Three flavor effects and Synergy between atmospheric and other experiments

Srubabati Goswami
Physical Research Laboratory
Ahmedabad, India

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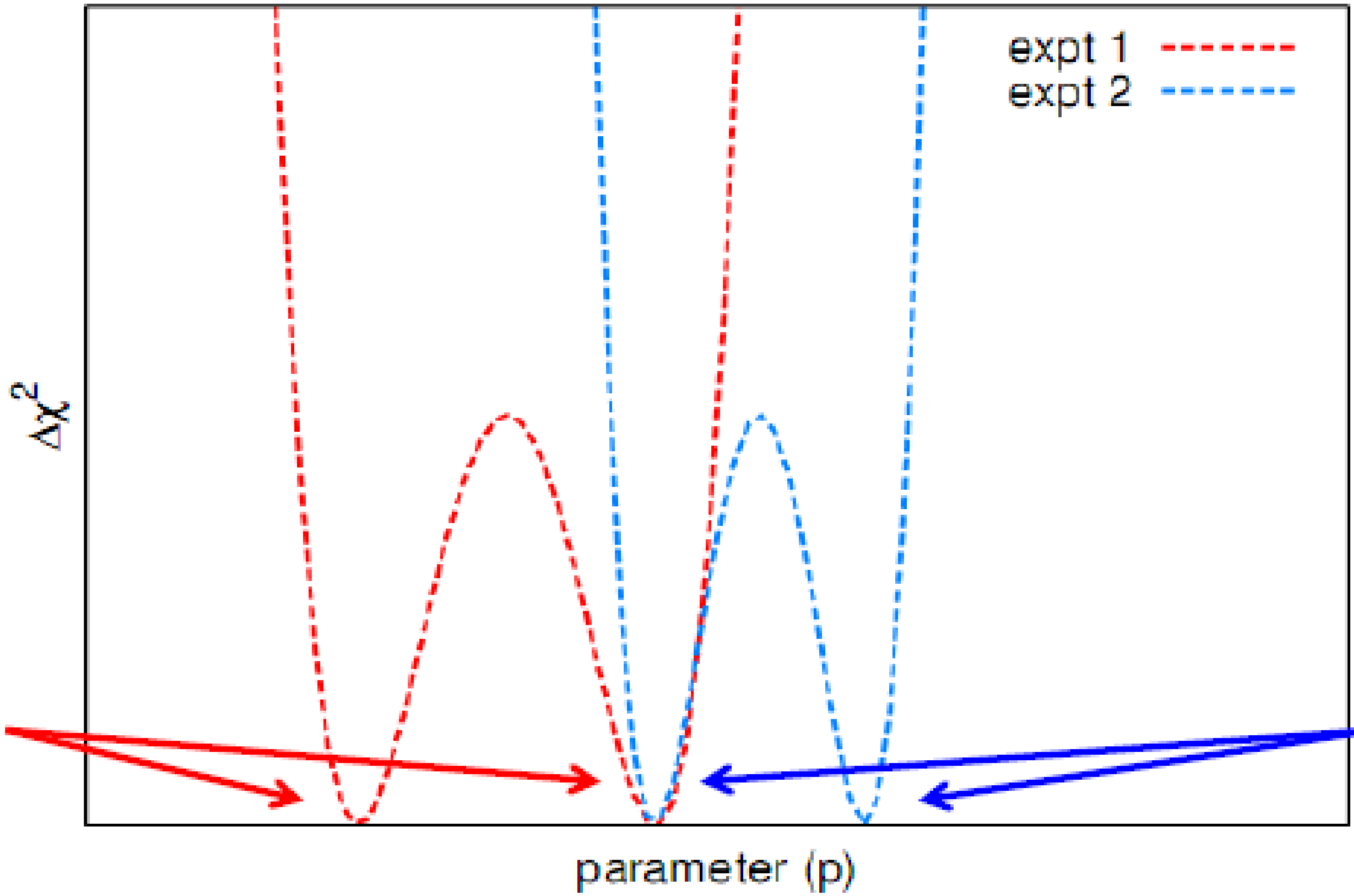
Synergy between atmospheric and LBL experiments

Synergies Between Experiments

Different experiments have different L,E dependence, therefore their functional dependence on a given parameter p is different.

two degenerate values for expt 1

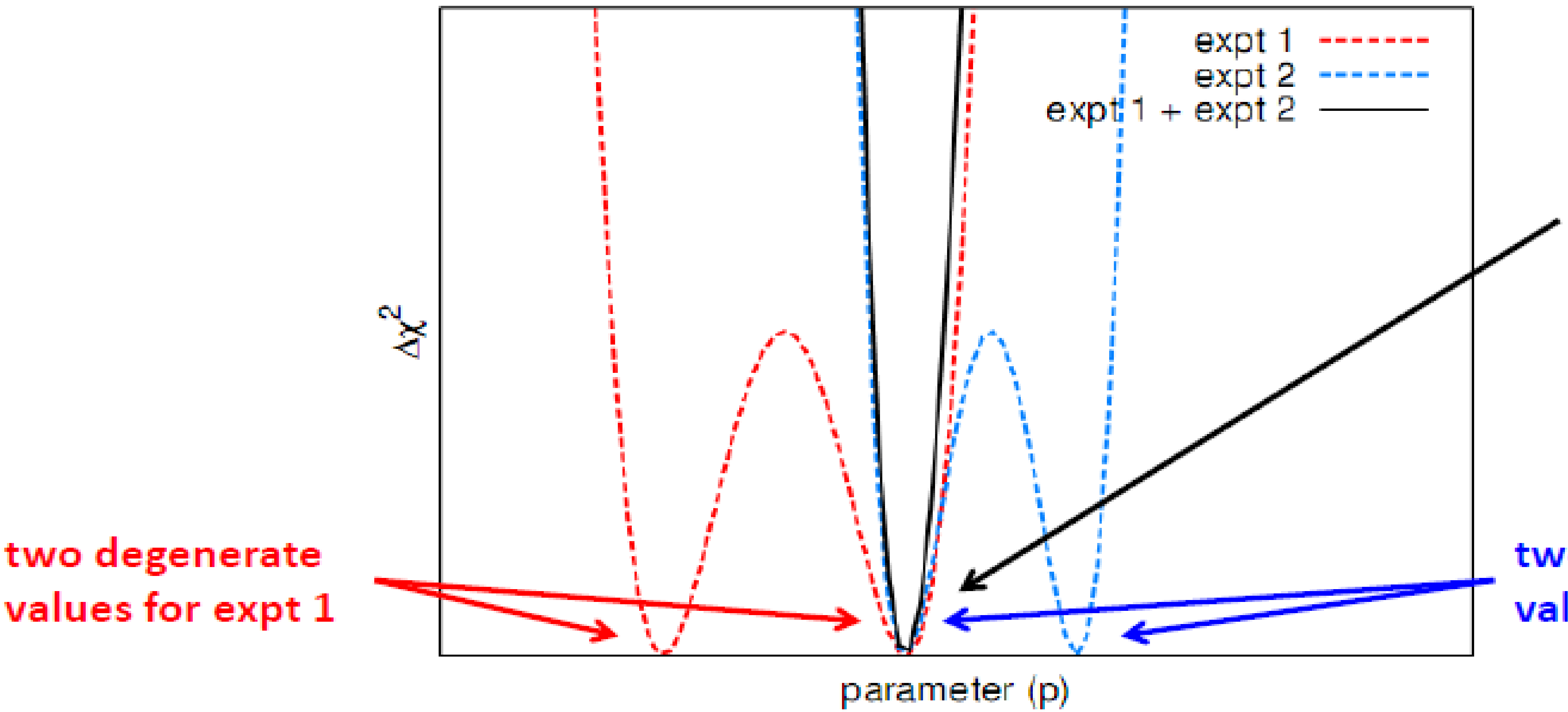


two degenerate values for expt 2

S. Raut. Talk @NUFACT 2017

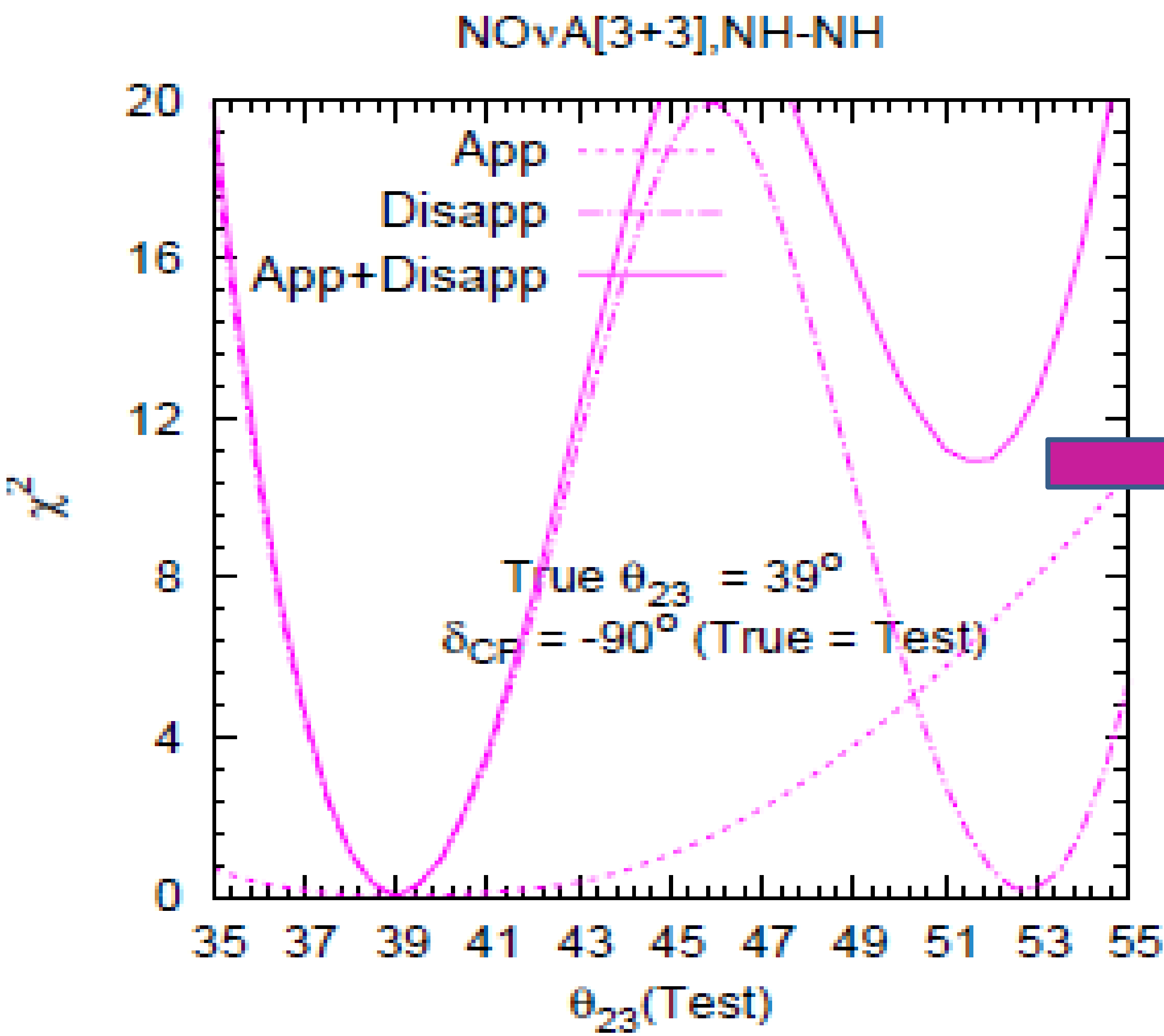
Synergies Between Experiments

Different experiments have different L,E dependence, therefore their functional dependence on a given parameter p is different.



S. Raut. Talk @ NUFACT 2017

Synergy between channels



Total χ^2 greater than individual Contribution

Three neutrino oscillation parameters

- 3 masses, 3 mixing angles, 1 phase

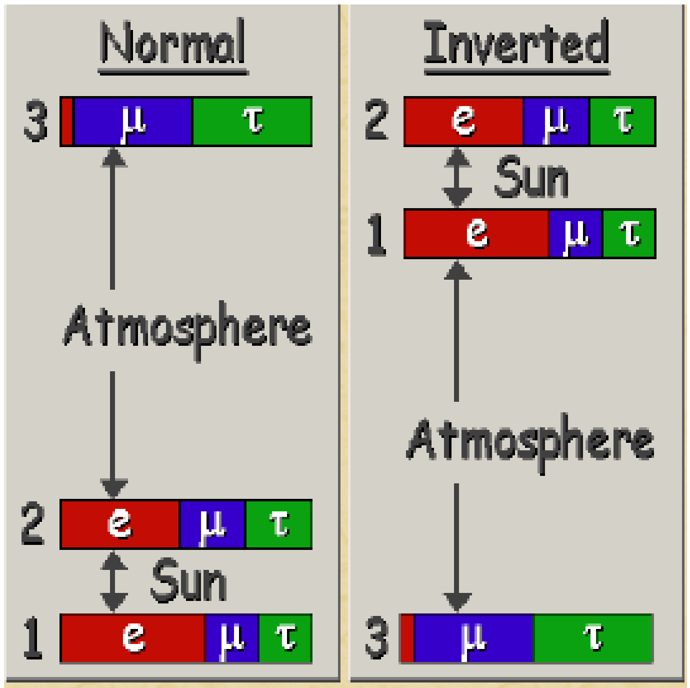
Atm +LBL Sol+KL

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

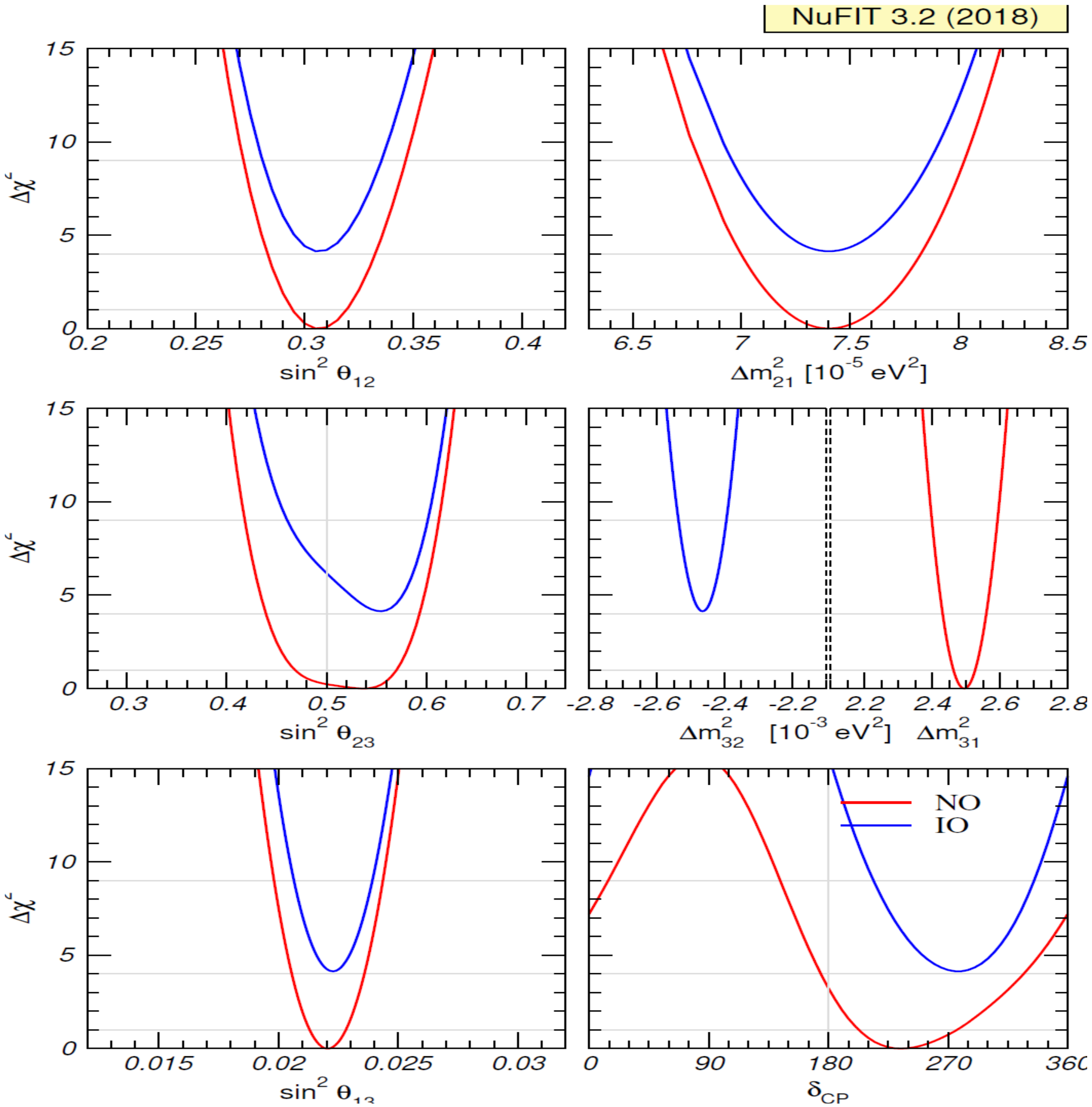
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

- Δm^2_{21}, θ_{12}, θ_{13} Solar + KamLND
- Δm^2_{31}, θ_{13} Reactor
- Δm^2_{31}, θ_{23}, θ_{13}, δ_{CP} Atm + LBL

Interplay among different sectors because of θ_{13}



Global Analysis (2018)



- **Best-fit in second octant**
- **Preference for NO**
- $\delta_{CP} = +90^\circ$ **disfavored at more than** 3σ **irrespective of mass ordering**

Talk by E. Lisi

Immediate Goals

Mass Hierarchy

- **Matter effects in atmospheric and long-baseline experiments (θ_{13})**
- **Interference effects in reactor experiments ($\Delta m^2_{21}, \theta_{13}$)**

Octant of θ_{23}

- **Matter effects in atmospheric and long baseline experiments** (θ_{13})
- **Matter effects in atmospheric neutrino experiments (Δm^2_{21})**

CP Violation

- **Long baseline experiments , needs to disentangle matter CP , atmospheric neutrino experiments** $\Longrightarrow$ **(Talk by S. Razzaque)**
- **Genuine three flavor effect ($\Delta m^2_{21}, \theta_{13}$)**

Current and Future Experiments

Current

Atmospheric
Super Kamiokande

Long-baseline
T2K, NOVA

Reactor
Daya-Bay, Double CHOOZ

Future

Atmospheric
INO, Hyper Kamiokande, PINGU, ORCA

Long-baseline
DUNE,T2HK,T2HKK, ESSnuSB

Reactor
JUNO

μ--Decay
μDar MOMENT

Long-baseline Experiments: Salient features

Expt	Baseline	E (GeV)		Details
T2K	295 km, Tokai to Kamioka	0.6		0.76 MW Super Kamiokande
NOVA	810 km, FNAL to ASH River	1.7		0.7 MW 14 kt TASD
DUNE	1300 km FNAL to South Dakota	0.5-8		1.2 MW Liquid Argon 10kt/40 kt
T2HK	295 km JPARC to Kamioka	0.6		1.3 MW , 187 kt X2 Hyper Kamiokande
T2HKK	295km, 1100 km	0.6		HK, Water Cherenkov in Korea
ESSnuSB	540 km , Lund to Gapenberg	2		500 kt Water Cerenkov,

Atmospheric Neutrino Detectors: Salient features

	Prototype	Salient features
Magnetized IRON	ICAL@INO	50 kt, muon energy and direction measurement, charge id, neutrino energy reconstruction
Water Cherenkov	Hyper Kamiokande	Megaton, no charge id, both electron and muon energy and direction
Water Cherenkov (Mediteranian)	ORCA	Multi- Megaton, tracks and showers, no charge id
ICE Cherenkov (Southpole)	PINGU	Multi megaton, tracks and showers , no charge id
Liquid Argon	DUNE	Liquid Argon, both muon and electron events Charge id for both ??

Salient Features of Atmospheric & LBL experiment

Atmospheric Neutrinos

- Path length 10 – 10,000 km
- Broad range of energy compared to other natural or artificial sources
- Can probe resonant matter effects
- Source of ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
- $N_\mu \sim N_\mu^0 P_{\mu\mu} + N_e^0 P_{e\mu}$
- $N_e \sim N_\mu^0 P_{\mu e} + N_e^0 P_{ee}$
- Cannot disentangle disappearance and appearance channels
- Both neutrinos and antineutrinos and only detectors with chargeID can probe these separately

Long-baseline Neutrinos

- Fixed Path Length < 1500 km
- Narrow band and wide band beams, smaller range for latter
- Can't probe resonant matter effect
- Source of ν_μ or $\bar{\nu}_\mu$
- Disappearance channel $N_\mu \sim P_{\mu\mu} N_\mu^0$
- Appearance Channel $N_e \sim P_{\mu e} N_\mu^0$
- Can probe disappearance and appearance channels separately
- The same experiment can also run in antineutrino mode

Matter Effects : Three flavors

- **The propagation equation in matter**

$$\tilde{H} = \frac{1}{2E}[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$A = 2\sqrt{2} G_F n_e E$$

- **Double Expansion in small parameters** $\alpha - s_{13}$ $\qquad \alpha = \Delta m^2_{21} / \Delta m^2_{31}$

Suitable for studying the current and proposed long-baseline experiments

- **One Mass Scale Dominance (OMSD) Limit** ($\Delta m^2_{21} = 0$), $\qquad \Delta m^2_{21} << \Delta m^2_{31}$
  - ✓ **Also** $\Delta m^2_{21} L / E << 1 \Rightarrow L/E \ll 10^4\ \mathrm{km/GeV}$
  - ✓ **Satisfied by atmospheric neutrinos of energy** $\mathcal{O}$**(GeV)**
  - ✓ **Valid for** $\sin\theta_{13} >> \alpha \Rightarrow \sin\theta_{13} >> 0.03$

⟶ **Resonance in the 1-3 sector**

The survival and oscillation probabilities ($\alpha - s_{13}$)

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

In matter of constant density

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

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

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

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

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

\+ for neutrinos
\- for antineutrinos

Depends on δ_{CP}

The survival and oscillation probabilities (OMSD)

$$\begin{aligned} P_{\mu\mu} &= 1 - \cos^2\theta_{13}^{\rm m}\ \sin^2 2\theta_{23}\sin^2\left[1.27(\Delta m^2_{31} + A + (\Delta m^2_{31})^{\rm m})L/2E\right] \\ &- \sin^2\theta_{13}^{\rm m}\ \sin^2 2\theta_{23}\ \sin^2\left[1.27(\Delta m^2_{31} + A - (\Delta m^2_{31})^{\rm m})L/2E\right] \\ &- \sin^4\theta_{23}\ \sin^2 2\theta_{13}^{\rm m}\ \sin^2\left[1.27\Delta m^2_{31}L/E\right]\ , \end{aligned}$$

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

No dependence on δ_{CP}

$$\tan 2\theta_{13}{}^{m} = \frac{\Delta m^2_{31}\sin 2\theta_{13}}{\Delta m^2_{31}\cos 2\theta_{13} \pm 2\sqrt{2}G_F n_e E}$$

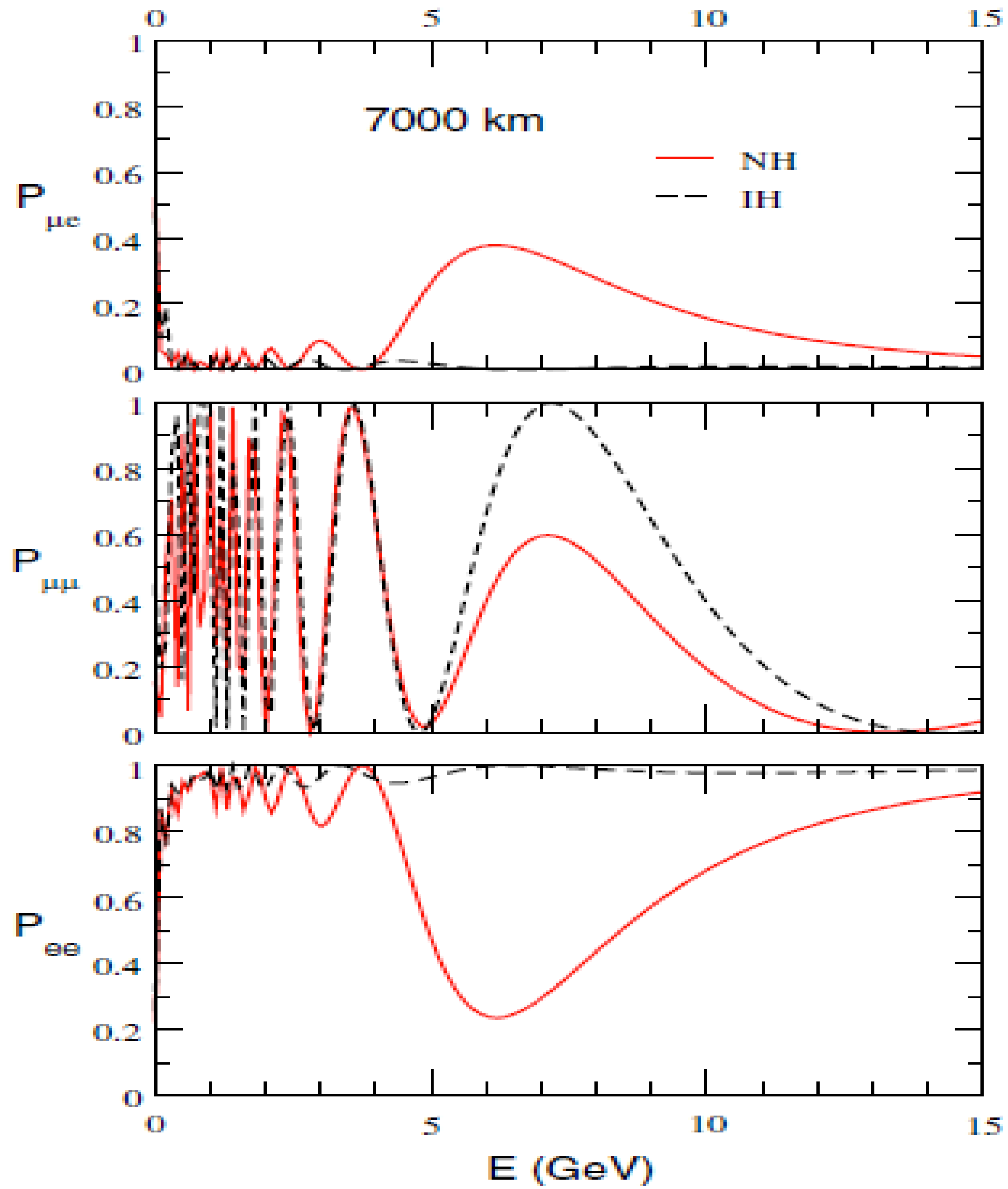
- For $\Delta m^2_{31} > 0$ resonance in neutrinos
- For $\Delta m^2_{31} < 0$ resonance in antineutrinos

$$(\Delta m^2_{31})^{\rm m} = \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}$$

Hierarchy sensitivity

Detectors with charge Id suitable

Matter Effect at large baselines



$$E_{\rm res} = \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F n_e}$$

L (km)	$\rho_{\rm avg}$(g/cc)	$E_{\rm res}$ (GeV)
1000	3.00	9.9
3000	3.32	9.4
5000	3.59	8.7
7000	4.15	7.5
10000	4.76	6.6

- **Atmospheric neutrinos can encounter resonance**
- **Matter effect opposite for $P_{\mu\mu}$ and $P_{\mu e}$**

Degeneracy Menace

The main problem in determination of hierarchy, octant and CP in long-baseline experiments is due to the presence of degeneracies.

- Degeneracy $\Longrightarrow$ Different set of parameters giving same probability
  $\Longrightarrow$ Equally good fit to the data

Hierarchy - δ_{CP} degeneracy

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

Minakata, NunoKawa, 2001

Intrinsic octant degeneracy

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

Fogli and Lisi, 1996

Octant - δ_{CP} degeneracy

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

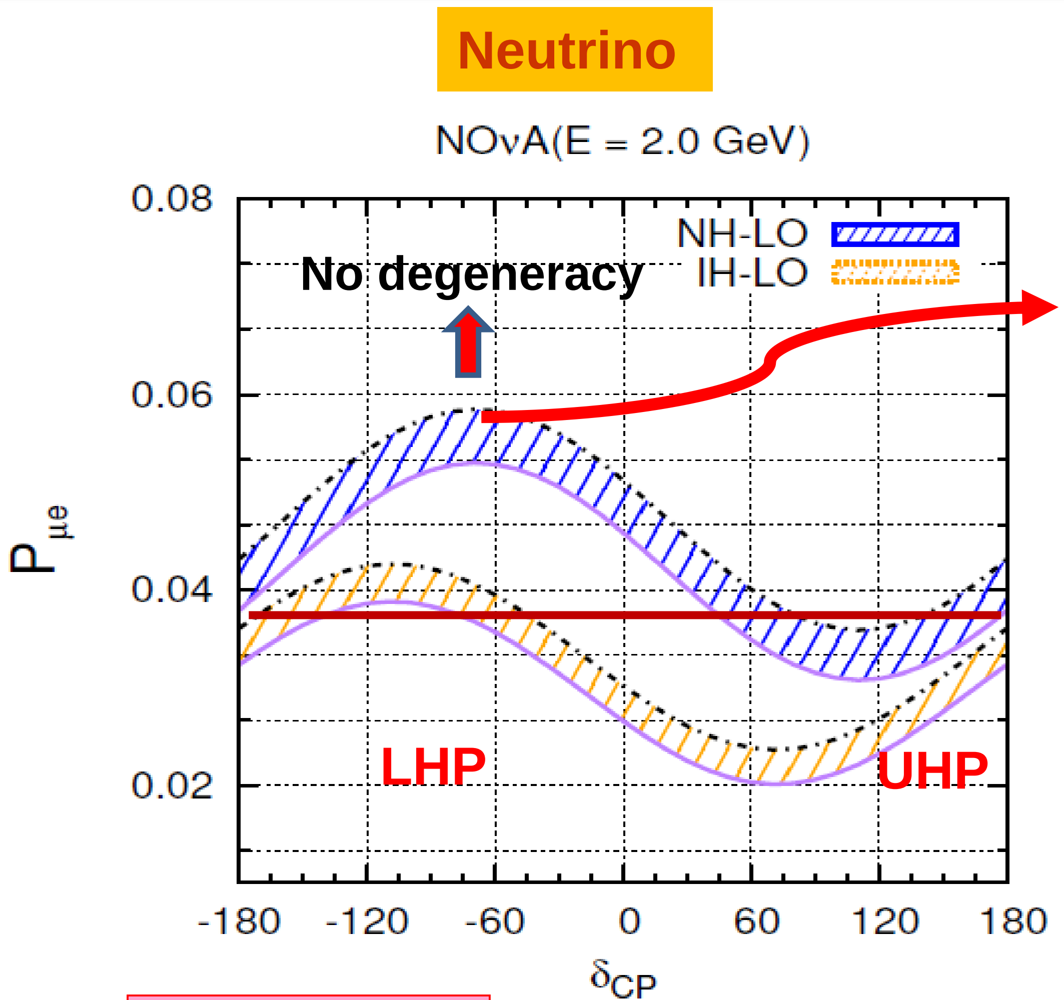
Gandhi, Ghosal, Goswami, Shankar 2005

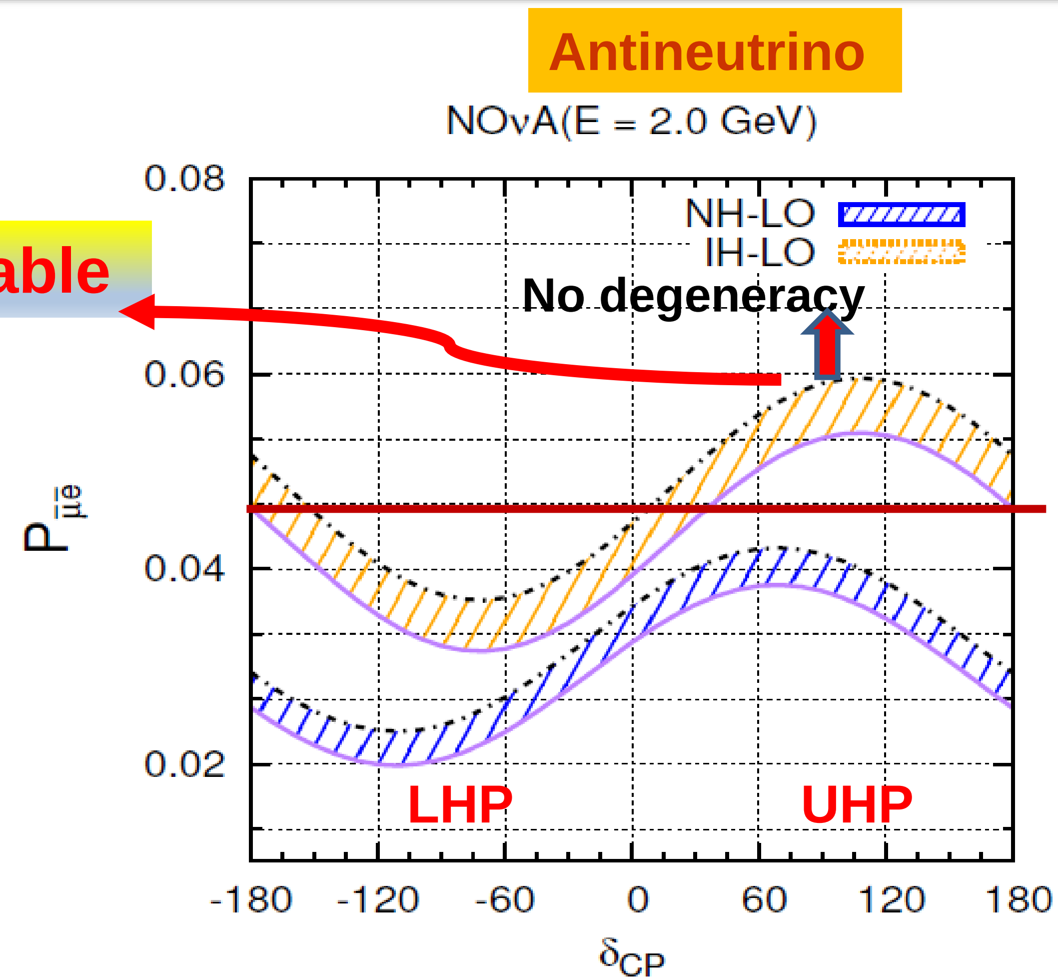
Comprehensive Approach

$$P_{\mu e}(\theta_{23}, \Delta, \delta_{CP}) = P_{\mu e}(\theta'_{23}, -\Delta', \delta'_{CP}) \Rightarrow \text{generalized}\,(\text{hierarchy} - \theta_{23} - \delta_{CP})\,\text{degeneracy}.$$

