The impact of O(1 eV) sterile neutrinos on CP measurements at long baselines

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(Work done with Debajyoti Dutta, Boris Kayser, Mehedi Masud and Suprabh Prakash)

(Based on JHEP 1511 (2015) 039 ; (arXiv:1508.06275) and arXiv: 1607.02152)

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3+0 and 3+1.....

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e) + \text{matter} + \text{smaller terms}$$

"atmospheric" term, large

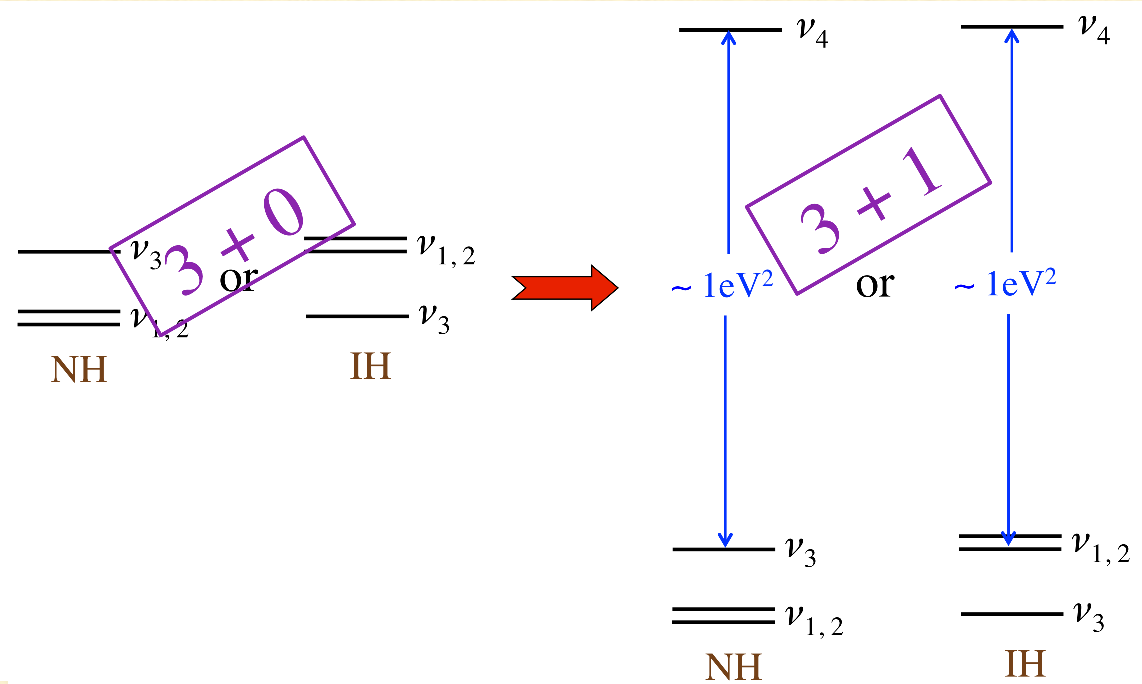
$$P_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)$$

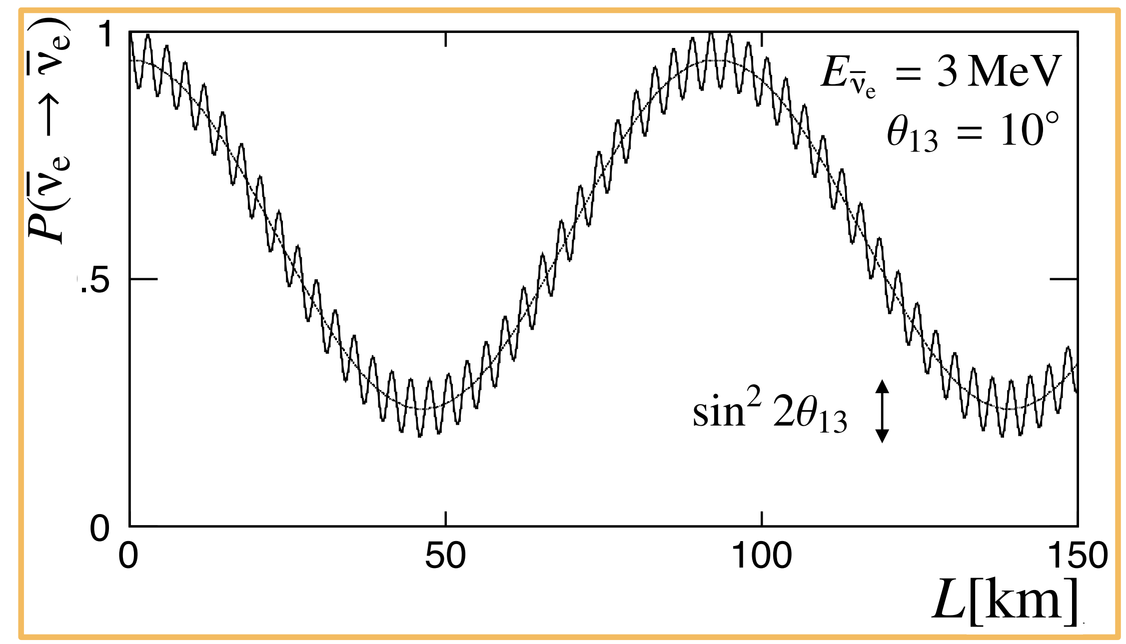
$$P_{II}(\nu_\mu \to \nu_e) = \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$
$$\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right)\times\left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right) + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right]$$

"interference" term, CP dependent

$$P_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

"solar" term, small





Thus, projections/predictions of sensitivities of LBL experiments have tended to ignore the effects of short wavelength oscillations so far, since it is expected that the finite energy resolution of a LBL detector will not probe them.

The introduction of 1 sterile neutrino to the standard 3 family picture leads to 6 mixing angles (instead of 3) and 3 CP phases (instead of 1) which affect oscillation.

Phases

$$U^{3+1}_{\rm PMNS} = O(\theta_{34}, \delta_{34}) O(\theta_{24}, \delta_{24}) O(\theta_{14}) O(\theta_{23}) O(\theta_{13}, \delta_{13}) O(\theta_{12})$$

Mixing angles

From Data

(reactors) $\theta_{14} \leq 13^\circ$ at 99% C.L.

(MINOS, IceCube) $\theta_{24} \leq 7^\circ$ can be allowed at 99% C.L.

(MINOS, CC & NC) $\theta_{34} \leq 25^\circ$ at 90% C.L.

Study the impact of these on CP measurements at long baselines

Related work: Hollander and Mocioiu, 1408.1749; Klop and Palazzo, 1412.7524; Berryman, de Gouvea and Kelly, 1507.03986; Agarwalla, Chatterjee and Palazzo, 1603.03759; deGouvea and Kelly, 1605.09376.

$P\mu e$ in vacuum for 3+1

$$
\begin{aligned}
P^{4\nu}_{\mu e} &= \frac{1}{2}\sin^2 2\theta^{4\nu}_{\mu e} \\
&+ (a^2\sin^2 2\theta^{3\nu}_{\mu e} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta^{4\nu}_{\mu e})\left[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right] \\
&+ \cos(\delta_{13}) b a^2 \sin 2\theta^{3\nu}_{\mu e}\left[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\right] \\
&+ \cos(\delta_{24}) b a \sin 2\theta^{4\nu}_{\mu e}\left[\cos 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} - \sin^2\theta_{13}(\sin^2\Delta_{31} - \sin^2\Delta_{32})\right] \\
&+ \cos(\delta_{13}+\delta_{24}) a \sin 2\theta^{3\nu}_{\mu e}\sin 2\theta^{4\nu}_{\mu e}\left[-\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21}\right. \\
&\left.+ \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\right] \\
&- \frac{1}{2}\sin(\delta_{13}) b a^2 \sin 2\theta^{3\nu}_{\mu e}\left[\sin 2\Delta_{21} - \sin 2\Delta_{31} + \sin 2\Delta_{32}\right] \\
&+ \frac{1}{2}\sin(\delta_{24}) b a \sin 2\theta^{4\nu}_{\mu e}\left[\cos^2\theta_{13}\sin 2\Delta_{21} + \sin^2\theta_{13}(\sin 2\Delta_{31} - \sin 2\Delta_{32})\right] \\
&+ \frac{1}{2}\sin(\delta_{13}+\delta_{24}) a \sin 2\theta^{3\nu}_{\mu e}\sin 2\theta^{4\nu}_{\mu e}\left[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\right] \\
&+ (b^2a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta^{3\nu}_{\mu e} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta^{4\nu}_{\mu e})\sin^2\Delta_{21}
\end{aligned}
\tag{2.3}
$$

large interference terms

Note that δ_{34} and θ_{34} do not appear, and θ_{14} and θ_{24} appear in a multiplicative combination

where

$$\sin 2\theta^{3\nu}_{\mu e} = \sin 2\theta_{13}\sin\theta_{23} \tag{2.4}$$

$$b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12} \tag{2.5}$$

$$\sin 2\theta^{4\nu}_{\mu e} = \sin 2\theta_{14}\sin\theta_{24} \tag{2.6}$$

$$a = \cos\theta_{14}\cos\theta_{24} \tag{2.7}$$

(2.8)

