Parameter degeneracy and hierarchy sensitivity of NOνA in presence of sterile neutrino

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Based on: MG, S. Gupta, Z. M. Matthews, P. Sharma and A. G. Williams, 1704.04771 (To appear in PRD)

Neutrino Oscillation

- Neutrino oscillation: transition from one flavor to another
- Reason: Flavour and mass eigenstates are not same

$$|\nu_\alpha\rangle \quad = \quad \sum_{i=1}^{N} U_{\alpha i}^{\mathrm{PMNS}} |\nu_i\rangle$$

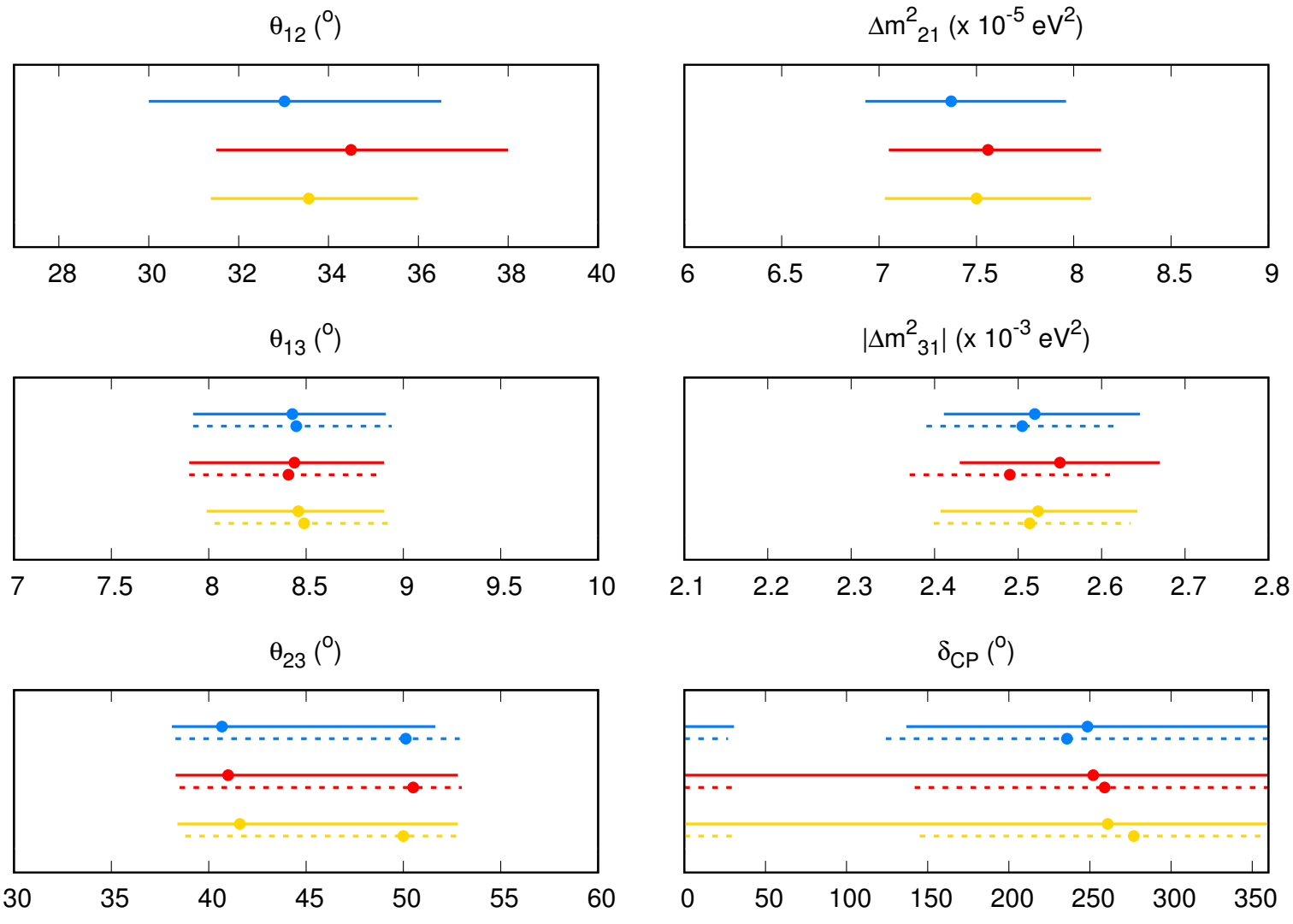
- The transition probability $\nu_\alpha \to \nu_\beta$:

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

Parameters of neutrino oscillation in 3ν:

- Elements of U: $U_{\mathrm{PMNS}}^{3\nu} = R(\theta_{23}, 0) R(\theta_{13}, \delta_{13}) R(\theta_{12}, 0)\,.$
- Two mass squared differences:
  $\Delta_{21} = m_2^2 - m_1^2$, $\Delta_{31} = m_3^2 - m_1^2$

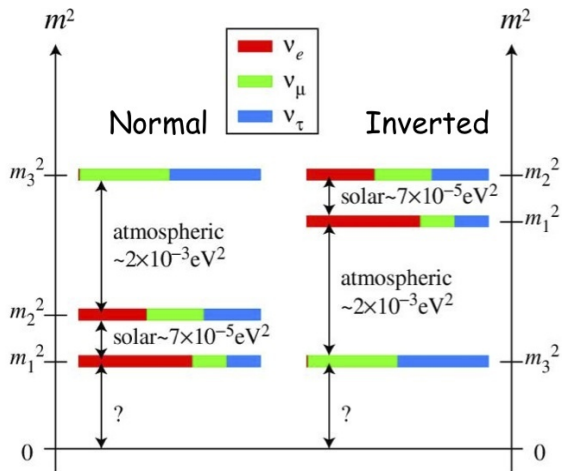
Current status of oscillation parameters



Bari, Valencia, Nufit (gnuplot script by Sushant k. Raut)

The Neutrino Mass Hierarchy

One of the major unknown:



The sign of Δm^2_{31} :

$\Delta m^2_{31} > 0 \Rightarrow$ Normal Hierarchy (NH) or
$\Delta m^2_{31} < 0 \Rightarrow$ Inverted Hierarchy (IH).

The expected hint

NOνA is expected to give the first hint of MH

Present best-fit: NH, $\delta_{13} = -90^\circ$

- Favourable region for NOνA
- Free from degeneracy
- Expected to give 2σ hint

But

If there is new physics

- There can be new degeneracies
- Hierarchy sensitivity of NOνA can be lost even for (NH, $\delta_{13} = -90^\circ$)

Aim

(i) Identify new degeneracies

(ii) Study their effect on MH determination

Assuming the existence of a light sterile neutrino

Sterile Neutrino

- Sterile neutrinos are the light SU(2) singlet
- Sterile means no standard model interactions
- Active neutrinos (ν_e, ν_μ, ν_τ) can oscillate into sterile neutrinos(ν_s)

Motivation

The data from various experiments suggests there is a still a scope of a light sterile neutrino at eV scale

The current status has been discussed yesterday in WG1+WG5 joint session

Another talk on tomorrow

The 3+1 scenario

$$U^{4\nu}_{\rm PMNS} = U(\theta_{34},\delta_{34})U(\theta_{24},0)U(\theta_{14},\delta_{14})U^{3\nu}_{\rm PMNS}\,.$$

$$\begin{aligned} P_{\mu e} \;\simeq\; & 4s^2_{23}s^2_{13}\sin^2\Delta + \\ & 8s_{13}s_{12}c_{12}s_{23}c_{23}(\alpha\Delta)\sin\Delta\cos(\Delta\pm\delta_{13}) + \\ & 4s_{14}s_{24}s_{13}s_{23}\sin\Delta\sin(\Delta\pm\delta_{13}\mp\delta_{14}) \end{aligned}$$

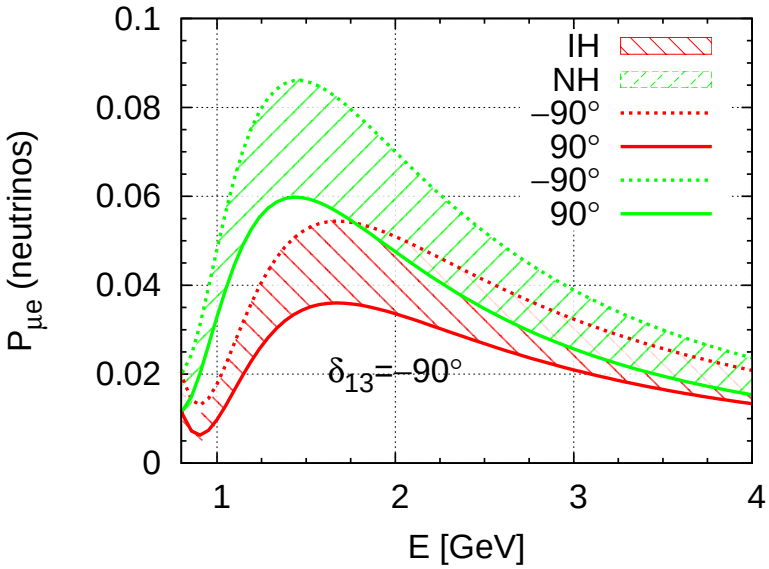
- $\Delta \equiv \Delta m^2_{31}L/4E$, $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$.
- Δm^2_{41} does not appear: oscillations get averaged out
- Vacuum expression: free from θ_{34}, δ_{34}
- New phase can give rise to new degeneracies

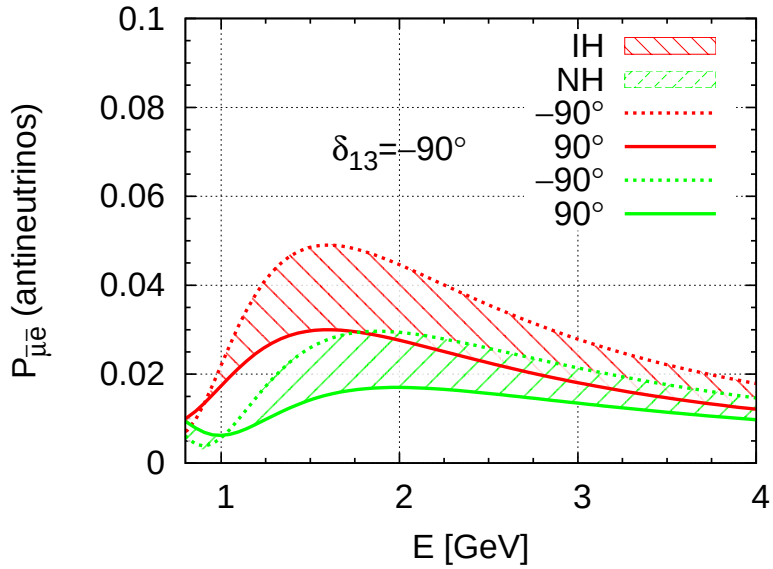
Choice of parameters

4ν Parameters	True Value	Test Value Range
$\sin^2\theta_{12}$	0.304	N/A
$\sin^2 2\theta_{13}$	0.085	N/A
$\theta_{23}^{\mathrm{LO}}$	40°	$(40^\circ, 50^\circ)$
$\theta_{23}^{\mathrm{HO}}$	50°	$(40^\circ, 50^\circ)$
$\sin^2\theta_{14}$	0.025	N/A
$\sin^2\theta_{24}$	0.025	N/A
θ_{34}	0°	N/A
δ_{13}	-90°	$(-180^\circ, 180^\circ)$
δ_{14}	$-90^\circ, 0^\circ, 90^\circ$	$(-180^\circ, 180^\circ)$
δ_{34}	0°	N/A
Δm^2_{21}	$7.5 \times 10^{-5}\mathrm{eV}^2$	N/A
Δm^2_{31}	$2.475 \times 10^{-3}\mathrm{eV}^2$	$(2.2, 2.6) \times 10^{-3}\mathrm{eV}^2$
Δm^2_{41}	$1\mathrm{eV}^2$	N/A

Degeneracy at the Probability level

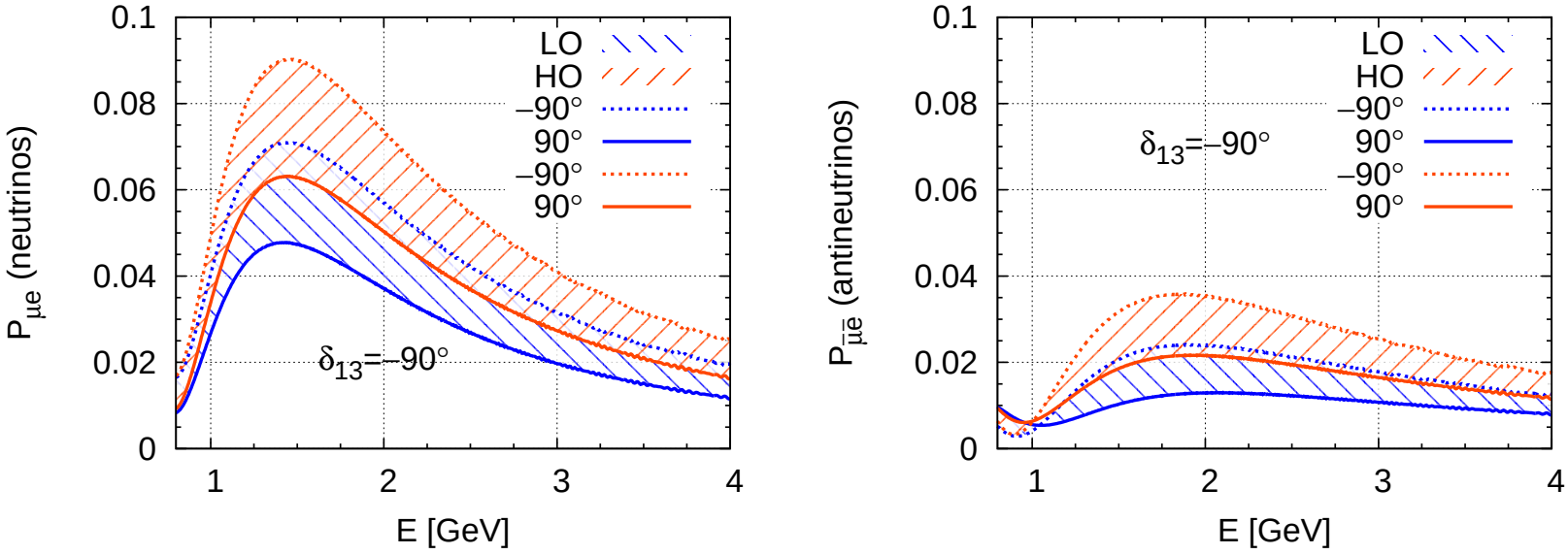
Hierarchy - δ_{14} degeneracy





- For ν: $\{\text{NH},\ \delta_{14} = 90^\circ\} = \{\text{IH},\ \delta_{14} = -90^\circ\}$
- For $\bar{\nu}$: $\{\text{NH},\ \delta_{14} = -90^\circ\} = \{\text{IH},\ \delta_{14} = +90^\circ\}$
- Removable: $\nu + \bar{\nu}$ can resolve

Octant - δ_{14} degeneracy



- For both ν and $\bar{\nu}$: $\{\text{LO}, \delta_{14} = -90°\} = \{\text{HO}, \delta_{14} = +90°\}$
- Unremovable: $\nu + \bar{\nu}$ can't resolve (discussed in S. K. Agarwalla, S. S. Chatterjee and A. Palazzo, PRL,031804 (2017))

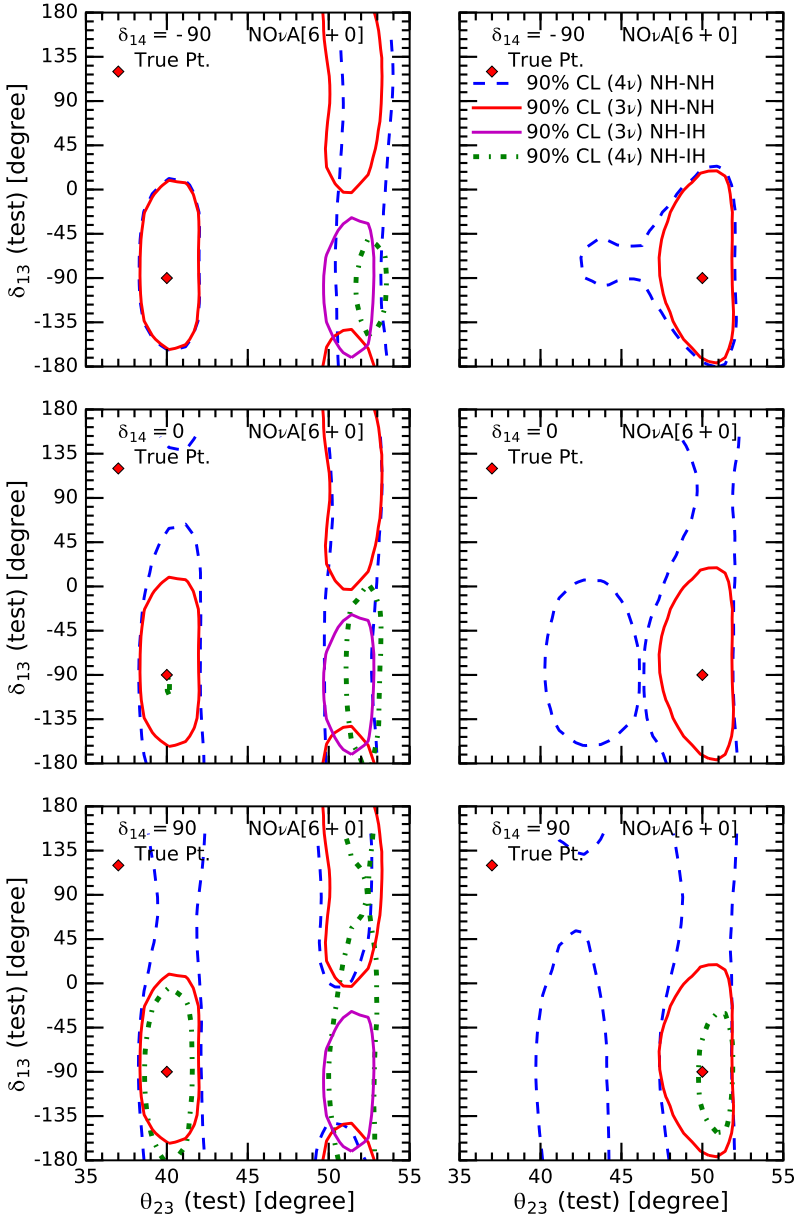
Recap

We have identified two new degeneracies with δ_{14}

(i) Hierarchy - δ_{14} degeneracy : Removable by combining ν and $\bar{\nu}$
(ii) Octant - δ_{14} degeneracy : Unremovable

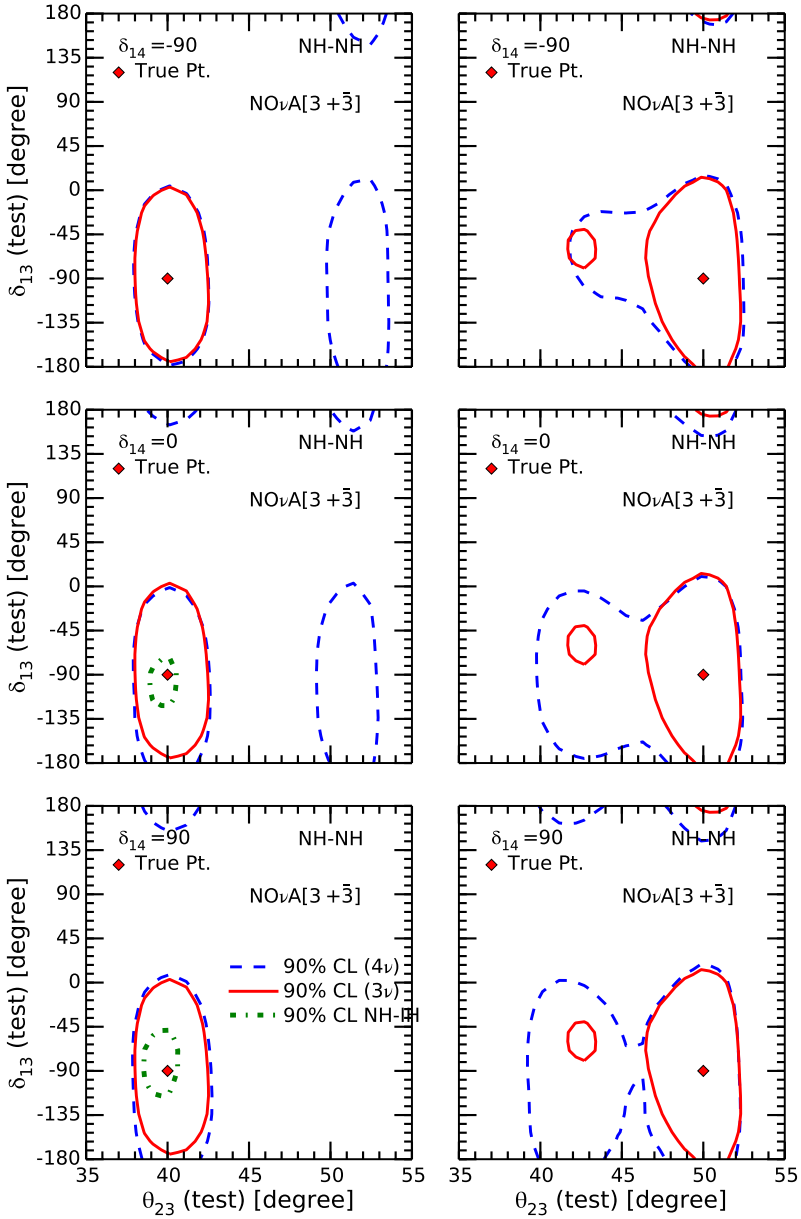
Now let's see the degeneracies at the event level

NOνA(6+0)



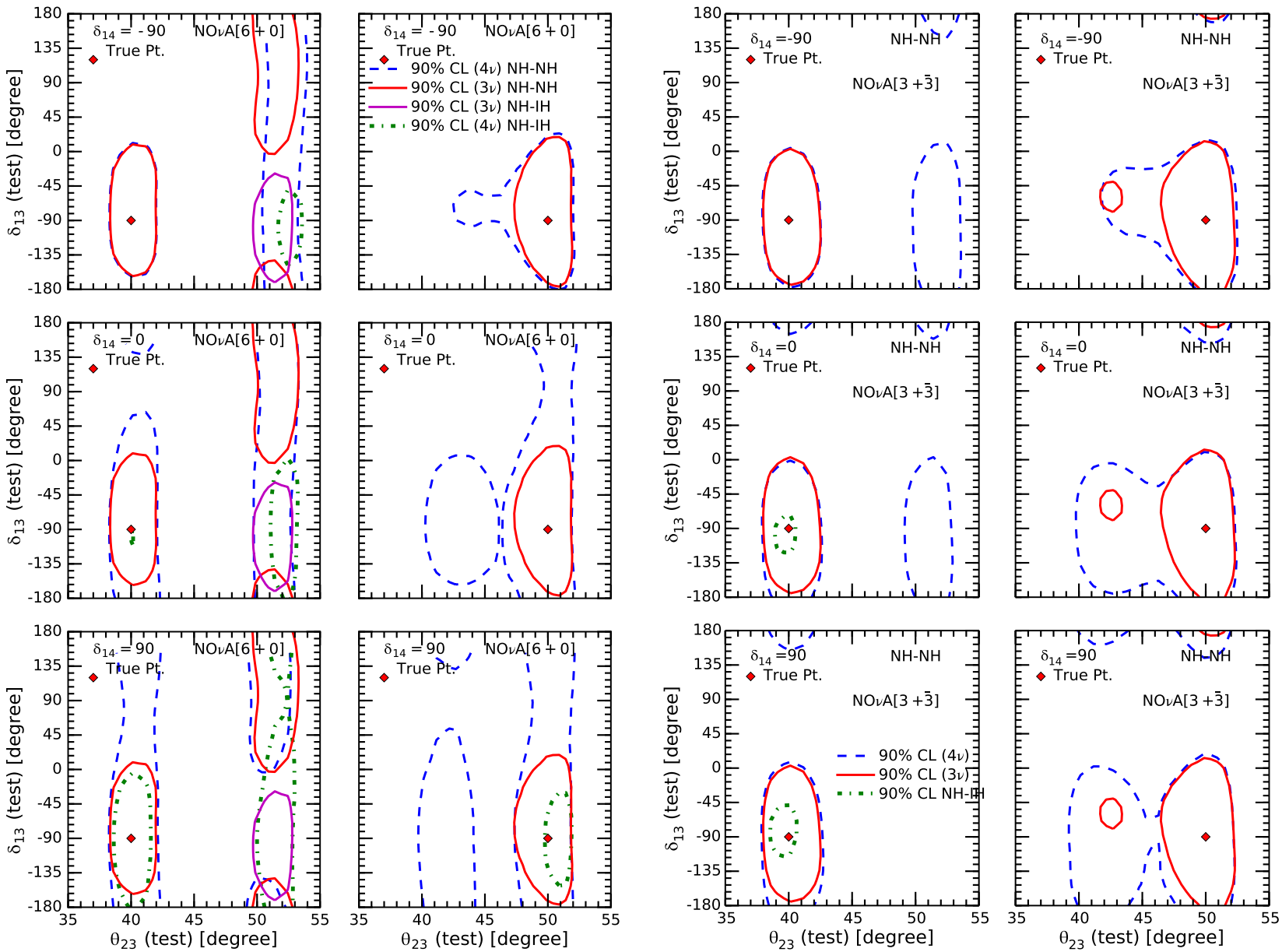
- True NH, $\delta_{13} = -90°$
- 3ν: red (right hierarchy), purple (wrong hierarchy)
- 4ν: blue (right hierarchy), green (wrong hierarchy)

NOνA(3+3)



- True NH, $\delta_{13} = -90°$
- 3ν: red (right hierarchy): degeneracy almost gone
- 4ν: blue (right hierarchy), green (wrong hierarchy)
- wrong hierarchy solutions almost gone
- wrong octant solution remains

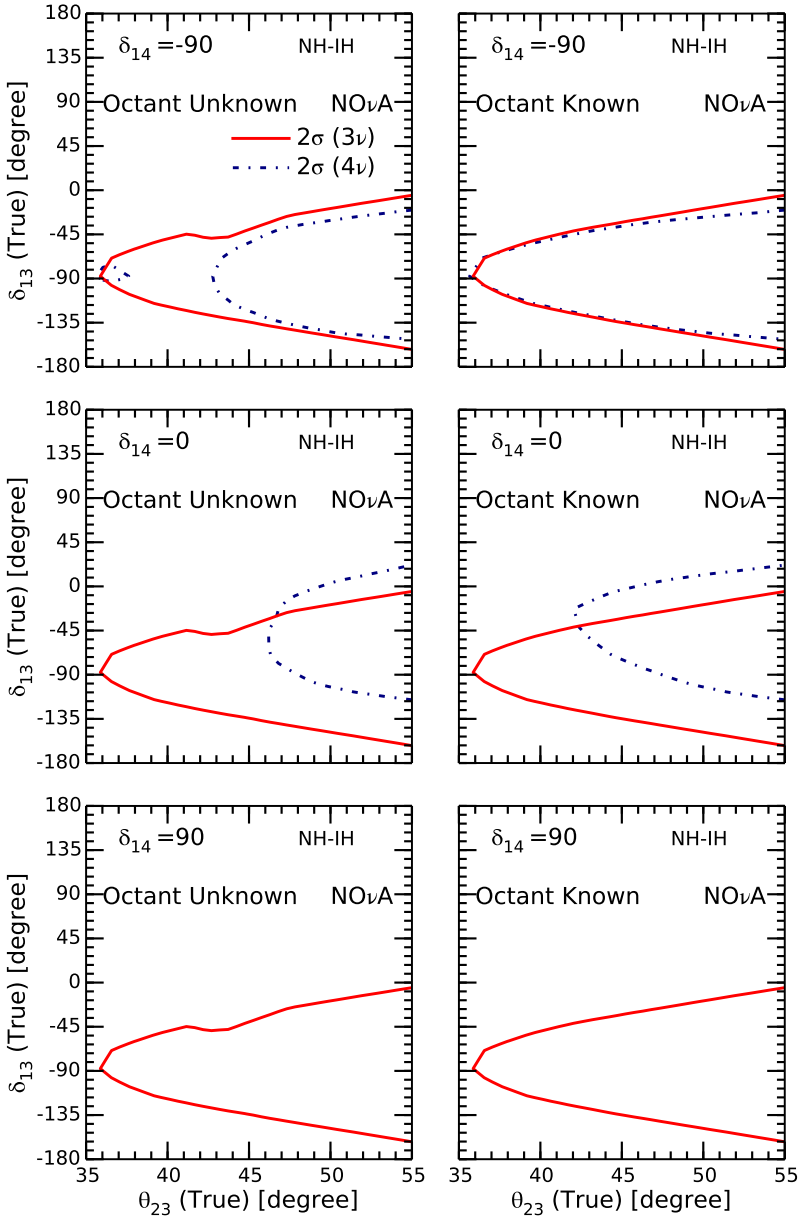
Effect of $\bar{\nu}$



Hierarchy

Lets see the effect the effect of these degeneracies on the hierarchy measurement

Hierarchy sensitivity of NOνA



- 3ν: good hierarchy sensitivity for $\delta_{13} = -90^\circ$
- $\delta_{14} = -90^\circ$: sensitivity lost for $\theta_{23} < 43^\circ$
- $\delta_{14} = 0^\circ$: sensitivity lost for $\theta_{23} < 46^\circ$
- $\delta_{14} = 90^\circ$: sensitivity completely lost

Summary

- We have identified two new degeneracies
- There are unsolved degenerate region in the 3+1 case
- Hierarchy sensitivity get affected depending on the true value of δ_{14}
- If the observed hierarchy sensitivity is less than expected: hint for sterile neutrinos

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Thank you