Coloma, Minakata, Parke, 2014
Ghosh, Ghoshal, Goswami, Nath, Raut, 2015

Hierarchy -- δ_{CP} Degeneracy





Favourable

LHP $-180^{\circ} \leq \delta_{CP} \leq 0^{\circ}$

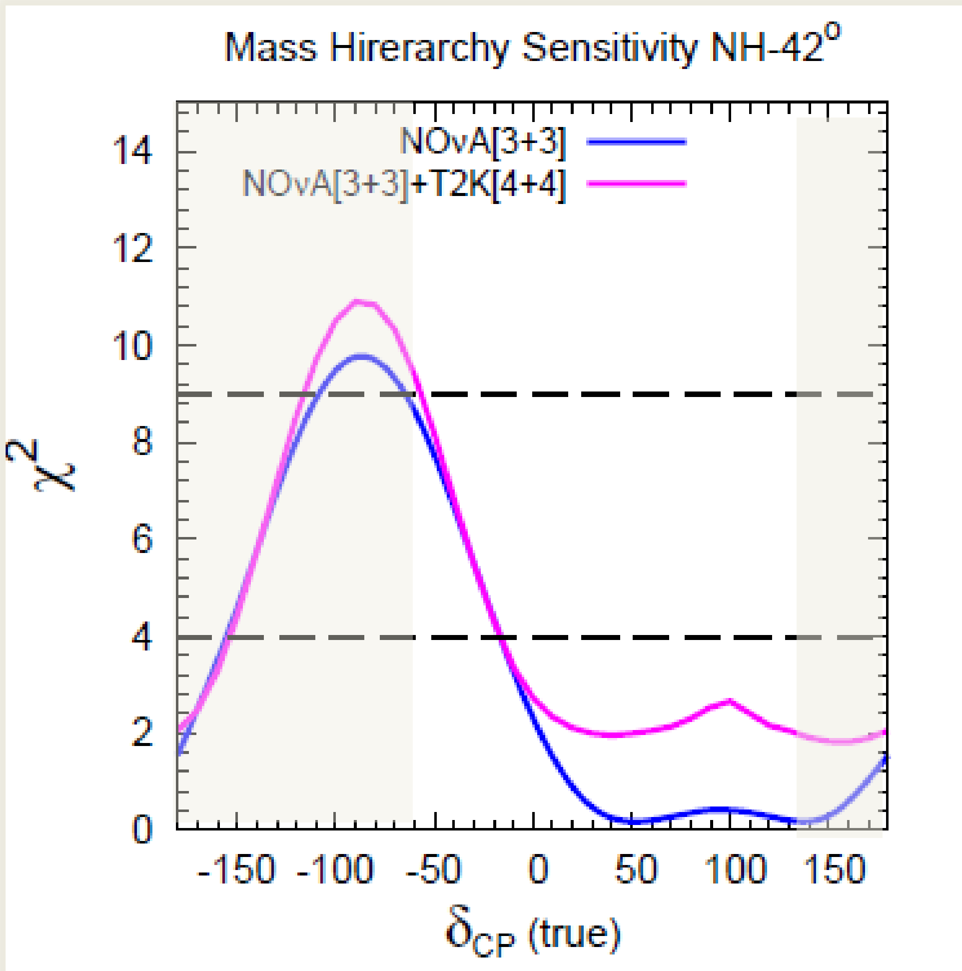
UHP $0^{\circ} \leq \delta_{CP} \leq 180^{\circ}$

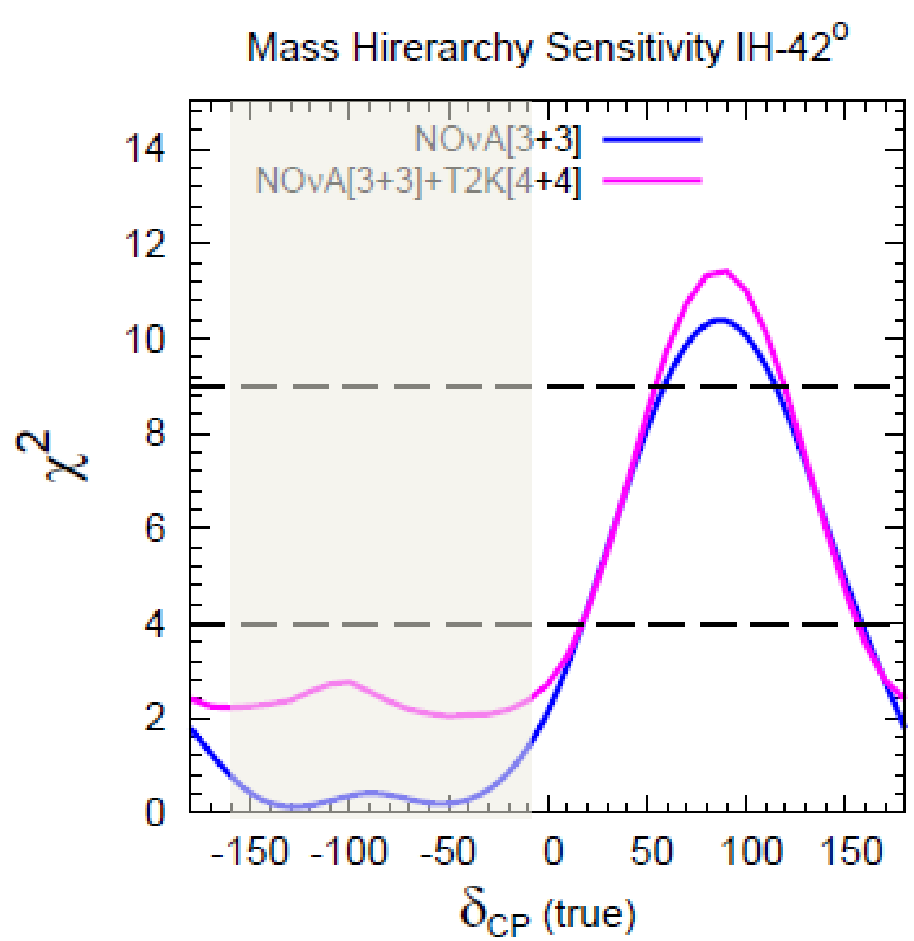
No degeneracy for NH-LHP and IH-UHP

IH-LHP degenerate with NH-UHP

Combining neutrino and antineutrino does not help in lifting degeneracy

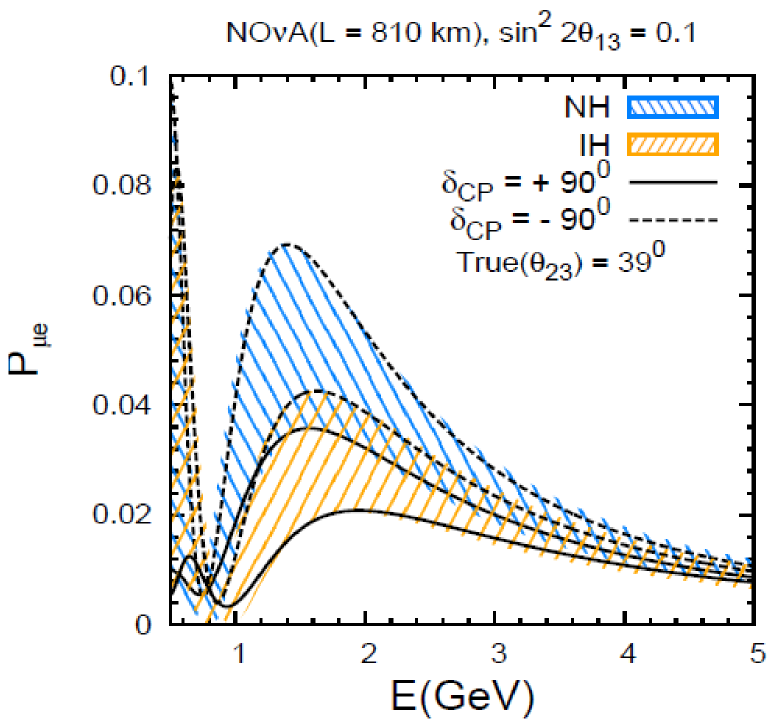
Hierarchy Sensitivity : T2K and NOVA

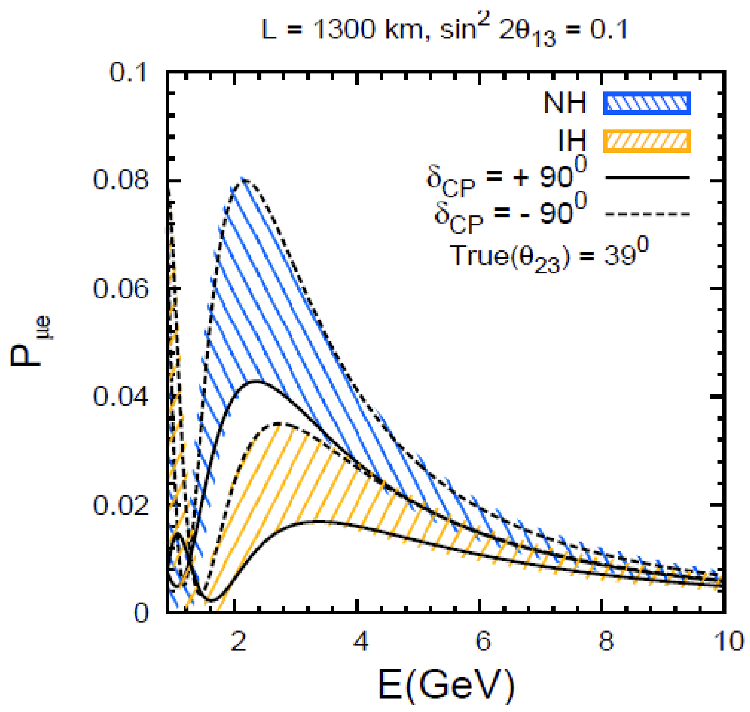


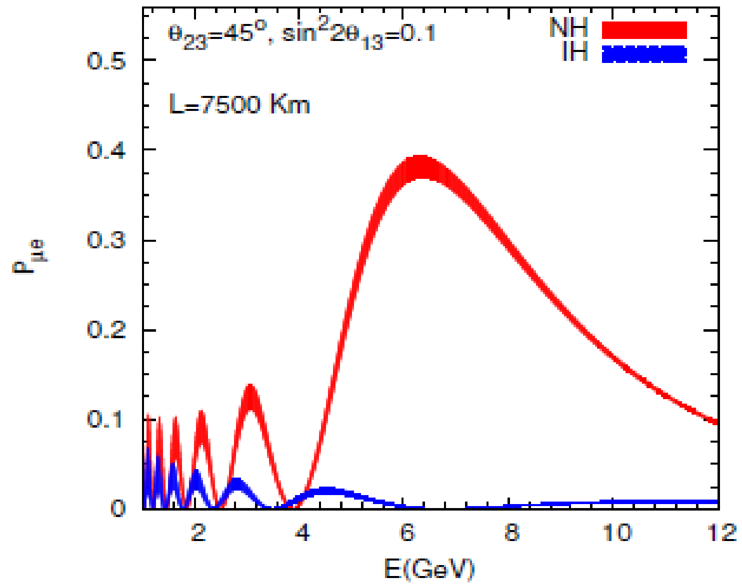


- **T2K + NOVA can give up to 3σ sensitivity in favorable zone** **(Praksh, Raut, Sankar, 2012)**
- **Hierarchy sensitivity less in the degenerate region**
- **Shaded region currently allowed at 3σ from global analysis**

Impact of Matter effect





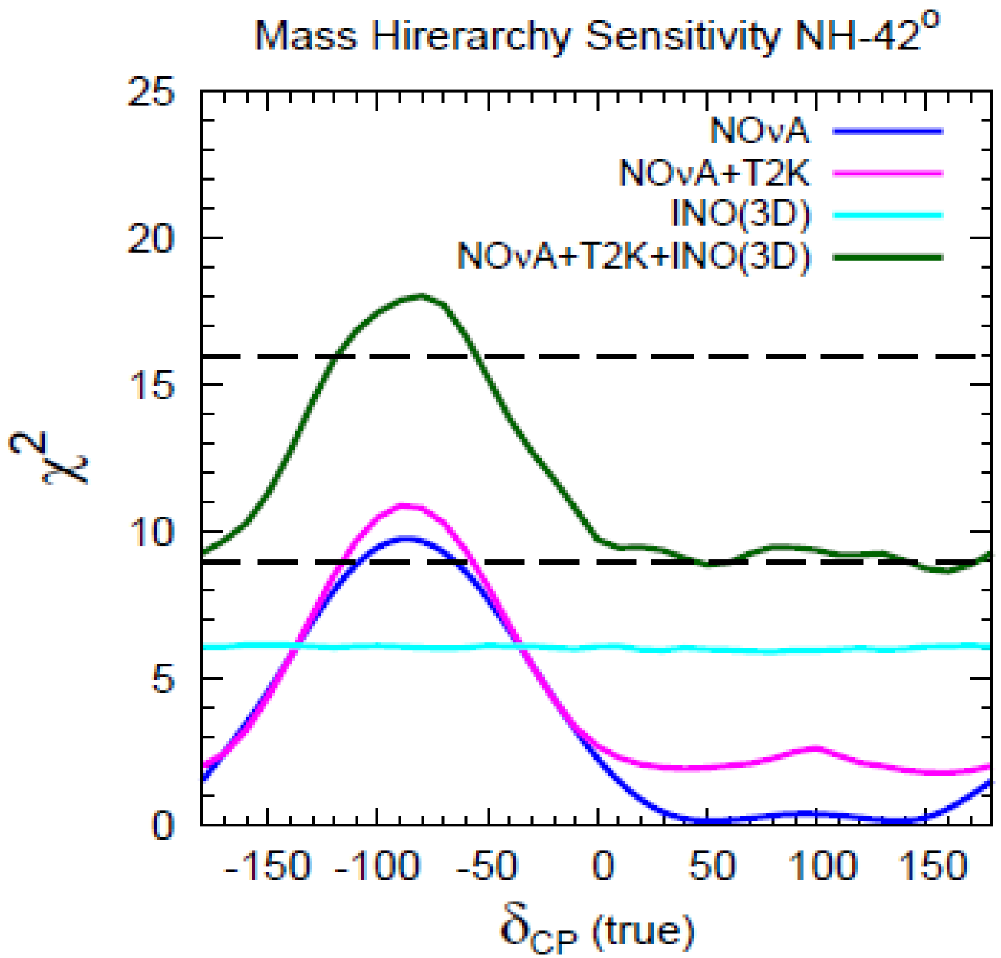


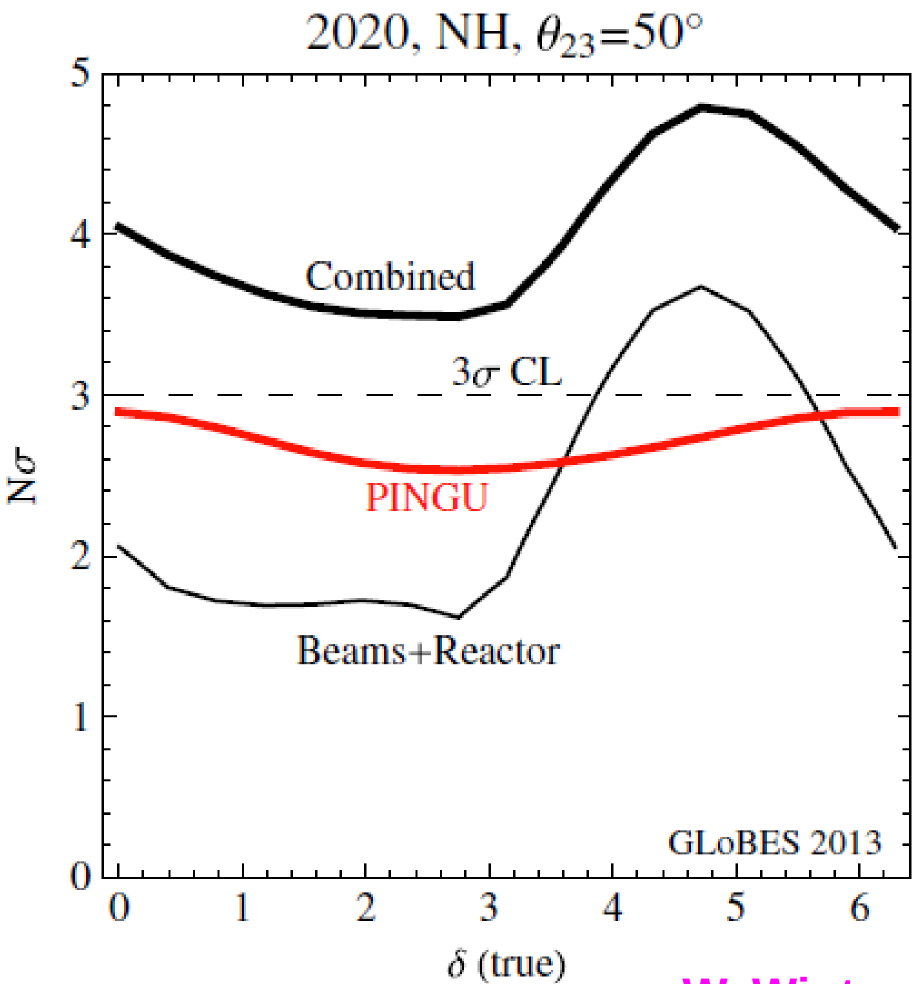
Degeneracy for NH +90 & IH -90

NH +90 and IH -90 separated ~ 2-4 GeV

Resonant matter effect
No $\delta_{\rm CP}$ degeneracy

Can atmospheric Neutrinos help ?



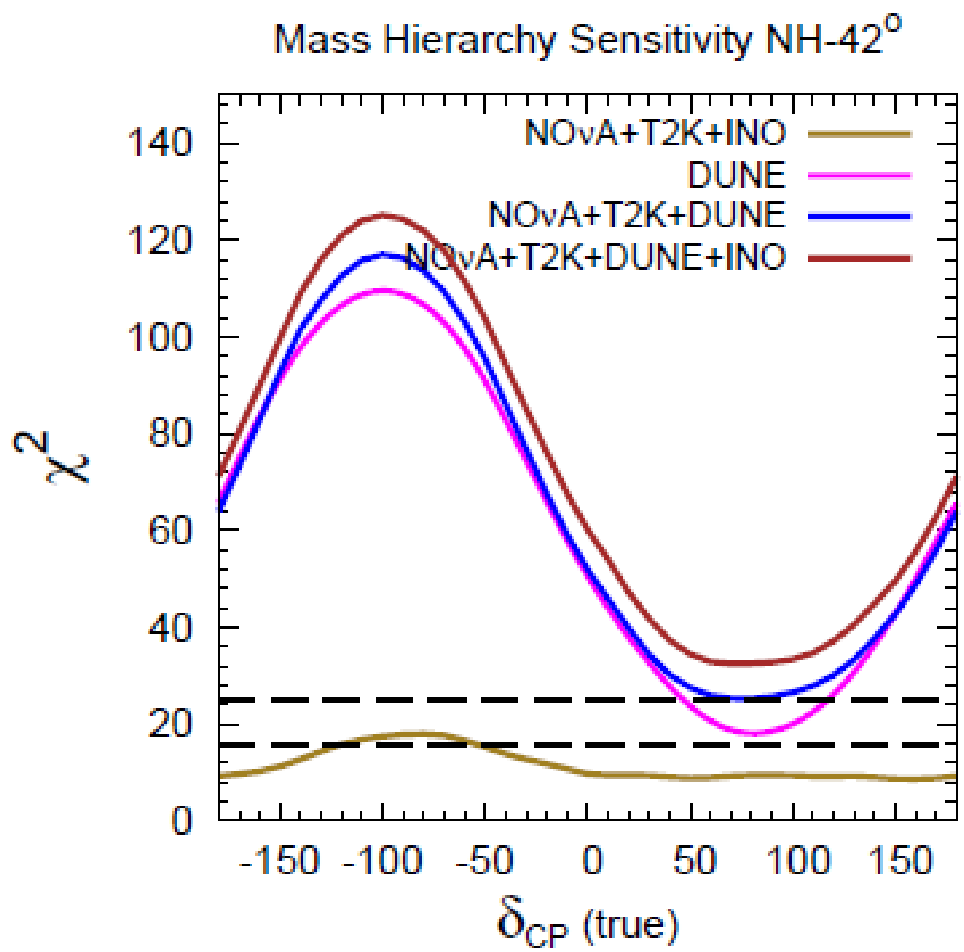


Devi, Thakore, Agarwalla, Dighe, 2014

W. Winter, 2013

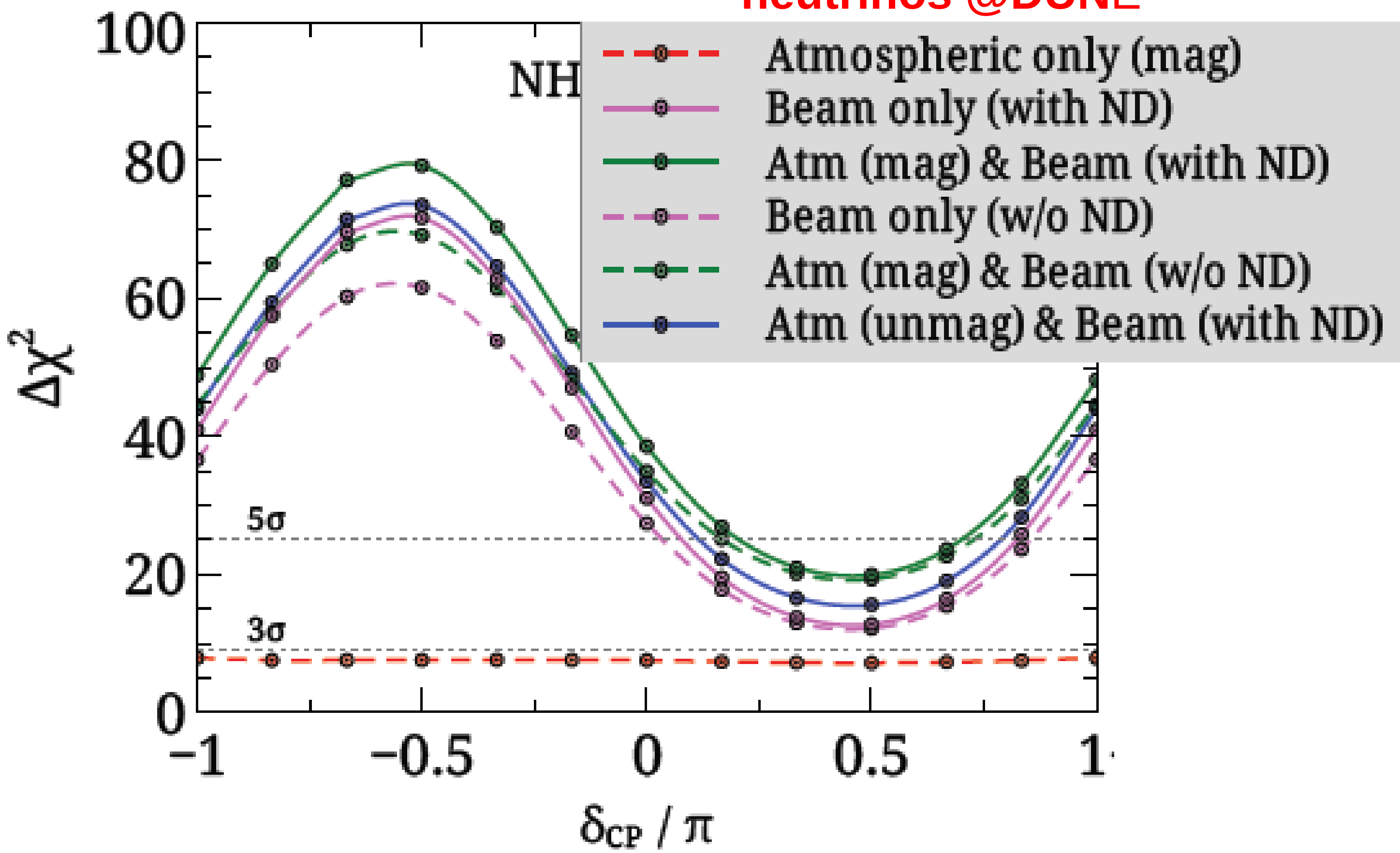
- For atmospheric neutrinos **hierarchy- δ_{CP} degeneracy** is **not present**
- Addition of atmospheric data **raises sensitivity** in the degenerate region

Next generation LBL experiments : DUNE



Ghosh, Goswami, Raut, 2014

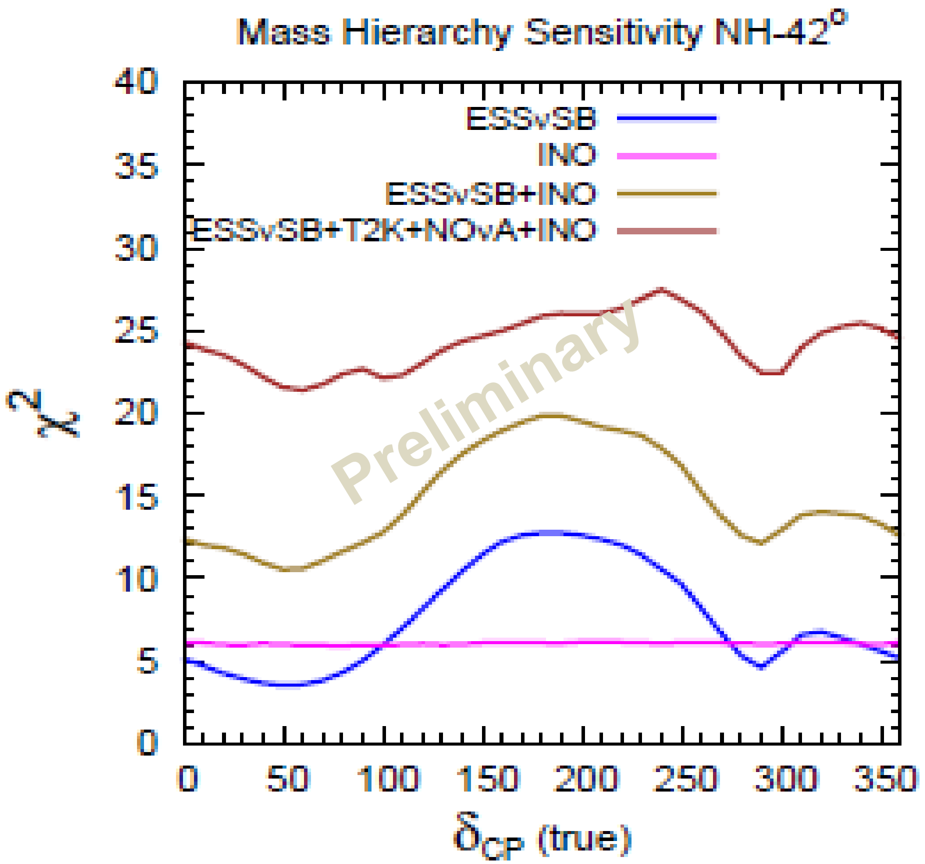
Using atmospheric neutrinos @DUNE

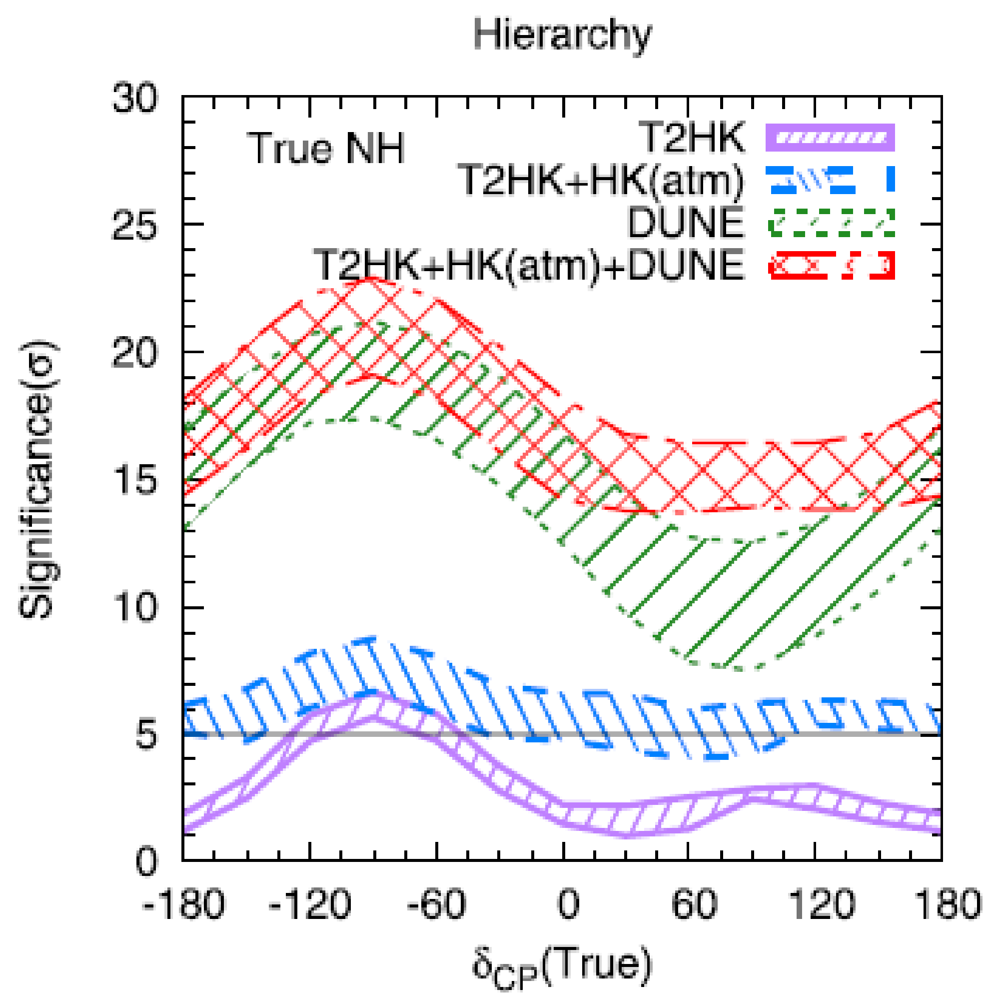


Barger et al, 2014

- **DUNE (10kt, 5+5 years) has close to 5σ hierarchy sensitivity over most δ_{CP}**
- **Adding other experiments results in slight increase in overall χ^2**

Next generation LBL: ESSnuSB and T2HK





- ESSnuSB + INO : upto 4σ
- ESSnuSB+T2K+NOVA+INO : upto 5σ

Chakraborty, Goswami, Gupta, Thakore, (2018)

- Enhanced sensitivity in T2HK by adding HK atmospheric data

Fukasawa, Ghosh, Yasuda (2017)

Octant sensitivity in long-baseline experiments

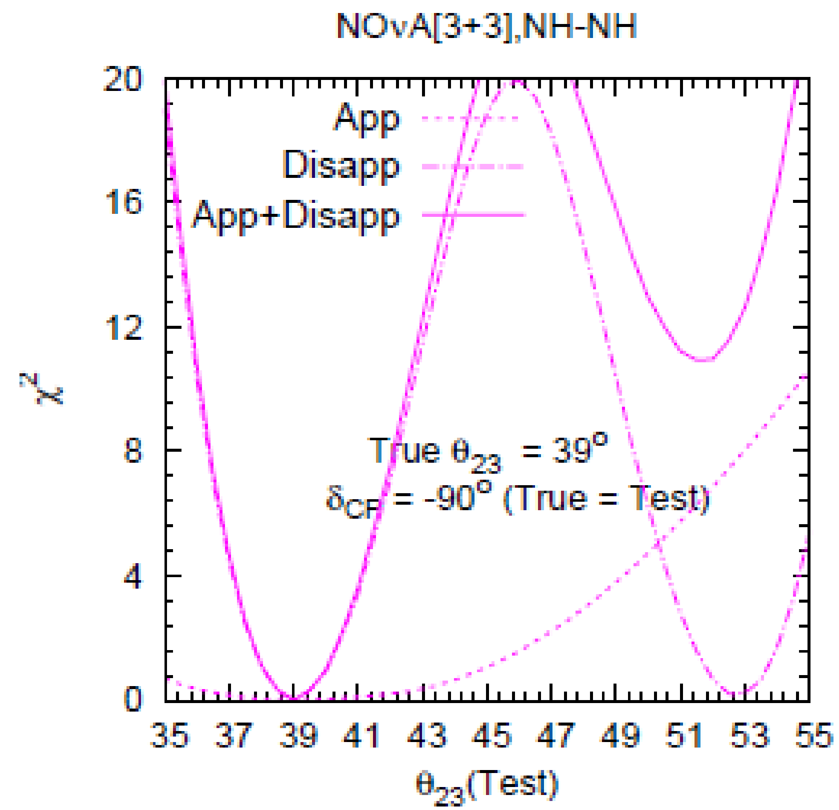
$$\boxed{P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \text{sub leading terms}}$$

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

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

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

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



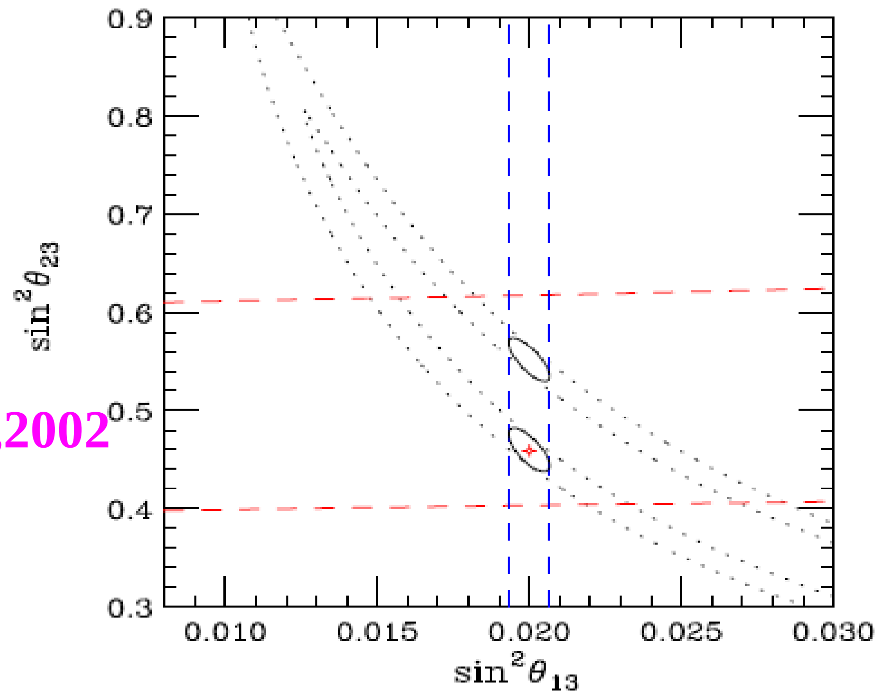
Octant sensitivity

Correlated to θ_{13}

Accelerator + Reactor data helpful

Huber,Lindner,Winter ,2002

Hiraide et al., 2006

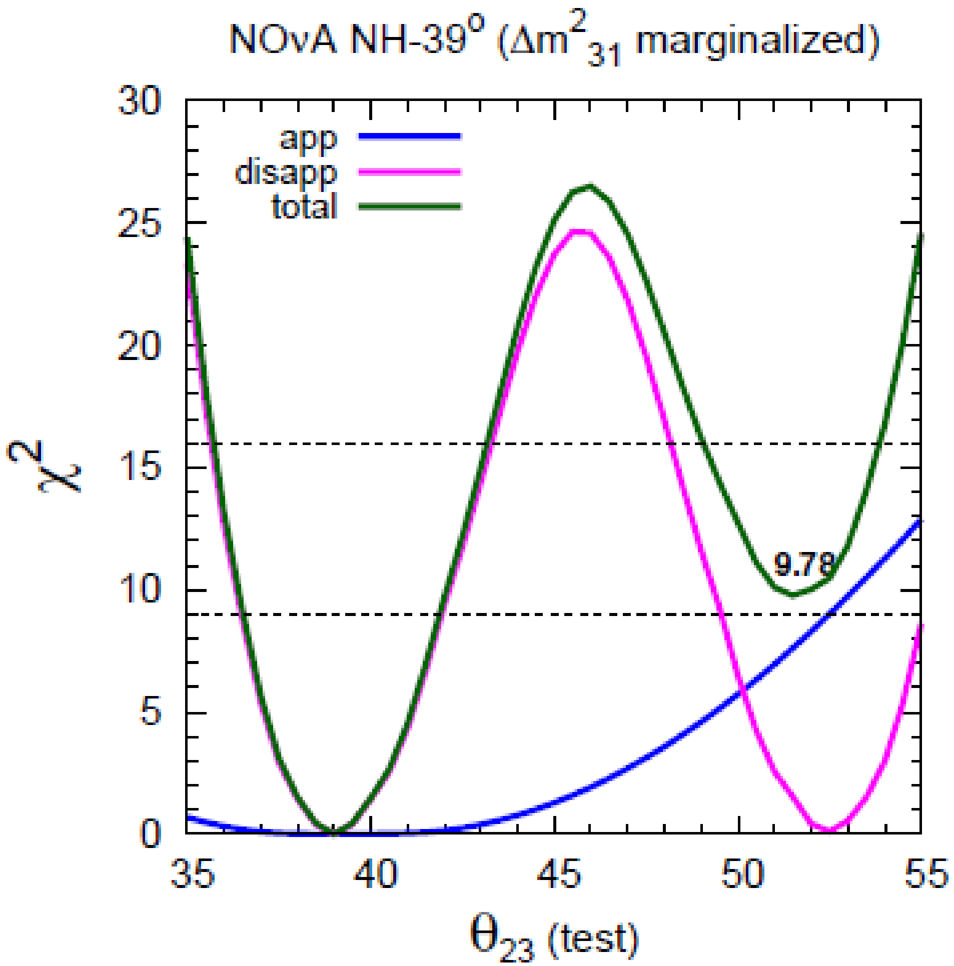


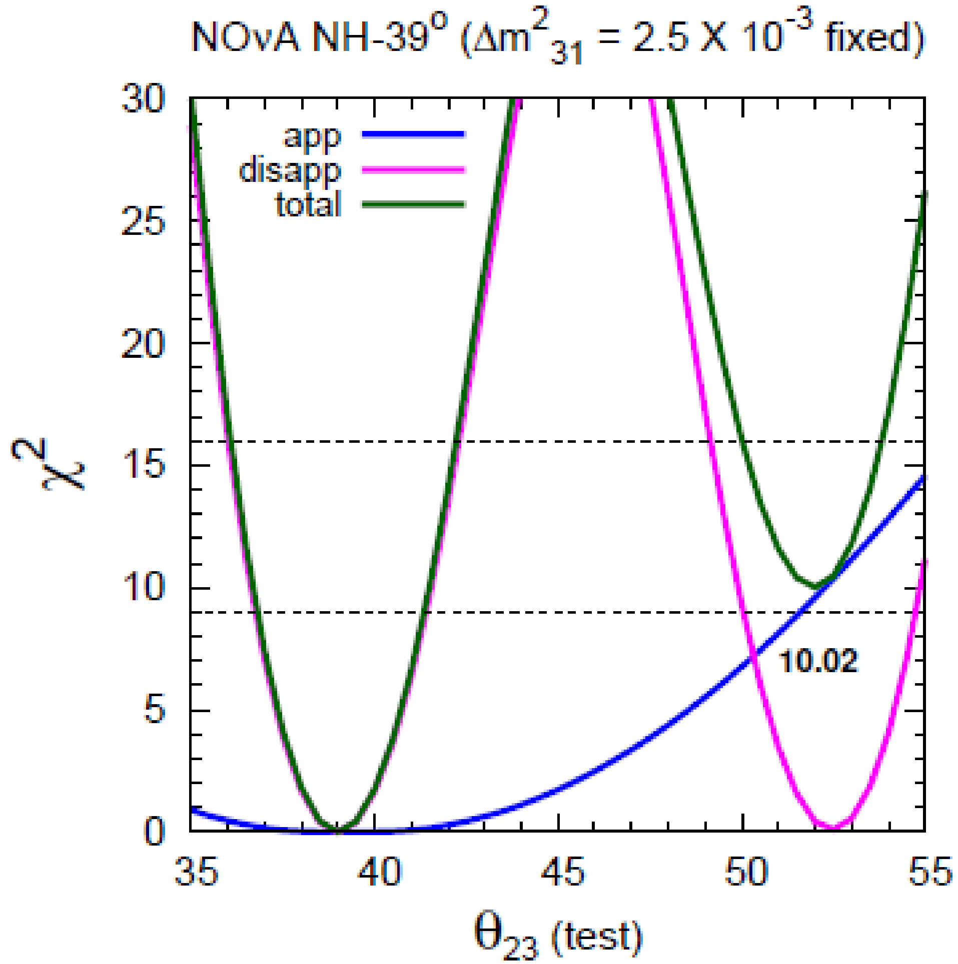
Coloma,Minakata, Parke, 2014

- Synergy between appearance and disappearance channel

➡ Octant Sensitivity

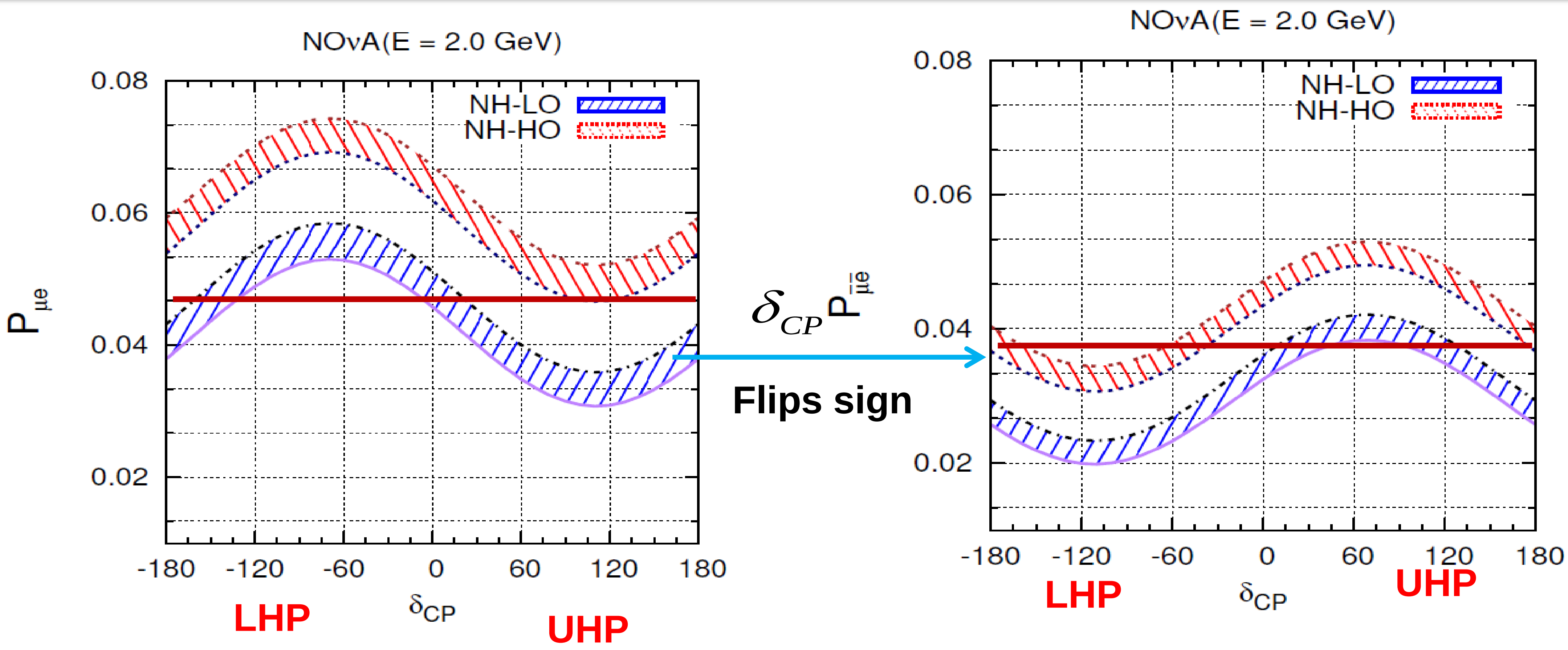
Marginalization and synergy





Marginalization over Δm^2_{31} leads to a χ^2 higher than the appearance value

Octant- δ_{CP} degeneracy



LO-LHP and HO-UHP degeneracy

LO-UHP and HO-LHP no degeneracy

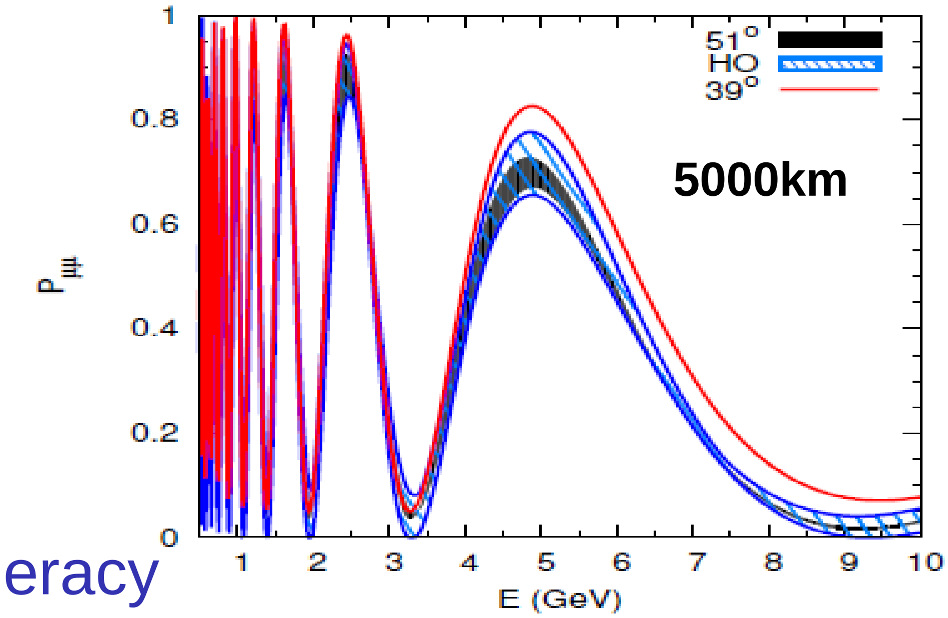
Combination of neutrino and antineutrino data can help in lifting octant degeneracy

Agarwalla, Prakash, Umasankar 2013

Machado et al. 2013

Octant Sensitivity: Atmospheric Neutrinos

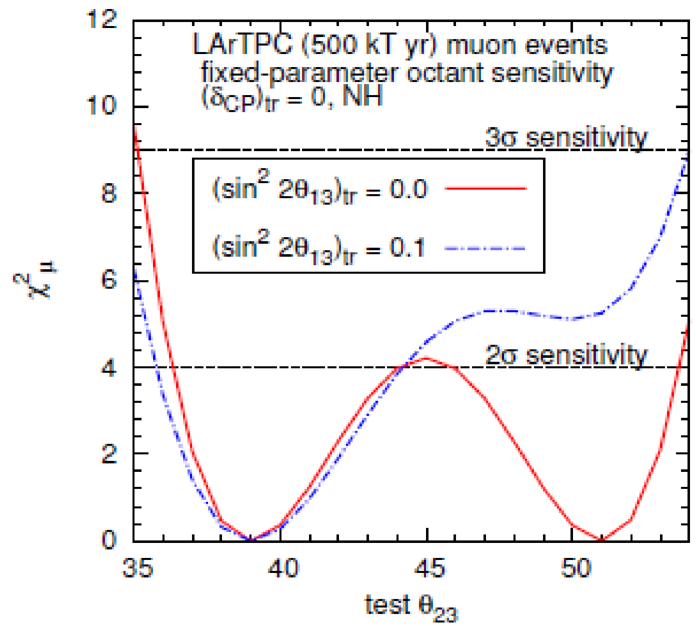
- $P^{m}_{\mu\mu} \longrightarrow \sin^4\theta_{23}\sin^2 2\theta^m_{13}\sin^2(1.27\Delta^m_{31}L/E)$



Choubey , Roy, 2005

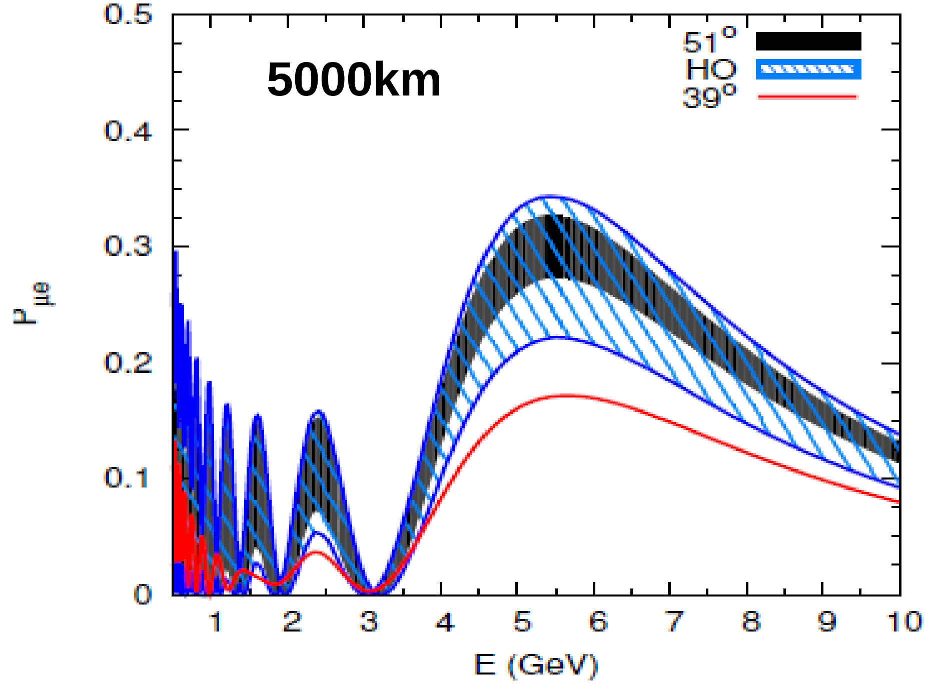
- $P^{m}_{\mu e} = \sin^2\theta_{23}\sin^2 2\theta^m_{13}\sin^2\left[1.27\,(\Delta m^2_{31})^m\frac{L}{E}\right]$

- Near resonance $\sin^2 2\theta^m_{13} \approx 1 \Longrightarrow$ No $(\theta_{23}-\theta_{13})$ degeneracy



δ_{CP} effects subdominant

θ_{23} dependence of survival and conversion probabilities opposite



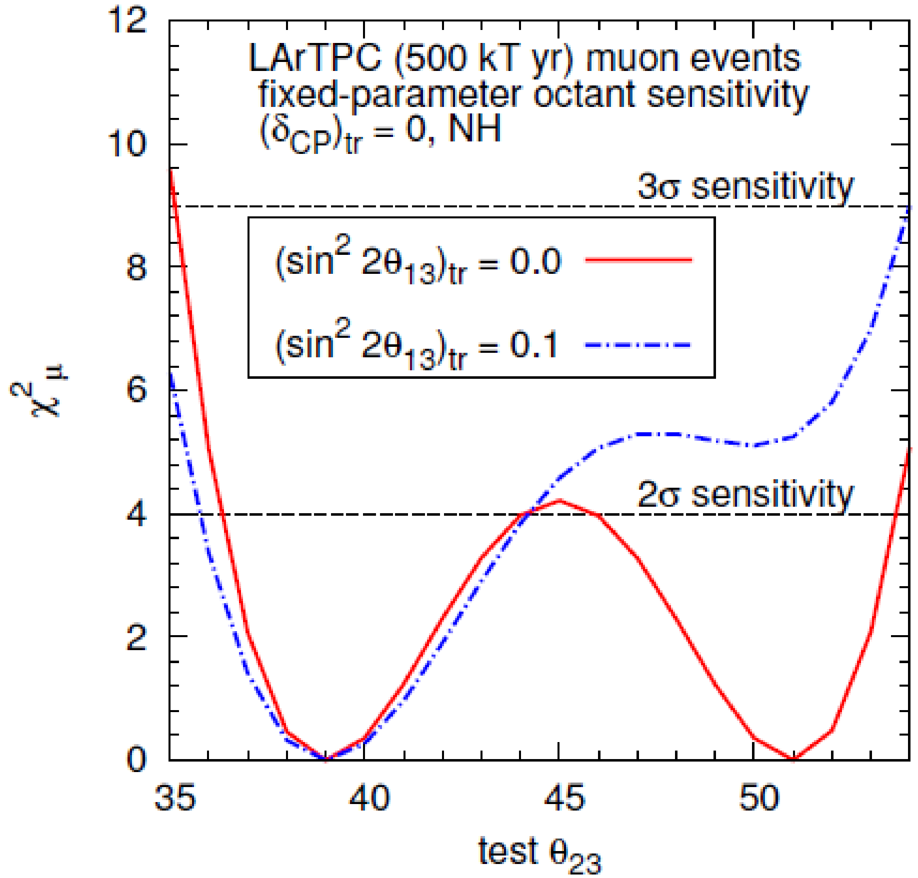
Chaterjee,Ghoshal, Goswami, Raut, 2013

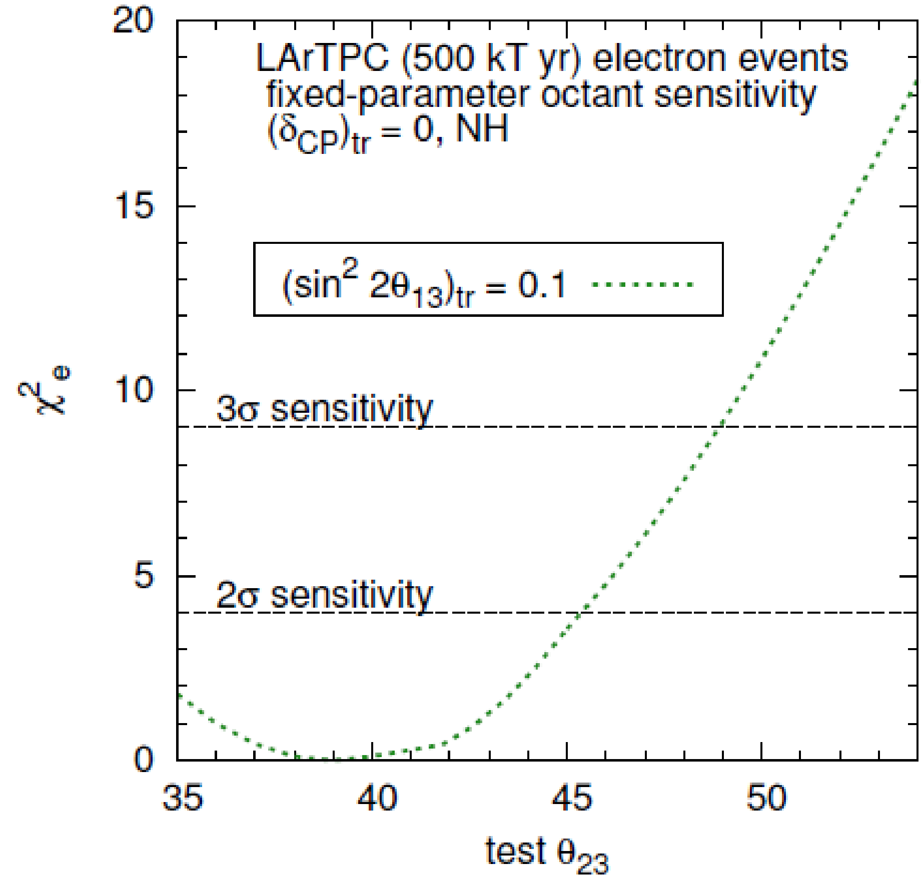
Octant sensitivity: Atmospheric neutrinos

For Liquid Argon detector 50 kton
Both Muon and Electron Events

Chaterjee,Ghoshal, Goswami, Raut, 2013

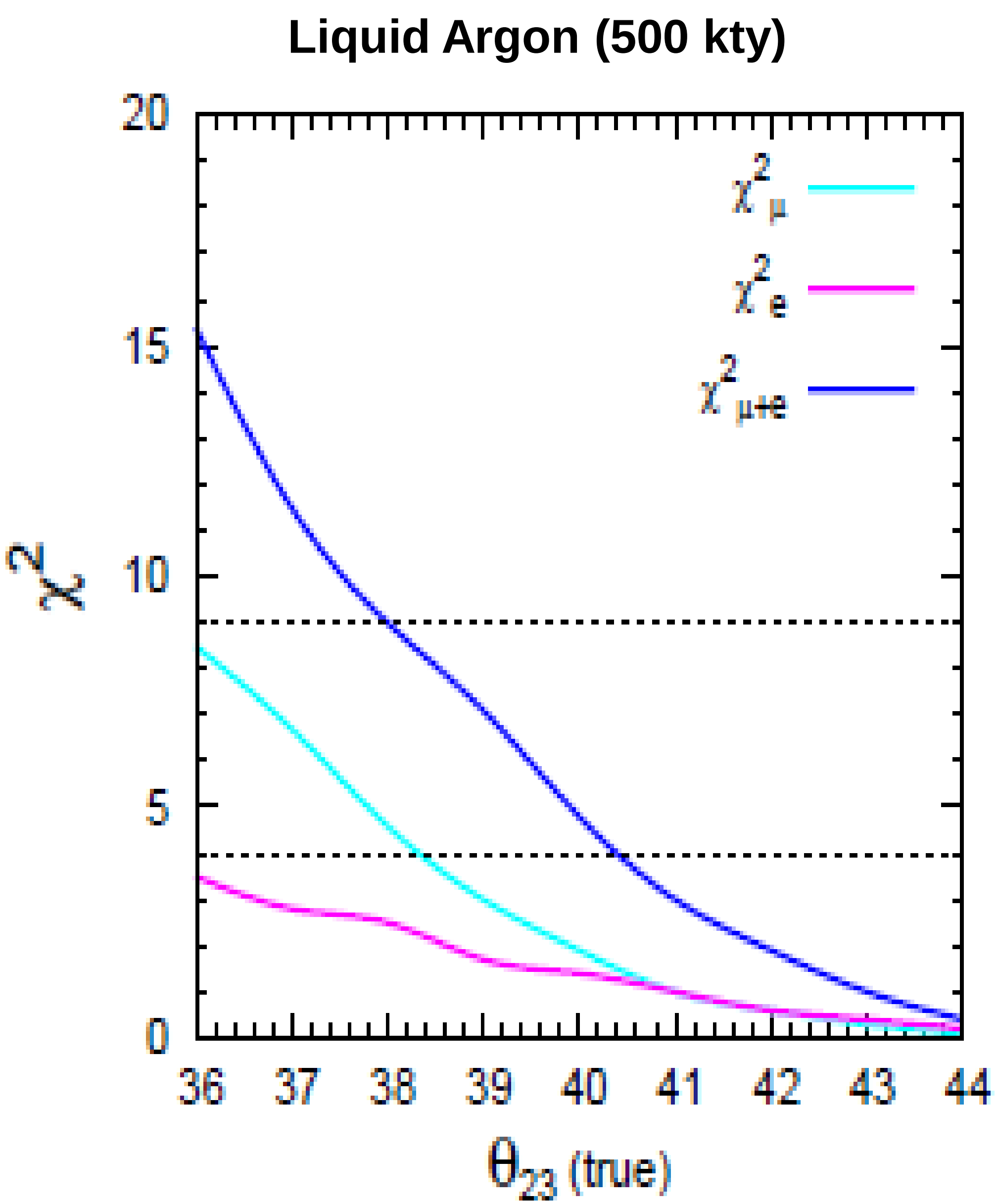
Barger et al., 2012





- **Matter effect breaks octant degeneracy in the muon channel**
- **Resultant octant sensitivity is due to both channels**

Muon vs Electron events

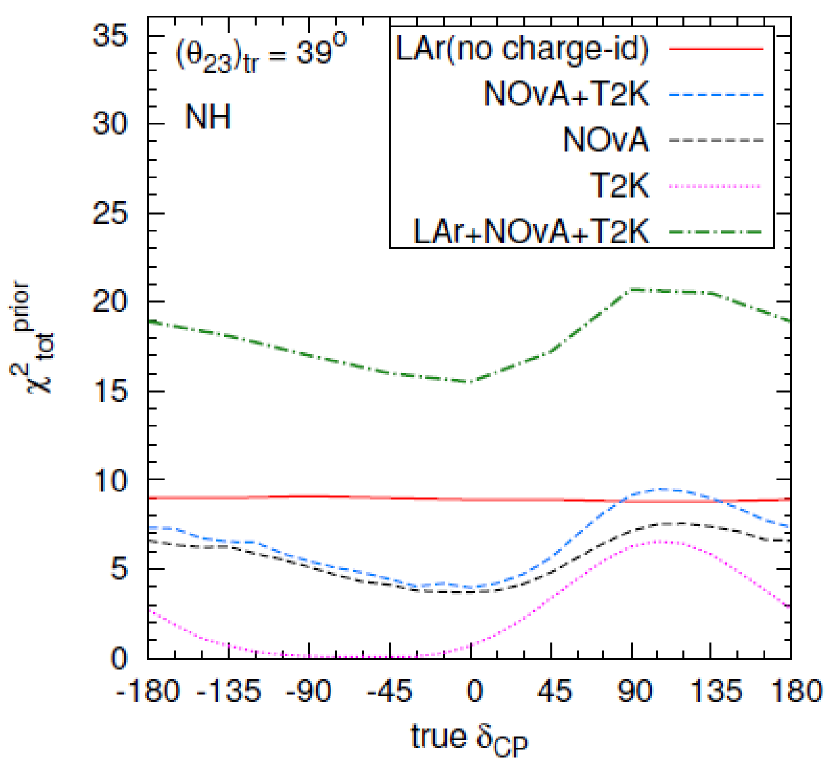


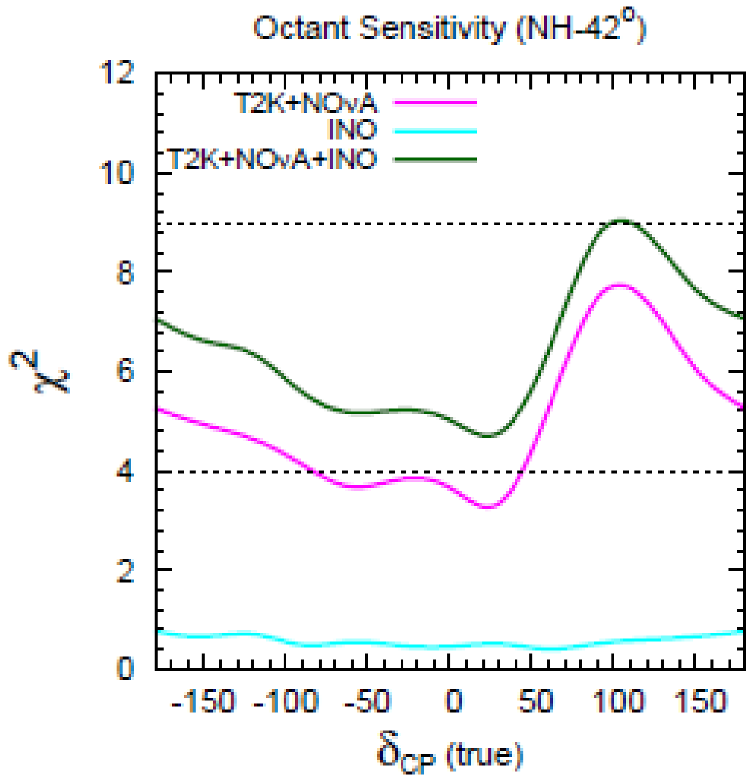
$$N_\mu \sim (\phi_\mu P_{\mu\mu} + \phi_e P_{e\mu})$$
$$N_e \sim (\phi_\mu P_{\mu e} + \phi_e P_{ee})$$

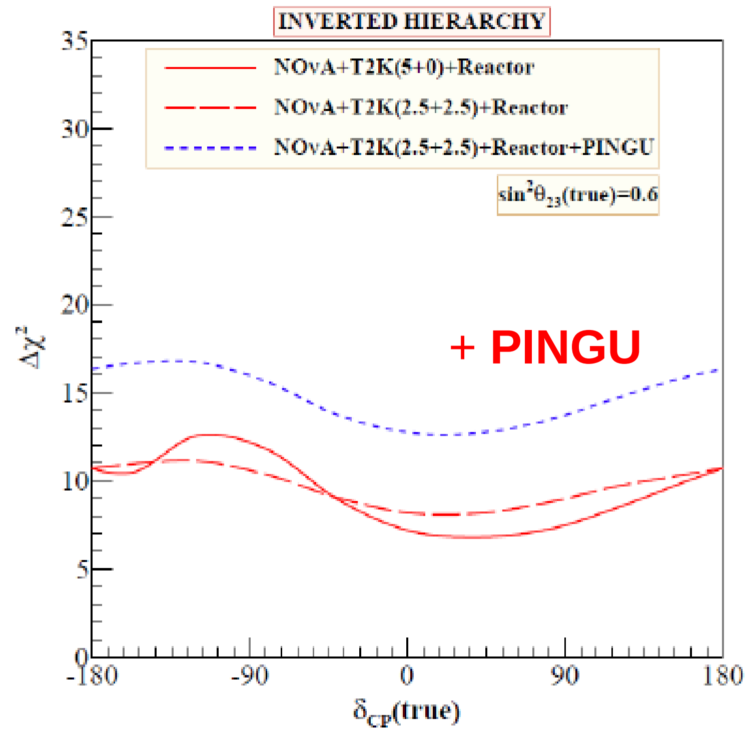
- **Atmospheric muon flux > electron flux**
- $\mathrm{P}_{\mu\mu}$ **and** $\mathrm{P}_{e\mu}$ **opposite octant sensitivity**
- P_{ee} **has no dependence on** θ_{23}
- **Dependence on** θ_{23} **stronger for muons**
- **Away from** 45° **muon contribution is more**

Chatterjee,Ghoshal, Goswami, Raut, 2013

Octant sensitivity : ATM+LBL





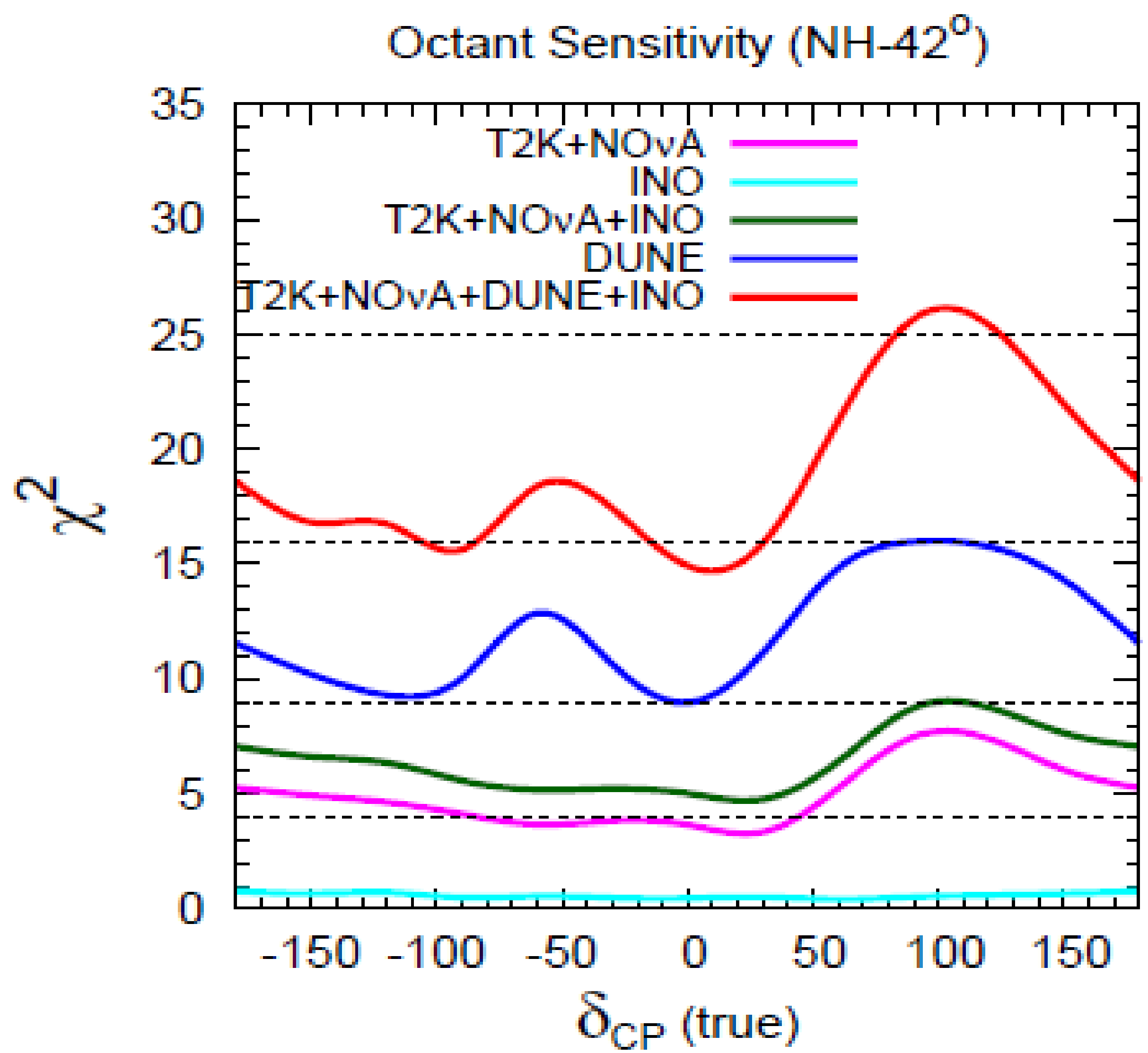


Chatterjee,Ghoshal, Goswami, Raut, 2013

Choubey, Ghosh, 2013

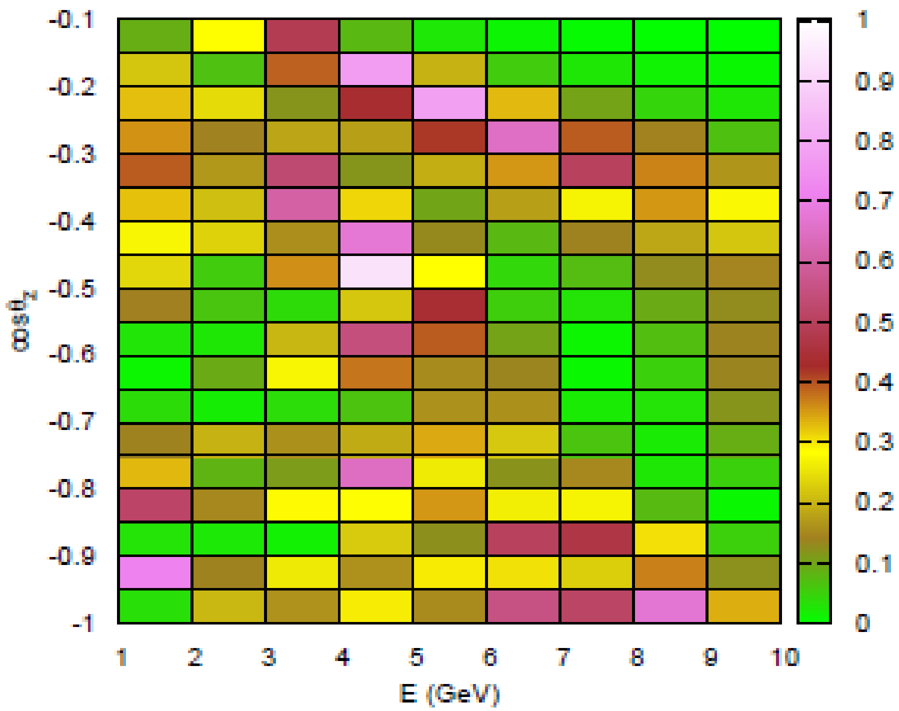
- **Octant sensitivity of T2K+NOVA increased combined with atmospheric data**
- **Synergy due to different data sets preferring different** θ_{23}

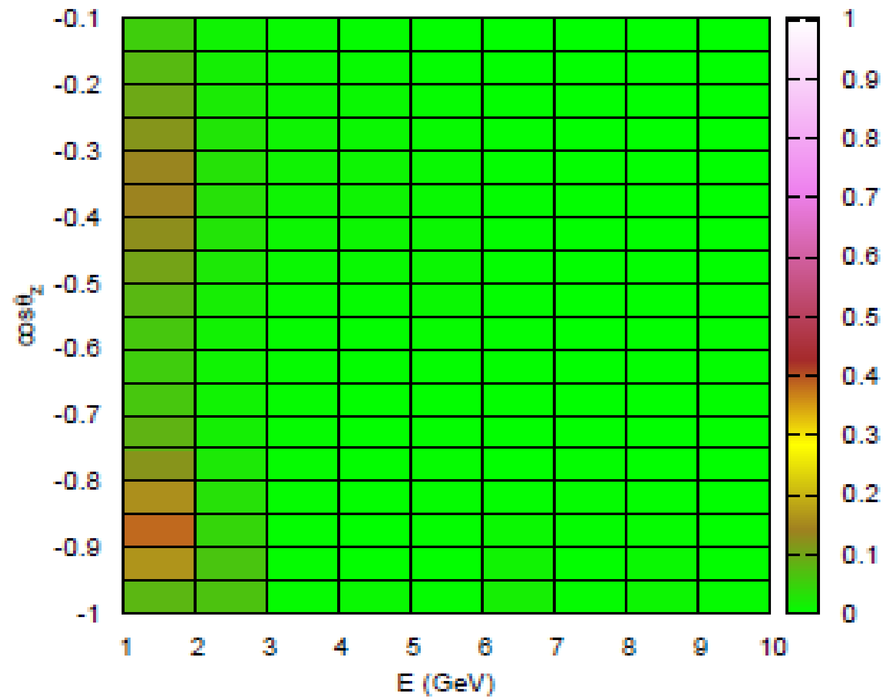
Octant sensitivity : T2K+NOVA+INO+ DUNE



- Octant sensitivity of DUNE enhanced when T2K+NOVA + INO added

δ_{CP} Sensitivity of Atmospheric Muon Neutrinos





$$S_\mu + S_{\overline{\mu}} = (\Delta N_\mu)^2 / N_\mu(\text{avg}),$$

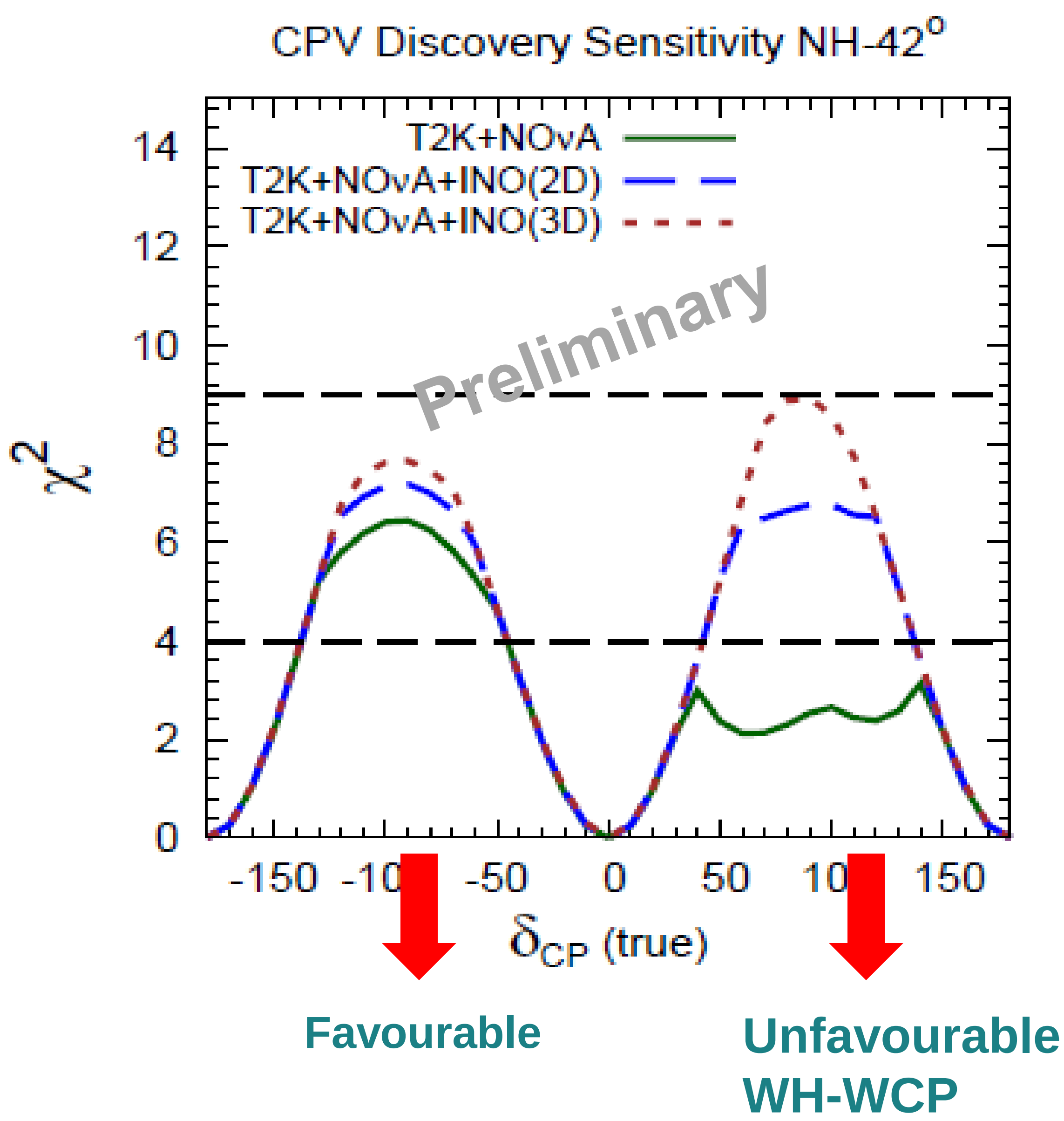
- ΔN_μ is the maximum difference in events by varying δ_{CP}, $N_\mu(\text{avg})$ is the average number of events over all values of δ_{CP}.
- **Variation washed out by angular smearing**

(See talk by S. Razzaque)

Ghosh, Ghoshal,Goswami, 2014

Ghosh, Ghoshal,Goswami, Raut , 2013

Discovery of δ_{CP} : T2K+NOVA+INO



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

Inclusion of Hadron information enhances hierarchy and hence CP sensitivity

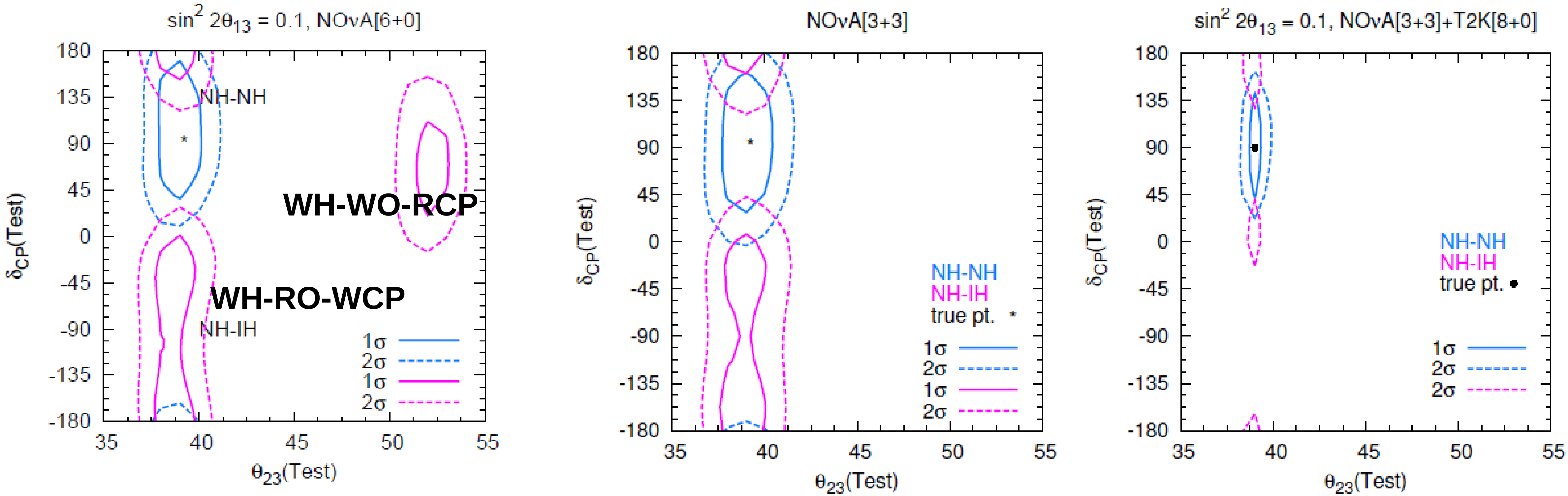
50% increase in CP coverage

In the favourable zone the sensitivity increases since addition of INO can resolve wrong octant solution

Ghosh, Ghoshal, Goswami, Raut, 2013
Gupta, Chakraborty, Goswami, 2018

Removal of Degeneracy: T2K+NOVA

Contours in test $\theta_{23} - \delta_{CP}$ plane (NH)



WO-WCP solution is removed by combining neutrinos and antineutrinos
(neutrinos and antineutrinos have degeneracy for opposite octants)

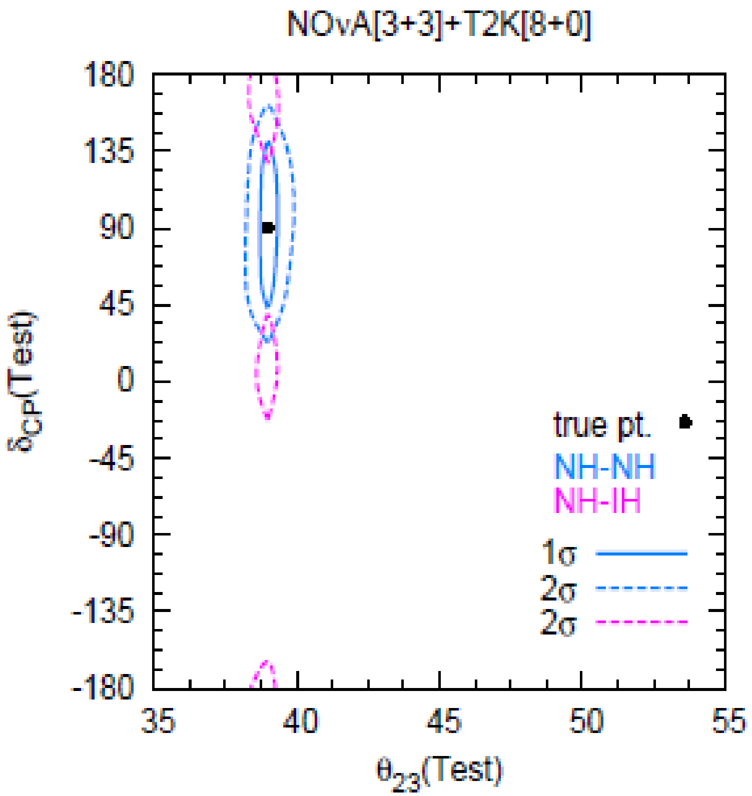
WH solution is removed by adding T2K and NOVA
(different dependence on δ_{CP} due to different baselines)

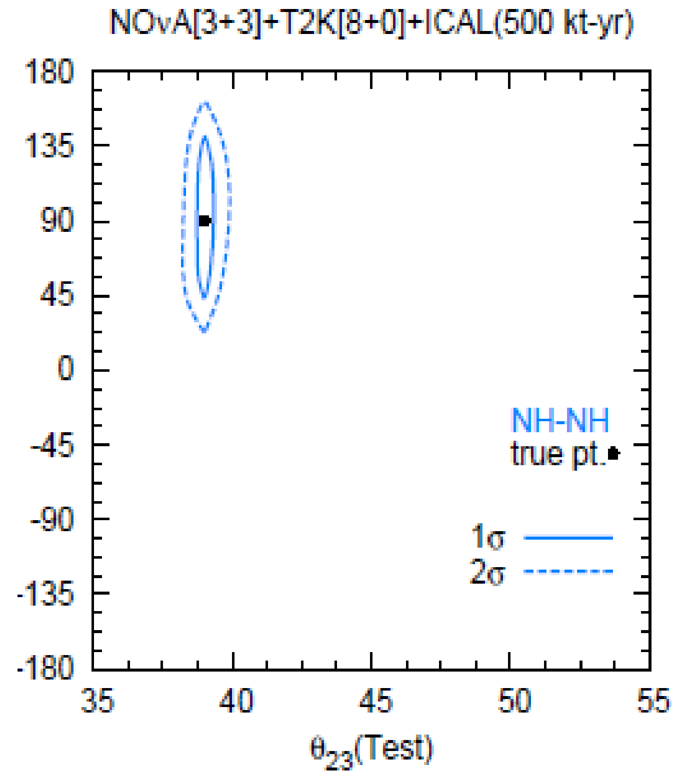
Ghosh, Ghosal, Goswami, Nath, Raut, 2015

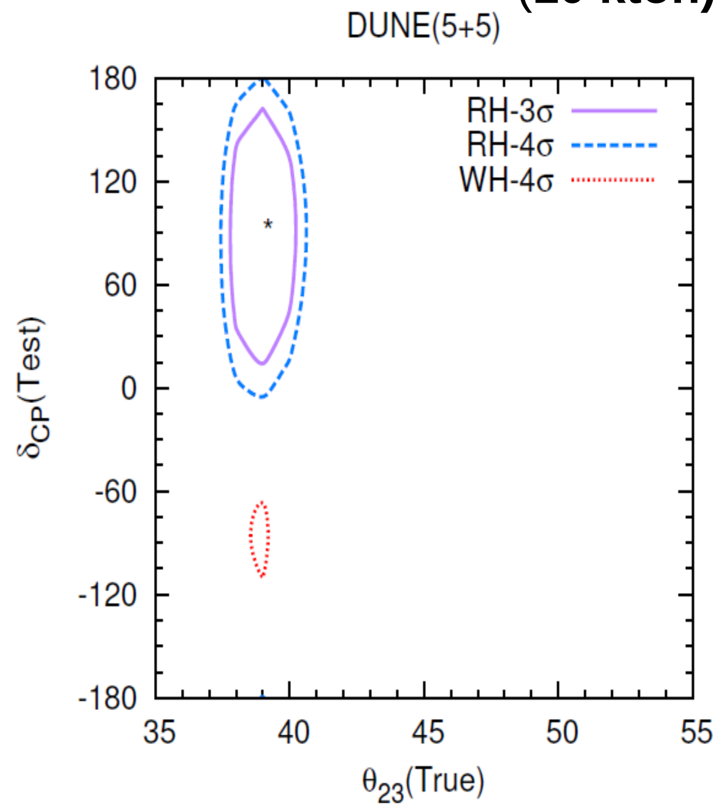
Removal of degeneracy : T2K+NOVA+ICAL , DUNE

Contours in test $\theta_{23} - \delta_{CP}$ plane (NH)

(10 kton)







WH –WCP solution removed by adding atmospheric data from ICAL
(matter effects break hierarchy degeneracies) (other atmospheric experiments)

Huber, Maltoni, Schwetz, 2005

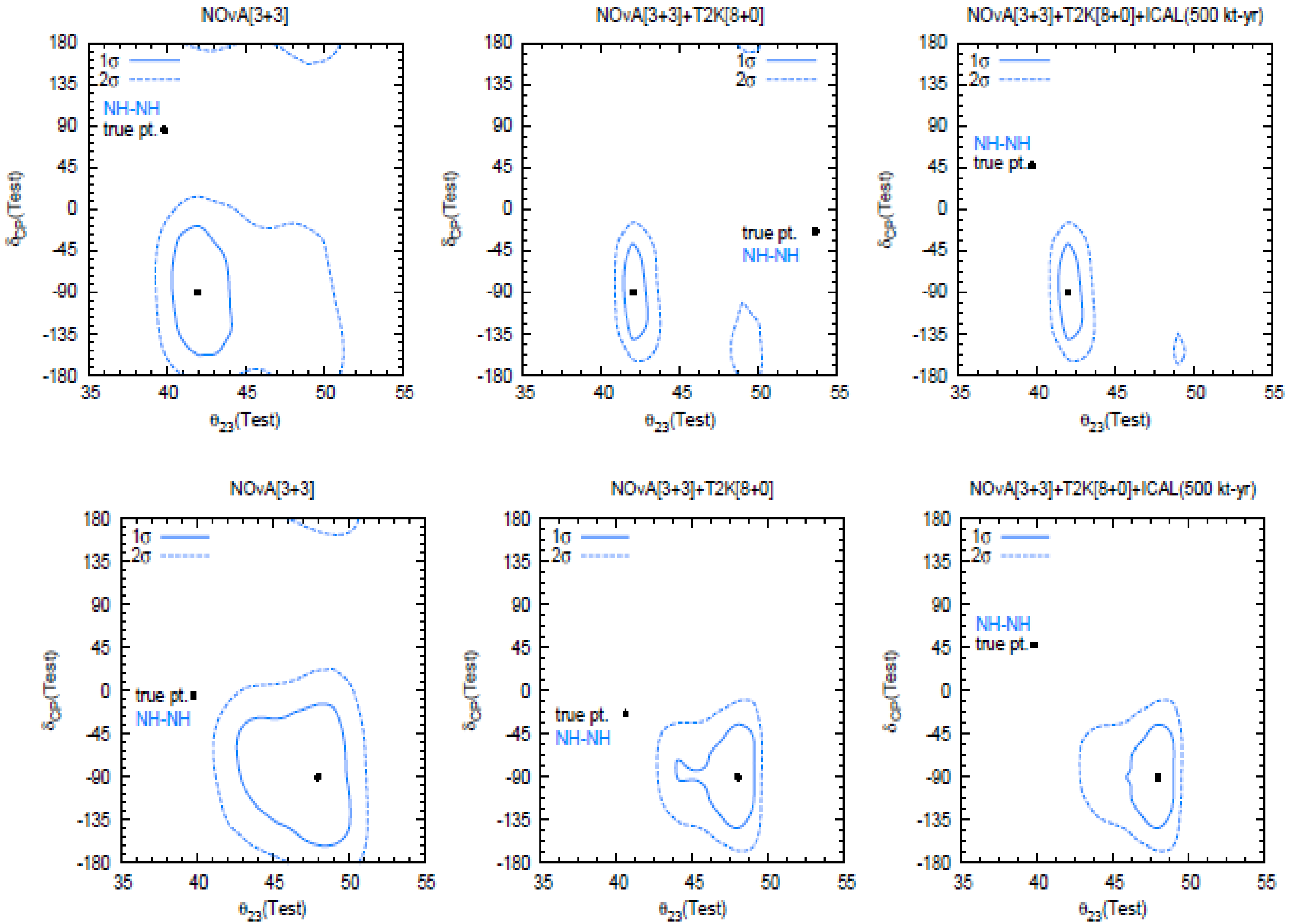
DUNE can resolve WH and WO solutions at almost 4σ
(large matter effects, pure ν_μ beam , known direction)

Ghosh, Ghosal, Goswami, Nath, Raut, 2015

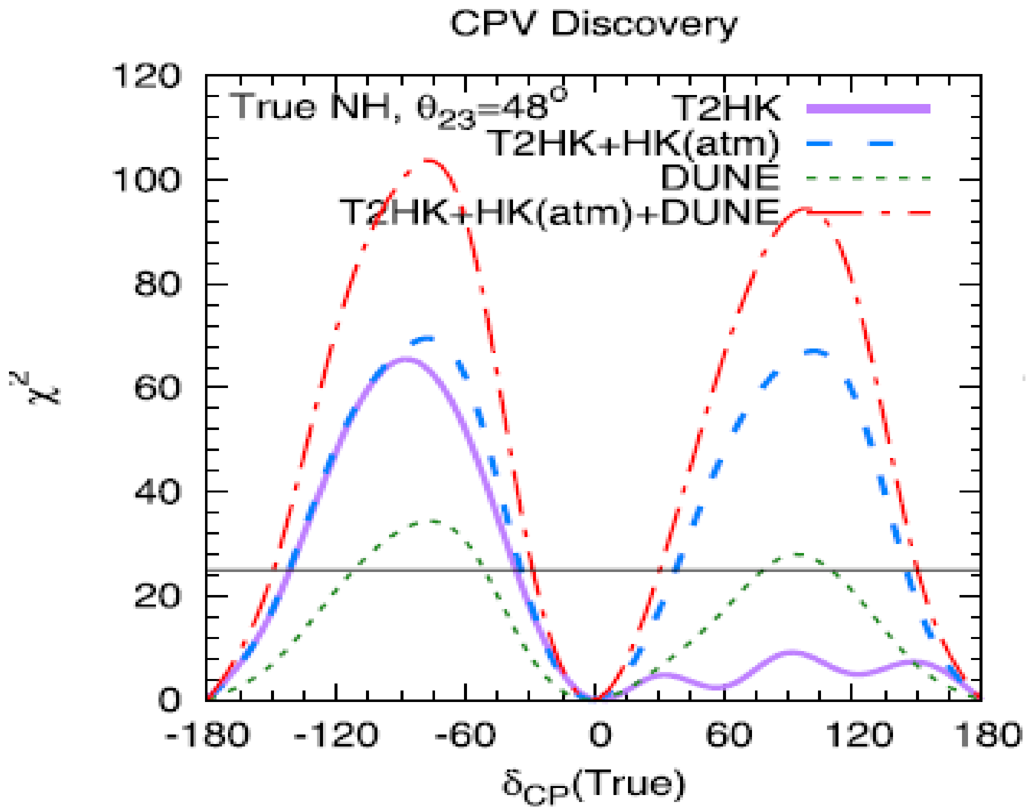
Contours in $\theta_{23}-\delta_{CP}$ plane for $\delta_{CP}=-90^{\circ}$

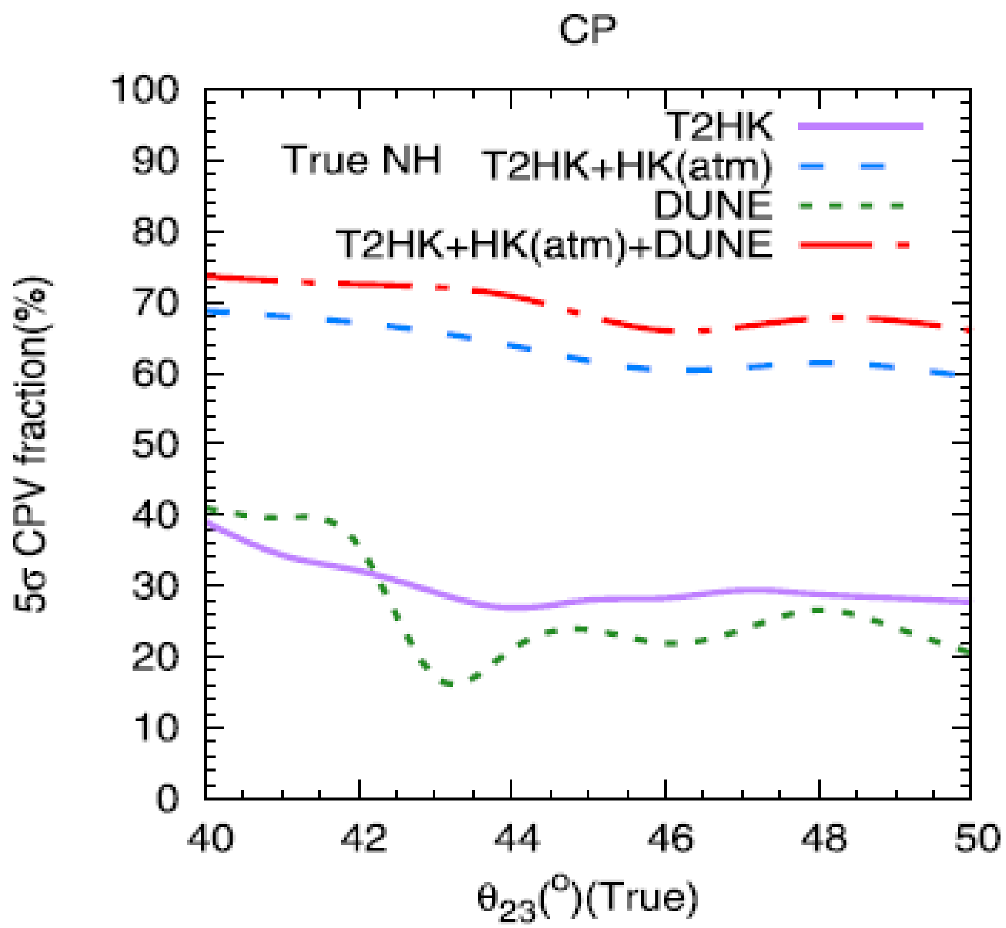
$\theta_{23}=42^{\circ}$

$\theta_{23}=48^{\circ}$



CP sensitivity : HK (atm) + T2HK+DUNE





CP discovery potential of T2HK enhanced substantially in the degenerate region by adding HK atmospheric data

CPV fraction for 5σ CP discovery enhanced by 30-40% Including HK atmospheric data

Fukasawa, Ghosh, Yasuda (2017)

Summary

- Synergies exist due to preference of different data sets or different channels for different values of parameters
- Captured during procedure of marginalization over a parameter
- Synergies between atmospheric and LBL also exist since atmospheric neutrinos do not have degeneracy with δ_{CP}
- Hierarchy sensitivity of LBL can be enhanced in the degenerate region by adding atmospheric data
- CP discovery potential of LBL can be increased by adding atmospheric neutrino data since it can remove wrong hierarchy – wrong CP solutions
- Increased CP coverage
- Octant sensitivity of LBL experiments can be enhanced by adding atmospheric data mainly due to parameter tension

New directions with New Physics ?

- With proposal of high statistics high precision experiments like DUNE, T2HK, T2HKK many studies on probing new physics in these experiments
- Sterile neutrinos, Non-standard Interactions, CPT violation, long range forces, neutrino decay, decoherence, extra dimensions ….

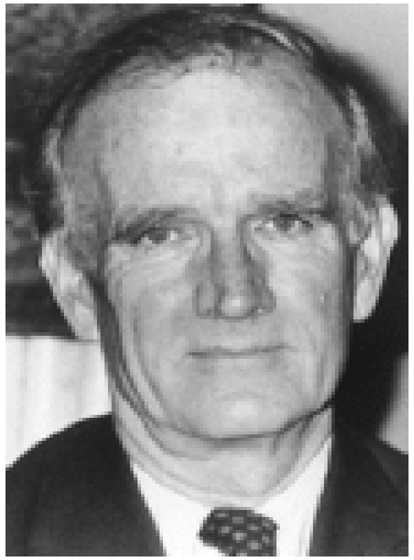
  (Salvado, Esmaili, Marfatia, Choubey, Umashankar, Nunokawa, Peres,Khatun, Delgado …)
- Sub leading effects to dominant oscillation
- New parameters, new degeneracies
- Synergy between atmospheric and long baseline --- largely unexplored, computationally intensive
- Addressing new degeneracies -- whether combining atmospheric and long-baseline data helps ?

Concluding Remarks

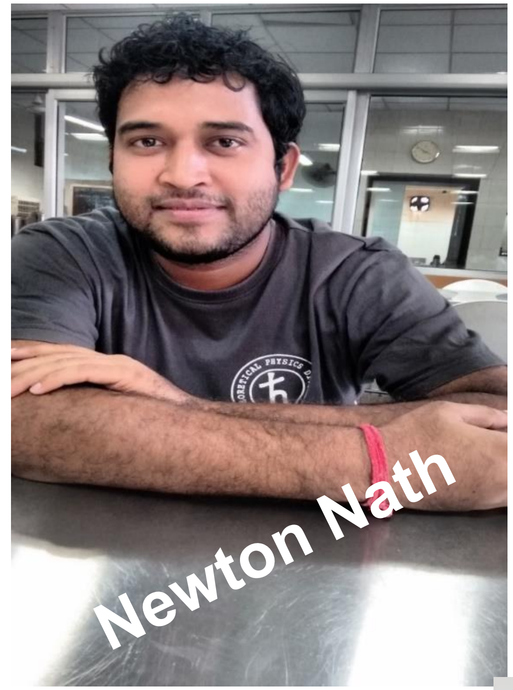
At any one time there is a natural tendency among physicists to believe that we already know the essential ingredients of a comprehensive theory.

But each time a new frontier of observation is broached we inevitably discover new phenomena which force us to modify substantially our previous conceptions. I believe this process to be unending, that the delights and challenges of unexpected discovery will continue always.

Val Fitch, Nobel Prize Speech 1980



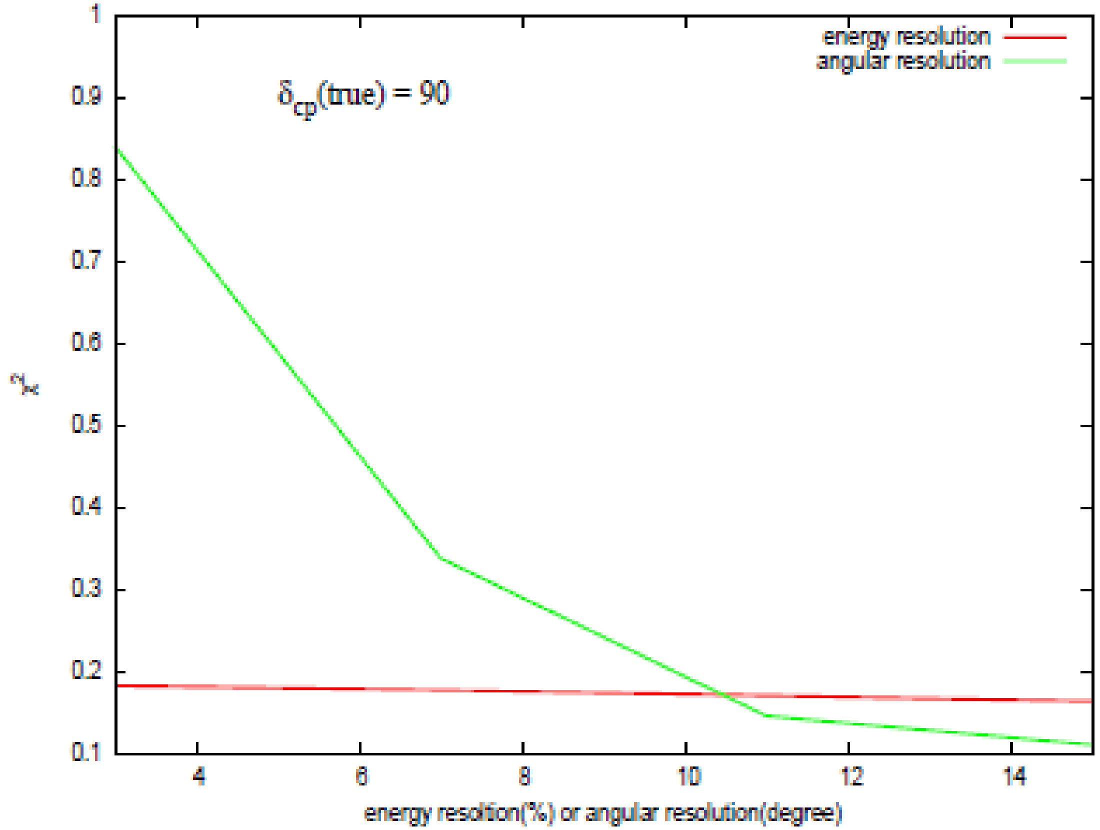
Thanks to current and former students and PDFs



Grazie

δ_{CP} Sensitivity of ICAL

- CP violation discovery potential of ICAL as a function of the detector energy and angular resolutions



- $\delta_{CP}^{tr} = 90^\circ$, $\theta_{23}^{tr} = 39^\circ$ and a true NH is assumed.
- CP sensitivity low, improves with angular resolution

Ghosh, Ghoshal,Goswami, Raut , Nucl. Phys. B, 2014

Ghosh, Ghoshal,Goswami, Raut , Phys. ReV D (Rapid) , 2013