Two reasons why short-wavelength effects may not be as benign as assumed: a) phases, when non-zero, may make interference terms larger and b) matter, which redefines the eigenstates, may introduce large changes to overall probabilities

3+1 effects at LBL….. matter brings in new aspects

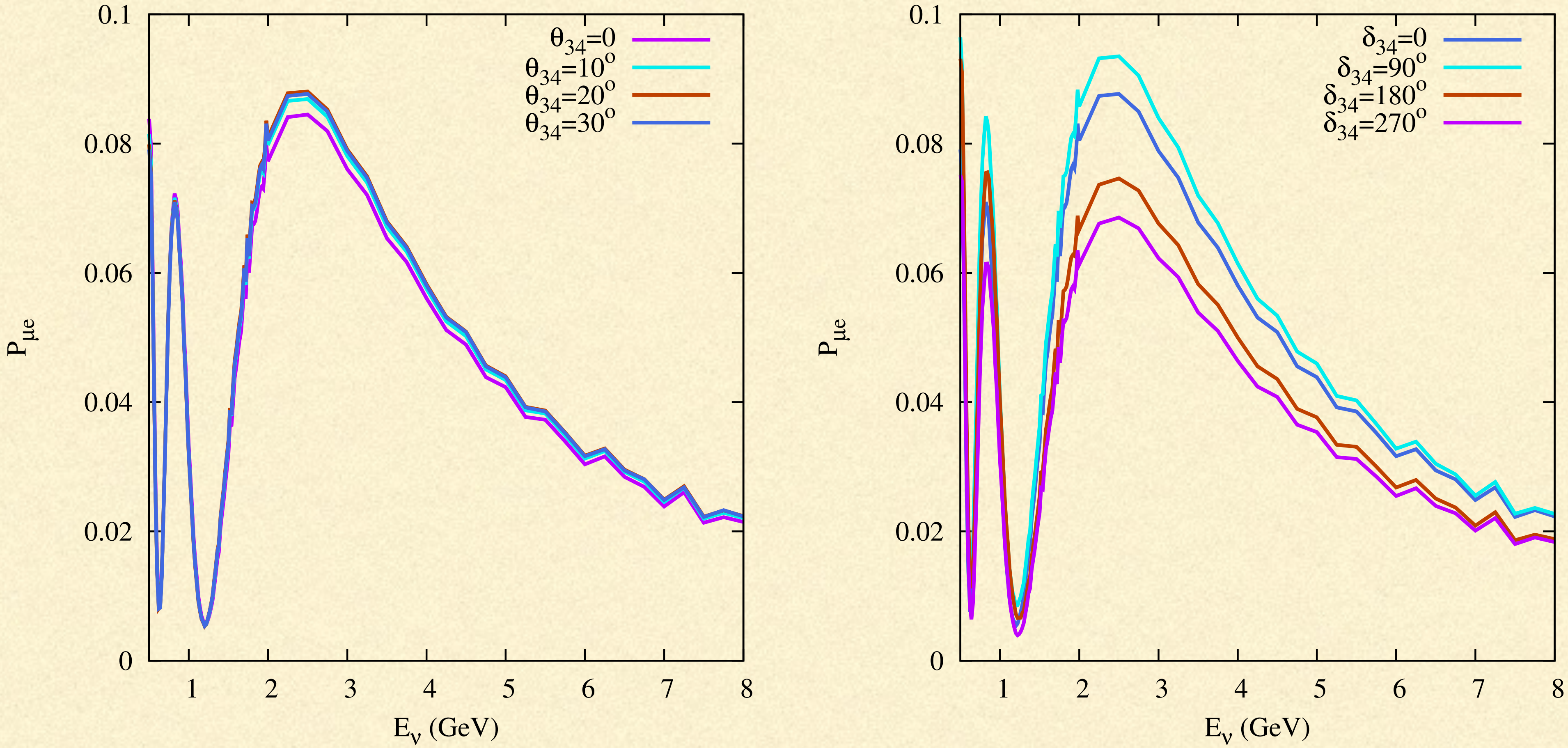


Figure 1: $P_{\mu e}$ vs E_ν(GeV) plots in earth matter for 1300 km, generated using GLoBES. Averaging has been done for Δm^2_{4i} induced oscillations. In the left panel, the effect of varying θ_{34} within its allowed range has been shown with all the CP phases kept equal to 0. We set $\theta_{14} = 20^\circ$, $\theta_{24} = 10^\circ$. In the right panel, we show the effect of varying the CP violating phase δ_{34} when $\theta_{34} = 30^\circ$. Other phases were set equal to 0. θ_{14} and θ_{24} set same as the left panel and parameters related to the 3+0 sector have been set at best-fit values specified in Section 3

Parameters which are dormant in vacuum play significant roles once matter effects come in

3+1 effects at LBL….. phases and matter brings in large effects

Solid: vacuum
Dashed:matter

Red: no CPV
Blue:CPV

Left panel: 3+0
Rt. panel:3+1

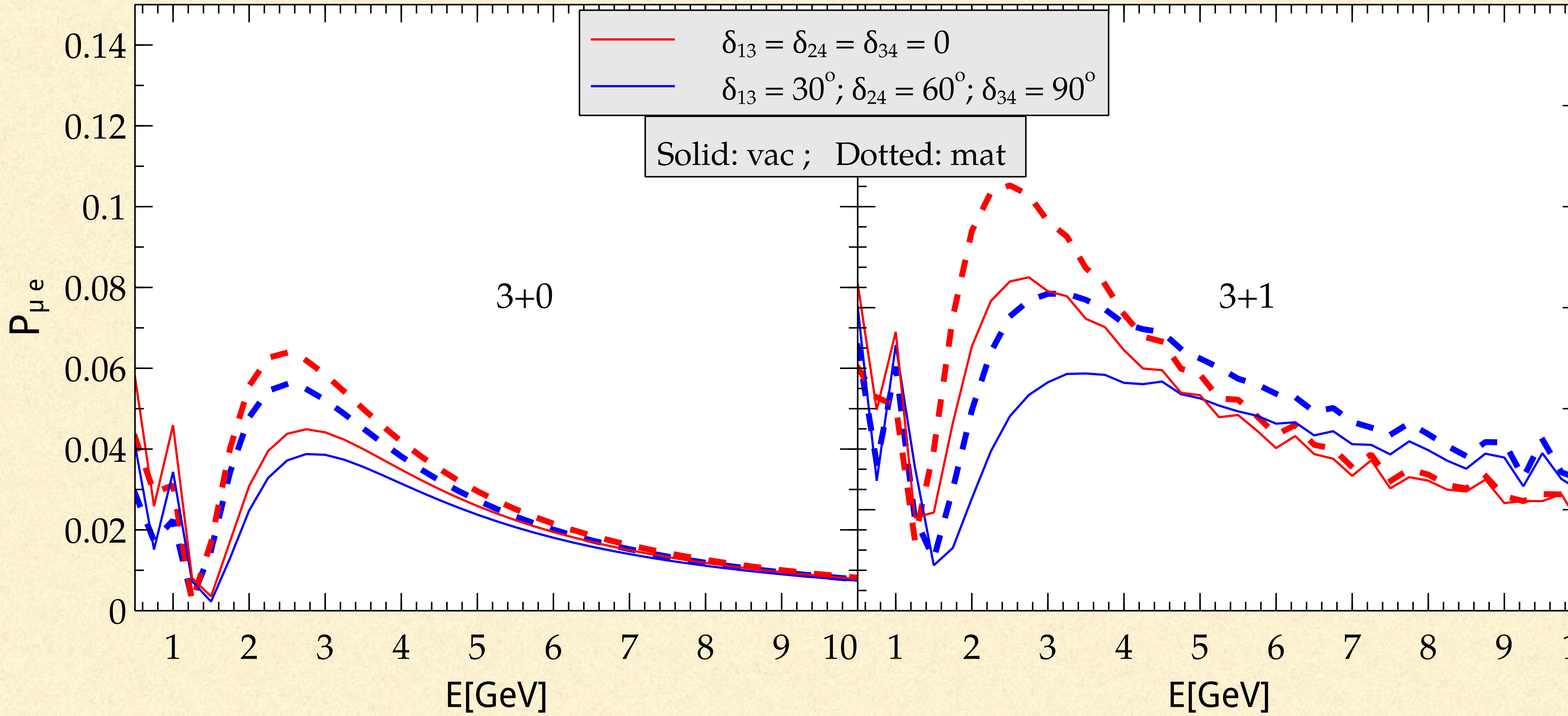


Figure 2: $P_{\mu e}$ (both for vacuum and matter) for 3+0 (left panel) and 3+1 (right panel) scenarios is shown as a function of energy. The red curves represent the CP conserving case, while the blue ones depict the case with phases set to non-zero fixed values (see the plot label). For the blue curve in the left panel, the relevant phase $\delta_{\rm CP}$ was taken as 30^o. Normal hierarchy is taken to be the true hierarchy here, and parameters related to the 3+0 sector have been set at best-fit values specified in Section 3

Conclusions:

Left vs Right: Even at LBL, a sterile ν causes large differences in amplitude

Red vs Blue: Phases play important role, more so in 3+1

Solid vs Dashed: matter plays an important role, more so in 3+1

Matter-Antimatter asymmetries in 3+0 and 3+1

$$A^{\alpha\beta}_{\nu\bar{\nu}} = \frac{P(\alpha \to \beta) - P(\bar{\alpha} \to \bar{\beta})}{P(\alpha \to \beta) + P(\bar{\alpha} \to \bar{\beta})} = \frac{\Delta P_{\alpha\beta}}{P(\alpha \to \beta) + P(\bar{\alpha} \to \bar{\beta})}$$

In the 3+0 scenario, there are three independent CP violating differences,

$\Delta P_{e\mu}$, $\Delta P_{\mu\tau}$ and $\Delta P_{\tau e}$

From Conservation of probability, $\Sigma P_{\alpha\beta} = 1$, $\Sigma P^{bar}_{\alpha\beta} = 1$,

Thus, $P_{e\mu} + P_{e\tau} + P_{ee} = P^{bar}_{e\mu} + P^{bar}_{e\tau} + P^{bar}_{ee} = 1$ and, by CPT, $P_{ee} = P^{bar}_{ee}$

and $\Delta P_{e\mu}$, $= \Delta P_{\tau e}$

Similarly, $\Delta P_{\tau e} = \Delta P_{\mu\tau}$.

Thus, CP violation in each channel is equal in 3+0, and in particular, if CP is conserved in one channel, it must be conserved overall.

However, if there are 4 neutrinos, on gets, via this reasoning, relations like

$\Delta P_{e\mu}$, $= \Delta P_{\tau e} + \Delta P_{se}$ etc

Thus, CP violation in the “active” channels need not be equal in 3+1, it may very well happen that if CP may be conserved in one channel, while having large violations in other difficult to measure channels.

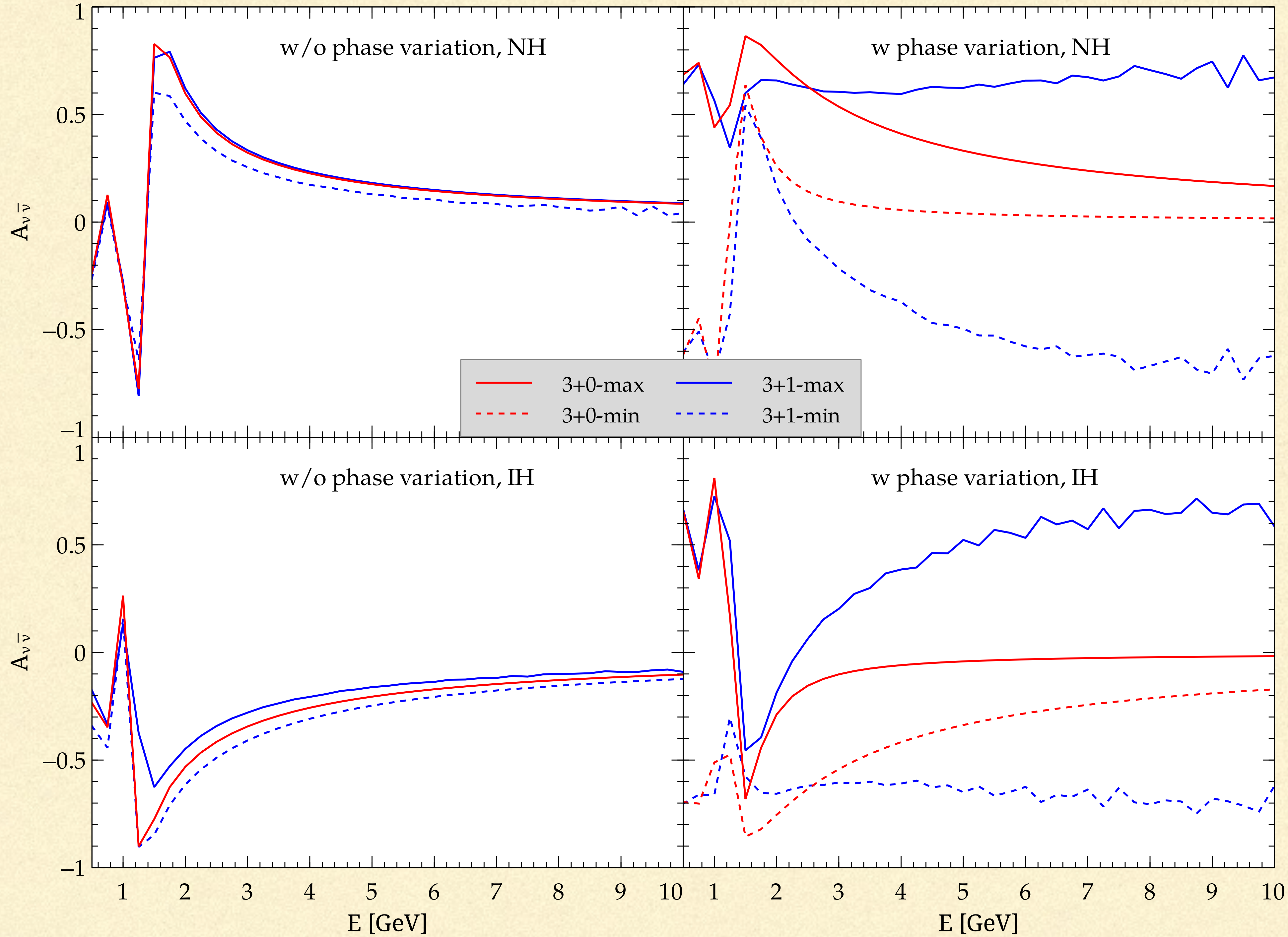
Matter-Antimatter asymmetries in 3+0 and 3+1 for DUNE

Red: 3+0
Blue:3+1

Left panels: all phases zero
Rt. panels:all phases running

Solid: Max intergrated asymm
Dashed:Min integrated asymm

Top : NH
Bottom:IH



Thus, if an experiment sees CP asymmetries consistently outside of the red/blue left panels, one can conclude that CP must be violated, though its origin may remain uncertain.

However, if one sees asymmetry lying within the bands of the left panels, then it is not obvious that it is conserved.

Event-rate spreads in 3+0 and 3+1 for DUNE

(White) No CPV in μe channel : 3+1

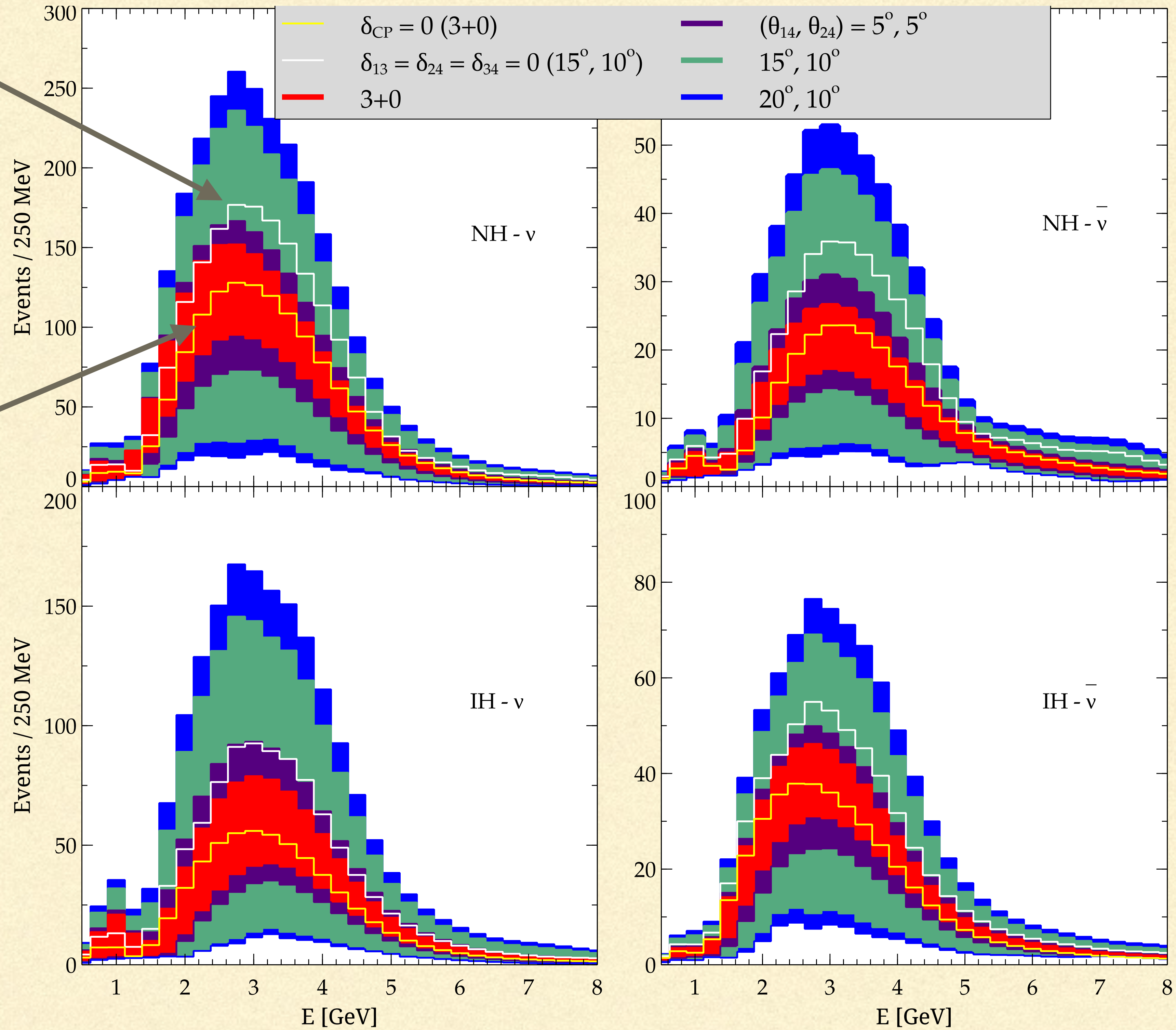
(Yellow) No CPV: 3+0

Left panel: neutrino events

Rt. panel: anti-neutrino events

Upper panels: NH

Lower panels: IH

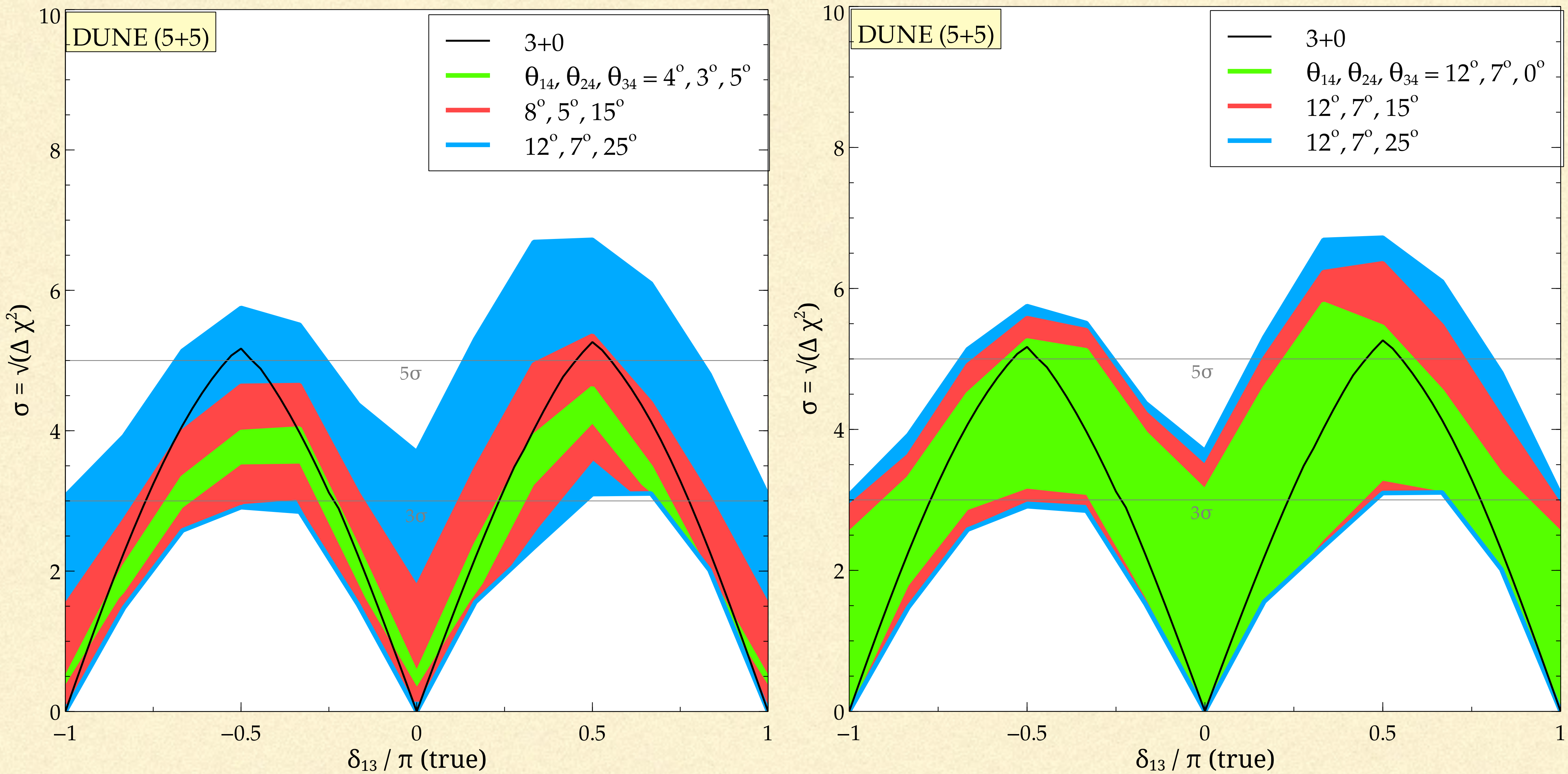


Gandhi, Kayser, Masud and Prakash, JHEP 1511 (2015) 039 ; (arXiv:1508.06275)

Why is the the effect of a fourth, sterile neutrino on CP violation at long baselines unexpectedly large?

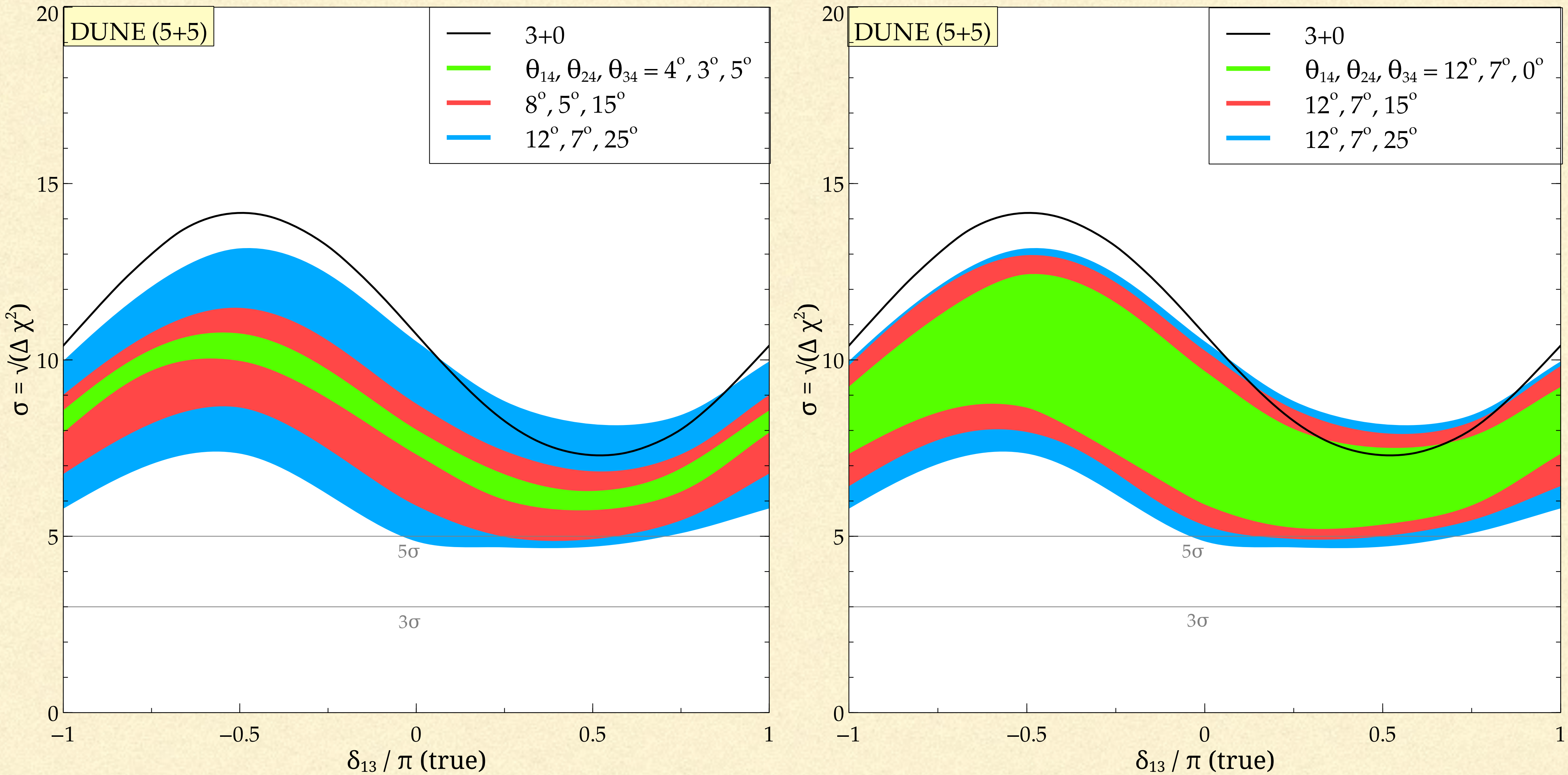
CP-violating phases affect physics through interferences between amplitudes. These effects get amplified by matter.

Around the first maximum of the atmospheric- wavelength oscillation, where the long-baseline experiments work, the (new, short wavelength oscillation) - (atmospheric-wavelength oscillation) interference, and the (atmospheric-wavelength oscillation) - (solar-wavelength oscillation) interference, can easily be of comparable size. Then, if the CP phases are right, 3+1 can be quite different from 3+0.



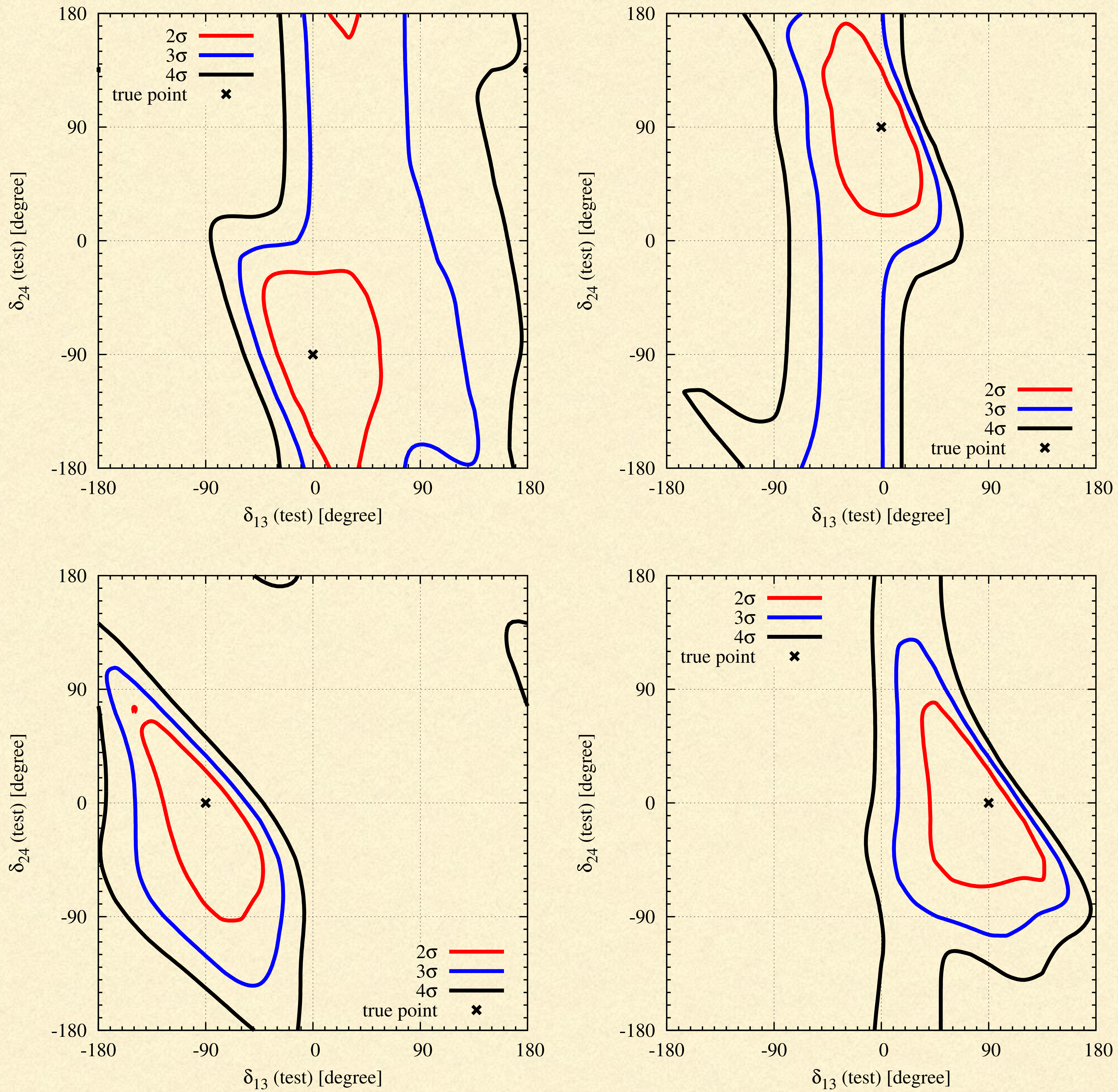
. When the active-sterile mixings are small, in general the sensitivity to CP violation of the experiment will be decreased compared to what we would expect in the 3+0 scenario.

For sufficiently large mixings, the sensitivity spans both sides of the 3+0 curve; and depending on the true value of the other phases - δ_{24} and δ_{34} the sensitivity to CP violation can be greatly amplified. Also, it can be very high in regions where there is almost no sensitivity in the 3+0 scenario.



In general, the presence of a sterile state lowers the hierarchy sensitivity. However, the hierarchy should still be determined at DUNE at ~ 5 sigma for the full space of parameters

Is DUNE sensitive to which 3+1 phase is causing CP violation?

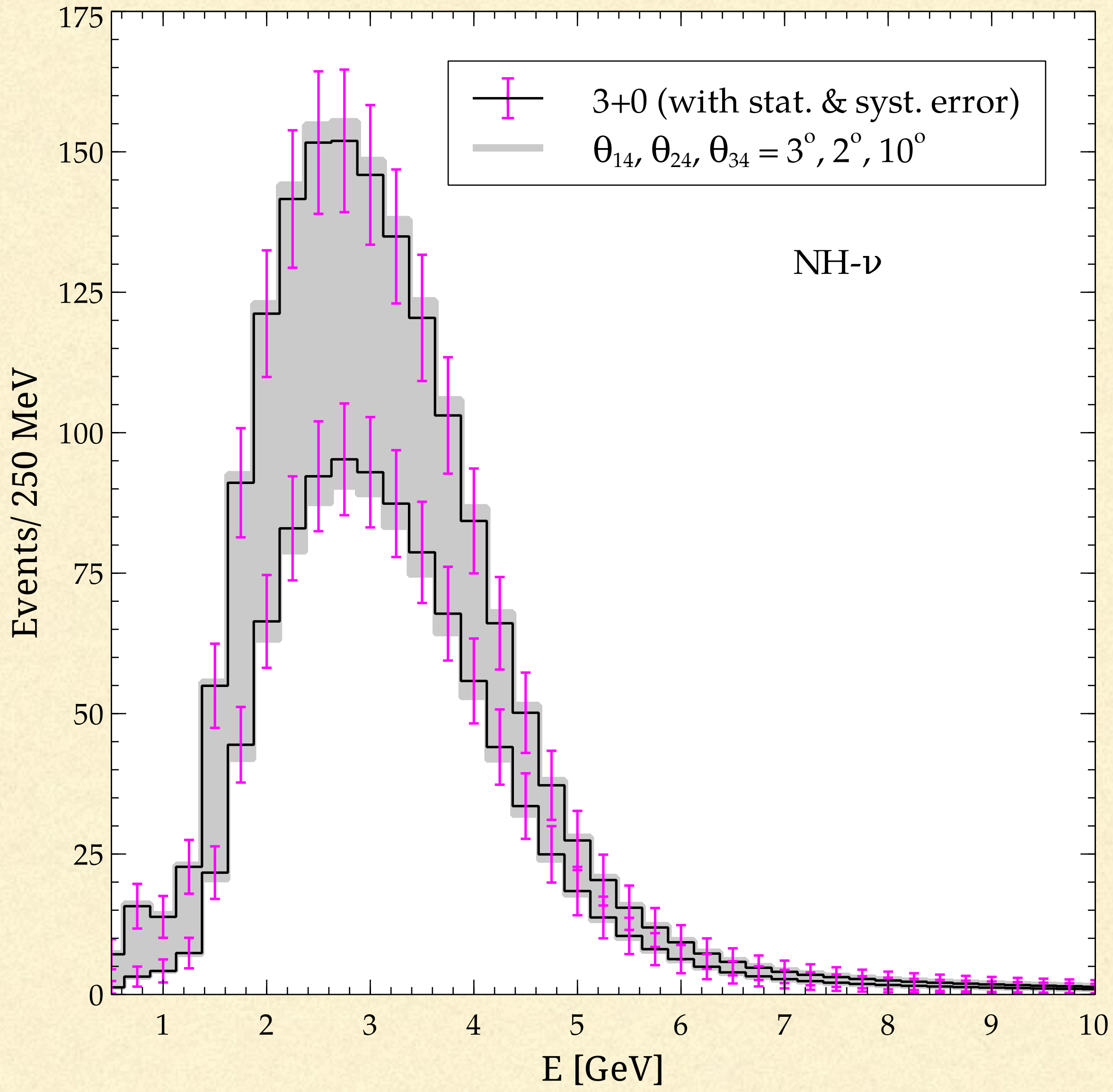


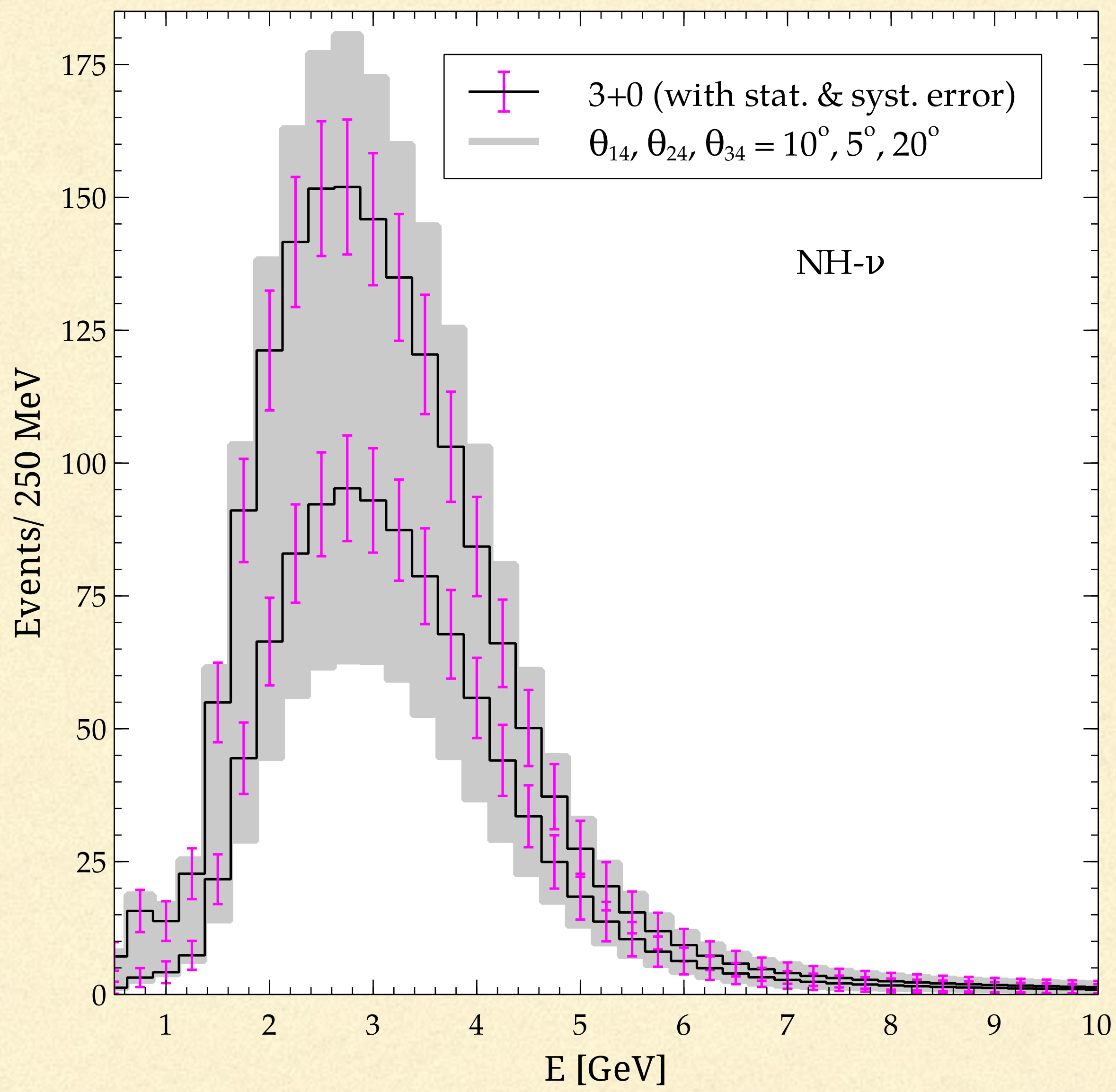
True (θ14,θ24,θ34) were taken to be (12°, 7°, 25°) and true δ34 = 0. Results have been shown for true (δ13, δ24) = (0, ±90°) and (±90°, 0), at 2σ, 3σ, and 4σ.

Top panels show that attributing CP violation unambiguously to δ24 is not possible at 3σ. Also, it is not possible to rule out CP conserving values of δ24 at this level.

Bottom panel (rt) shows distinguishing maximally CP-violating δ13 and CP conserving δ24 from maximally CP-violating δ24 and CP conserving δ13 may not be possible at 4σ.

Is DUNE sensitive to small values of active sterile mixing?





- For $\Delta m^2_{41} \sim 1\ \mathrm{eV}^2$ induced oscillations, the short baseline experiments can see a 3σ effect only if $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24} \geq 0.001$.

The left plot compares 3+0 with 3+1 for very small mixing angles - $\theta_{14},\theta_{24},\theta_{34}$ 3°, 2°, 10° ($\sin^2 2\theta_{\mu e} \approx 0.00008$) .The right panel shows the comparison for θ_{14} , θ_{24} , $\theta_{34} = 10^\circ$, 5° , 20° ($\sin^2 2\theta_{\mu e} \approx 0.0009$). DUNE may exhibit sensitivity to values of mixing angles below the sensitivity of SBL experiments. However, such signals may be mimicked by other new physics. The presence of a sterile sector requires confirmation via SBL oscillations.

Implications and Conclusions ....

In the presence of even a single sterile neutrino, conclusions at DUNE such as, a) Whether CP is conserved or violated, and b) if the latter, whether the violation is ascribable to the active neutrinos or the additional sterile neutrino, or a combination of the two, are all rendered significantly ambiguous.

Unless the presence of a sterile sector is conclusively ruled out by SBL experiments, measurements which, when interpreted in the context of the standard three family paradigm, indicate CP conservation at long baselines, may, in fact hide large CP violation if there is a sterile state. Conversely, measurements indicating CP violation may in fact point to CP conserving new physics in the mu-e channel.

The presence of sterile states in general causes a reduction in the anticipated sensitivity to hierarchy.

The presence of sterile states can cause either a decrease or an increase in the anticipated sensitivity to CP violation.

Implications and Conclusions ....

We find that while the discovery potential for the violation could be large, determining its origin (i.e. ascribing it unambiguously to either the 3+0 phase δ_{cp} or one of the 3+1 phases, δ_{13},δ_{24},δ_{34}) is much more challenging.

DUNE may exhibit signals hinting at the presence of a sterile sector even if the relevant mixing angles lie below the sensitivity of the planned short-baseline experiments.

The sensitivity of DUNE to sterile neutrinos is truly complementary to the sensitivity of SBL experiments, because it stems from amplification by matter of the interference terms containing 3+1 CP phases

Definitive confirmation or refutation of the presence of sterile neutrinos must come from the SBL experiments from measurements of short-wavelength oscillations, since it is possible the effects s at DUNE for such neutrinos could be mimicked by other new physics as well.

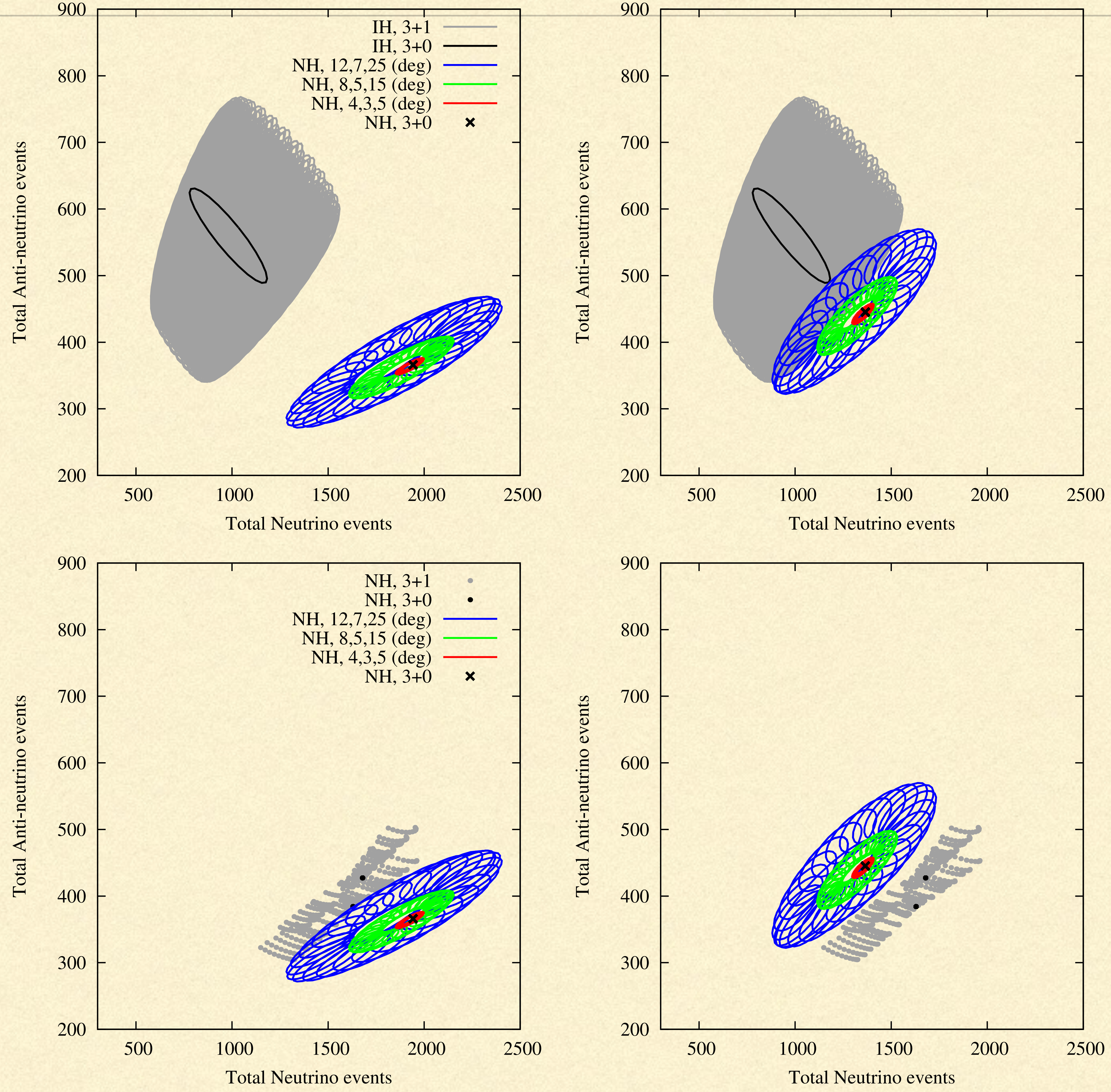
Implications and Conclusions ....

The rates expected at the FD depend on fluxes and cross-sections measured, along with their energy dependence, to significantly high accuracy at the ND for all four species of neutrinos, ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$.

In the 3 + 0 scenario, these measurements, while very demanding, are assumed to be made under conditions where there are no oscillations between the source and the ND. This task is rendered significantly more complex, however, in the presence of a sterile sector capable of altering the fluxes between the source and the ND over the planned distance of ~ 500 m in DUNE.

Thank you for your attention!

Back-up Slides



IH, 3+1
IH, 3+0
NH, 12,7,25 (deg)
NH, 8,5,15 (deg)
NH, 4,3,5 (deg)
NH, 3+0
NH, 3+1
NH, 3+0
NH, 12,7,25 (deg)
NH, 8,5,15 (deg)
NH, 4,3,5 (deg)
NH, 3+0
Total Anti-neutrino events
Total Neutrino events
200
300
400
500
600
700
800
900
500
1000
1500
2000
2500

Matter-Antimatter asymmetries in 3+0 and 3+1 for NOvA+T2K

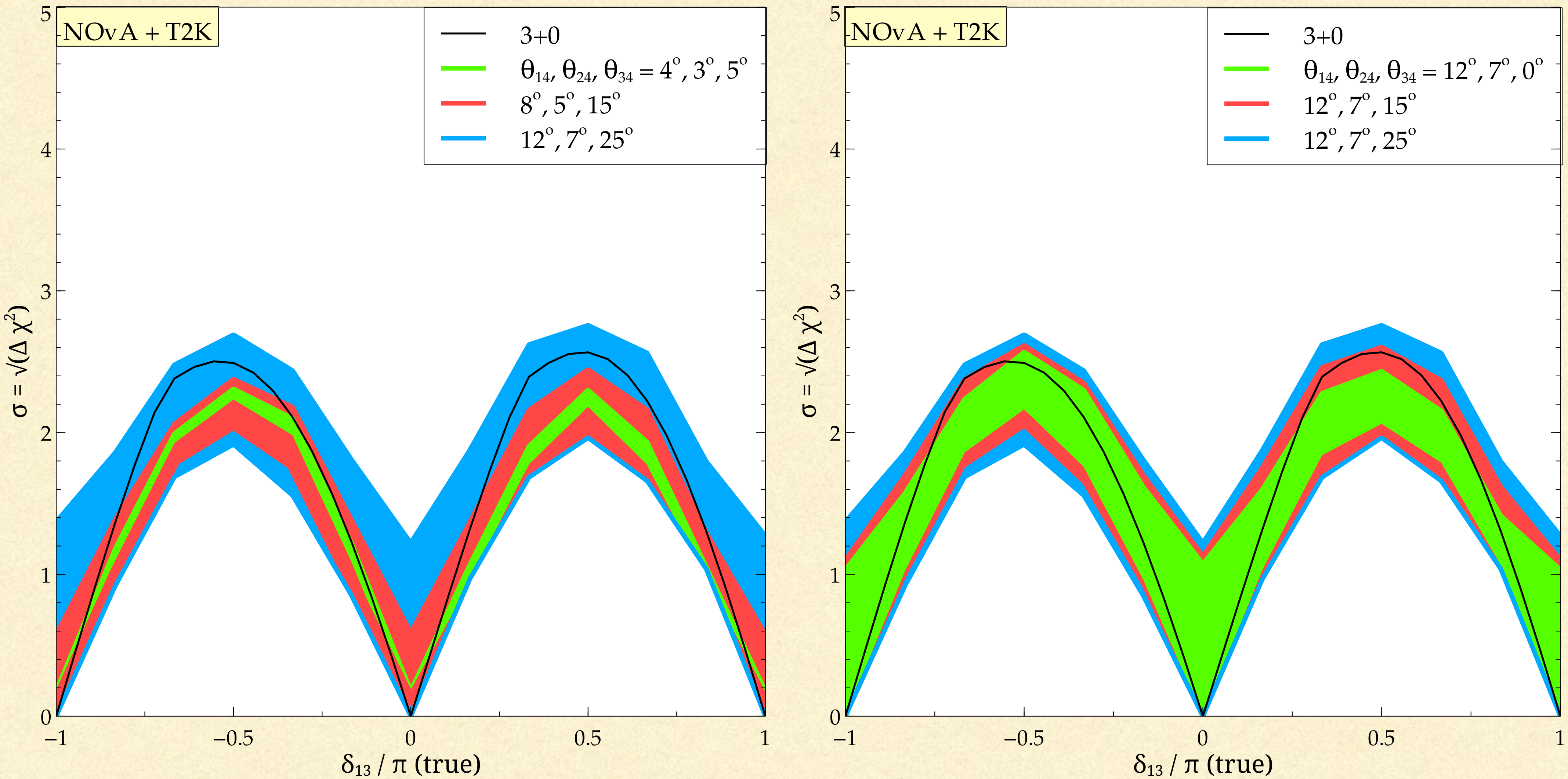
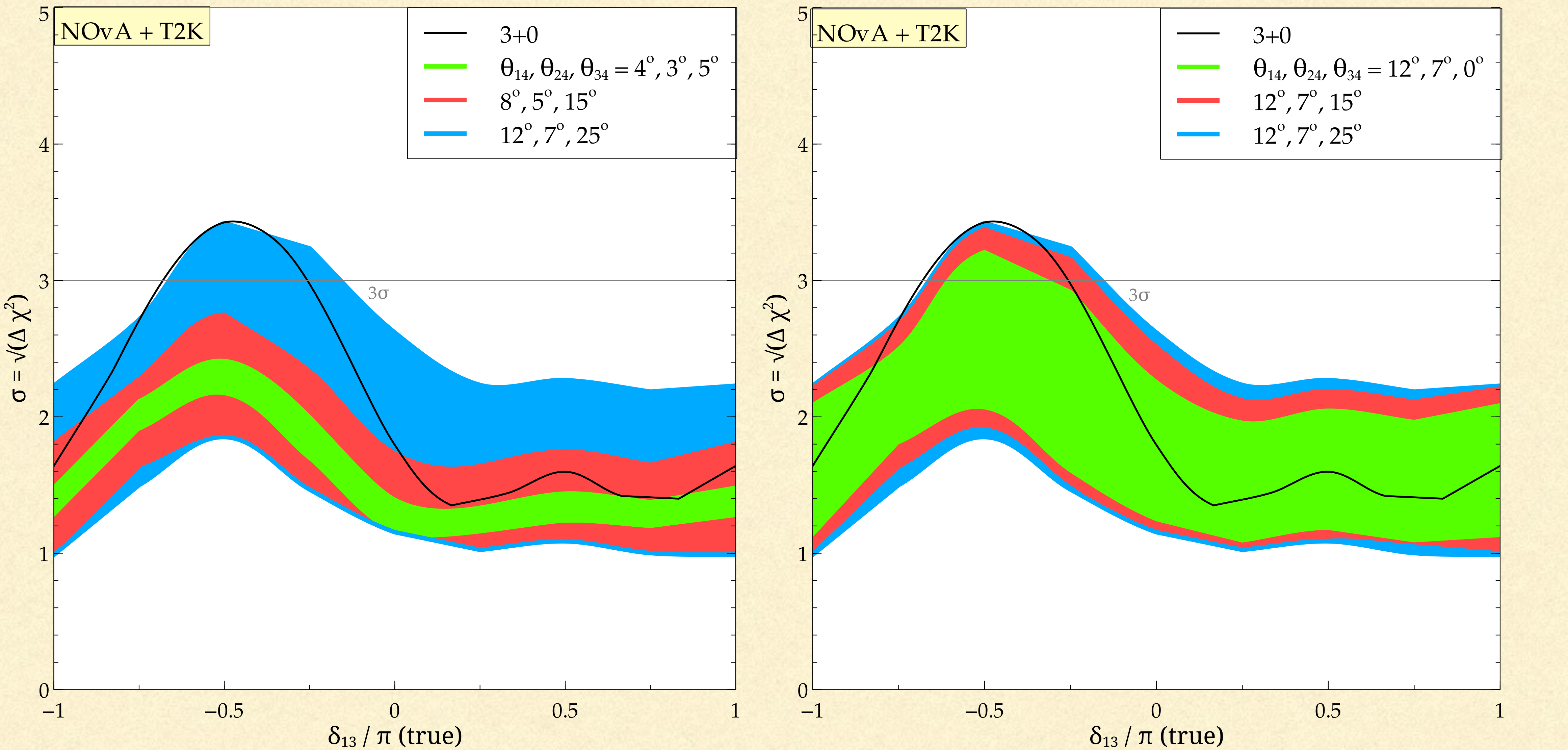
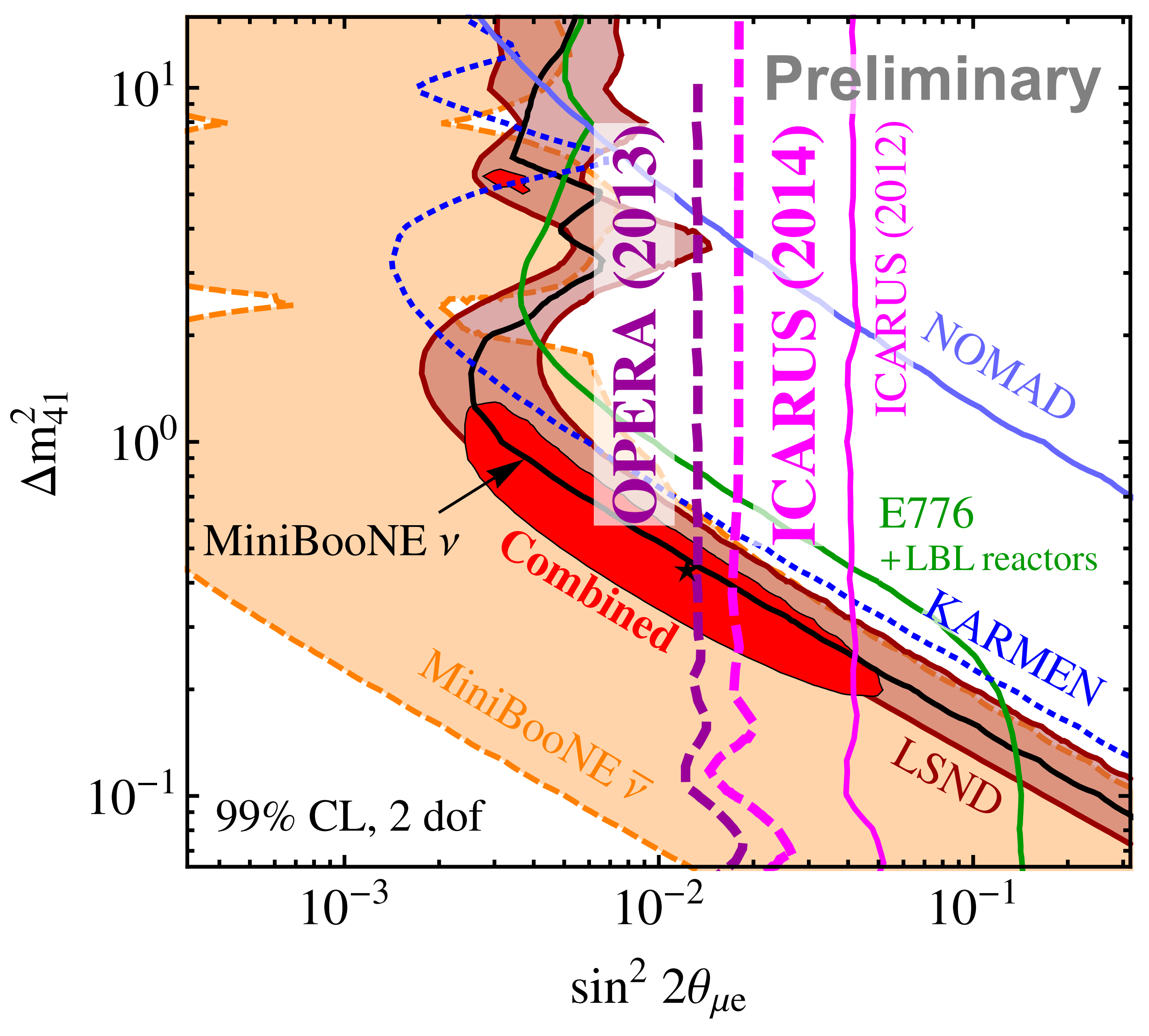


FIG. 1: Sensitivity to CP violation as a function of the true CP violating phase δ13 for the combined data from T2K and NOvA. Different colors correspond to different choice of true θ14, θ24, θ34 as shown in the key. Variation of true δ24 and δ34 results in the colored bands which show the minimum and maximum sensitivity that can be obtained for a particular δ13. The black curve corresponds to sensitivity to CP violation in 3+0. Left panel: Shows the effect as all the three active-sterile mixings are increased. Right panel: Shows the effect of the 3-4 mixing when the true θ14 and θ24 have been fixed at 12◦ and 7◦ respectively for all three bands.



. FIG. 4: Sensitivity to Mass hierarchy as a function of the true CP violating phase δ13 for the combined data from T2K and NOvA. Different colors correspond to different choice of true θ14, θ24, θ34 as shown in the key. