ICHEP 2014 VALENCIA

37th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

2 - 9 - JULY - 2014 - VALENCIA

Neutrino Phenomenology:

Highlights of oscillation results and future prospects

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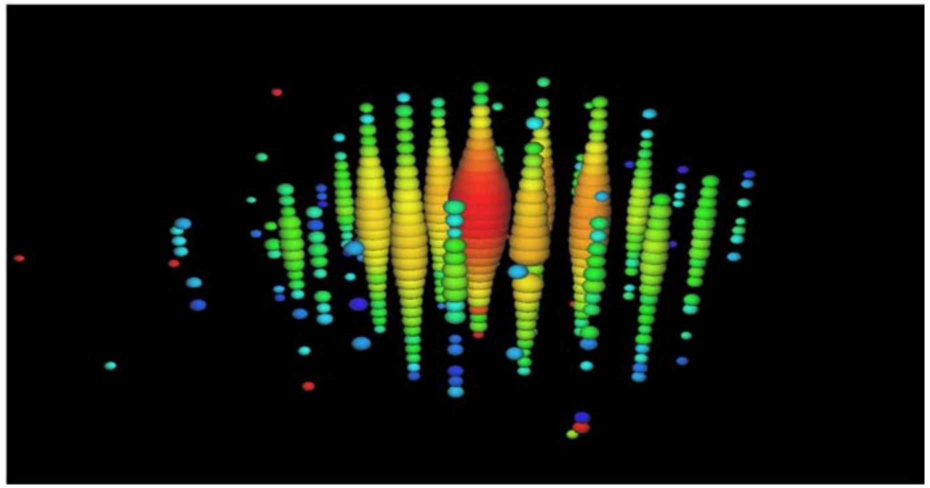
Evolution of Neutrino Physics

- **The impossible dreams**



- **To the unreachable stars**
  - First detection of ultra-high energy neutrinos of extra-terrestrial origin by the ICECUBE experiment



Neutrino Oscillations

- Neutrinos are weakly interacting unlike…
- But they mix with their friends..

So much so that they get confused who they are …

Neutrino Oscillations

- If neutrinos have mass then **Flavour states** $\nu_\alpha = \Sigma_i U_{\alpha i} \nu_i$ **Mass states**
- This leads to neutrino flavour oscillation in vacuum

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

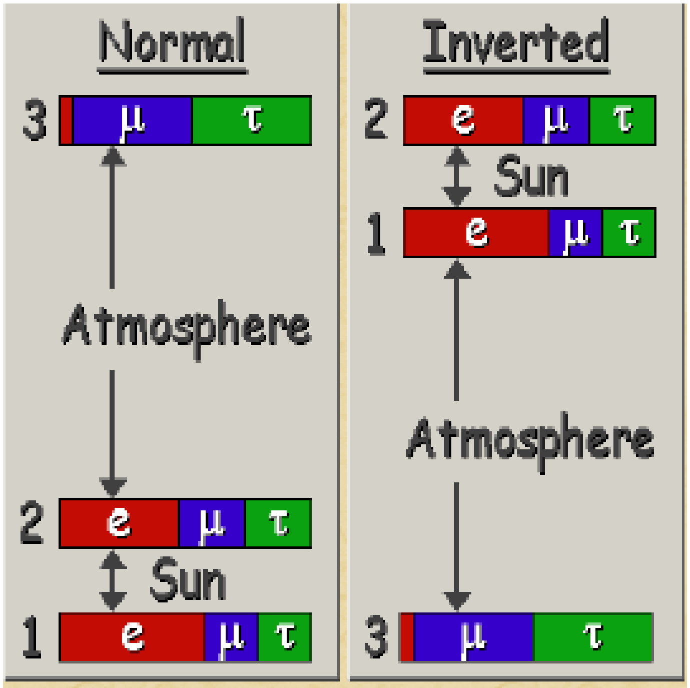
- $\Delta_{ij} = \Delta m^2_{ij} L / 4E$ $\quad$ $\Delta m^2_{ij} = m^2_i - m^2_j$ $\quad$ $\bar{\nu} : U \to U^*$
- Interaction with matter modifies the mass, mixing and probability
- Probabilities are obtained by solving propagation equation in matter
- Depends on density profile of matter

Three Neutrino Parameters

- 3 masses, 3 mixing angles and 1 Dirac +2 Majorana phases

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

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

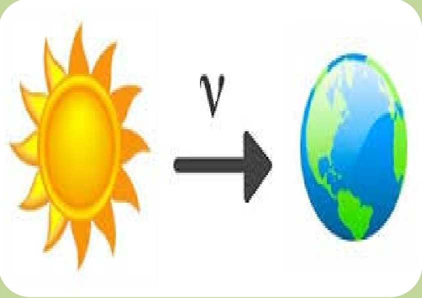


- Oscillation experiments sensitive to mass squared differences $\Delta m^2_{21} = m^2_2 - m^2_1 , \Delta m^2_{31} = m^2_3 - m^2_1$

- Two possible mass orderings

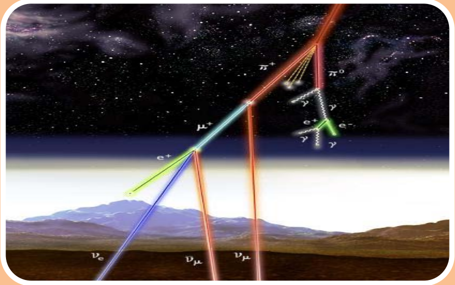
- Oscillation experiments not sensitive to Majorana phases

A snapshot of the oscillation experiments



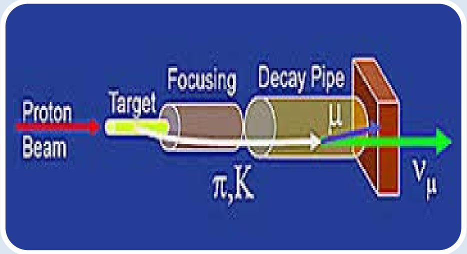
Solar Neutrinos :

Cl , Gallex/GNO/SAGE ,
SK , SNO, Borexino



Atmospheric Neutrinos

Superkamiokande



Accelerator Neutrinos

K2K, MINOS ,T2K

Reactor Neutrinos

KamLAND,Palo-Varde
CHOOZ,Double-CHOOZ

Global analysis of data

$\theta_{12}, \Delta m^2_{21}, \theta_{13}$ Solar + KamLAND

$\Delta m^2_{31}, \theta_{13}$ Reactor

$\Delta m^2_{31}, \theta_{23}, \theta_{13}, \delta_{CP}$ Atmospheric +LBL

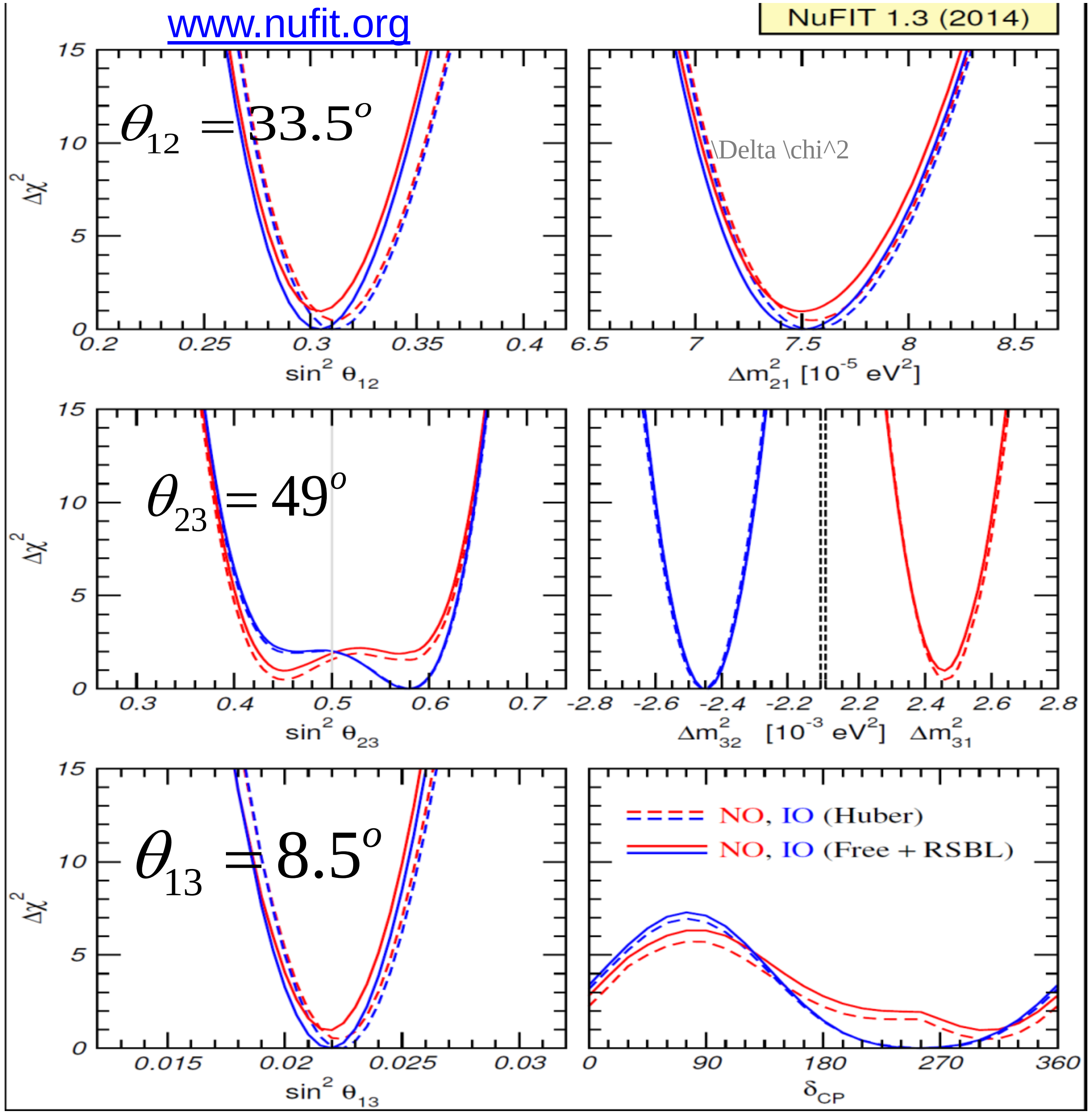
Interplay among different sectors
because of θ_{13}

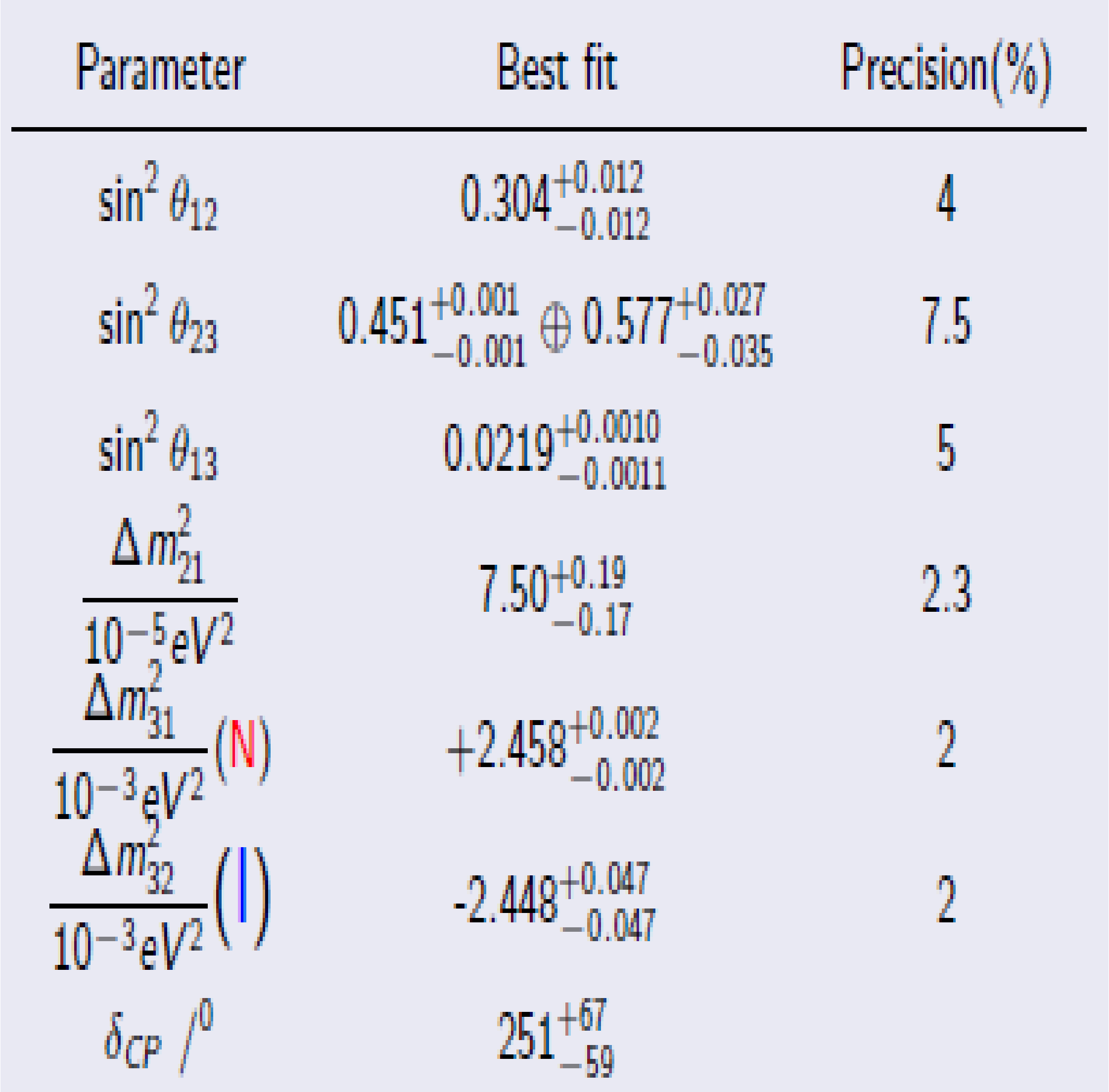
New data in 2014

- New data from reactor experiments Double-Chooz, Daya-bay, Reno
- Excess around 5 MeV in RENO and Double-Chooz
- New data from ICECUBE, MINOS+ , SK4 atmospheric
- SK4 1306 day energy and zenith spectrum for solar
- T2K disappearance data

Talks by M. Schiozawa , H. Sekiya (SK), J. Haser (Double-CHOOZ, W. Wang(Daya-Bay), in ICHEP 2014

Status of oscillation parameters (post- Nu2014)



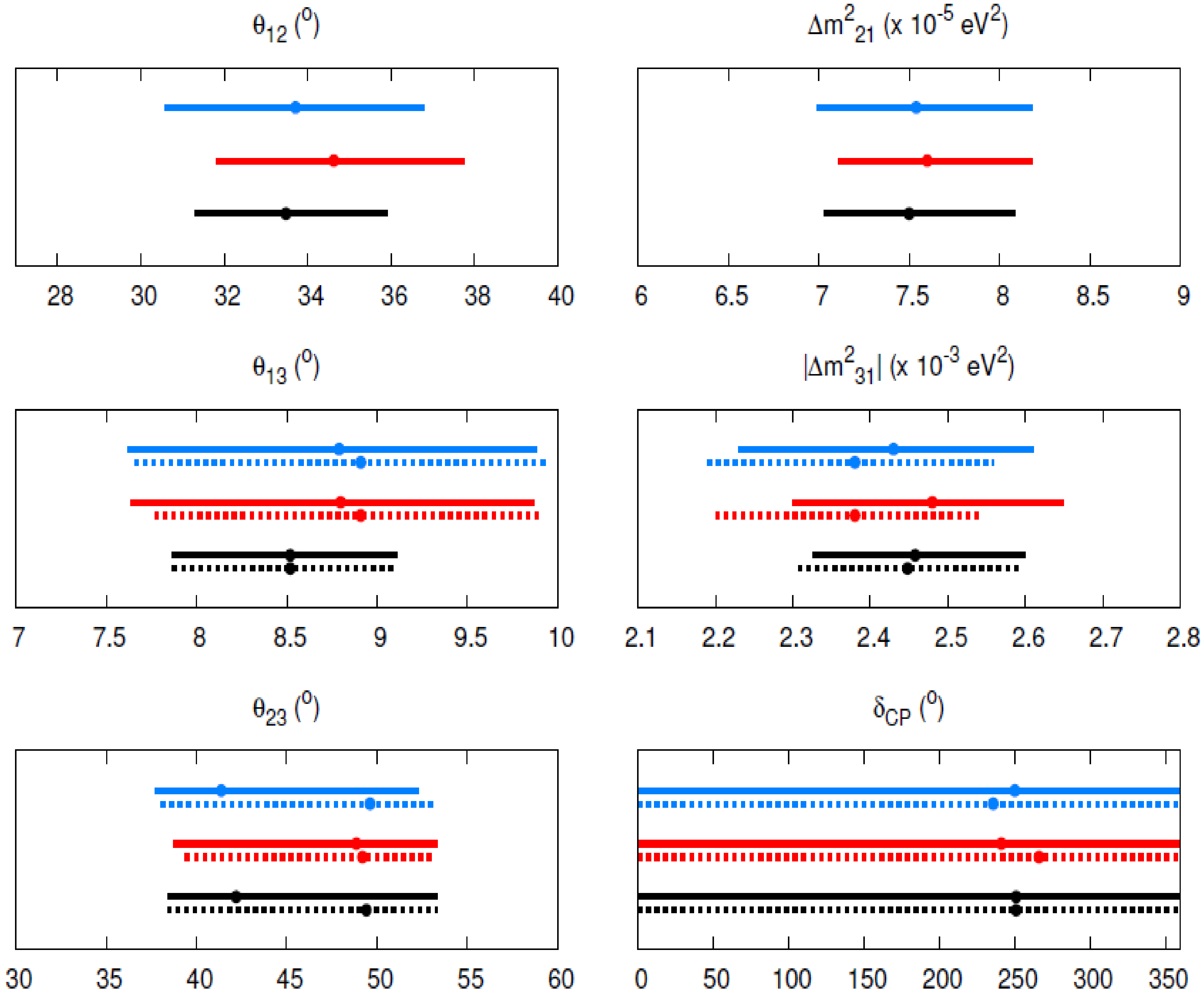


Parameter	Best fit	Precision(%)
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	4
$\sin^2\theta_{23}$	$0.451^{+0.001}_{-0.001} \oplus 0.577^{+0.027}_{-0.035}$	7.5
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0011}$	5
$\frac{\Delta m^2_{21}}{10^{-5}eV^2}$	$7.50^{+0.19}_{-0.17}$	2.3
$\frac{\Delta m^2_{31}}{10^{-3}eV^2}$(N)	$+2.458^{+0.002}_{-0.002}$	2
$\frac{\Delta m^2_{32}}{10^{-3}eV^2}$(I)	$-2.448^{+0.047}_{-0.047}$	2
$\delta_{CP}\ /^0$	251^{+67}_{-59}	

No hierarchy sensitivity

$$\chi^2(NH) - \chi^2(IH) < 1$$

Oscillation parameters at a glance (2014)



🟦	1312.2878
🟥	1405. 7540
⬛	Nu-fit

Solid line : NH
Dashed line: IH

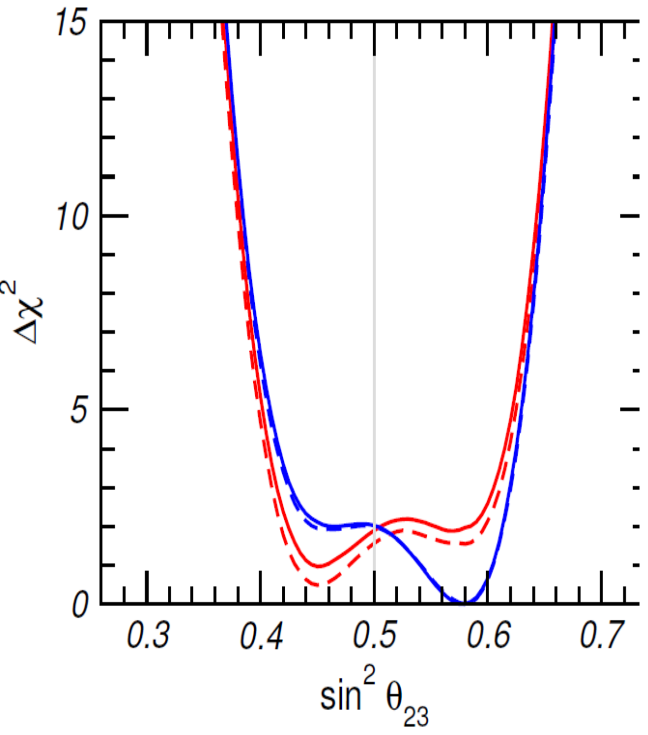
Best-fit values and 3σ range

Analysis by different groups are in agreement excepting θ_{23}

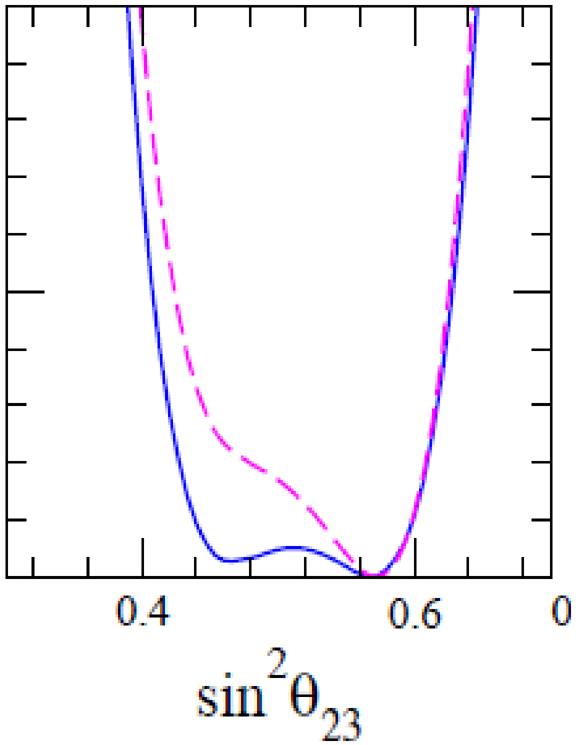
Talk by M. Tortola , ICHEP 2014

Status of θ_{23}

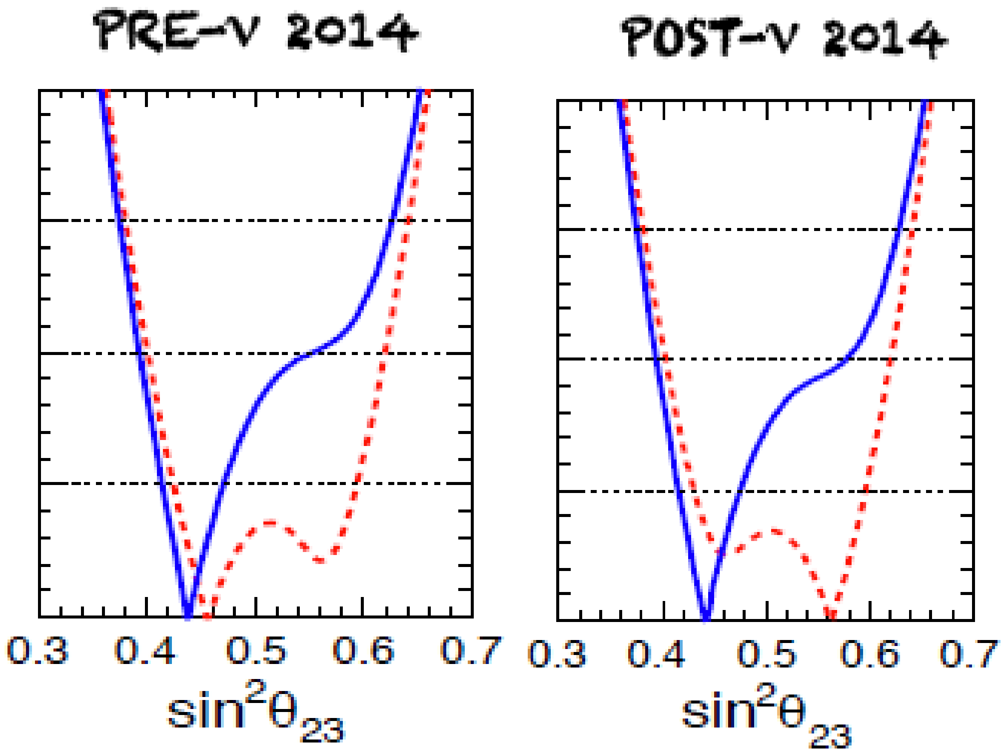
Nu-fit 2014



Forero et al 1405.7540



Capozzi et al. 1312.2878



Global best-fit at 2nd octant and IH

NH : local best-fit at 1st octant

NH and IH separate fit

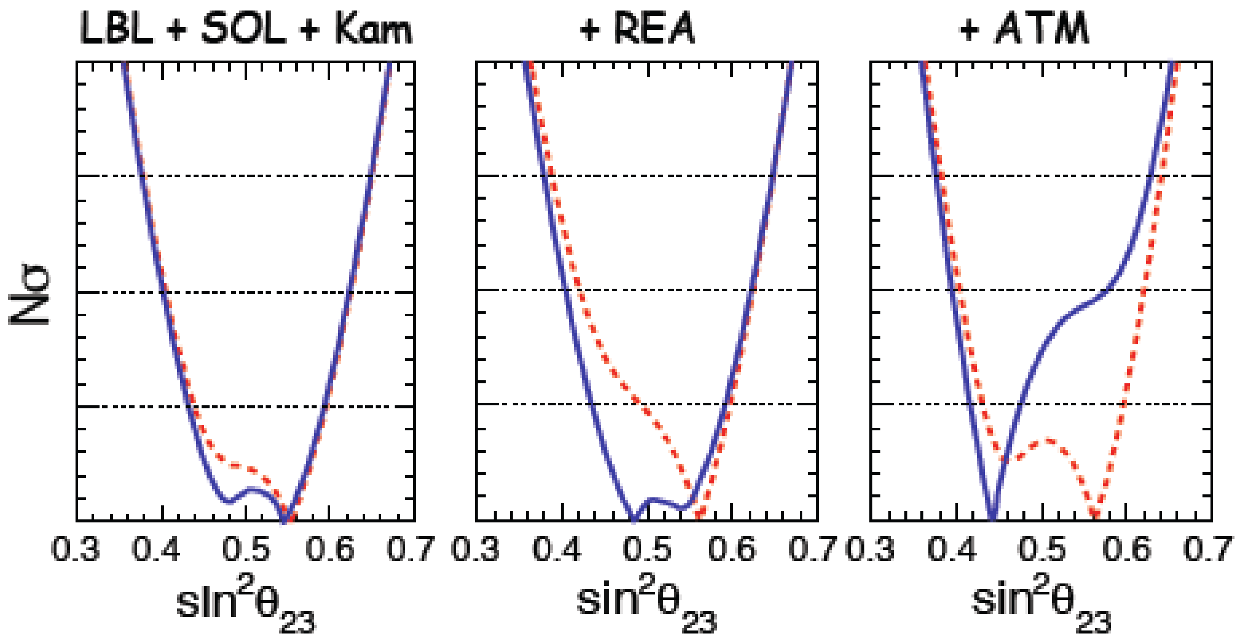
Best-fit at 2nd octant for both NH and IH

NH and IH separate fit

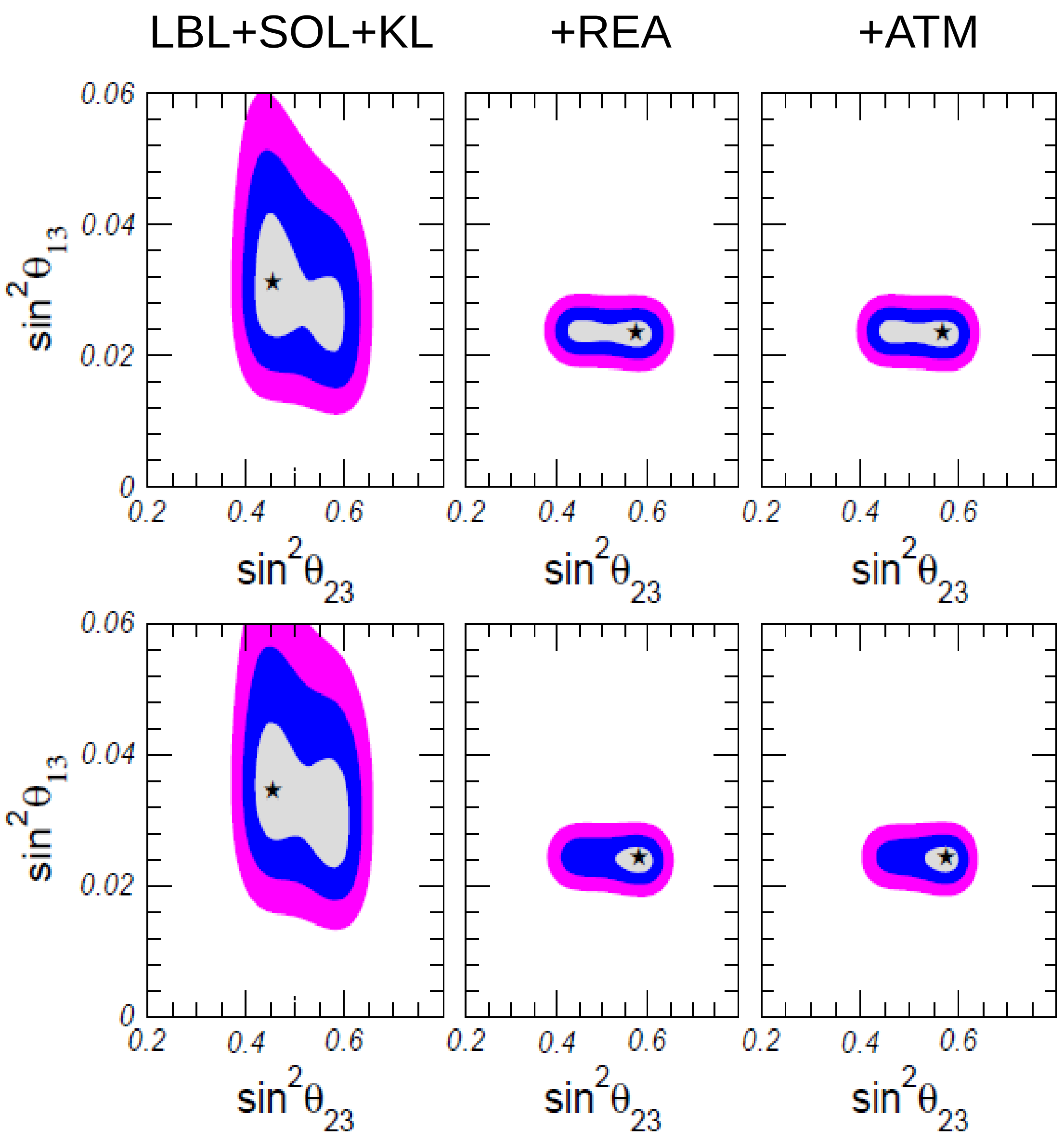
Best-fit in 2nd octant for IH post Neutrino 2014

Status of θ_{23} : Interplay of data

Capozzi et al. 1312.2878



Forero et al 1405.7540

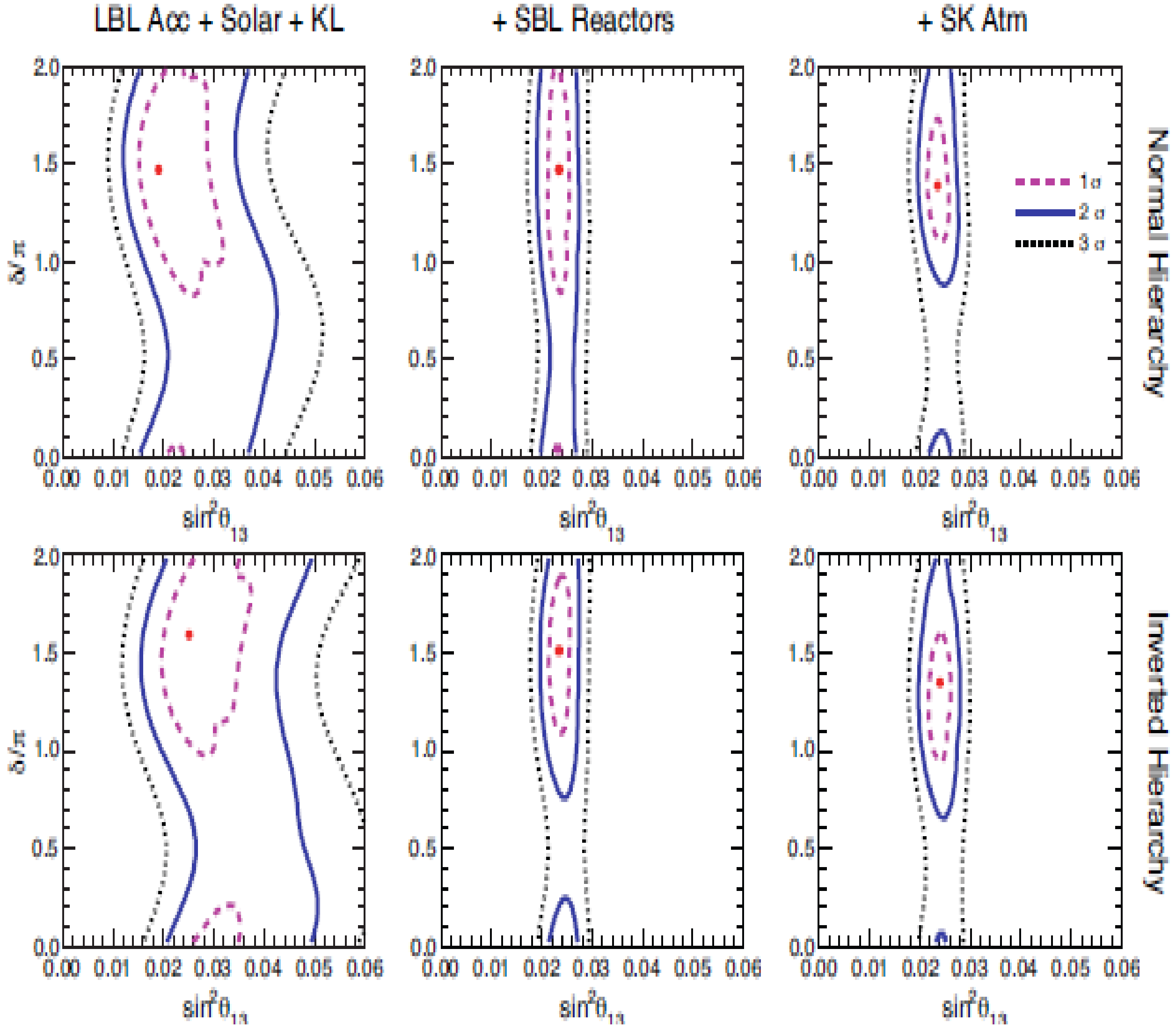


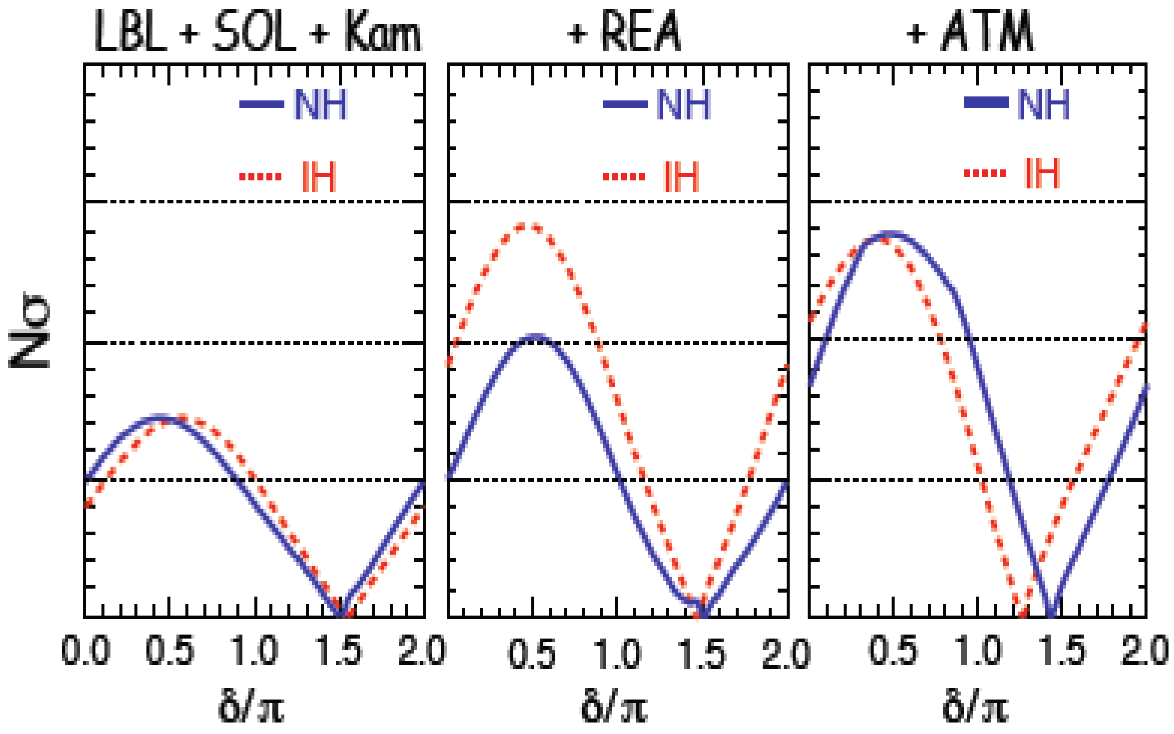
Preference for lower octant for NH driven by SK atm

θ_{23} is still unstable

Status of δ_{CP} : interplay of different experiments

Capozzi et al. 1312.2878





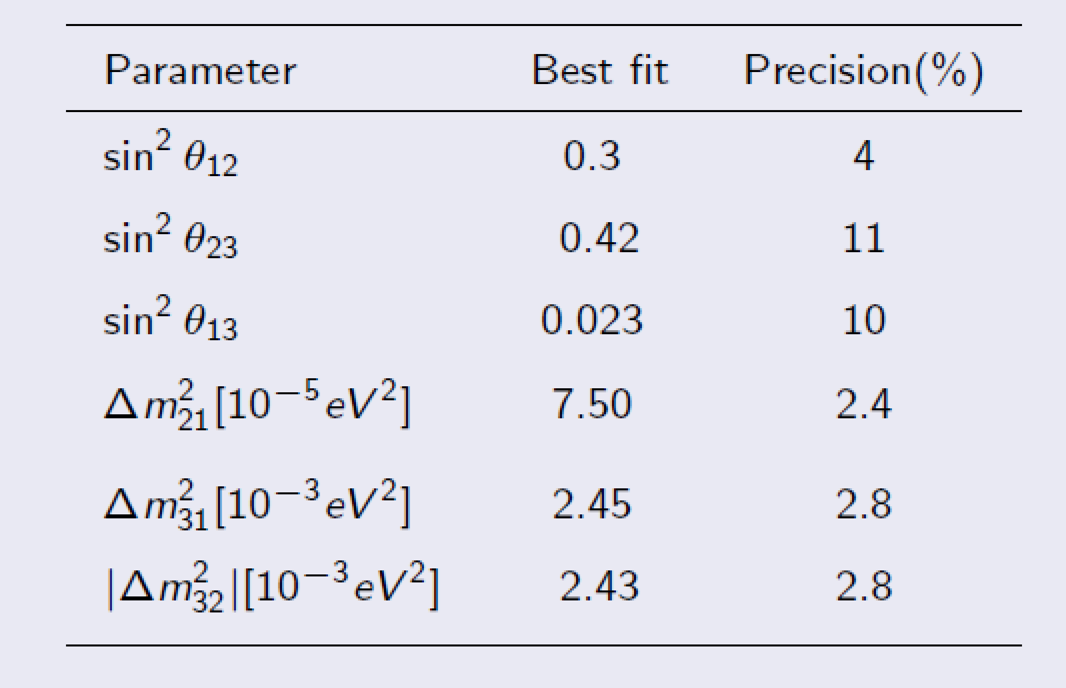
Continued hint for $\delta_{CP} \sim 1.5\pi$

Driven mainly by T2K appearance data

Also SuperK atmospheric data

Progress since ICHEP – 2012

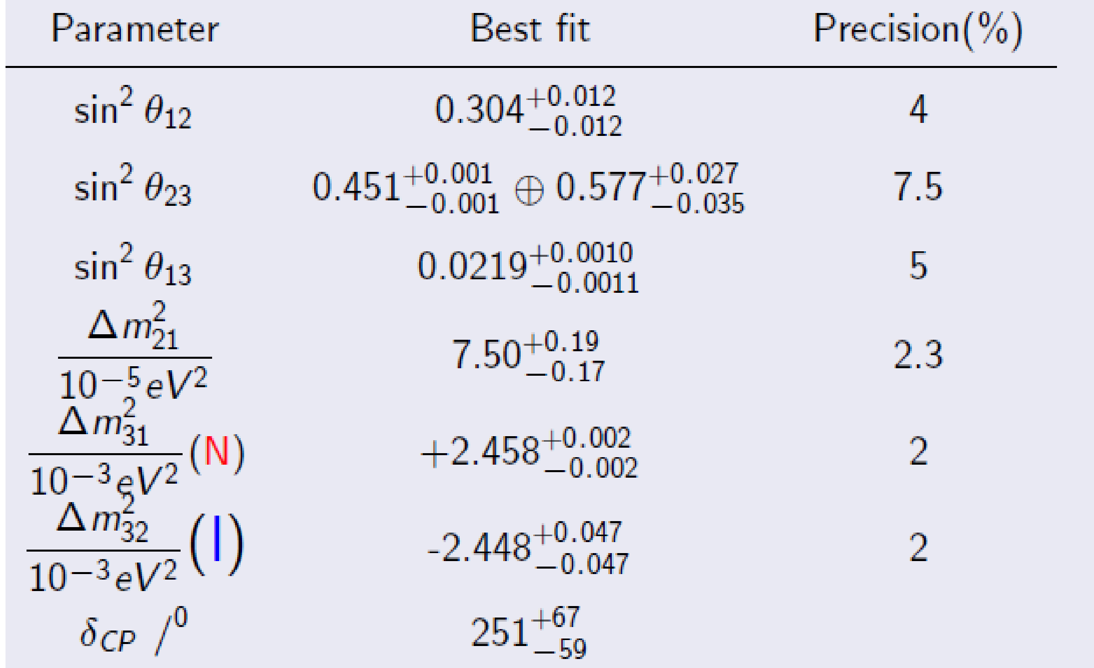
ICHEP 2012



Parameter	Best fit	Precision(%)
$\sin^2\theta_{12}$	0.3	4
$\sin^2\theta_{23}$	0.42	11
$\sin^2\theta_{13}$	0.023	10
$\Delta m^2_{21}[10^{-5}eV^2]$	7.50	2.4
$\Delta m^2_{31}[10^{-3}eV^2]$	2.45	2.8
$\lvert\Delta m^2_{32}\rvert[10^{-3}eV^2]$	2.43	2.8

M.C. Gonzalez-Garcia , ICHEP 2012

ICHEP 2014



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Nu-fit 2014

Improvement in precision of θ_{13}

Improvement in precision of θ_{23}

Hint for $\delta_{CP} \sim 1.5\pi$

Precision still not as good as quark sector

The main unknowns

The absolute mass scale of neutrinos

Are neutrinos their own antiparticles

Experiments to probe this

Talk by Manfred Lindner

The neutrino mass hierarchy ✡

The octant of the 2-3 mixing angle

CP violation in the lepton sector

Are there sterile neutrinos

Can be probed in Oscillation Experiments

What is the mechanism of neutrino mass generation

What explains the pattern of neutrino mixing

Is low energy CP violation related to leptogenesis

Note on referencing: Some current results, initial works and ICHEP talks .Not complete (My sincere apologies) , http://www.nu.to.infn.it/

Future Experiments for hierarchy, octant and CP

Current Generation Superbeam Experiments

T2K : Tokai to Kamioka, 295 km . 0.76 GeV , 0.75 MW , Detector: SuperK ,taking data

NOvA : FNAL to Ash River , 810 km, 1.7 GeV, 0.7 MW, 14 kt TASD detector, commissioning

Next generation Superbeam experiments

T2HK: JPARC to Kamioka, detector: HyeperK, 1.6 Mw

LBNO : CERN to Phyasalami , 2290 km, 0.77MW, Detector: 24 kt LArTPC

LBNE : FNAL-LEAD , 1300km, 0.7 MW, Detector ,Detector: 34 kt LiqArTPC

ESS: European Spallation source Linac , configurations under study , 540 km, 2 GeV

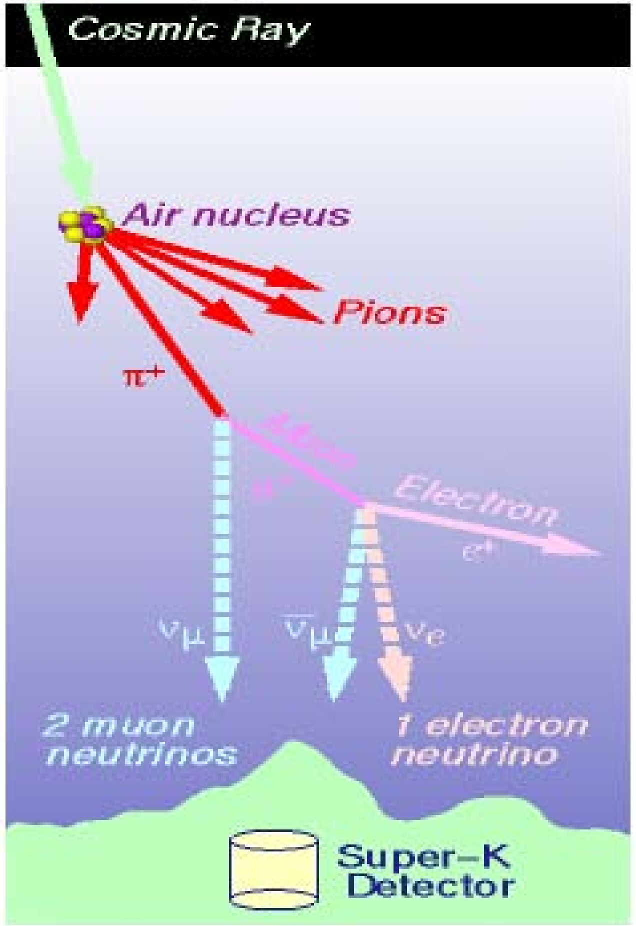
Proton decay at rest experiments

DAE δDALUS : low energy, low distance (50 MeV, 20 km)

Reactor Experiments

JUNO (China), RENO50 (Korea) , reactor neutrinos, 50 km

Future Atmospheric Neutrino Experiments



Atmospheric neutrinos
Provide a broad L/E band

- Magnetized Iron Detector (Prototype: INO)
  - ▻ 50 - 100 kT
  - ▻ Excellent Muon energy measurement, direction reconstruction and & charge discrimination capability
  - ▻ Can determine the neutrino energy through Hadron shower reconstruction
- Megaton Water Cerenkov Detector (HK, MEMPHYS)
  - ▻ Large volume (~ Mega Ton)
  - ▻ SK-type detector with no charge ID
  - ▻ Both electron and muon events can be used
- Liquid Argon detector (ICARUS) ▻ Time projection chamber
  - ▻ Both electron and muon events can be used, charge ID for both?
- (IceCube, PINGU)
  - ▻ Huge Volume (Multi-Mton)

The survival and oscillation probabilities

In matter of constant density the survival and conversion probabilities

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \text{sub leading terms}$$

Cerverra et al.,Kimura et al .
Freund et al
Akhmedov et al ,

Talk by Yasuda, ICHEP 2014

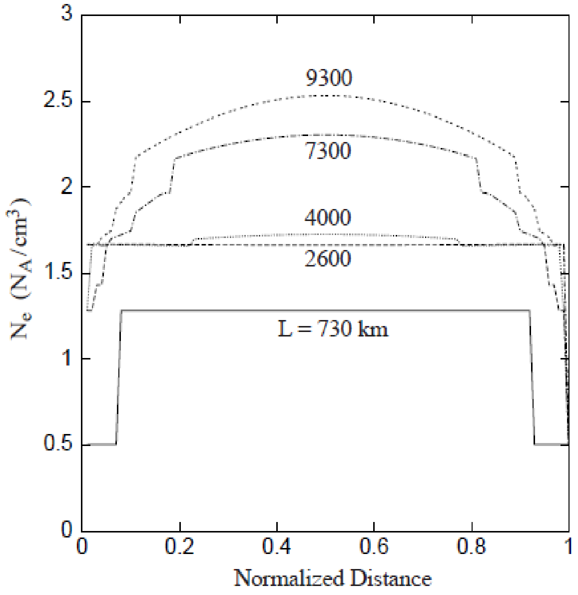
$$P_{\mu e} \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\hat{A}-1)\Delta}{(\hat{A}-1)^2}$$

$$+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{cp}) \frac{\sin(\hat{A}-1)\Delta}{(\hat{A}-1)} \frac{\sin(\hat{A}\Delta)}{\hat{A}}$$

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

$$\Delta = \Delta m^2_{31} L / 4E$$

$$\alpha = \Delta m^2_{21} / \Delta m^2_{31}$$



Expanded in small parameters α and $\sin^2\theta_{13}$

Also Asano & Minakata,2011, Agarwalla et al.2013

$\hat{A} = \pm 2\sqrt{2} G_F n_e E / \Delta m^2_{31}$ ⟶ Changes sign with $\text{sgn}(\Delta m^2_{31})$ ⟶ Hierarchy sensitivity

\+ for neutrinos
\- for antineutrinos

$P_{\mu e}(\Delta, \delta_{CP}) = P_{\mu e}(-\Delta, \delta'_{CP})$ ⟶ Hierarchy -δ_{CP} degeneracy

Minakata, Nunokawa (2001)

Hierarchy sensitivity: T2K/NOVA

Median Sensitivity using
Asimov data set (no fluctuations)

$$\Delta\chi^2 = \chi^2(NH) - \chi^2(IH)$$

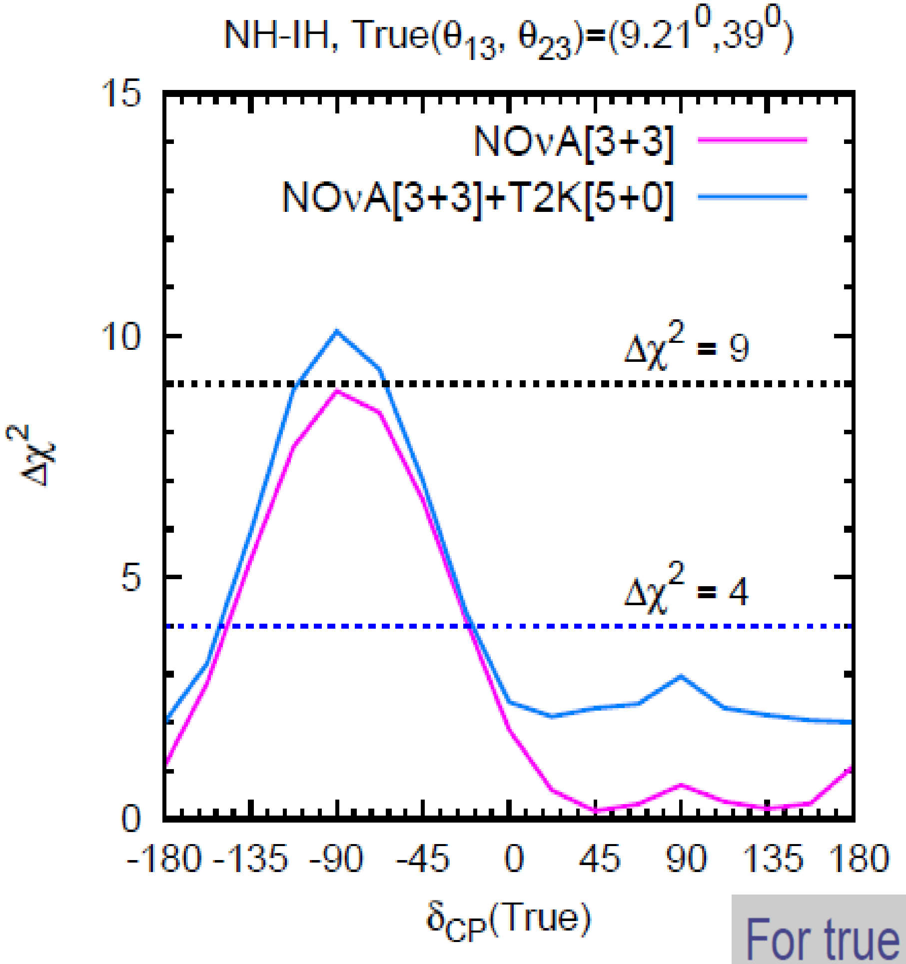
Simulated
Exptl data

Theory
Marginalized
over relevant
parameters

For statistical issues see Talk
by M. Blennow ICHEP 2014

Degeneracy for NH +90 & IH -90

For true NH $(-180^o < \delta_{CP} < 0)$ is favourable



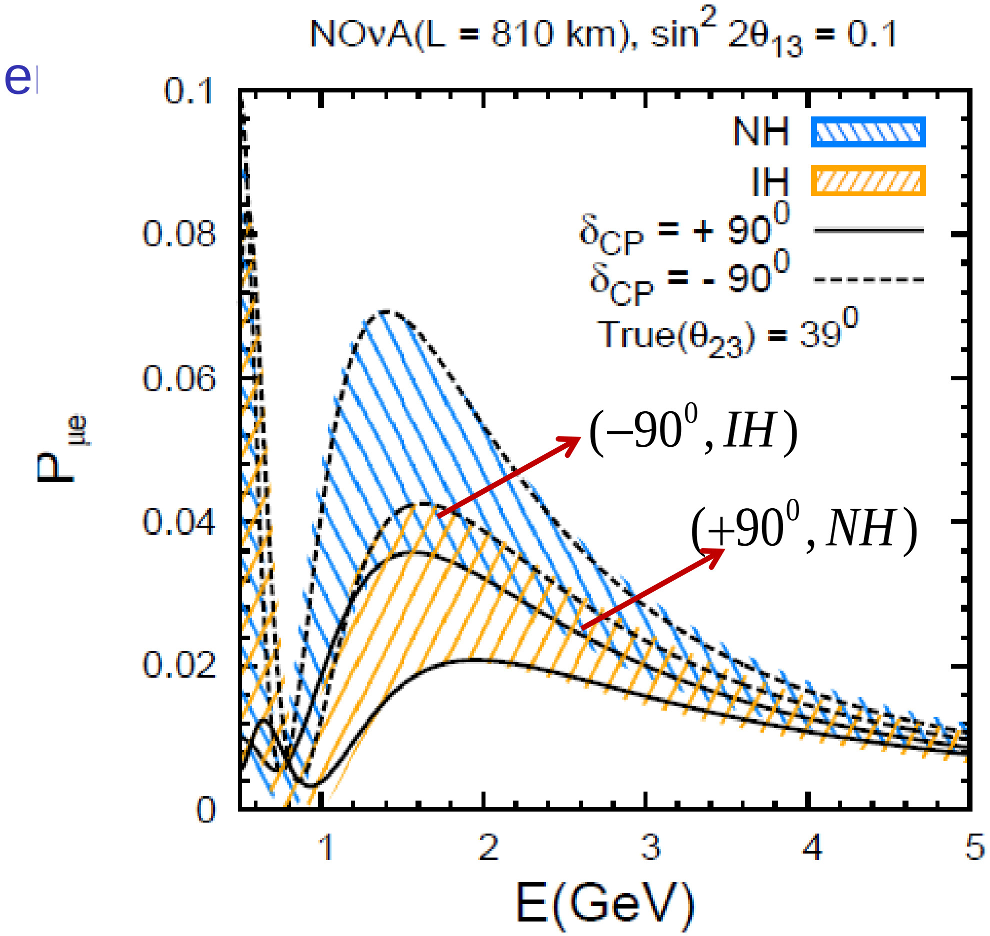
GLoBES (Huber,Kopp,Lindne
Rolinec,Winter)

T2K total pot 7.8×10^{21}

Synergy between T2K and NOvA

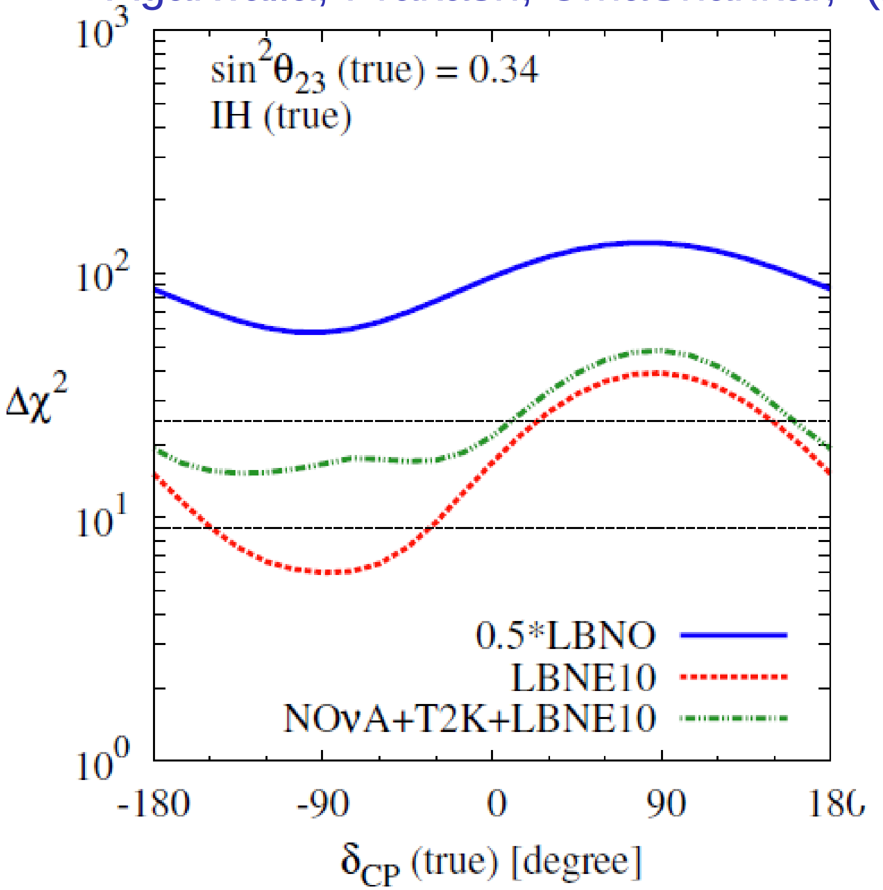
Agarwalla, Prakash, Raut
Umasankar (2012)

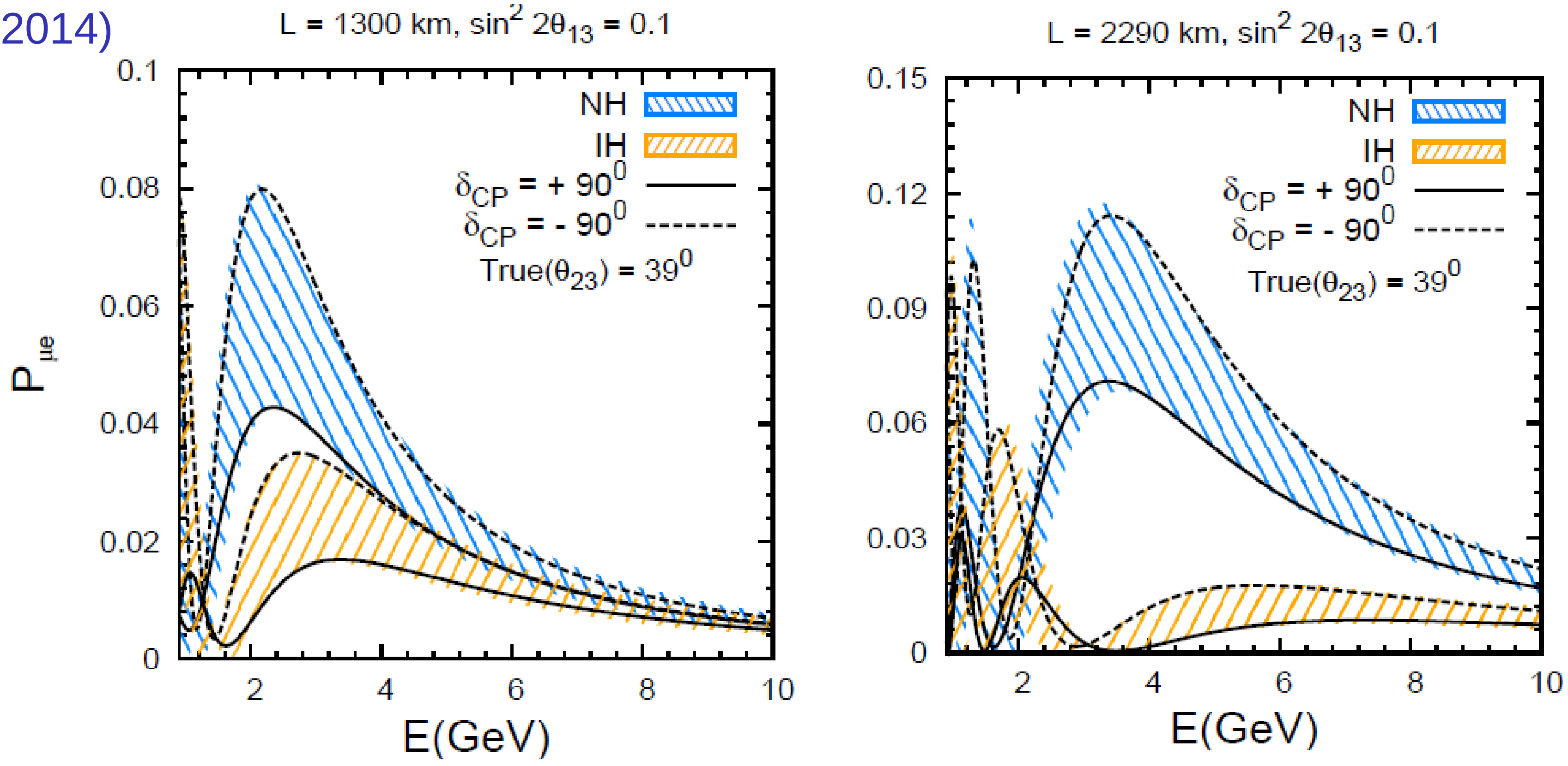
For true IH $(0 < \delta_{CP} < 180)$ is favourable



Hierarchy Sensitivity: LBNE/LBNO

Agarwalla, Prakash, UmaShankar, (2014)





LBNE + T2K + NOvA $> 3\sigma$ for all δ_{CP}

L BNO close to 7σ for all δ_{CP}

Increased hierarchy sensitivity due to enhanced matter effects

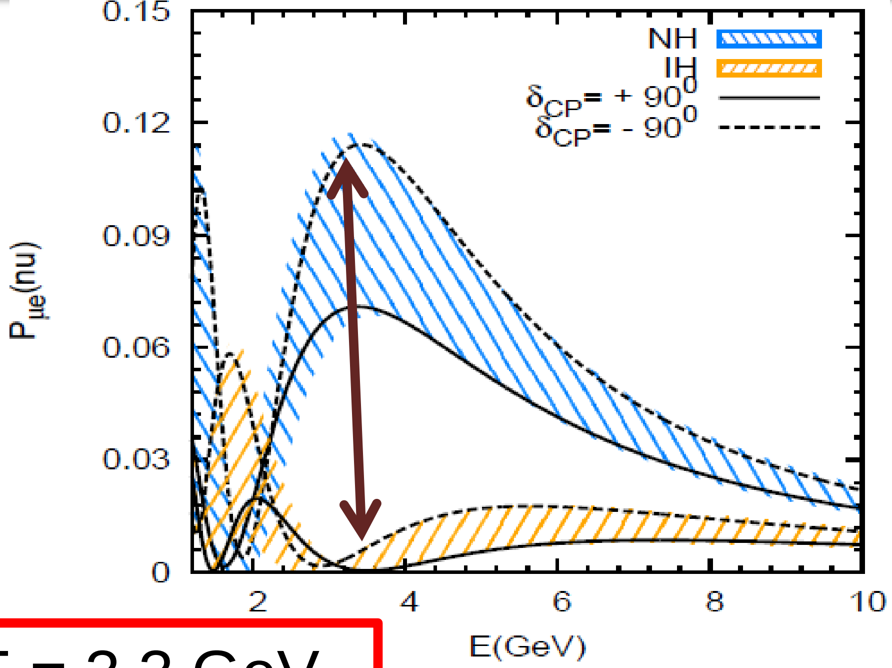
2290 km close to Bi-Magic baseline

Talks by Z. Djurcic (LBNE), V. Galymov (LBNO) ICHEP 2014

LAGUNA-LBN01312.6580, LBNE 1307.7335

Hierarchy Sensitivity: The Bi-magic baseline

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



Bi-magic Condition $$\frac{\sin(1-\hat{A}\Delta)}{(1-\hat{A})} = 0$$ Depends on hierarchy

IH–NoCP

$$(1+|\hat{A}|)\cdot|\Delta| = n\pi, n>0$$

NH–max

$$(1-|\hat{A}|)\cdot|\Delta| = (m-\tfrac{1}{2})\pi$$

L = 2540 km , E = 3.3 GeV
Minima for IH , CP for NH

Raut,Singh, Umasankar,2009

NH–NoCP

$$(1-|\hat{A}|)\cdot|\Delta| = n\pi, n \neq 0$$

IH–max

$$(1+|\hat{A}|)\cdot|\Delta| = (m-\tfrac{1}{2})\pi$$

L = 2540 km , E = 1.9 GeV
Minima for NH , CP for IH

Dighe, Goswami, Ray, 2010

Recall Magic baseline $$\frac{\sin \hat{A}\Delta}{A} = 0$$

L = 7500 km for both NH and IH ⟹ no CP sensitivity

Barger ,Marfatia, Whisnant 2001, Huber, Winter 2003

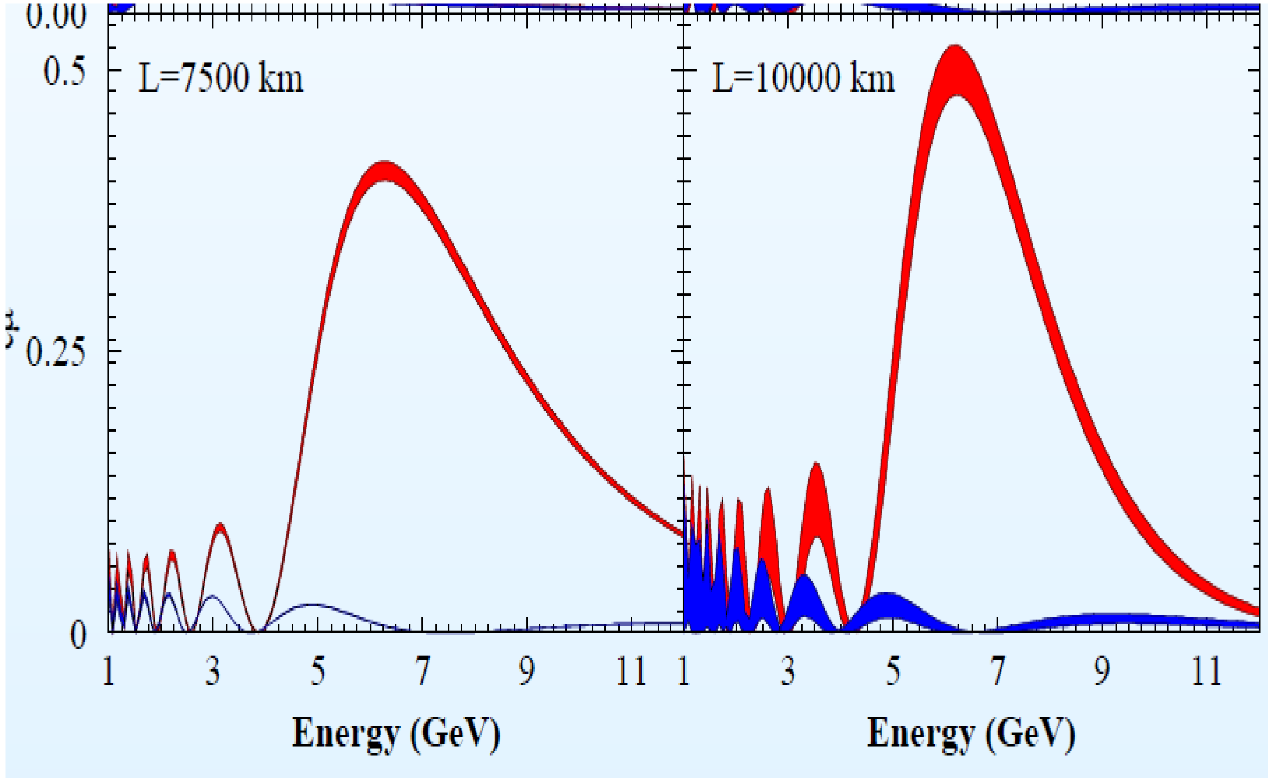
Resonant matter effect at large baselines

- Atmospheric neutrinos cover large distances in matter $\Longrightarrow$ Broad L/E band
- Can encounter resonance $\boxed{\Delta m^2_{31}\cos 2\theta_{13} = 2\sqrt{2}G_F n_e E}$
- $$\tan 2\theta_{13}{}^{m} = \frac{\Delta m^2_{31}\sin 2\theta_{13}}{\Delta m^2_{31}\cos 2\theta_{13} \pm 2\sqrt{2}G_F n_e E}$$

$$\Delta m^2_{31} = 2.5\times 10^{-3}\,eV^2$$
$$\rho_{av} = 4.1\,gm/cc$$
$$E_{res} = 7.5\,GeV$$

Agarwalla, Choubey, Raychaudhuri, 2006

- For $\Delta m^2_{31} > 0$ resonance in neutrinos
- For $\Delta m^2_{31} < 0$ resonance in antineutrinos $\Downarrow$
- Hierarchy Sensitivity $\rightarrow$ Depends on θ_{13}
- Large θ_{13} $\Longrightarrow$ Good news
- Detector with charge id important
- Hierarchy - δ_{CP} degeneracy absent

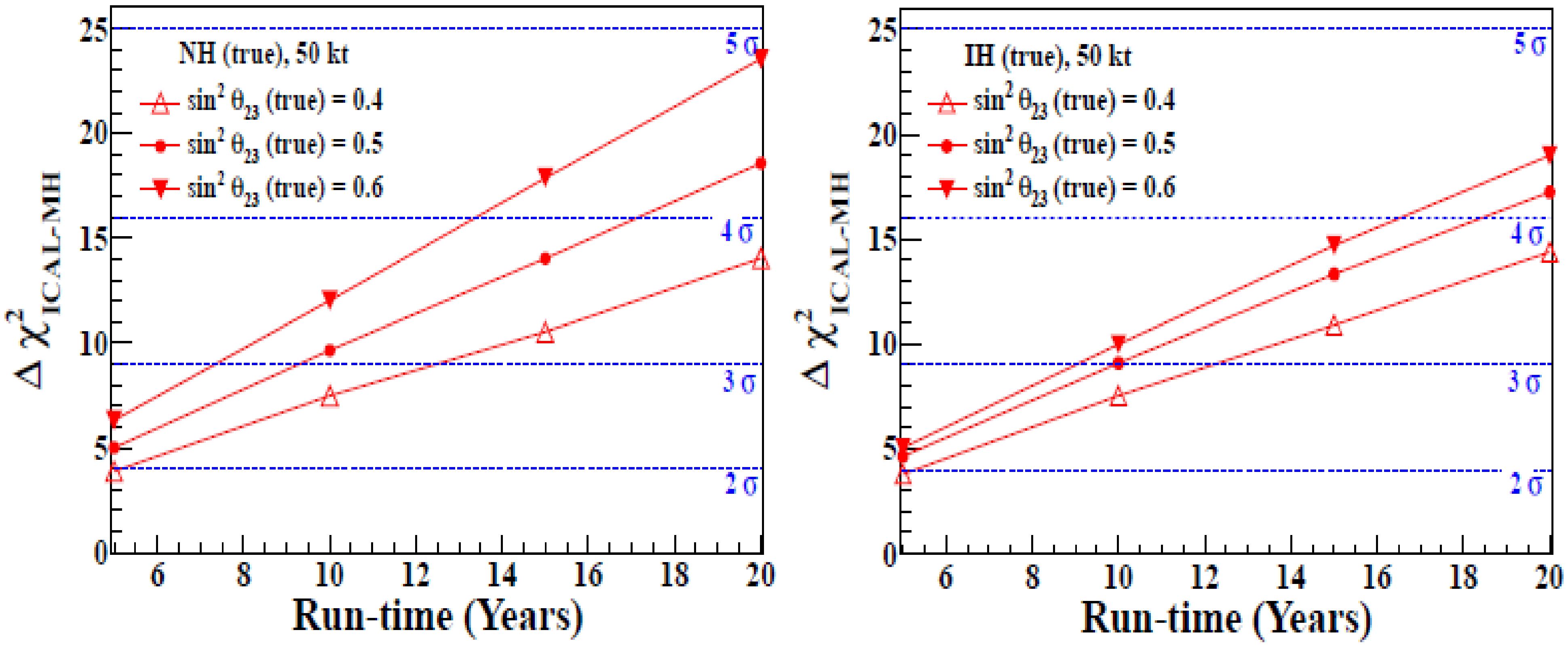


Wofenstein,'78 Barger et al,'80 , Mikheyev,Smirnov'86

,

Hierarchy Sensitivity : Atmospheric Neutrinos (INO)

- Incorporation of Hadron information : event by event analysis in $E_\mu, \cos\theta_\mu, E_{had}$
- Improves the hierarchy sensitvity significantly : 40 % increase in χ^2



3D analysis with Information on hadron energy

Devi,Thakore,Agarwalla Dighe (2014)

Talk by Agarwalla, ICHEP 2014

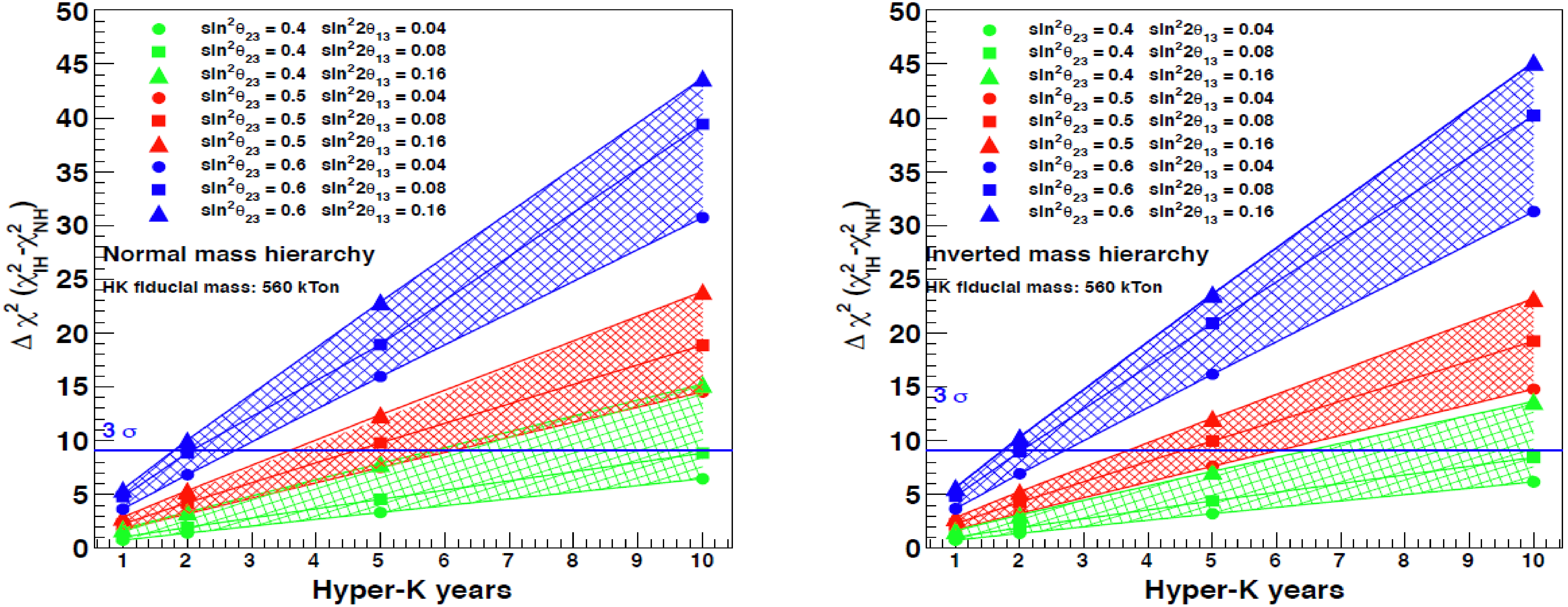
3σ sensitivity in 10 years for $\sin^2 2\theta_{13}(true) = 0.1$

$$P_{e\mu} \sim \sin^2\theta_{23}\sin^2 2\theta_{13}$$

Hierarchy sensitivity more for higher octant and higher θ_{13}

Hierarchy sensitivity : Hyper-Kamiokande

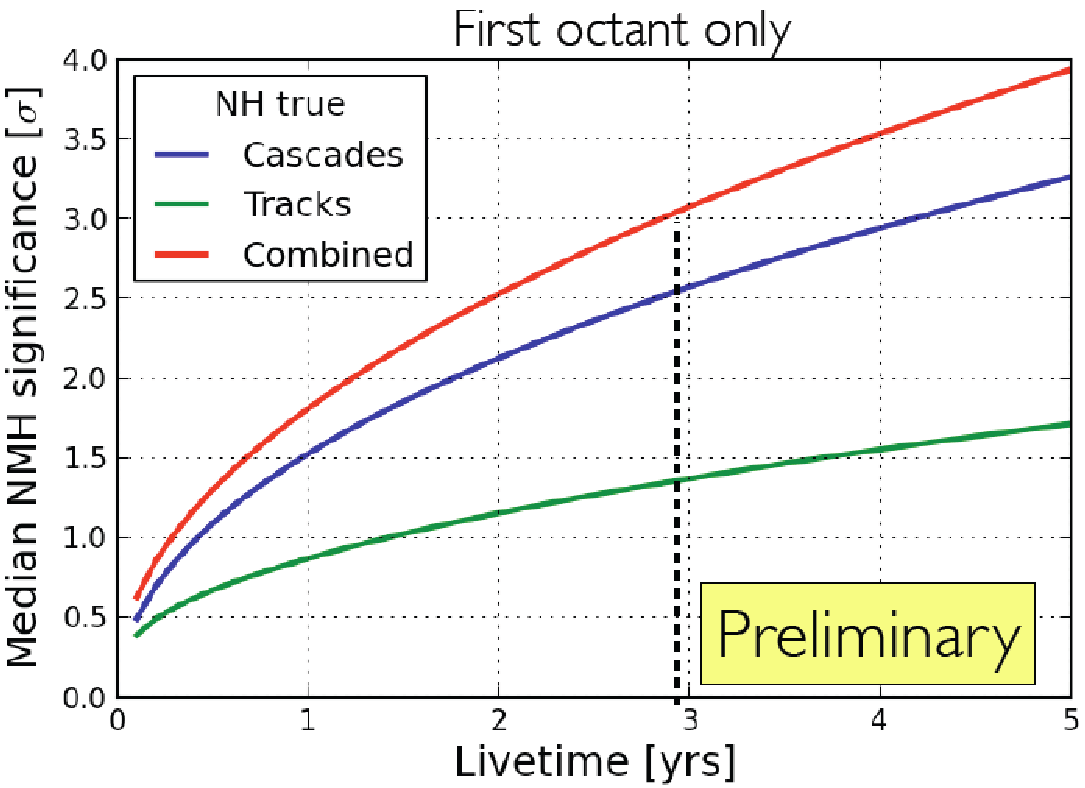
arXiv: 1109.3262 (HK Collaboration)



Sensitive to both electrons and muons

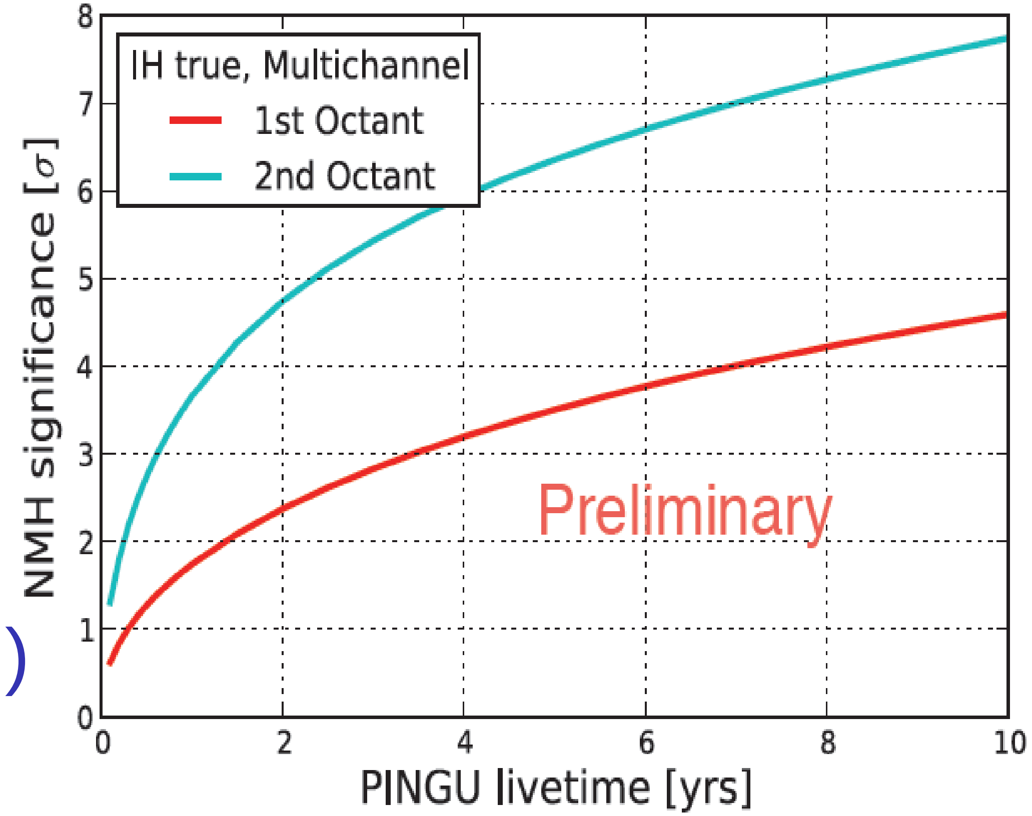
3σ sensitivity in approximately in 5 years for $\sin^2 2\theta_{13} = 0.08$

Hierarchy sensitivity : PINGU



Initial baseline geometry : 40 new strings and 60 optical modules in the deep core region of Icecube

arXiv:1401.2046



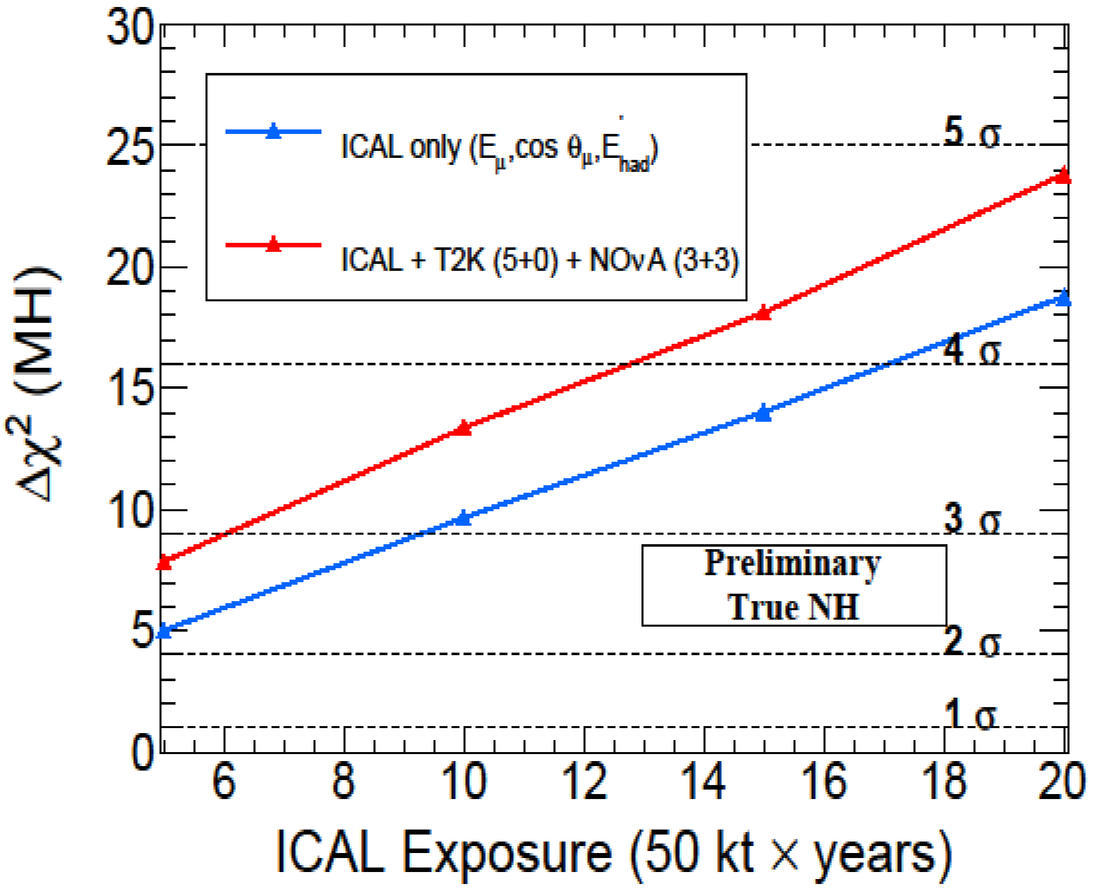
- 3σ in ~ 3 yrs for 1st octant (multichannel)

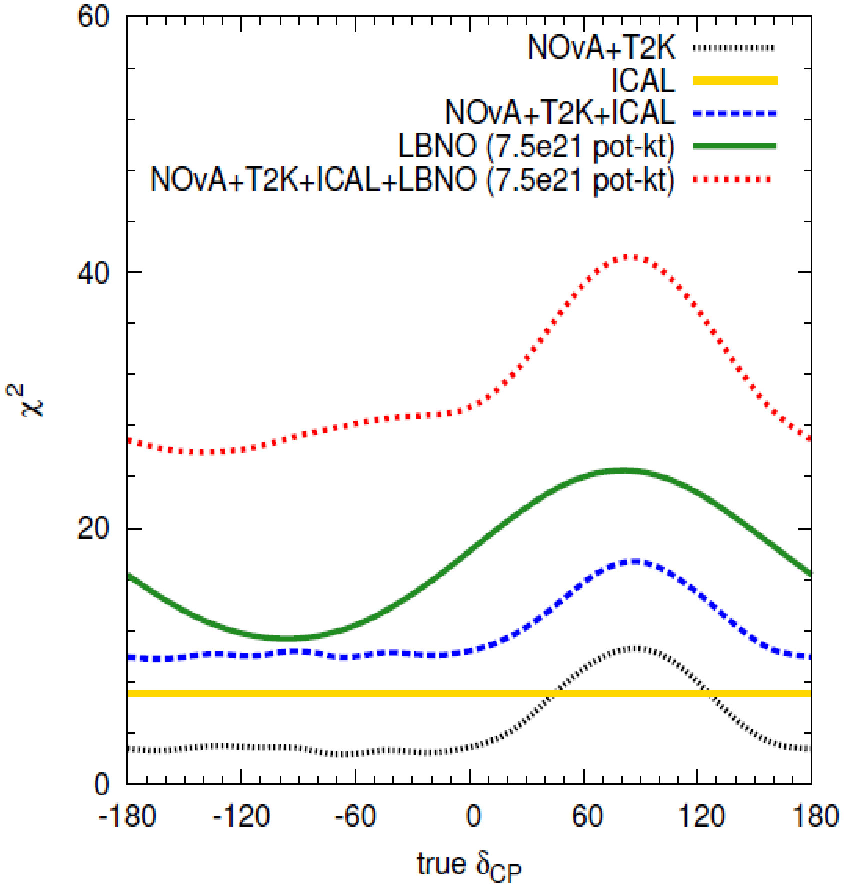
Including Cascades important

Talk by K. Clark , ICHEP 2014

Hierarchy Sensitivity: Atmospheric + LBL

$\sin^2 2\theta_{13} = 0.1, \sin^2 2\theta_{23} = 0.5$





Sensitivity improves by adding INO-ICAL

Reduced exposure for LBNO including Available information

Economizing configurations --- staged approach

3σ median sensitvity in 6 years with 50 kton ICAL by adding T2K and NoVA

Ghosh,Ghoshal,S.G. ,Raut, 2013 .Ghosh,Thakur,Choubey, 2013, Blennow ,Schwetz, 2012

Hierarchy Sensitivity : reactor neutrinos

$$P_R(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \begin{cases} \cos^4\theta_{13}\sin^2 \boxed{2\theta_{12}} \sin^2 \boxed{\Delta_{21}} \\ + \sin^2 2\theta_{13}\sin^2\theta_{12}\left(\cos 2\Delta_{31}\sin^2\Delta_{21} - \frac{1}{2}\sin \boxed{2\Delta_{31}} \sin 2\Delta_{21}\right) \end{cases}$$

Maxima for $\sin^2\Delta_{21}$ (SPMIN)

Precise value of θ_{12}

Bandyopadhay,Choubey, S.G. 2003

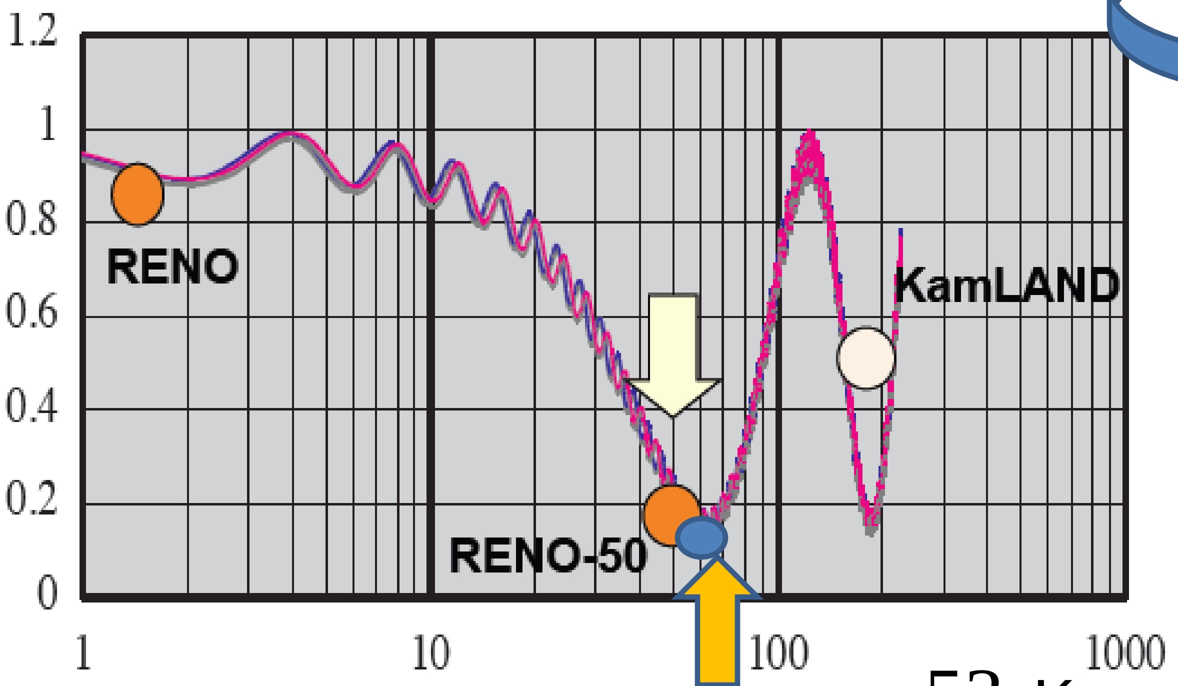
Bandyopadhyaya,choubey,S.G,Petcov, 2005

Minakata

Hierarchy sensitivity

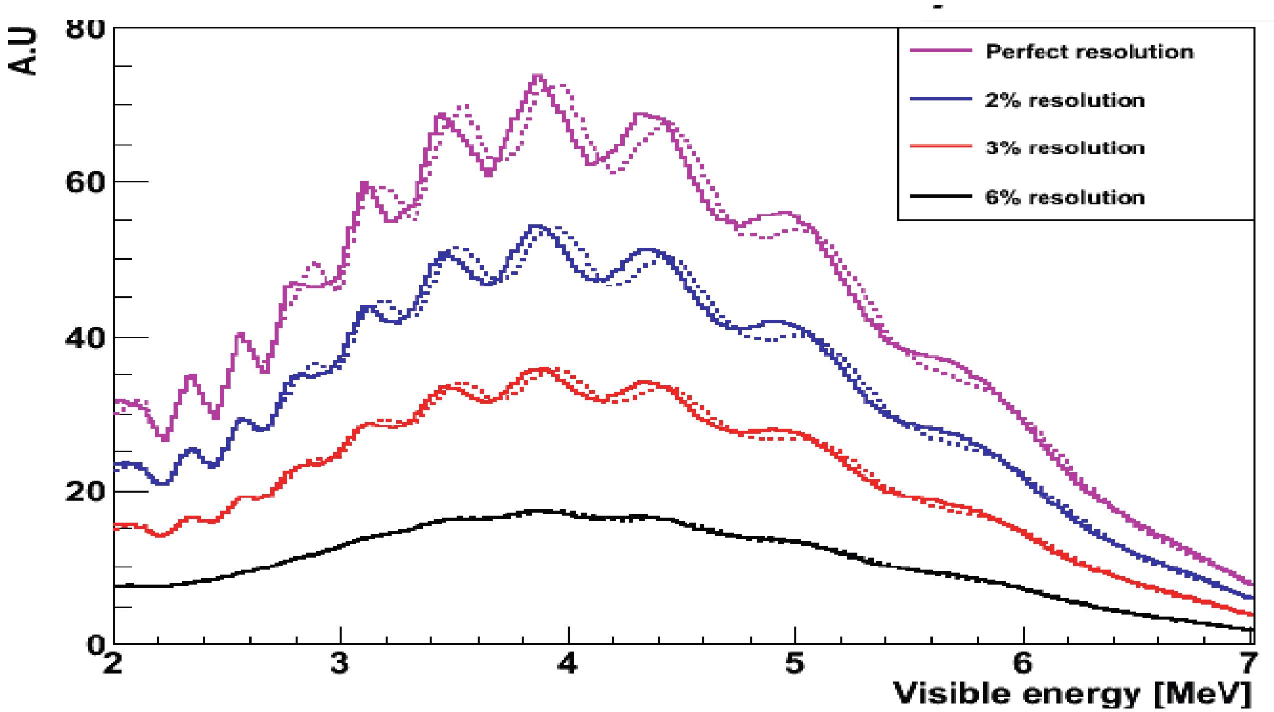
Petcov, Piai, 2001,

Choubey,Petcov,Piai, 2003



JUNO ~ 53 Km

Distortions in the energy specturm

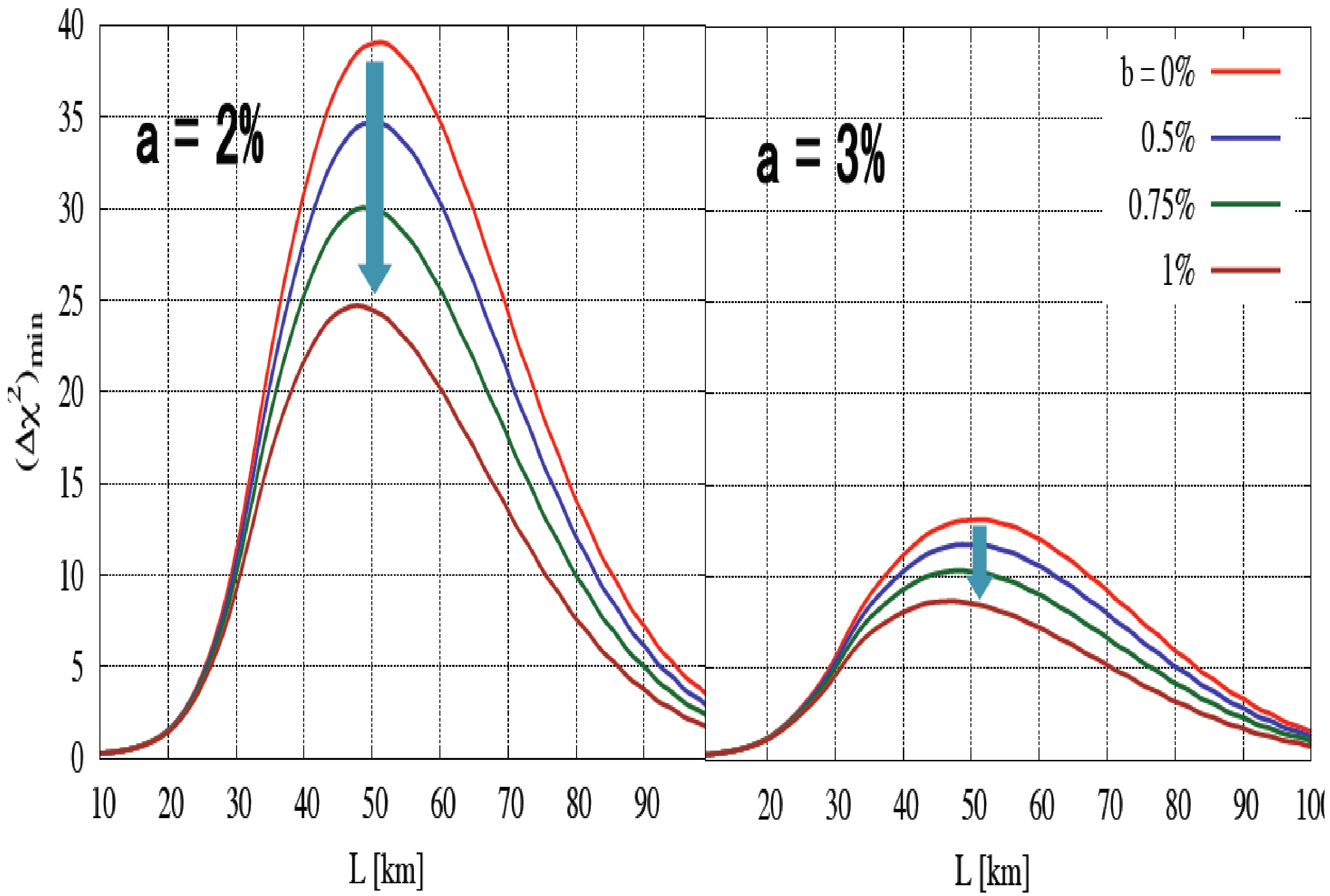


Better than 3% energy resolution needed

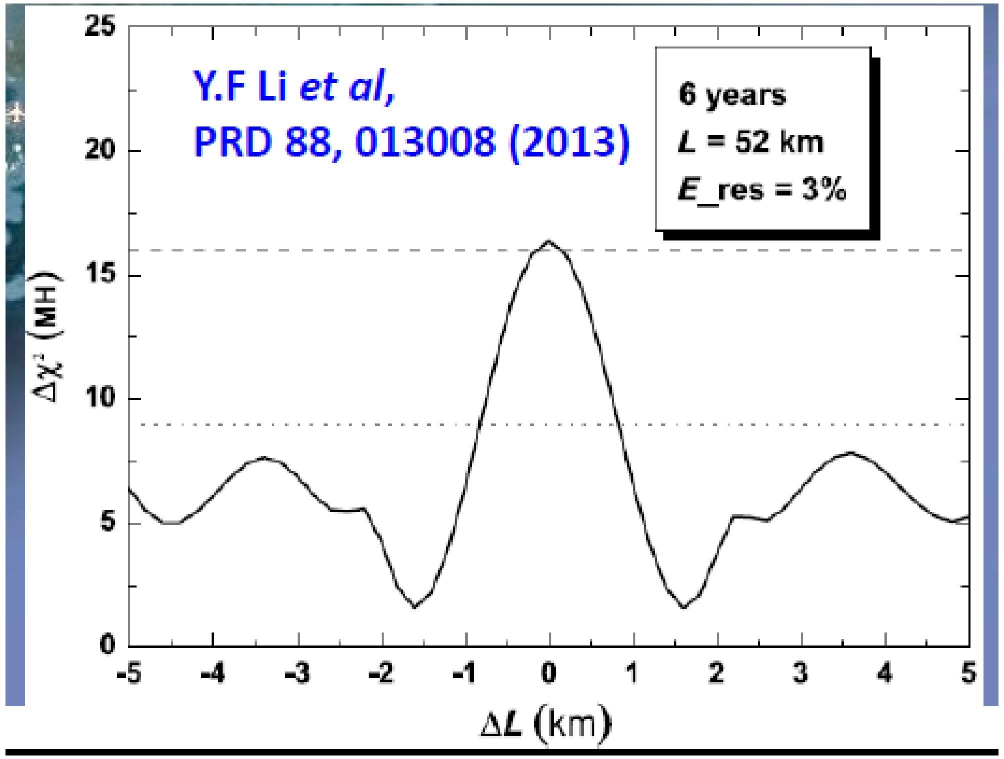
Figs : S.Seo RENO-50 workshop (2013)

Sensitivity to mass hierarchy: reactor neutrinos

RENO -50



JUNO



Y.F Li *et al*,
PRD 88, 013008 (2013)

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/MeV}} + b$$

Energy non-linearity correction important for shape analysis< 1% understanding of energy scale

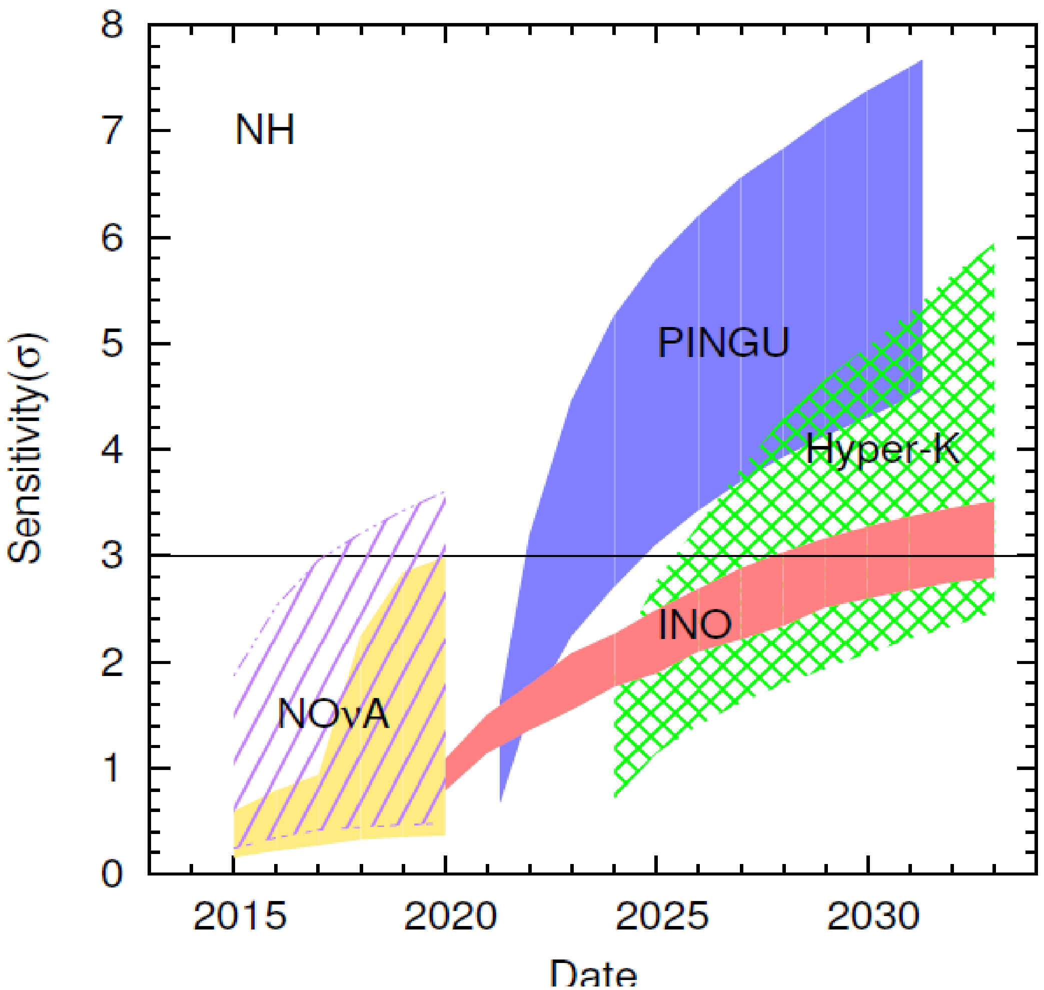
Y.Takaesu et al. JHEP05(2013)131

Talk by L. Zhan. ICHEP 2014

Hierarchy sensitvity in future experiments

Hierarchy sensitvity of NOvA atmospheric experiments

After Blenow et al. 1311.1822



NOvA δ_{CP}

Atmospheric θ_{23}

INO/SK $40^o - 50^o$

Pingu : $38.7^o - 51.3^o$

NoVA : $3\nu + 3\overline{\nu}$

INO : arXiv:1406.3689

HK : arXiv 1109.3262

PINGU: arXiv 1401.2046

The lower end of the bands denote worst sensitivity

Pingu/HK huge statistics help for higher 2-3 angle

For favourable CP values early hint from Nova
and for unfavourable CP values from NOvA + INO

Different statistical procedure followed by different groups

Octant Degeneracy

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \text{sub leading terms}$$

$$P_{\mu\mu}(\theta_{23}) = P_{\mu\mu}(\pi/2 - \theta_{23})$$

Fogli and Lisi ’96

Intrinsic octant degeneracy

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

$$P_{\mu e}(\theta_{13}, \theta_{23}, \delta_{CP}) = P_{\mu e}(\theta'_{13}, \theta'_{23}, \delta'_{CP})$$

Generalized Octant Degeneracy

Agarwalla,Prakash, Sankar, 2013

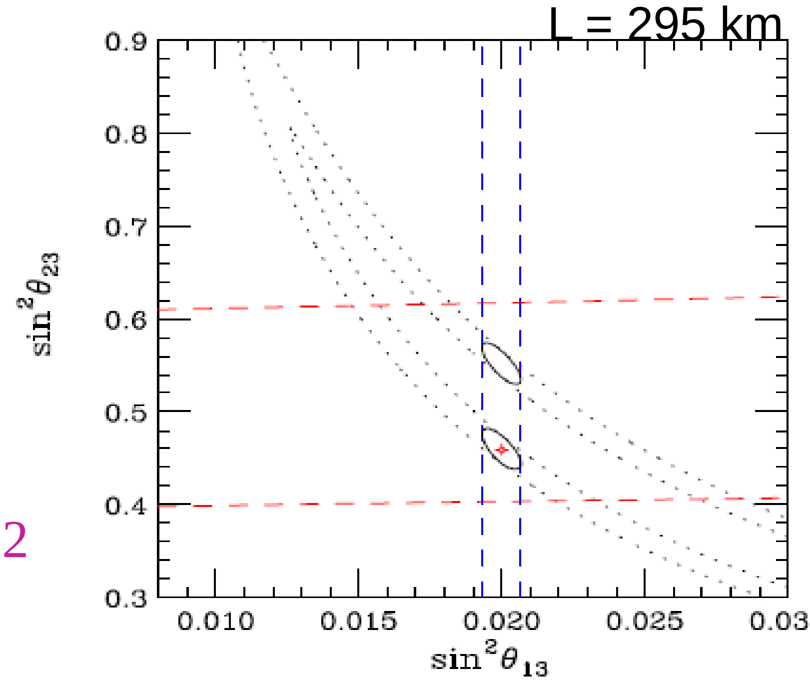
Chaterjee,Ghosal,Goswami, Raut, 2013

Octant sensitivity

Correlated to θ_{13}

Accelerator + Reactor data helpful

Huber,Lindner,Winter , 2002
Hiraide et al., 2006

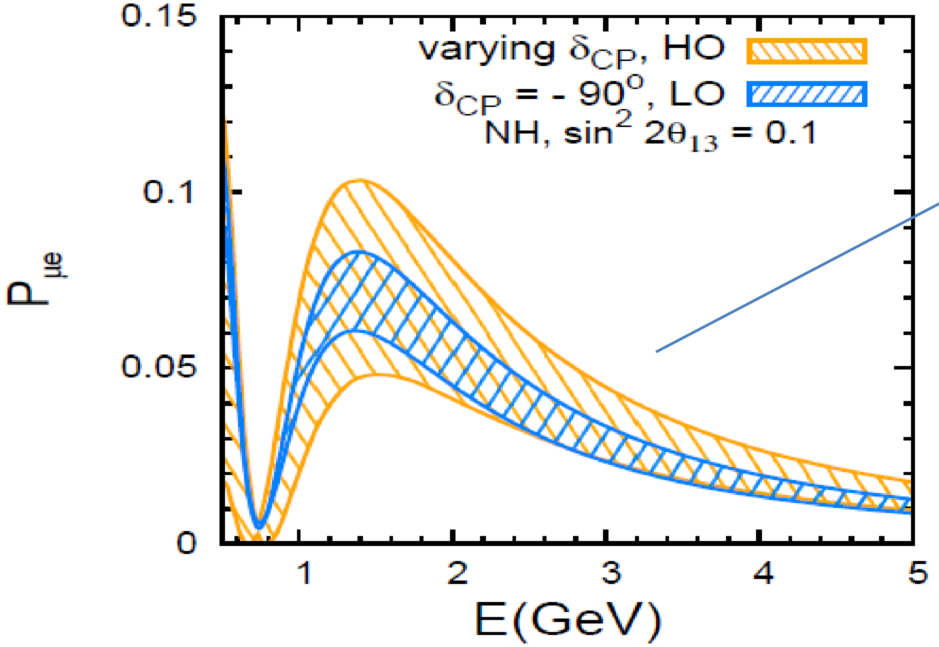


Coloma,Minakata, Parke, 2014

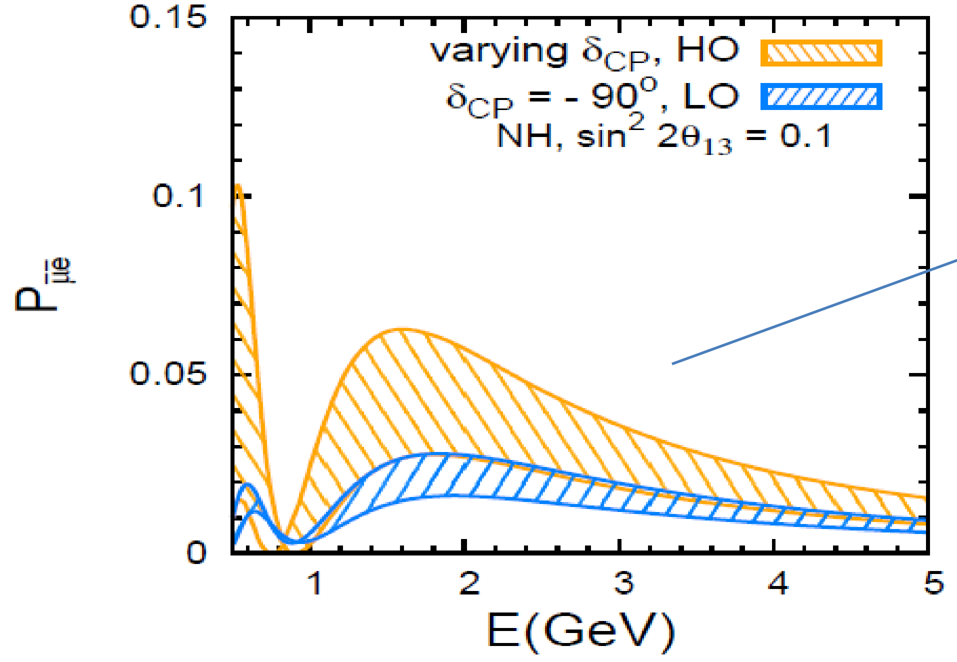
Depends on L/E
Spectrum information useful
Unknown δ_{CP} can be a problem

Octant degeneracy and δ_{CP}

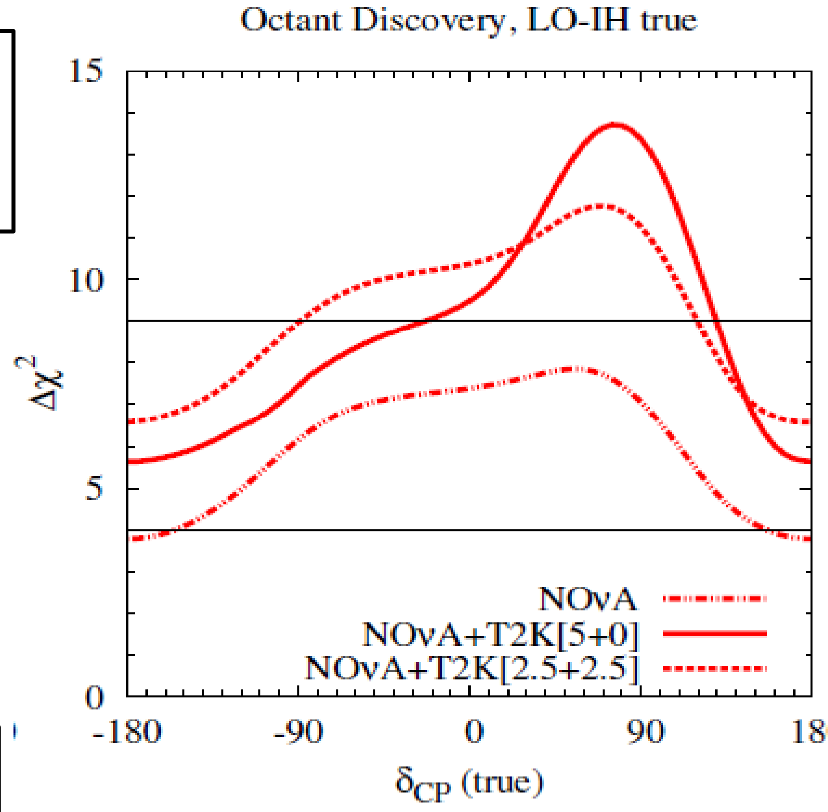
L = 810 km



For $\nu : \delta_{CP} = -90^0$
and LO bad



For $\bar{\nu} : \delta_{CP} = -90^0$
and LO good



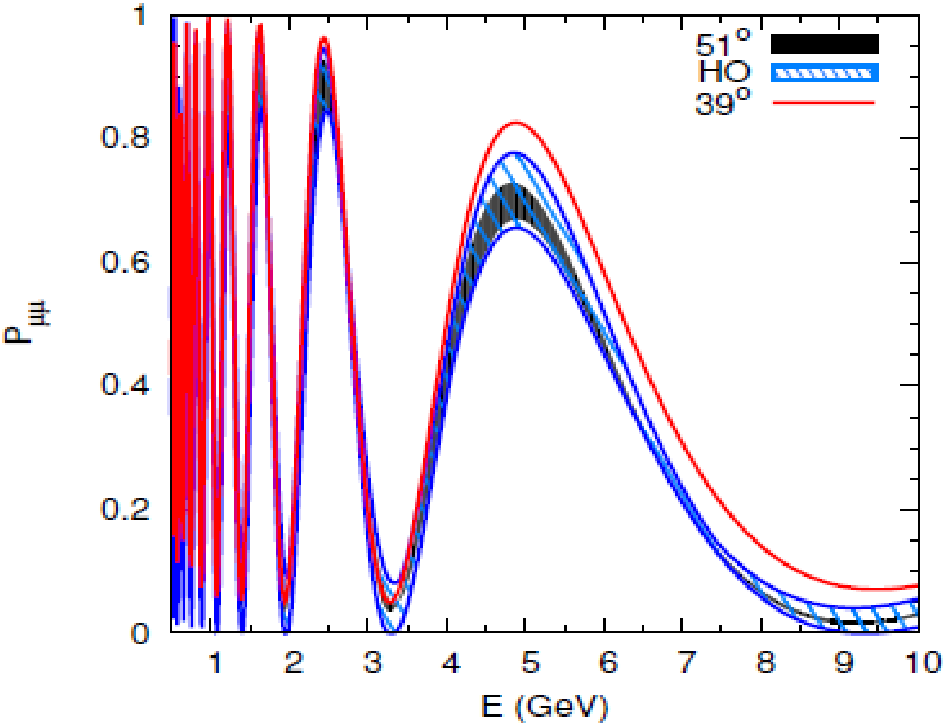
Agarwalla, Prakash, Umasankar 2013

Machado et al. 2013

Combination of ν and $\bar{\nu}$ can be helpful lifting octant degeneracy (depending on δ_{CP})

Talk by S. Umasankar , ICHEP 2014

Octant Sensitivity: Atmospheric Neutrinos



$$P^{m}_{\mu\mu} \longrightarrow \sin^4\theta_{23}\sin^2 2\theta^{m}_{13}\sin^2(1.27\Delta^{m}_{31}L/E)$$

Octant Sensitivity

Choubey , Roy, 2005

Near resonance

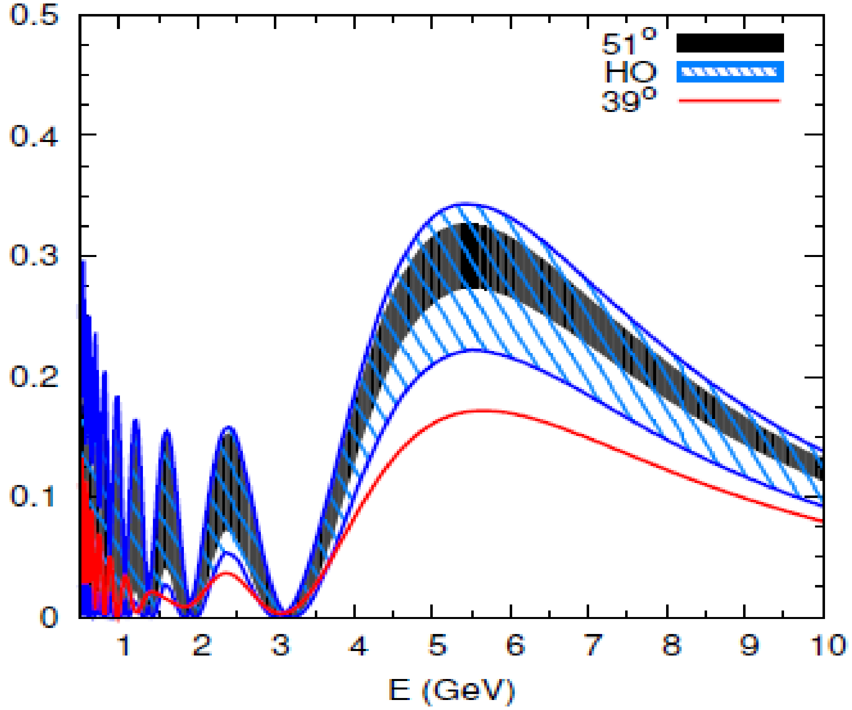
$$\sin^2 2\theta^{m}_{13} \approx 1$$

$\Rightarrow$ No $(\theta_{23}-\theta_{13})$ degeneracy

$$P^{m}_{\mu e} = \sin^2\theta_{23}\ \sin^2 2\theta^{m}_{13}\ \sin^2\left[1.27\ (\Delta m^2_{31})^{m}\ \frac{L}{E}\right]$$

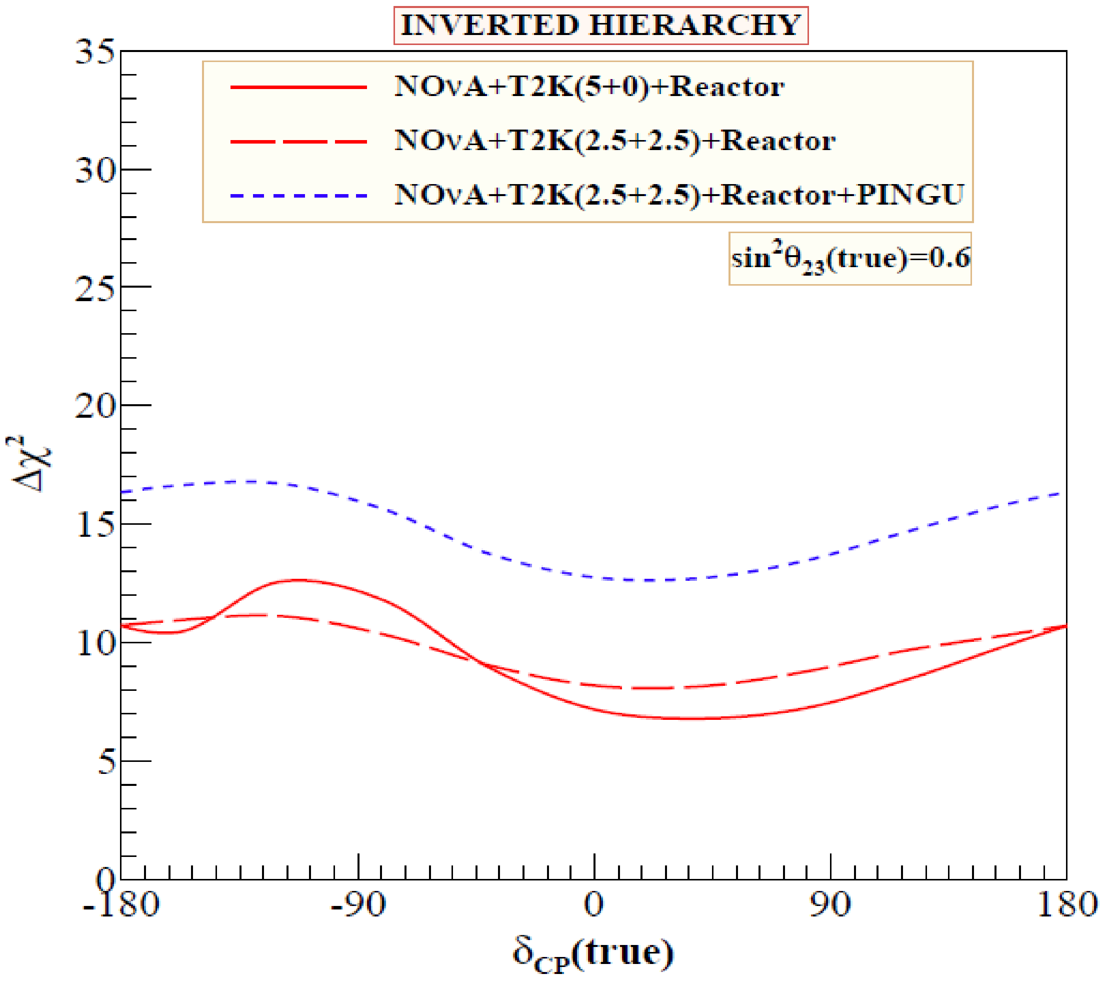
δ_{CP} effects subdominant

θ_{23} dependence of survival and conversion probabilities opposite



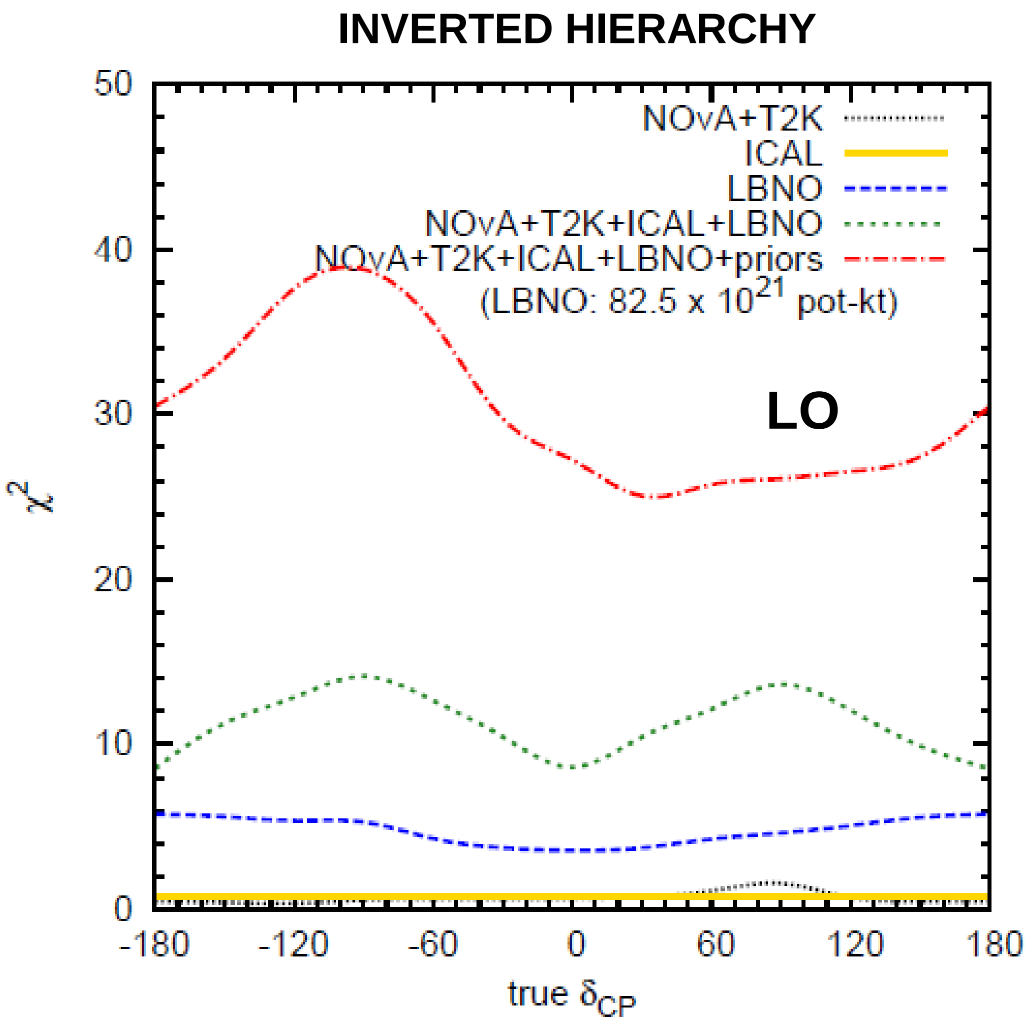
Chaterjee,Ghoshal, Goswami, Raut, 2013

Octant Sensitivity : atmospheric + LBL



Synergy between atmospheric and LBL experiments increase octant sensitivity

Choubey and Ghosh, 2013



Precision of 1-3 mixing angle plays a very important role

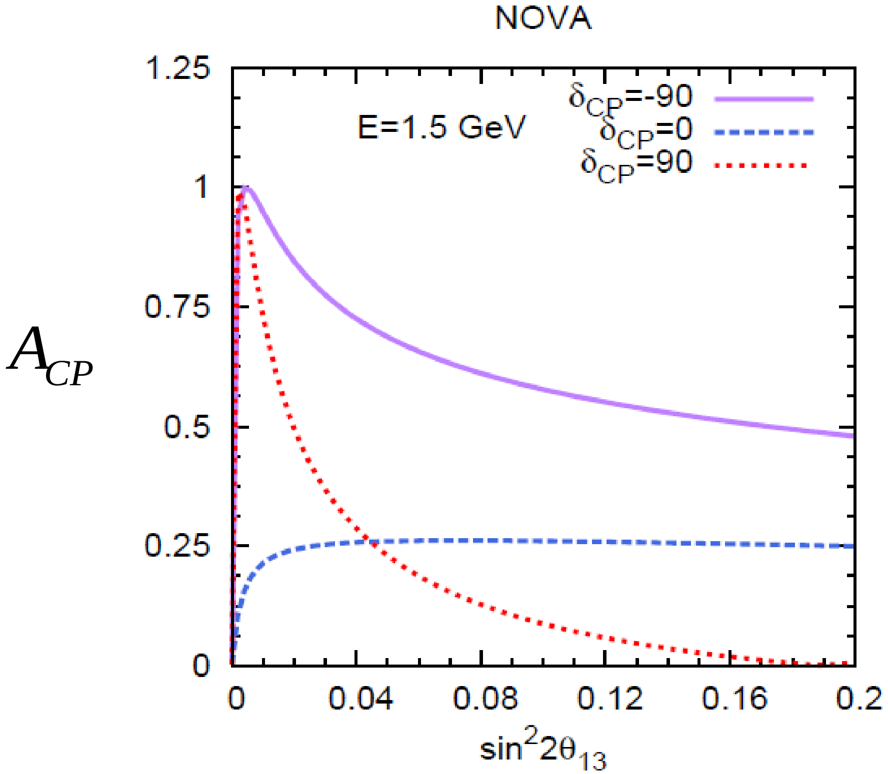
Ghosh. Ghosal, Goswami, Raut, 2013

CP violation in neutrino oscillations

- CP violation due to the phase δ_{CP}

$$\boxed{P_{\mu e} - P_{\overline{\mu e}} = 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta_{CP} \left[\sin\frac{\Delta m_{21}^2 L}{2E} + \sin\frac{\Delta m_{23}^2 L}{2E} + \sin\frac{\Delta m_{31}^2 L}{2E}\right]}$$

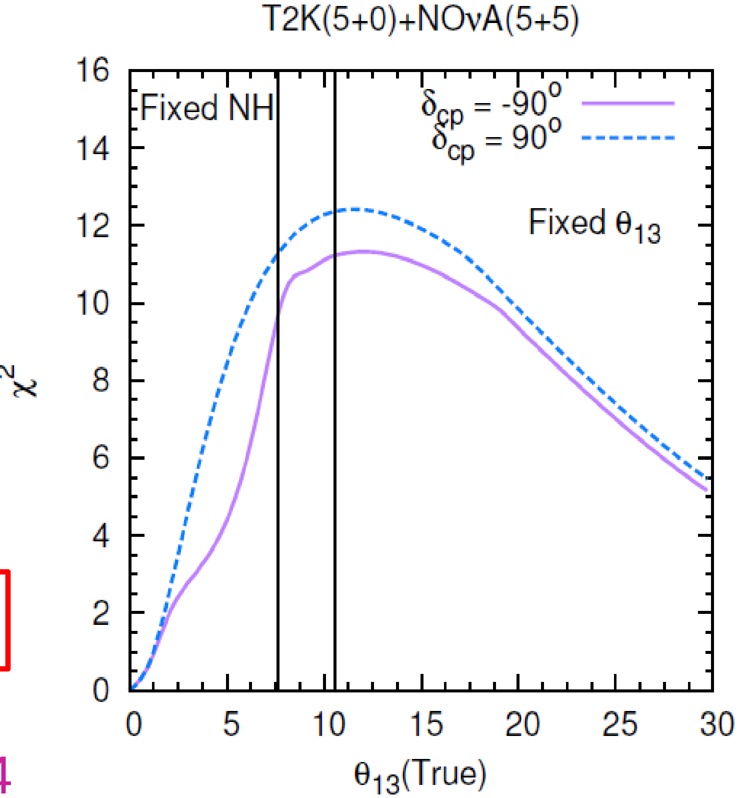
Genuine three flavour effect : require all angles and Δm_{21}^2 to be non-zero



$$A_{CP} = \frac{P_{\mu e} - P_{\overline{\mu e}}}{P_{\mu e} + P_{\overline{\mu e}}} \sim \frac{\sin\delta_{CP}}{\sin\theta_{13}}$$

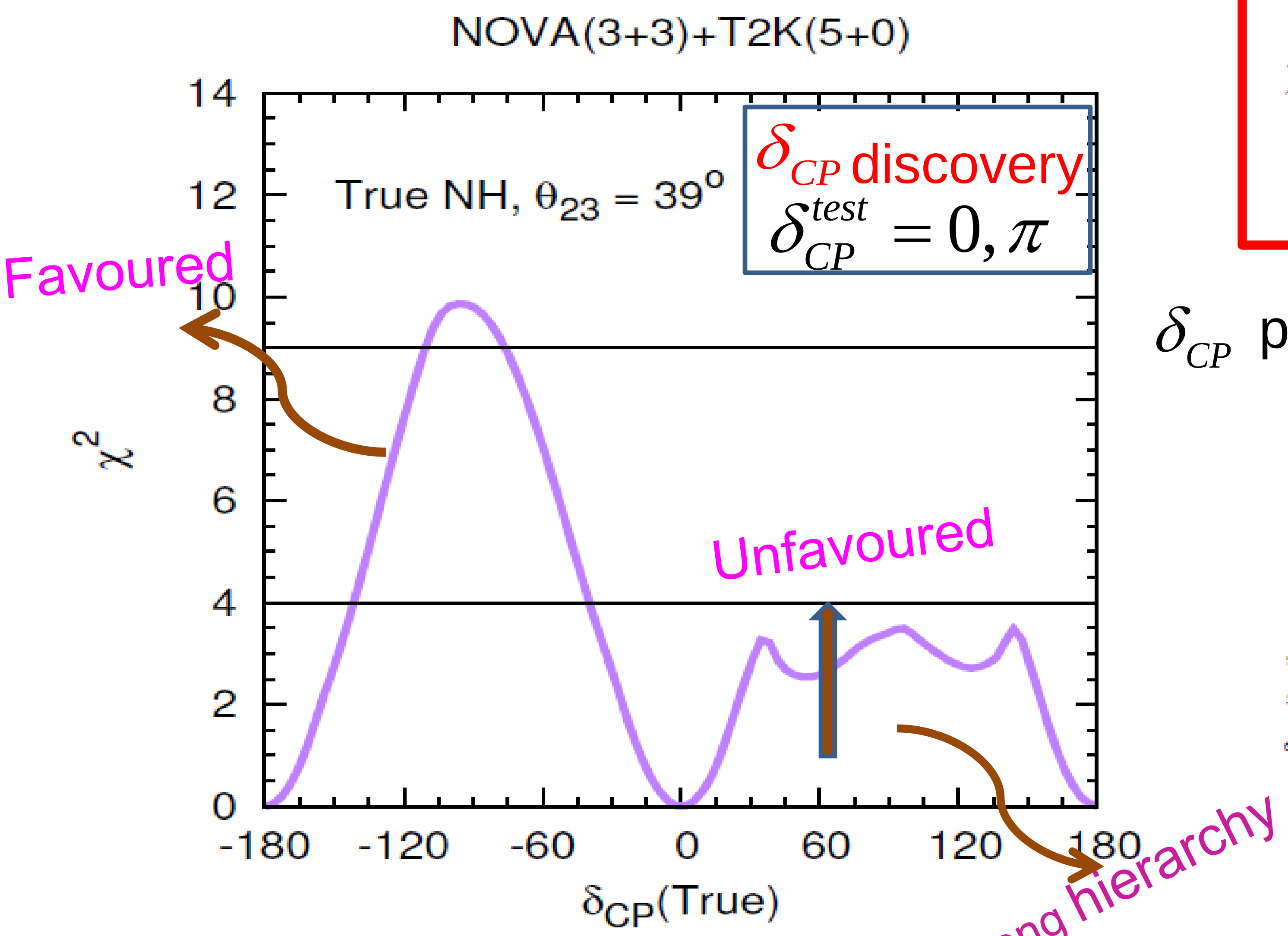
$$\chi^2 \sim \frac{P(\delta_{CP})\sin^2 2\theta_{13}}{Q\sin^2\theta_{13} + R(\delta_{CP})\sin 2\theta_{13}}$$

Current θ_{13} range optimal



Ghosh, Ghoshal,Goswami, Raut 2014

δ_{CP} in long-baseline experiments



δ_{CP} discovery

$\delta_{CP}^{test} = 0, \pi$

Favoured

Unfavoured

Wrong hierarchy

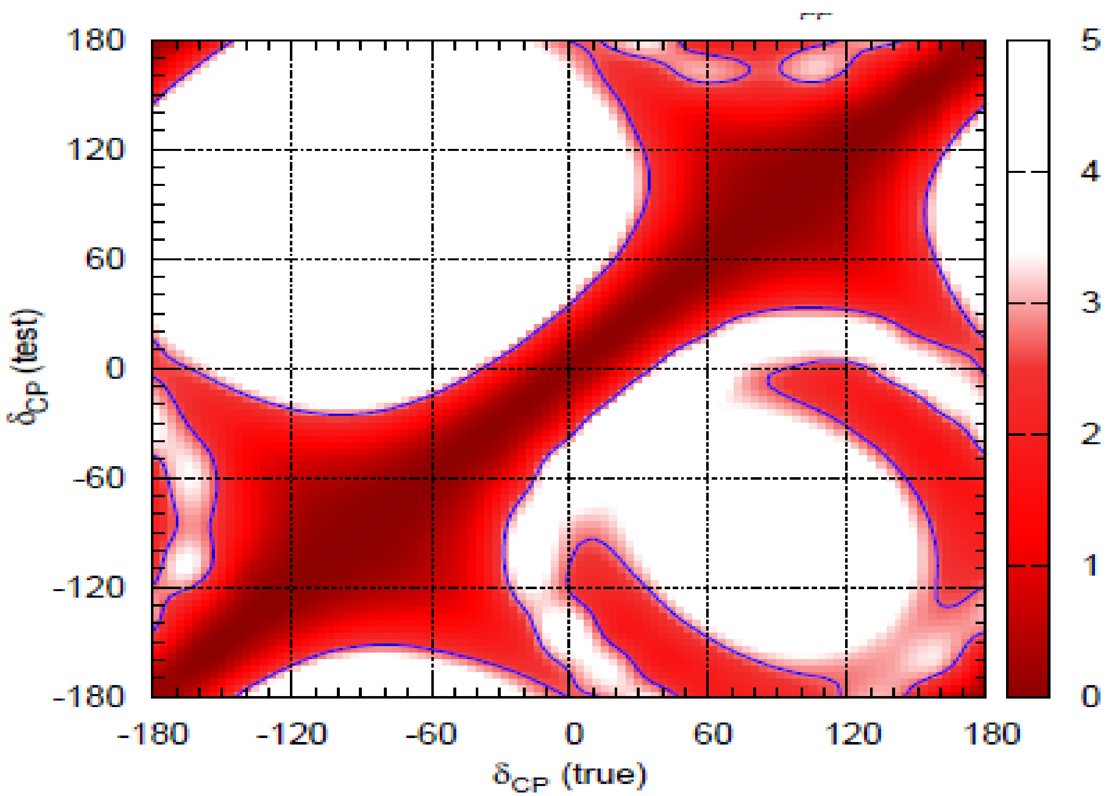
2σ for 24% values of δ_{CP}

Talk by L. Escudero , ICHEP 2015

$$\chi^2 = \min \frac{(N_{ex}(\delta_{CP}^{tr}) - N_{th}(\delta_{CP}^{test}))^2}{N_{ex}(\delta_{CP}^{tr})}$$

$$\chi^2 = \chi_\nu^2 + \chi_{\bar{\nu}}^2$$

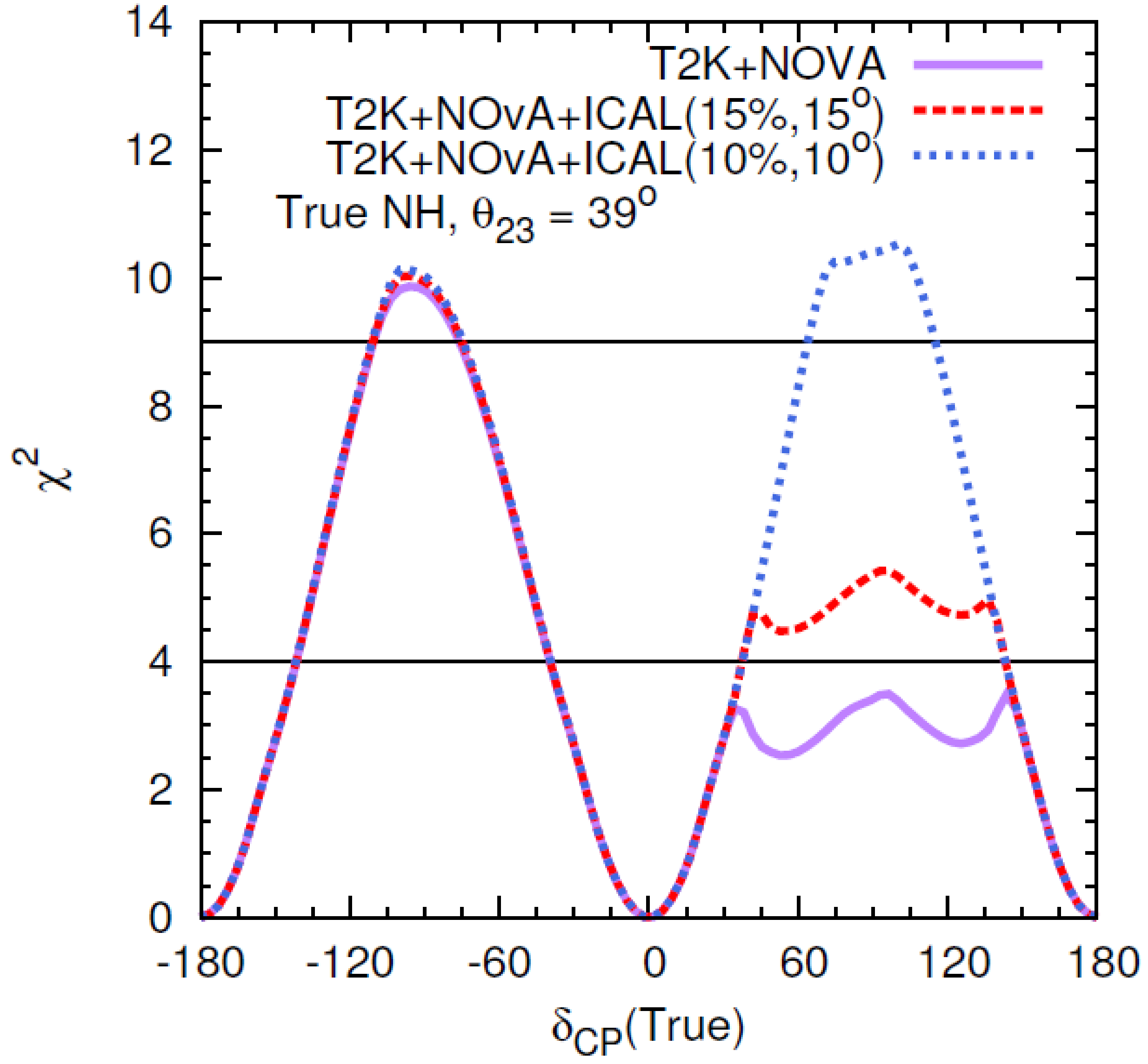
δ_{CP} precision : δ_{CP} varied over full range



Ghosh,Ghoshal,Goswami, Raut (2014)

CP sensitivity : atmospheric + LBL

T2K (5+0) , NOvA (3+3) + ICAL (500 kt yr)



Adding hierarchy information from INO-ICAL data increases the CP sensitvity in wrong hierarchy region

50% increase in CP coverage

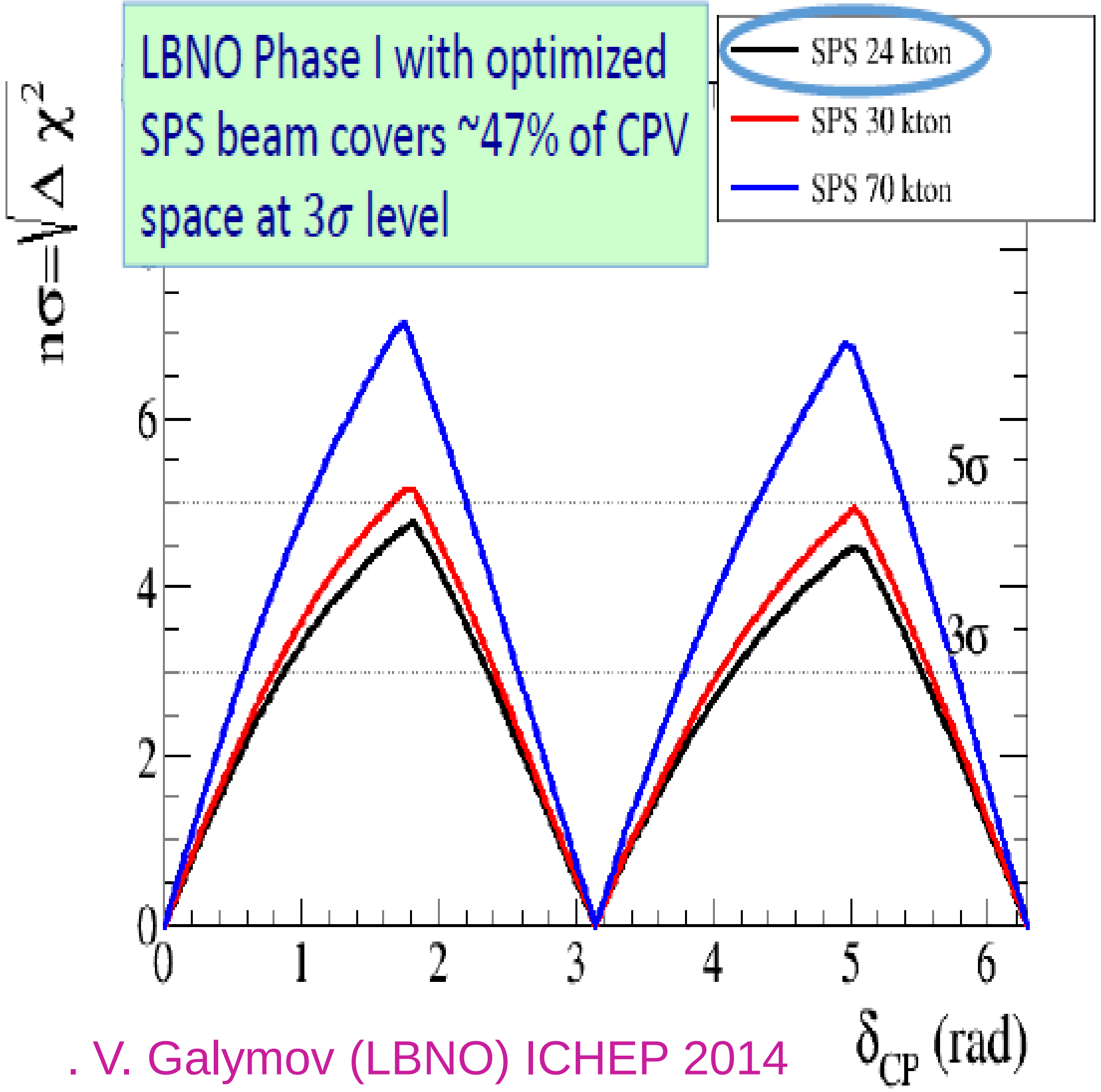
For unfavorable CP values first hint of non-zero δ_{CP} may come after adding ICAL data

(also true for other atmospheric experiments)

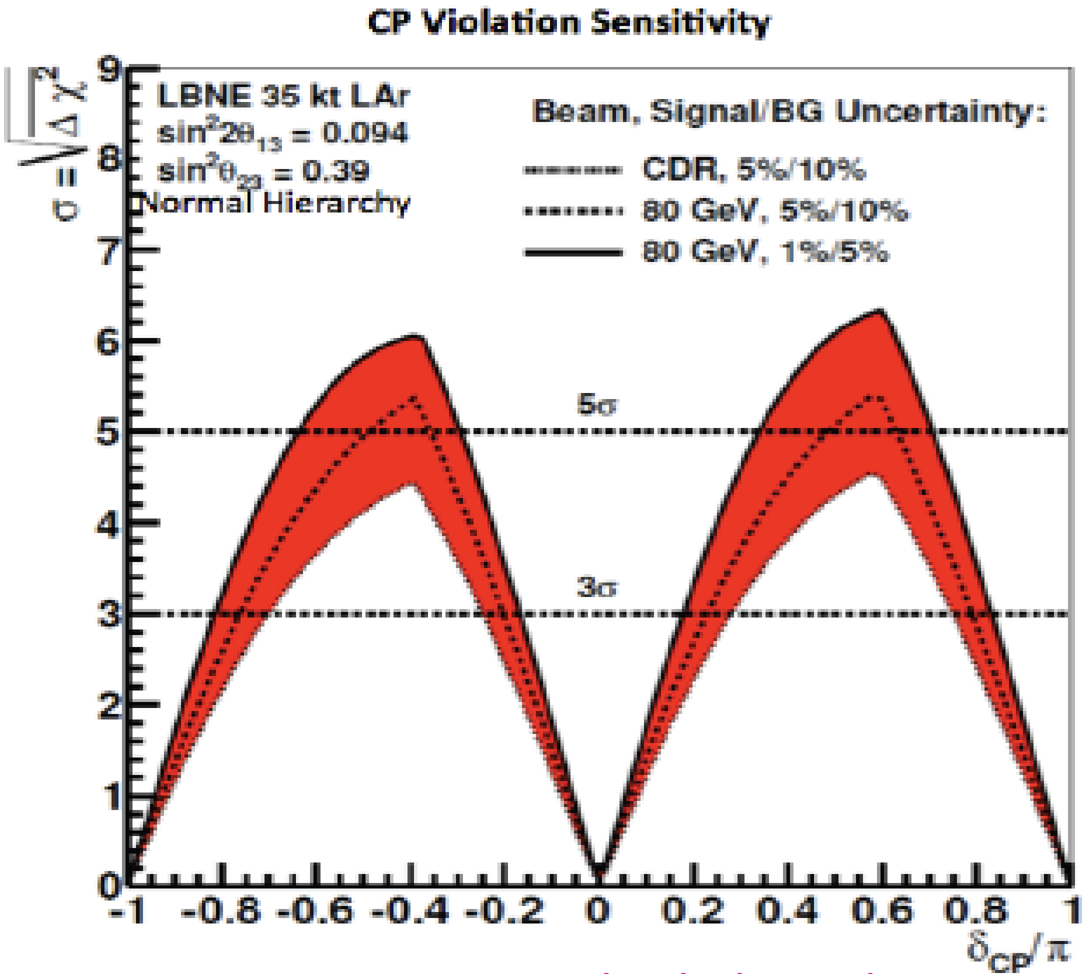
Ghosh,Ghosal, Goswami, Raut (2013),

δ_{CP} in Long-Baseline experiments

LBNO Phase I with optimized SPS beam covers ~47% of CPV space at 3σ level



. V. Galymov (LBNO) ICHEP 2014



Z. Djurcic (LBNE),ICHEP 2014

More than 5σ for some fraction of CP phases

See also talks by M. Dracos (ESS), M. Shaevitz (DAEδDALUS),H. Tanaka (HK)

Status of sterile neutrinos oscillations

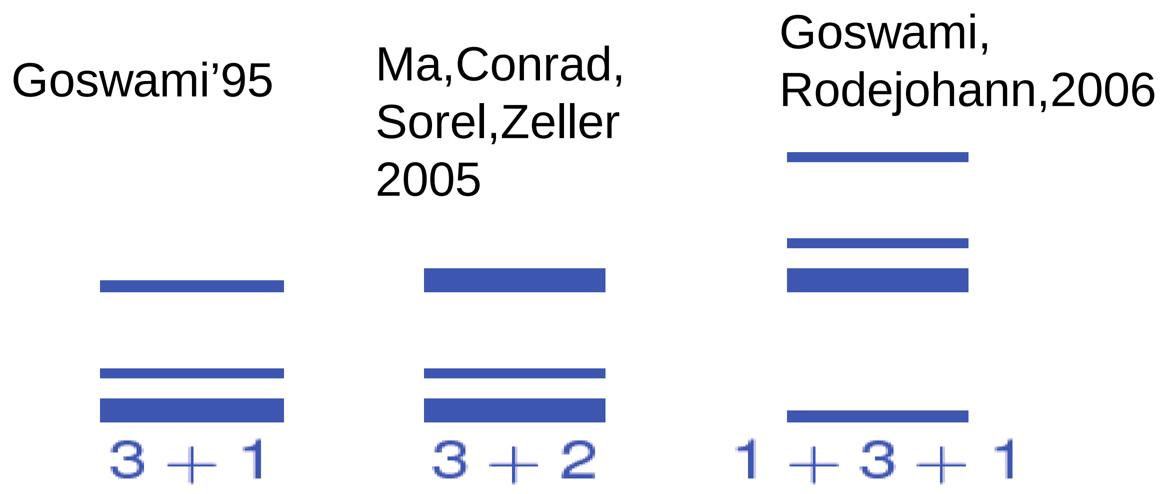
Evidences

- $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations reported in LSND and MiniBOONE
- Reactor Anomaly : Recalculated reactor fluxes are 3.5% more than the previous calculation
- Ga Anomaly : Deficit of ν_e from ^{51}Cr and ^{37}Ar sources in the reaction $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

Future Projects :

Talks by L.Stanco, M. Shaevitz , B. David, W. Ketchum,J. Lagrange, ICHEP 2014

Status of sterile neutrino fits



J. Kopp, Neutirno 2014

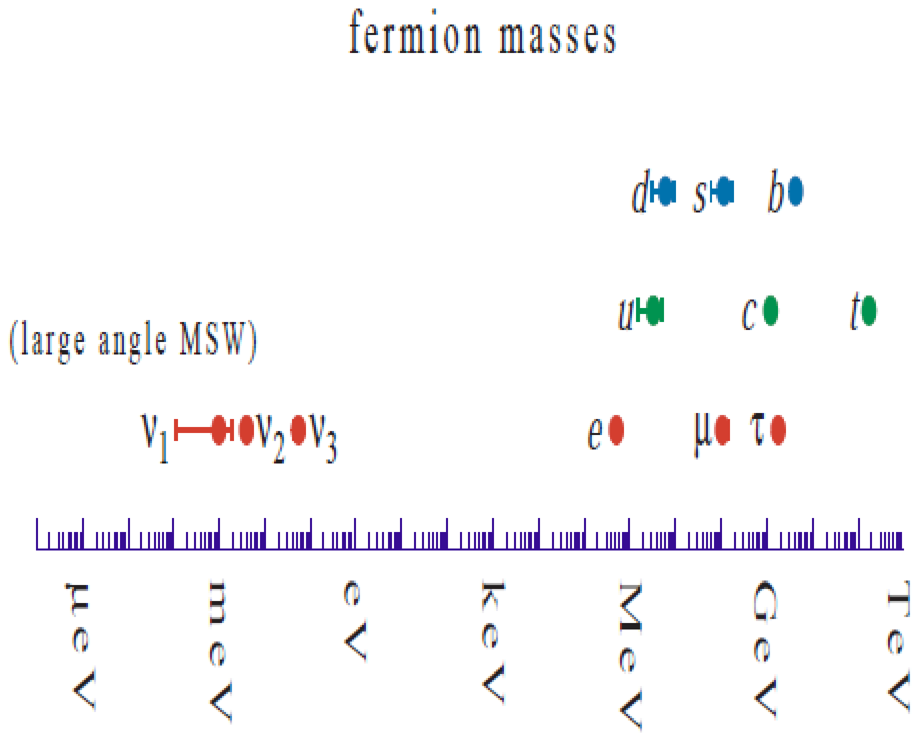
Appearance data can be fit in all three schemes 3+2 and 1+3+1 better

Severe tension when disappearance data is added

Kopp, Machado,Maltoni,Schwetz,
Giunti-et al.
Conrad et al.

Two fundamental questions

- Why neutrino masses are so small ?



Seesaw, Radiative mass generation,
Seesaw + radiative … .

Why neutrino mixing angles so different ?

Quark Mixing angles

$$\boxed{\begin{aligned} \theta_{12} &= 13^0 \\ \theta_{23} &= 2.3^0 \\ \theta_{13} &= 0.2^0 \\ \delta_{CP} &= 68.5^0 \end{aligned}}$$

Neutrino mixing angles

$$\boxed{\begin{aligned} \theta_{12} &= 33.5^o \\ \theta_{23} &= 49^0 \\ \theta_{13} &= 8.5^0 \\ \delta_{CP} &= 250^0 \end{aligned}}$$

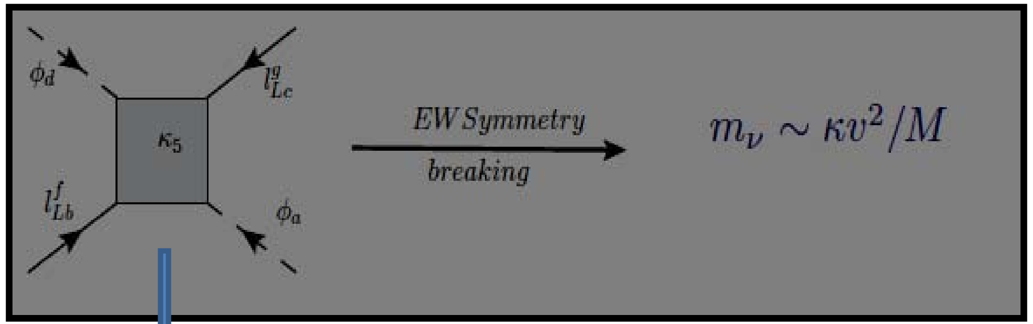
Flavour symmetries, Anarchy
TBM, QLC …

Seesaw and its implications : Neutrino connections

Standard Model is an effective therory and one can add non-renormalizable operators

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{d=5} + \mathcal{L}_{eff}^{d=6} + \cdots , \quad \text{with} \quad \mathcal{L}_{eff}^{d} \propto \frac{1}{\Lambda_{\mathcal{NP}}^{d-4}} \mathcal{O}^{d} .$$

Dimension 5 : only one operator $\mathcal{L} = c_5 LLHH$ $c_5 = \kappa/M$ Weinberg, 1979



$\Rightarrow m_\nu$ can be small for high M $\Rightarrow 10^{15}$ GeV

Neutrinoless double beta decay

M. Malinsky, ICHEP 2014

GUTS

SO(10)

Lepton number violation

Majorana nature

SU(5)

LR

Three ways to generate the above operator -- Type-I, Type-II, Type-III

Like sign di-lepton at LHC

Large light -heavy mixing

TeV scale seesaw

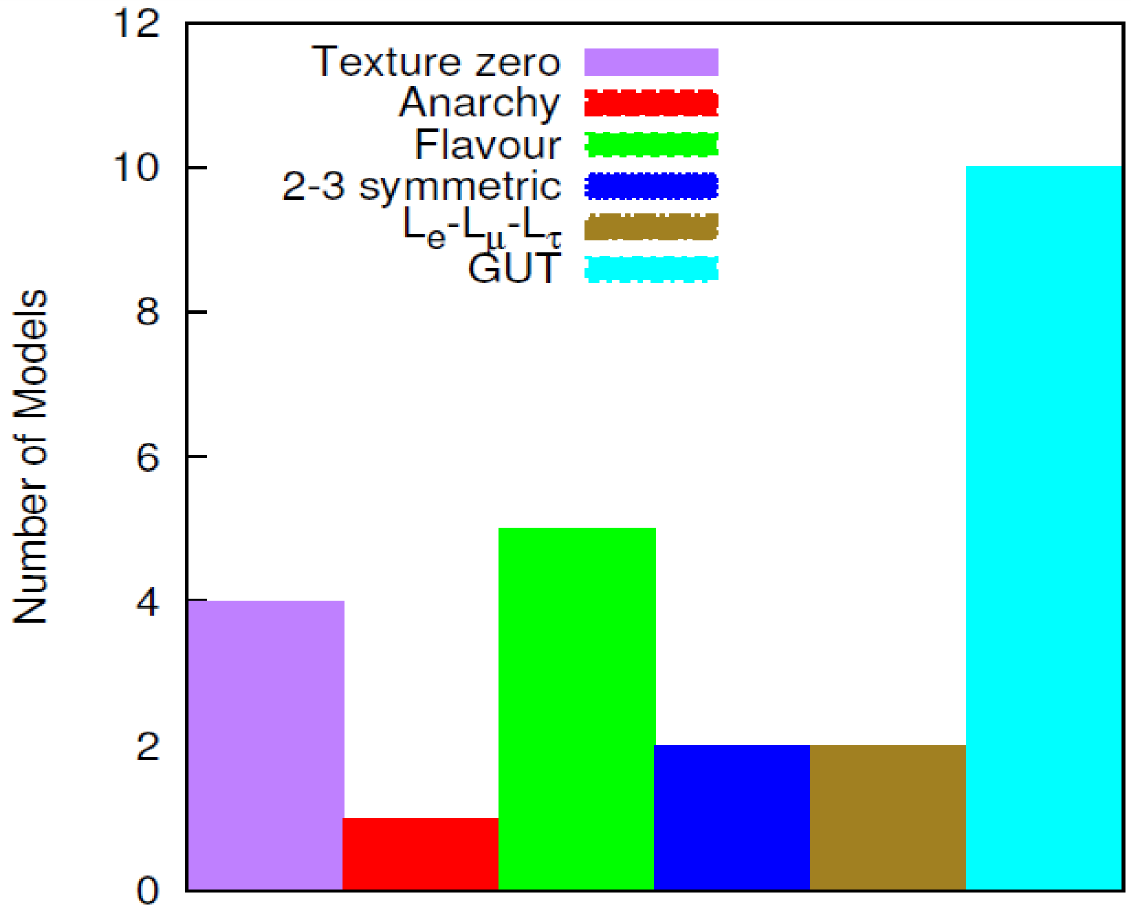
Can't be probed at LHC

Lepton Flavour Violation

Inverse Seesaw, Higher dim operators, textures

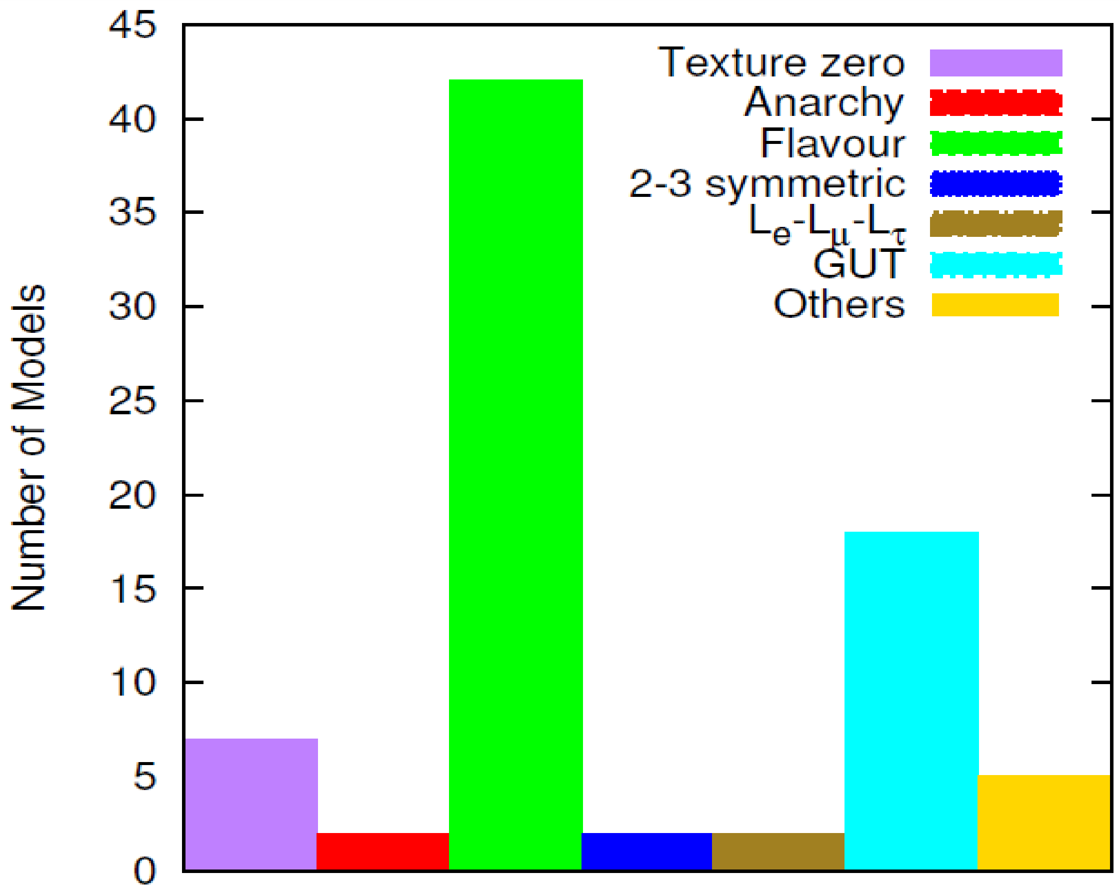
Talk by A. Blondel on search for heavy Neutrinos at Z and H factory , ICHEP 2014

Is there a case for precision measurements ?



Models from 0905.0146 (Albright) that survive the present 3σ range

24 Models survive out of 86



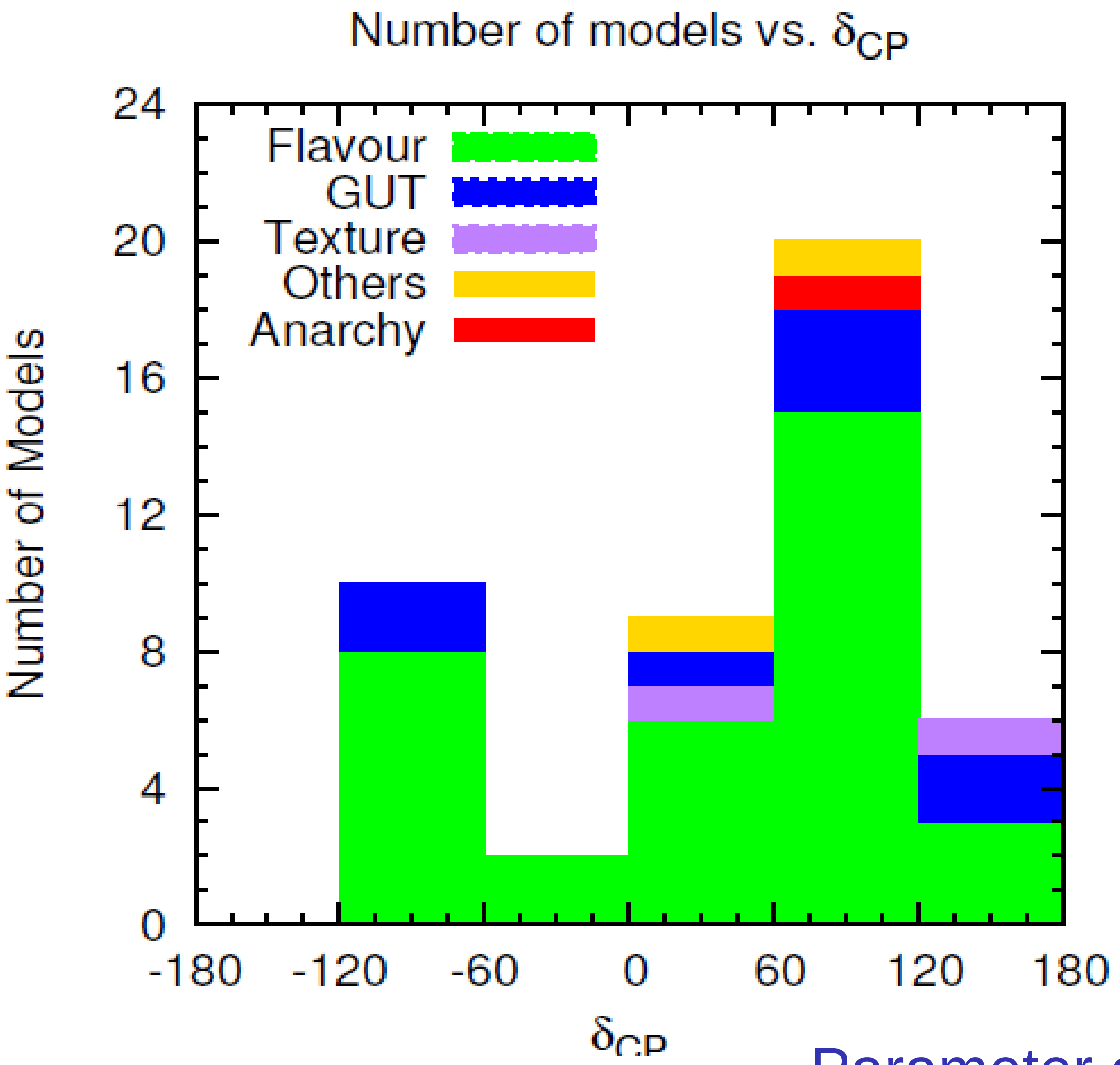
54 new models ! (incomplete survey)

Flavour boom

Difficult to beat theoreticians

Bambhanya, Ghosh (2014)

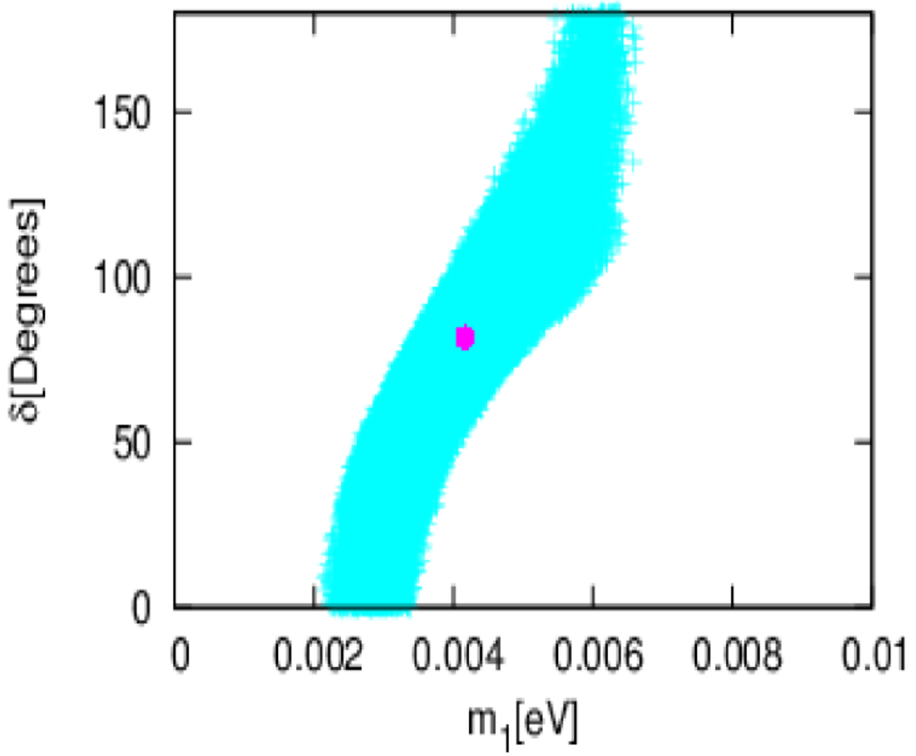
Prediction for δ_{CP}



Bambhanya, Ghosh (2014)

$$A_1 : \begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$$

Frampton, Glashow, Marfatia. 2002
Xing 2002



Parameter correlation important

Babu, Devi, Goswami, 2014
Liao,Marfatia, Whisnant, 2014

Concluding Remarks

- Impressive progress in determination of neutrino oscillation parameters
- Discovery of θ_{13} has opened the avenues for determination of mass hierarchy, octant of θ_{23} and δ_{CP}
- Many future experiments
- The findings of the current generation experiments will be crucial input
- Synergistic aspects between various experiments important
- Precision measurements help in disfavouring models but also many new models
- Parameter correlation may be important …

Finally…

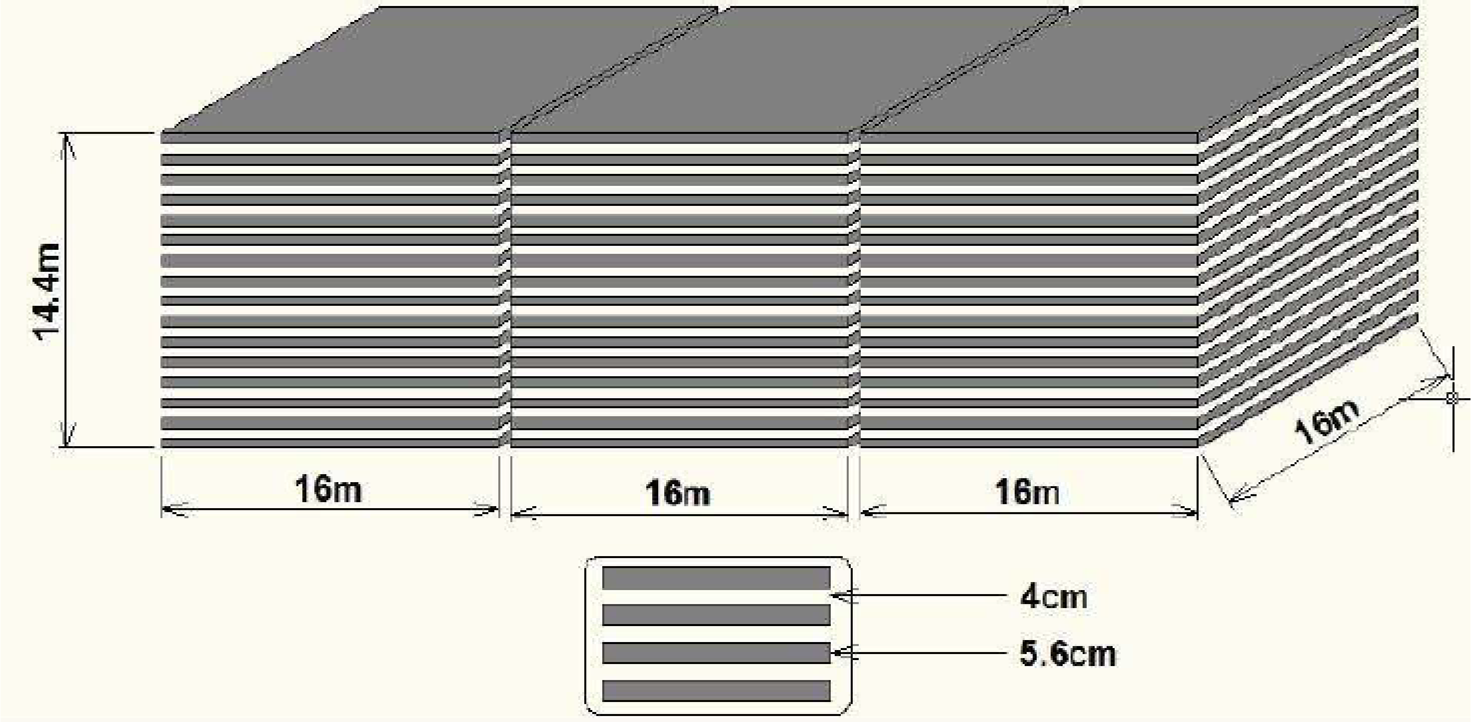
Acknowledgement:

G. Bambhanya, M. Ghosh, P. Ghoshal, C. Gupta N. Nath, S, Raut

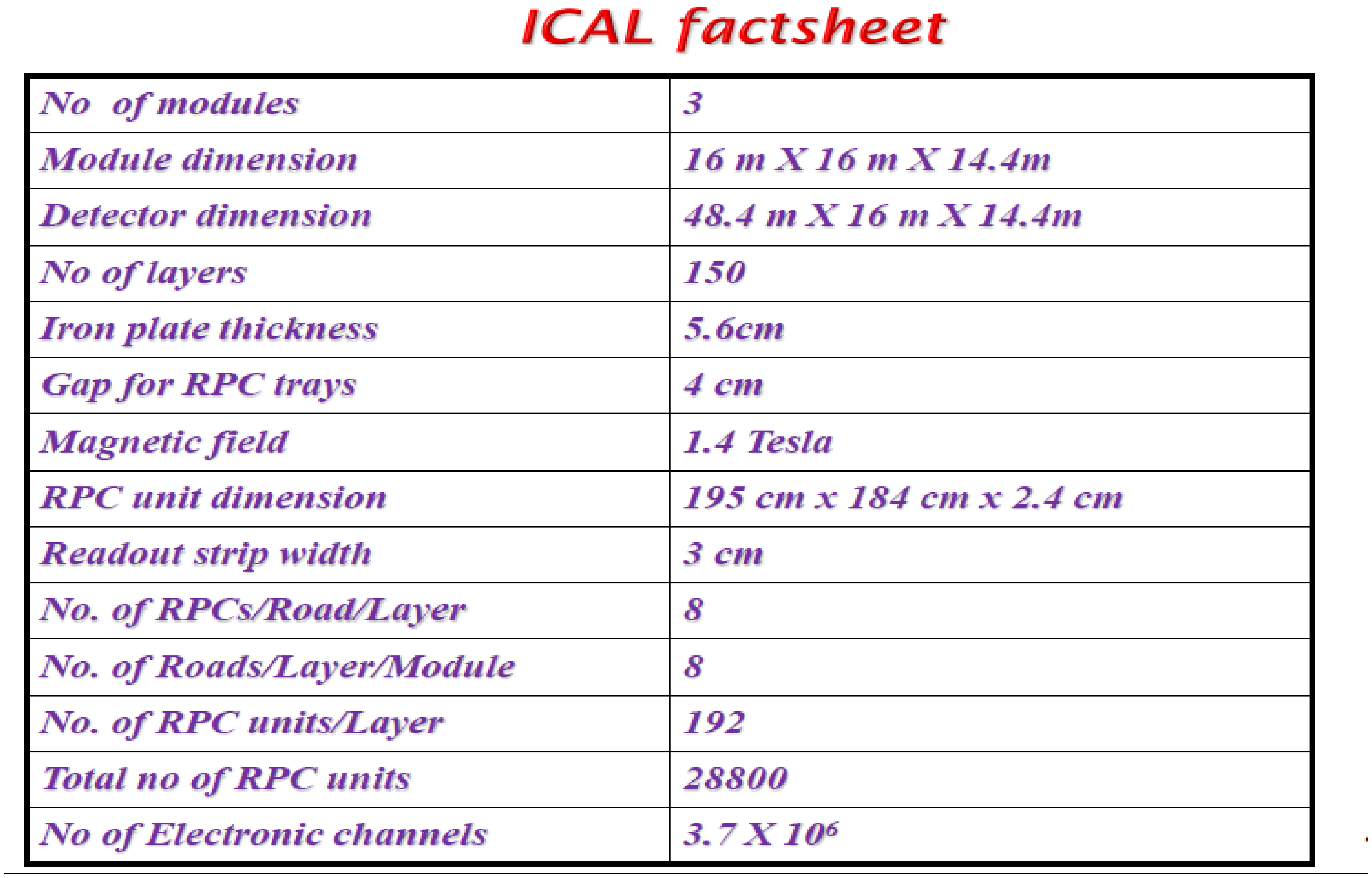
S. Agarwalla, D. Cowen , A. Ghosh, E. Lisi, M. Maltoni, S. Seo, T. Thakur

Backup slides

INO-ICAL Detector



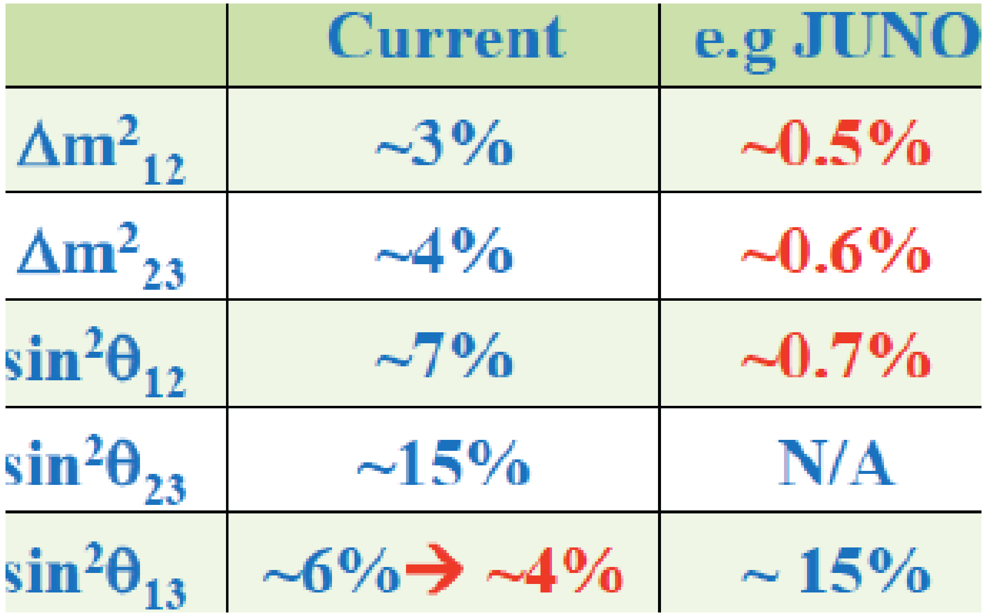
Backup Slides



ICAL factsheet

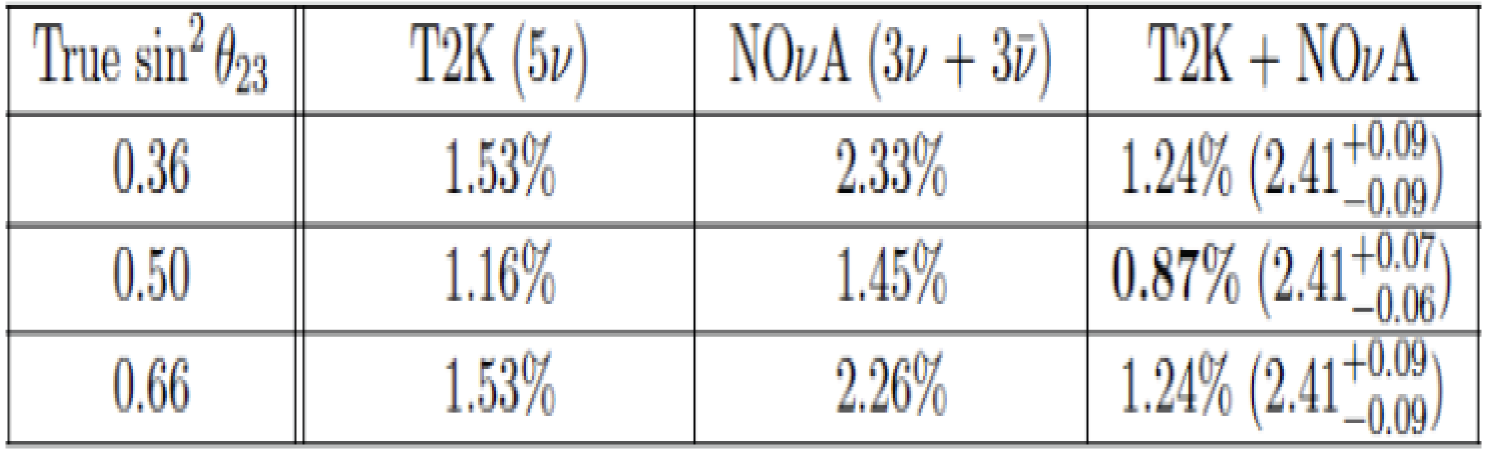
No of modules	3
Module dimension	16 m X 16 m X 14.4m
Detector dimension	48.4 m X 16 m X 14.4m
No of layers	150
Iron plate thickness	5.6cm
Gap for RPC trays	4 cm
Magnetic field	1.4 Tesla
RPC unit dimension	195 cm x 184 cm x 2.4 cm
Readout strip width	3 cm
No. of RPCs/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no of RPC units	28800
No of Electronic channels	3.7 X 10^6

Parameter Precision : Future Projections



	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%

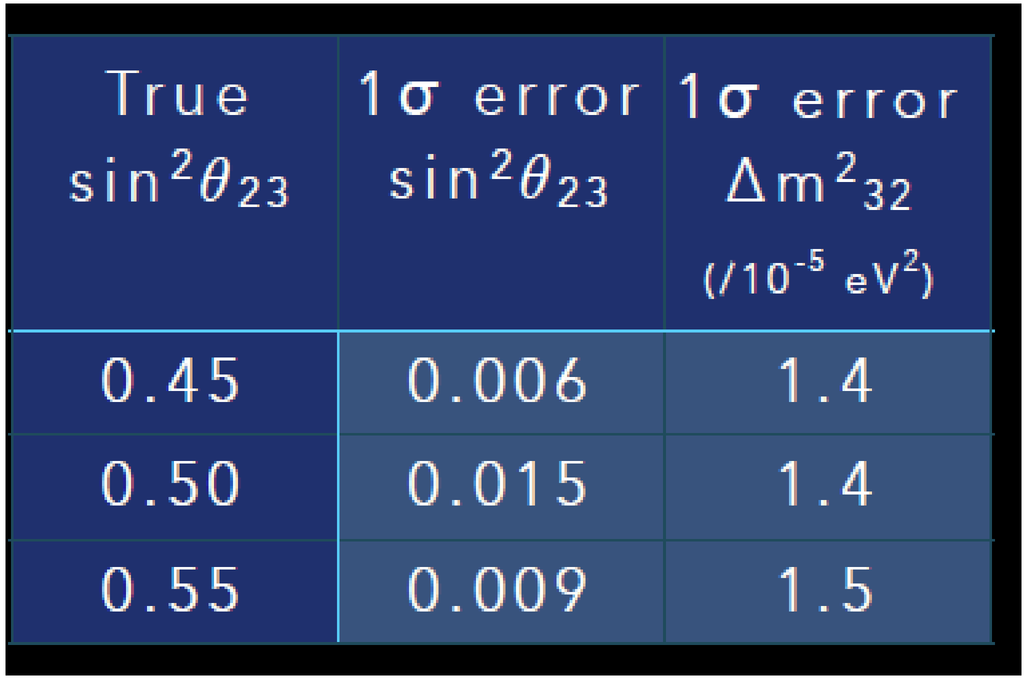
L. Wen, talk at Nu2014



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]

HK



True $\sin^2\theta_{23}$	1σ error $\sin^2\theta_{23}$	1σ error Δm^2_{32} ($/10^{-5}$ eV^2)
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5

H.A. Tanaka, ICHEP 2014