10}\mathrm{Ne} \to {}^{18}_{9}\mathrm{F} + e^+ + \nu_e \qquad \nu_e \to \nu_\mu$$

Future LBL exp. (under construction / proposed)

- superbeam

T2K phase II (2.2MW+HK(+Okinoshima), E~1GeV, L=295km, 658km)

NOvA (FNAL→ Ash River (MN), E~2GeV, L=810km)

LBNE (FNAL→Homestake, E~a few GeV, L=1290km)

CN2PY (CERN→Pyhasalmi, E~several GeV, L=2300km)

- neutrino factory (E_ν~20GeV, L~4000km)
- beta beam (E_ν=0.5-1.5GeV, L~130km)

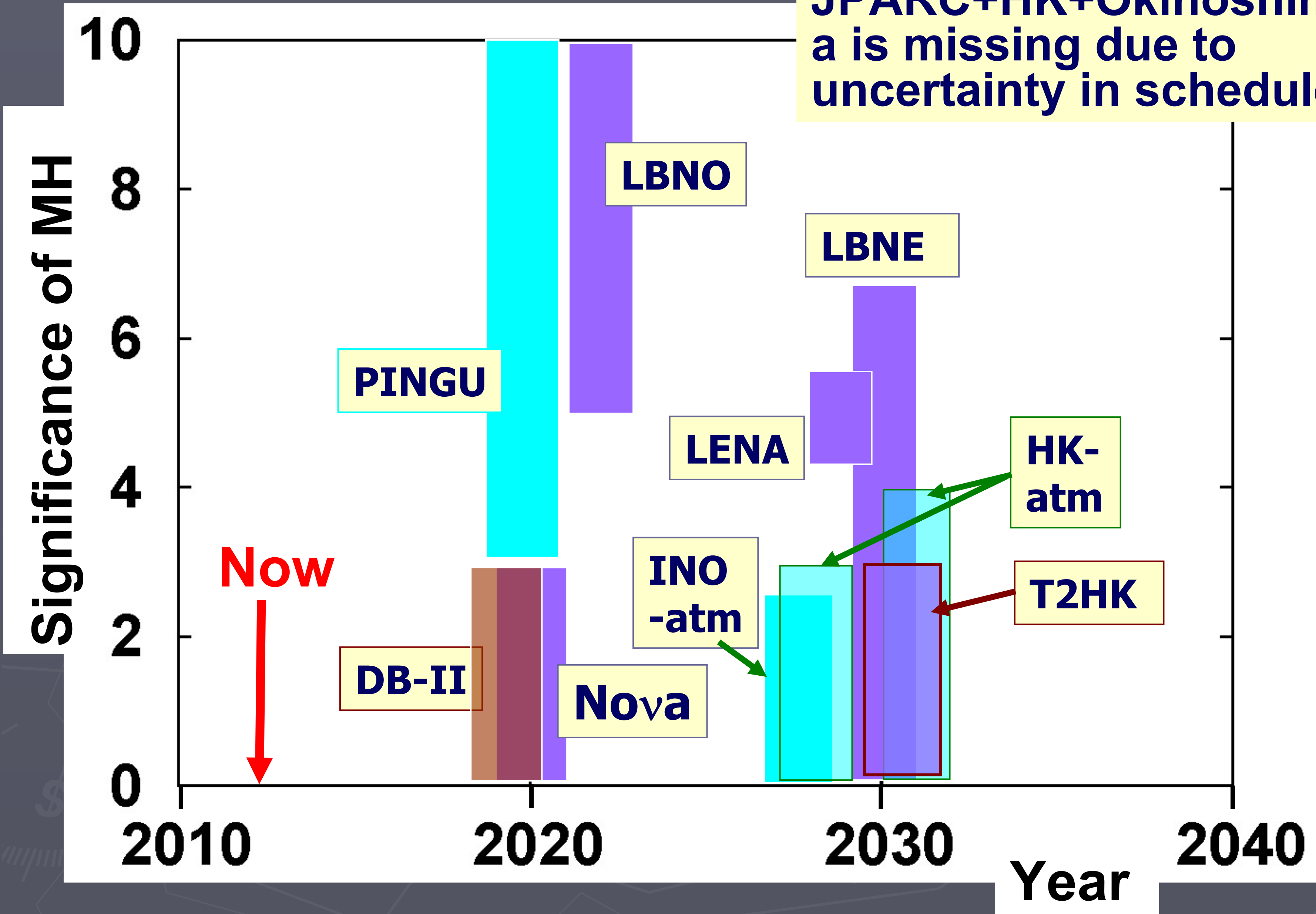
Future exp. vs MH

Bertolucci et al., arXiv:1208.0512

Project			Separation of IH and NH	Pre-requisite and date of achievement	Reference
DayaBay II	reactor 60km	20 kt LS	3 σ in 6 years	R&D on E-resolution 2020 ?	Karsten Heeger at Neutrino 2012
ICAL@INO	atmospherics	50 kt MID (RPCs)	2.7 σ in 10 years	2027	Sandhya Choubey at Neutrino 2012
HyperK	atmosherics	1 Mt Water Cerenkov	3 σ in 5 years 4 σ in 10 years	2027/28 2033/34	HyperK LOI Sandhya Choubey at Neutrino 2012
T2HK	LBL accel. 295 km	1 Mt Water Cerenkov	0..3 σ in 10 years	2028	Masashi Yokoyama at Neutrino 2012
PINGU	atmospheircs	Ice (South pole)	3...11 σ in 5 years	feasibility study ongoing, understanding of resolution and systematics on atmospherics Around 2020 if it works.	Uli Katz at neutrino Town meeting
GLADE	LBL accel. 810 km	LAr 5 kt	In combination with NOvA and T2K: ≤ 2 σ	Letter-of-Intent	Jenny Thomas at neutrino Town meeting
NOνA	LBL AshRiver 810 km	TASD 14 kt	0...3 σ in 6 years depending on δ	Full operation in 2014 2020	Ryan Patterson at Neutrino 2012
LBNE	LBL Homestake LBL Soudan LBL AshRiver	LAr 10 kt LAr 15 kt LAr 30 kt	1.5...7 σ in 10 y 0...3 σ in 10 y 0.5...5 σ in 10 y	2030	Bob Swoboda at Neutrino 2012
LBNO	LBL accel. 2300 km	LAr 20 kt	> 5σ in a few y.	2023 + If decision in 2015	André Rubbia at Neutrino 2012
LENA	LBL accel. 2300 km	Liq. Scint. 50 kt	5 σ in 10 years	2028 + number of years to the decision	Lothar Oberauer at Neutrino 2012
Neutrino Factory	LBL accel. 2000 km	MIND 100kton	>> 5 σ		Ken Long at Neutrino 2012

Future exp. vs MH

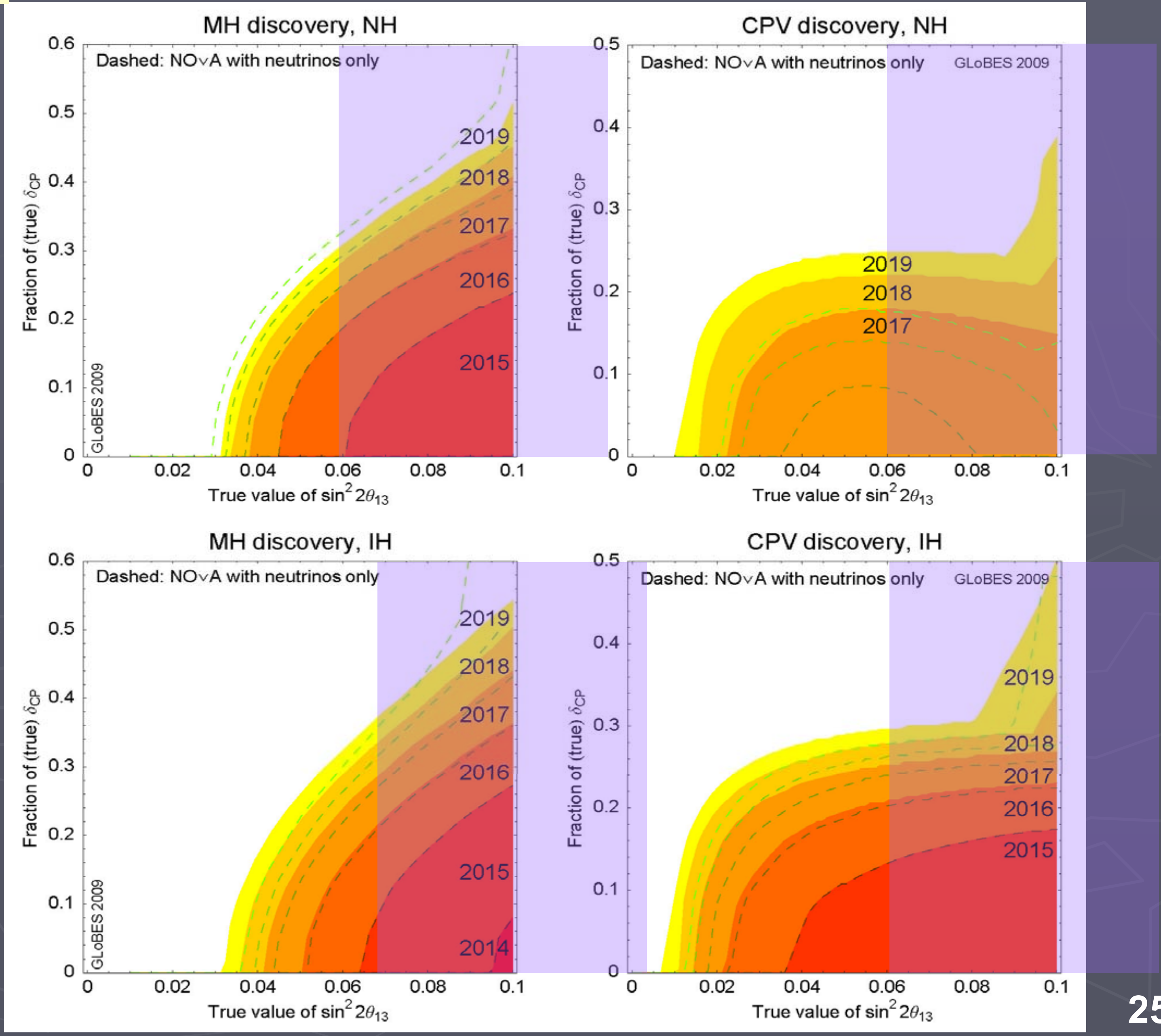
NB:
JPARC+HK+Okinoshima is missing due to uncertainty in schedule



T2K&Nova

Huber et al., arXiv:0907.1896v1

90%CL



Atmospheric ν @PINGU

Minakata@ν2012

Doug Cowen, NuSky, ICTP, June 2011

*IceCube → DeepCore → **PINGU***

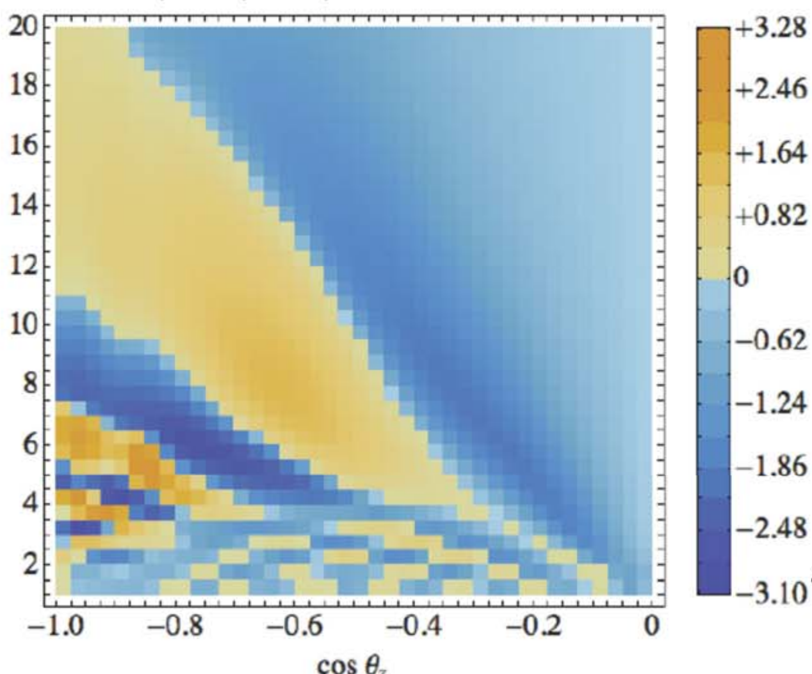
Akhmedov-Razzaque-Smirnov June 12

- *~20 additional strings within DeepCore*
- *lower threshold to few GeV*
- *~10 Mt effective volume*
- *construction within 1 yr, ~$25 M*

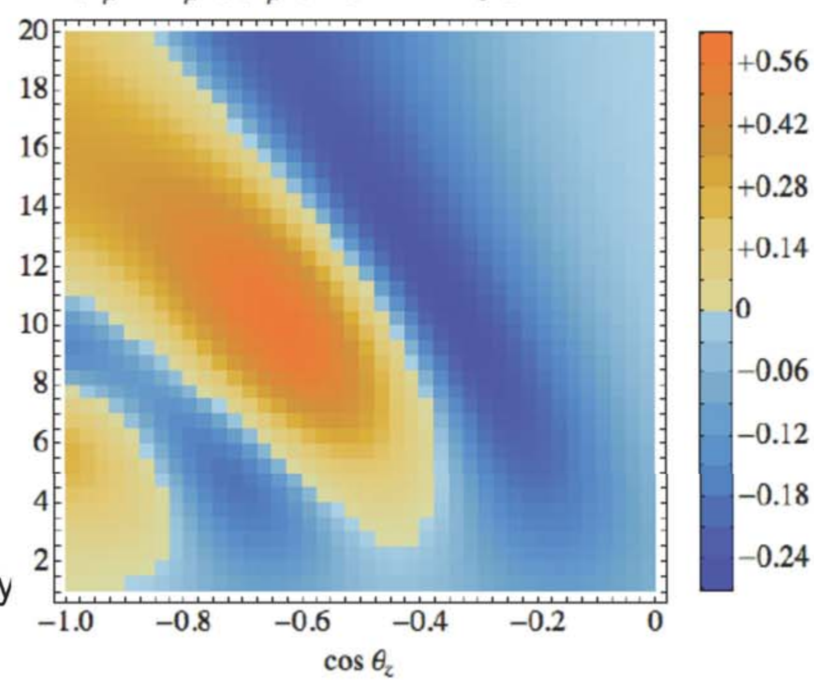
MH resolution
3σ-11σ in 5 years !

σ_E=2 GeV
σ_θ=11.25°

$(N_\mu^{IH} - N_\mu^{NH})/(N_\mu^{NH})^{1/2}$ [PINGU 1 yr]



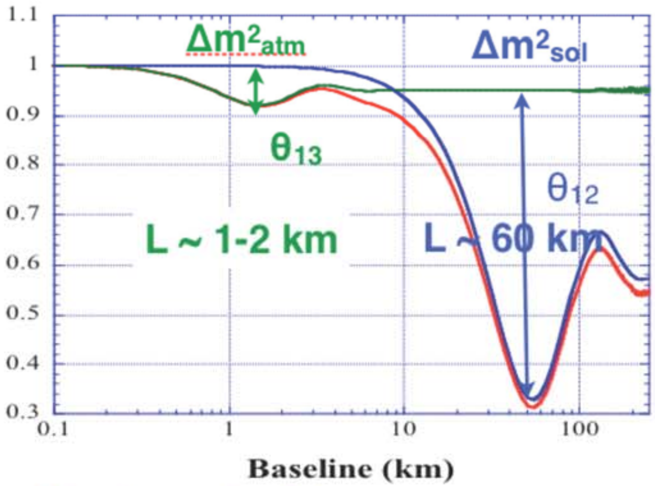
$(N_\mu^{IH} - N_\mu^{NH})/(N_\mu^{NH})^{1/2}$ [PINGU 1 yr] Smoothed

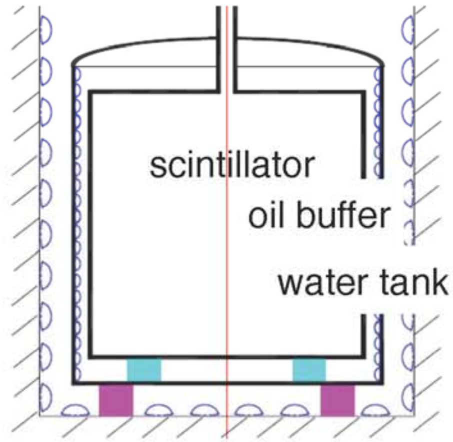


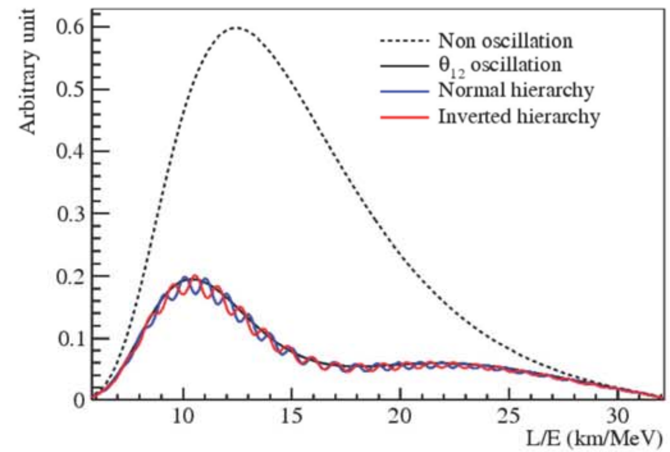
Mass Hierarchy and Reactor $\overline{\nu}_e$ Oscillation

Heeger@ν2012

Daya Bay II

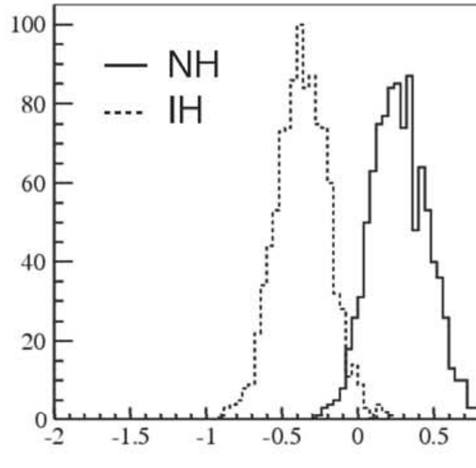






Site Investigation

Mass Hierarchy Sensitivity



50k events = 20 kton, 3 years
→ 96%
100k events
→ 3σ

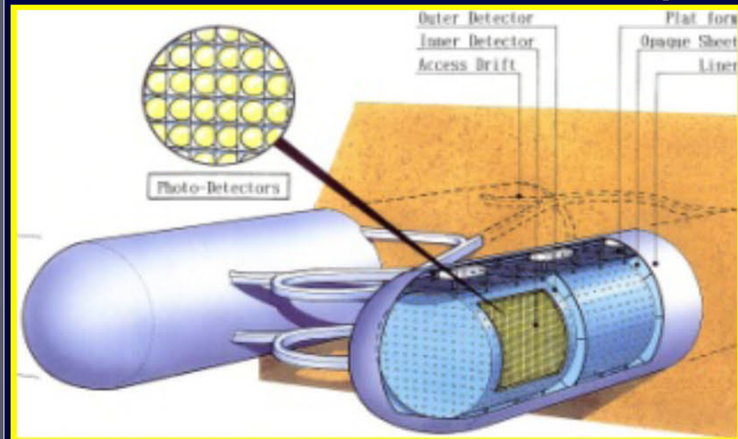
Ref: Y. Wang, J. Cao, et al
nuTurn 2012

Sub-1% precision 3-ν oscillation physics in Δm^2_{12}, Δm^2_{23}, and $\sin^2\theta_{12}$ possible

Future LBL plans using J-PARC

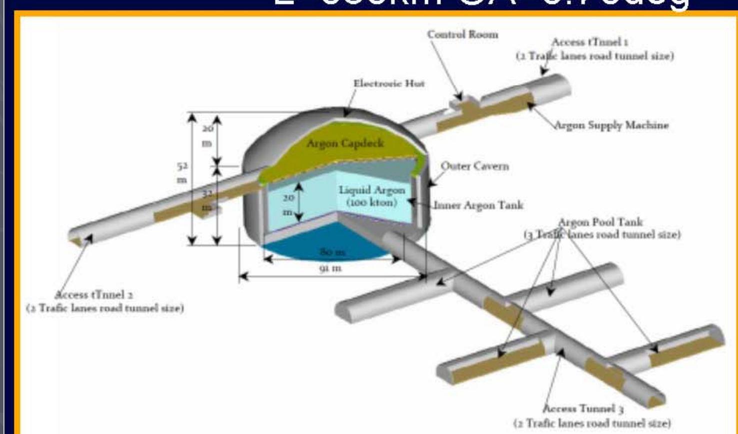
Current: T2K
J-PARC ~0.75MW
+ 50kt WC @ 295km 2.5°

J-PARC+HK @ Kamioka
L=295km OA=2.5deg

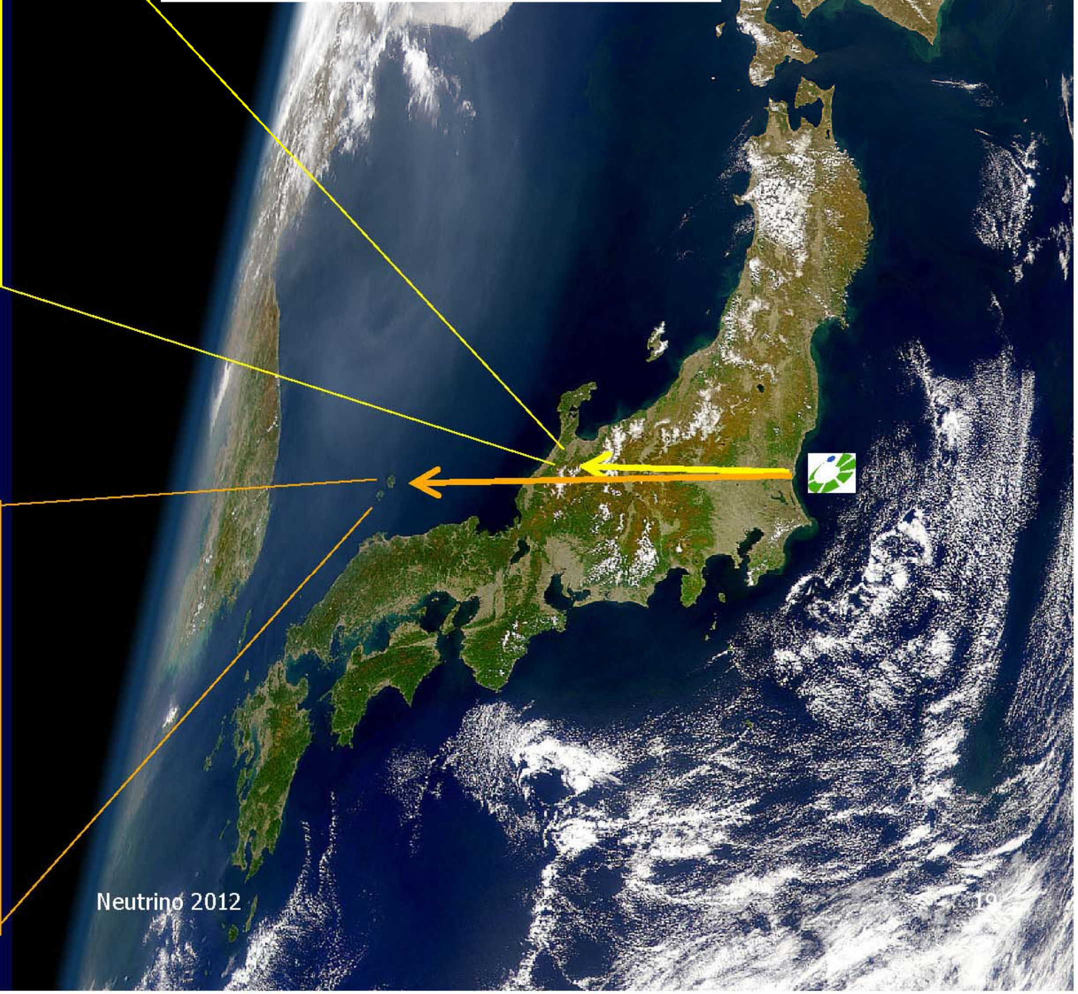


LoI: The Hyper-Kamiokande Experiment
arXiv:1109.3262v1

J-PARC+LAr @ Okinoshima
L=658km OA=0.78deg

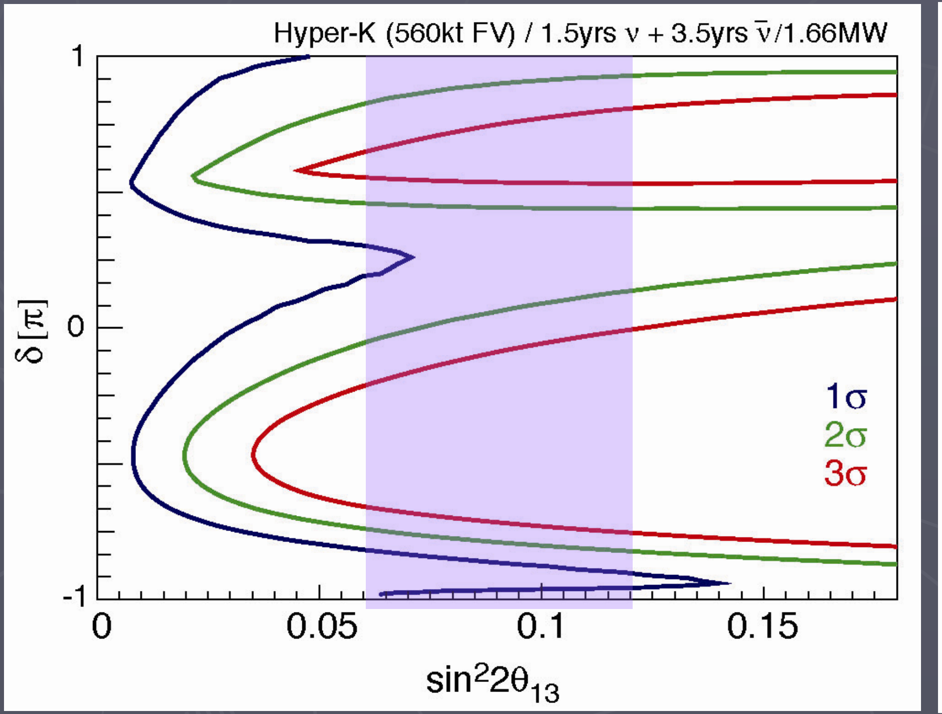


J-PARC P32 (LAr TPC R&D), arXiv:0804.2111

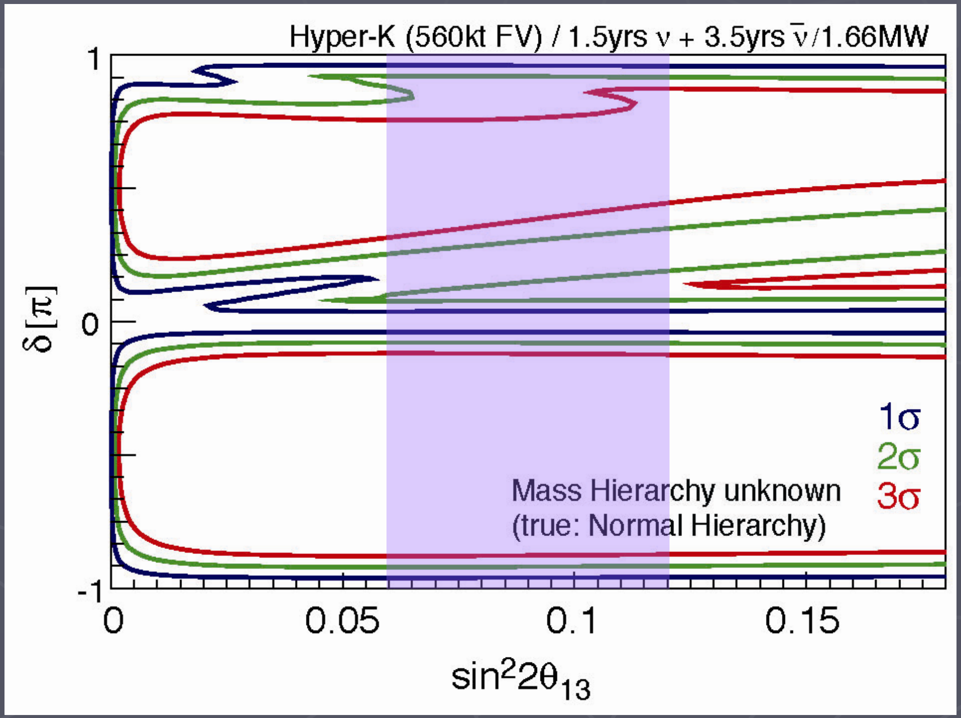


JPARC+HK

Mass Hierarchy



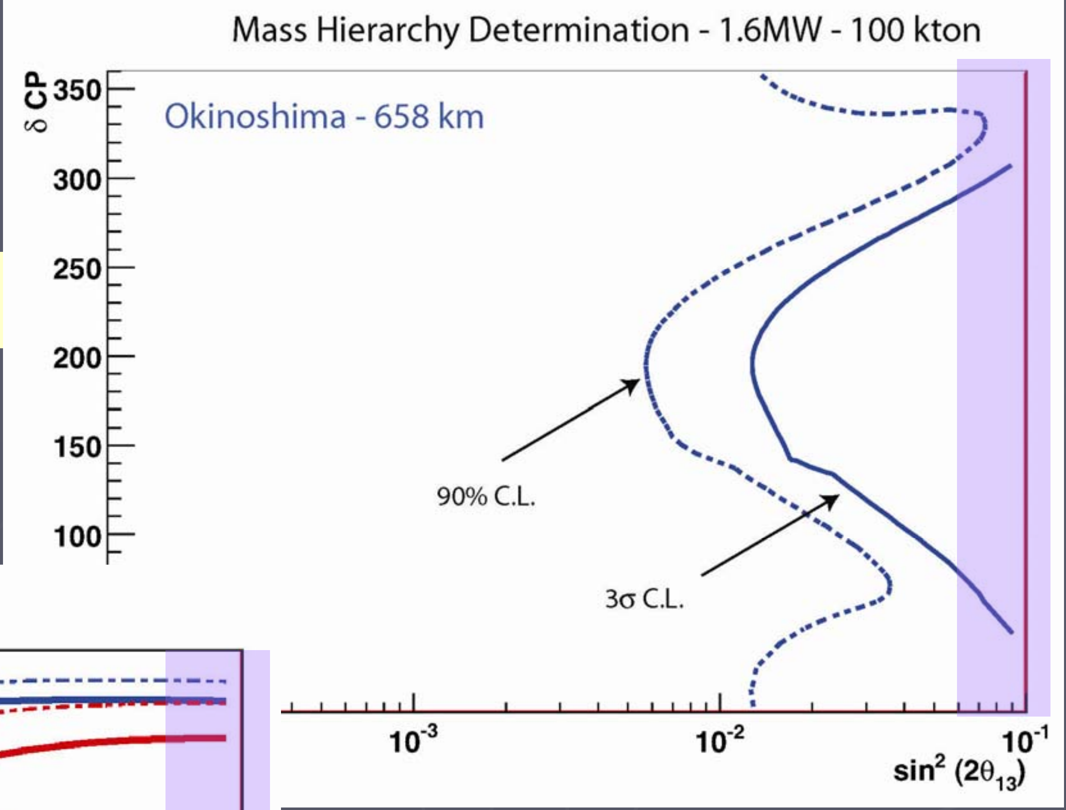
CPV

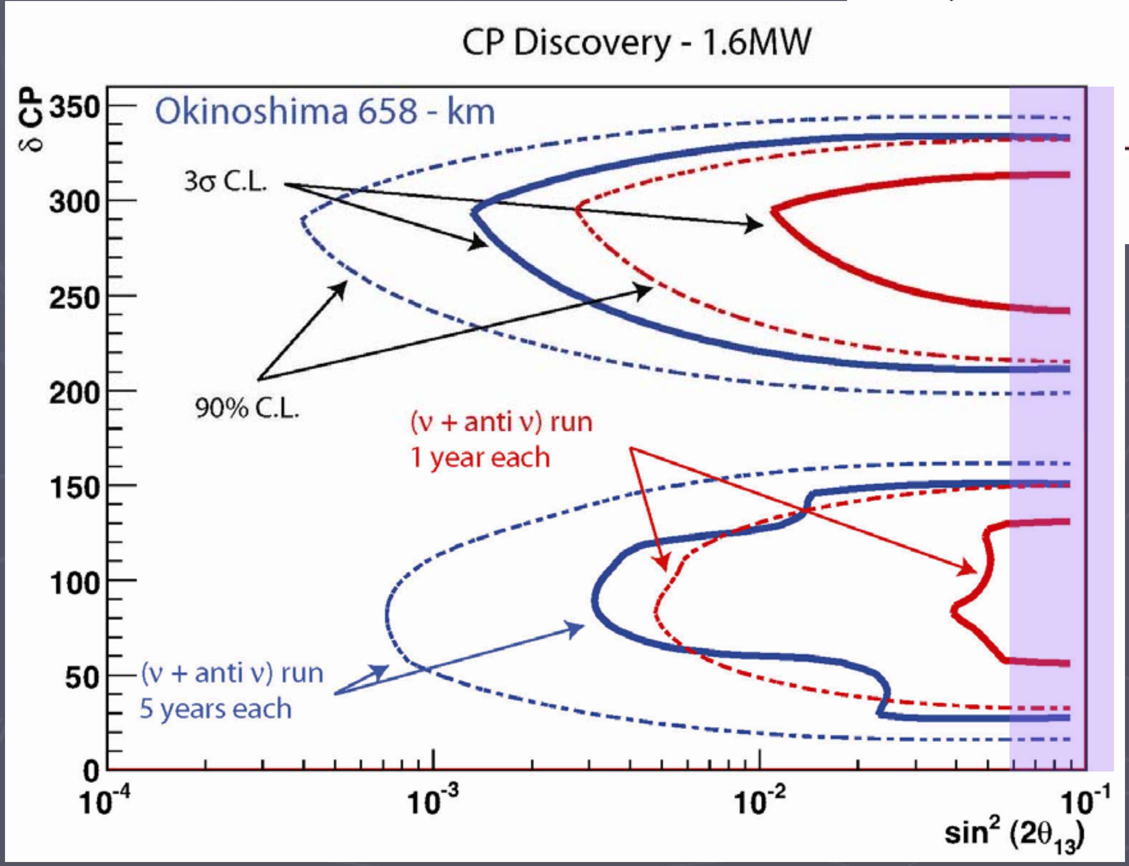


Hyper-Kamiokande LOI, arXiv:1109.3262v1 [hep-ex]

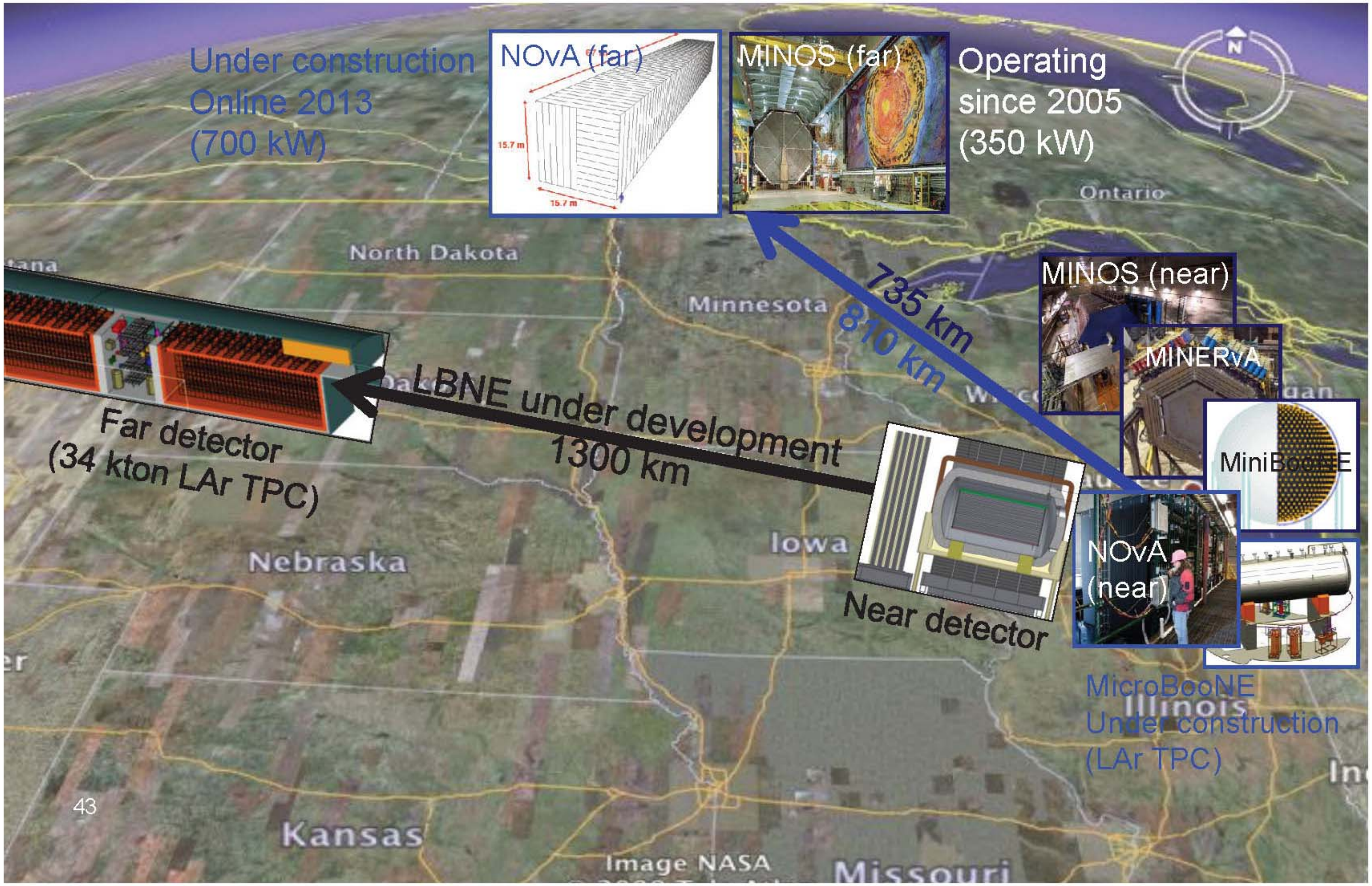
JPARC+LAr @Okinoshima

KEK_J-PARC-PAC2009-10





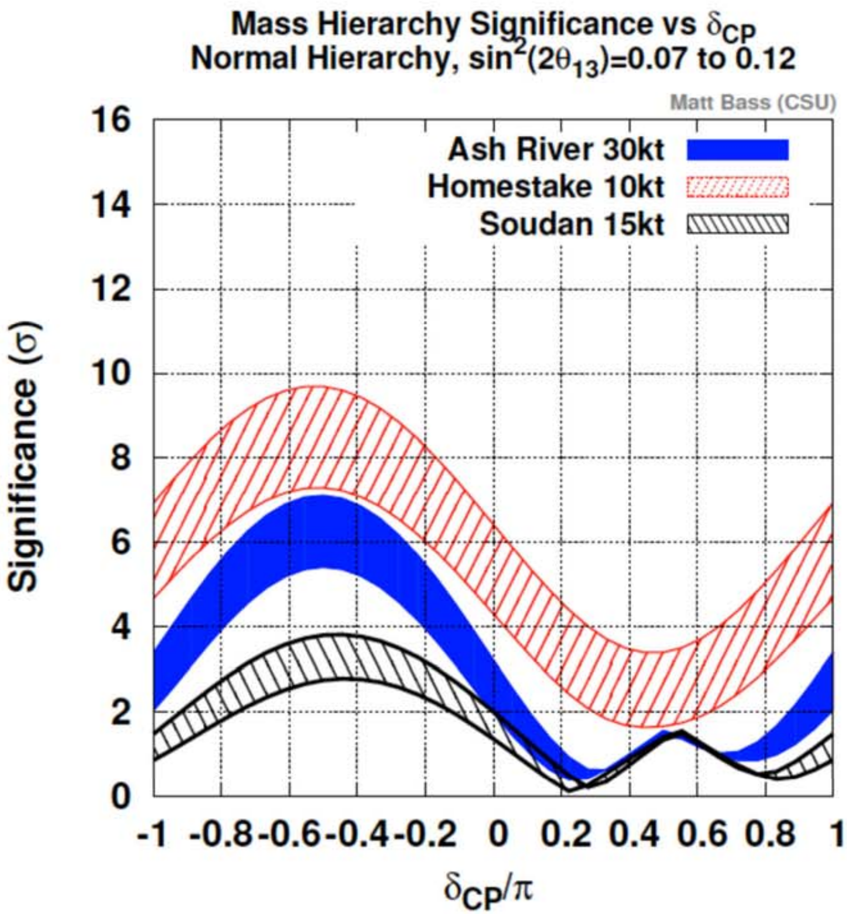
LBNE

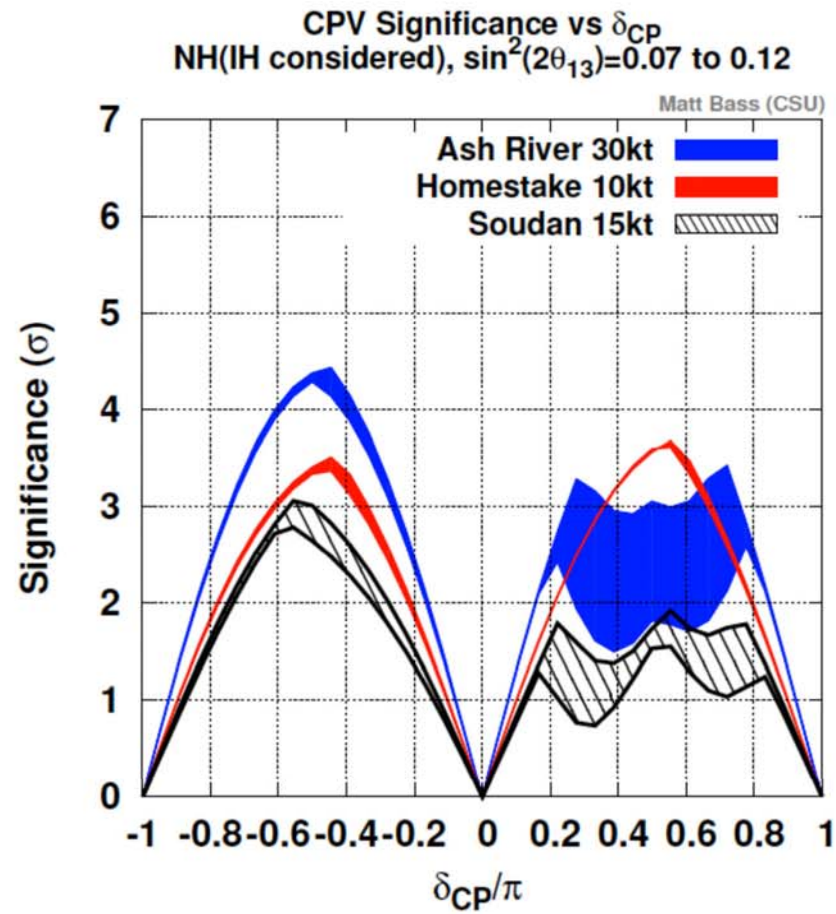


Under construction
Online 2013
(700 kW)
NOvA (far)
15.7 m
15.7 m
MINOS (far)
Operating
since 2005
(350 kW)
Ontario
North Dakota
Minnesota
735 km
810 km
MINOS (near)
MINERvA
MiniBooNE
LBNE under development
1300 km
Far detector
(34 kton LAr TPC)
Near detector
Iowa
Nebraska
NOvA
(near)
MicroBooNE
Under construction
(LAr TPC)
Illinois
43
Kansas
Image NASA
Missouri

Comparison of Phase 1 Sensitivities to Mass Hierarchy and CP Violation

Svoboda@ν2012





Preliminary: LBNE Physics Working Group

5 years neutrino + 5 years antineutrino

European sites: LAGUNA-LBNO

arXiv:1003.1921 [hep-ph]

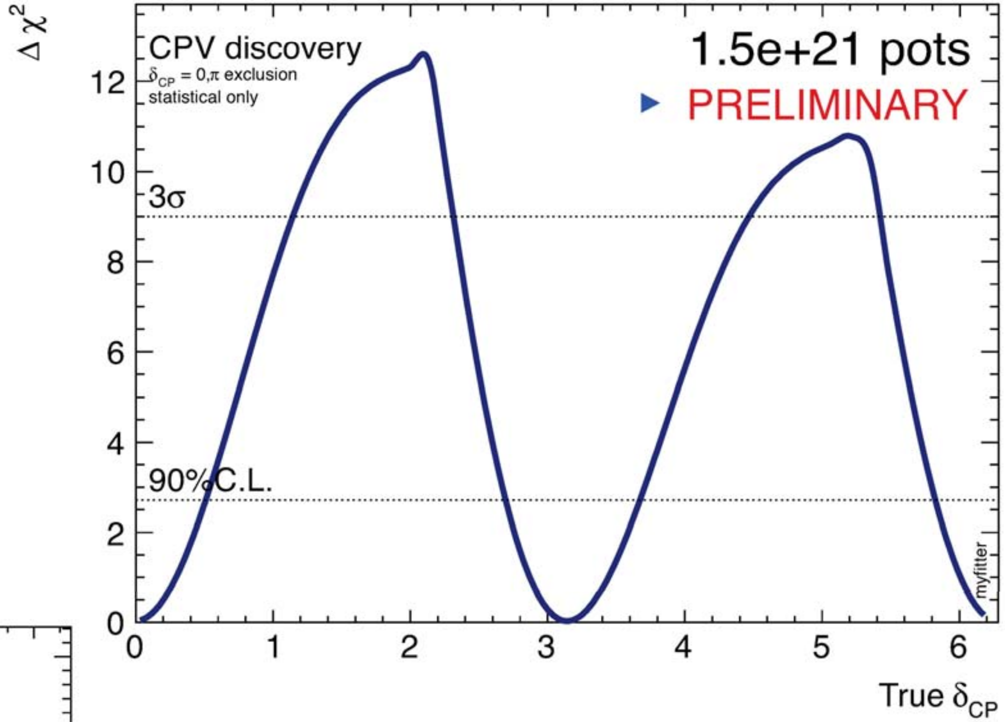
Three far sites considered in details

- Large Water Cerenkov Detector. CERN-Fréjus is a short baseline. It offers good synergy for enhanced physics reach with β-beam at γ=100
- Liquid Argon TPC & magnetized iron + Liquid Scintillator detectors CERN-Pyhäsalmi is the longest baseline. It offers good synergy for enhanced physics reach with a NF
- [CNGS is an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]

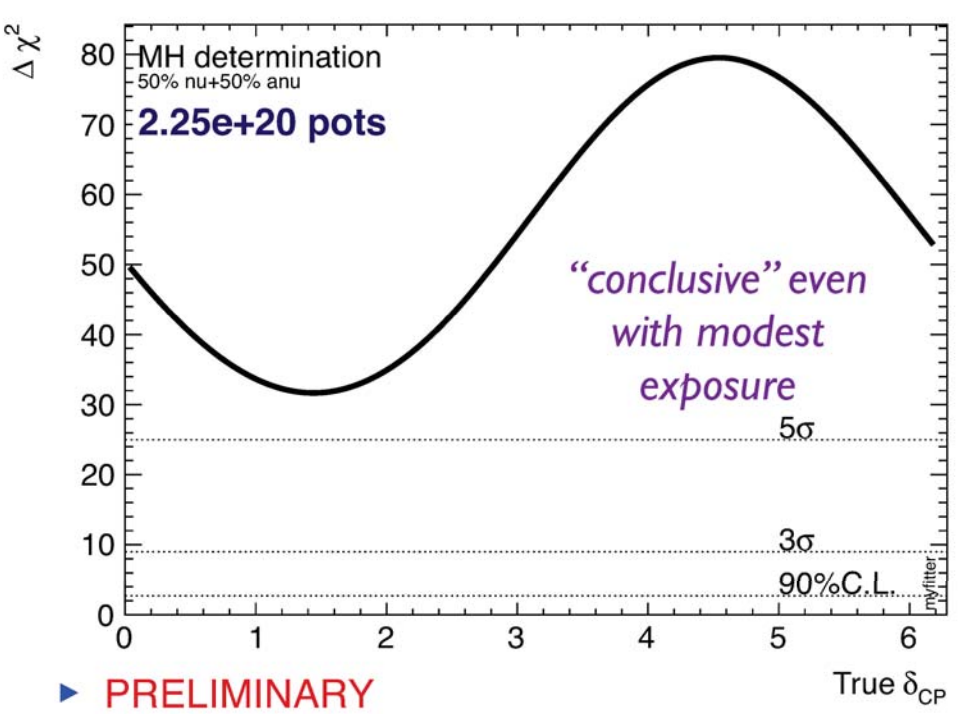
CP2PY

Rubbia@ν2012

CPV discovery



MH determination



4. Summary

- Three mixing angles have been determined : $\theta_{12} \simeq \pi/6$, $\theta_{23} \simeq \pi/4$, $\theta_{13} \simeq \pi/20$.
- The remaining parameters to be measured are sign(Δm^2_{31}), sign($\theta_{23} - \pi/4$) and δ .
- To determine δ, parameter degeneracy (particularly of mass hierarchy) must be resolved.
- Accelerator and reactor experiments are expected to determine sign(Δm^2_{31}) and δ in 10-20 years.

Backup slides

Global Fits:

Fogli, Lisi, Marrone, Montanino , Palazzo, Rotunno
Phys.Rev. D86 (2012) 013012
arXiv:1205.5254

Global Fit

Forero, Tortola, Valle
arXiv:1205.4018

Rotunno '12

parameter	best fit $\pm 1\sigma$	best fit $\pm 1\sigma$
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	7.62 ± 0.19	$7.54^{+0.26}_{-0.22}$
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.43^{+0.07}_{-0.09}$ $-(2.42^{+0.07}_{-0.10})$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	$0.307^{+0.018}_{-0.016}$
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	$0.398^{+0.030}_{-0.026}$ $0.408^{+0.035}_{-0.030}$
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	$0.0245^{+0.0034}_{-0.0031}$ $0.0246^{+0.0034}_{-0.0031}$
δ	$(0.83^{+0.54}_{-0.64})\,\pi$ 0.07π [a]	$(0.89^{+0.29}_{-0.44})\pi$ $(0.90^{+0.32}_{-0.43})\pi$

3 flavor atmospheric ν oscillations

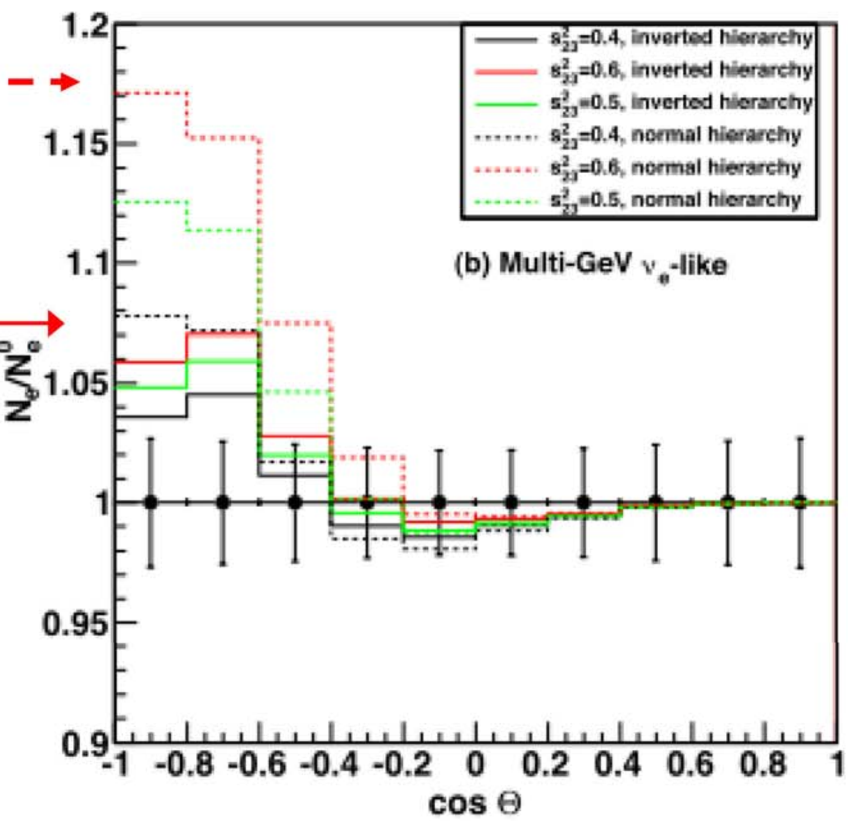
$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1)$$

$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$

$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1)$$

Normal Hierarchy

Inverted Hierarchy



10 years HK
(5.6Mt year)
= 248year SK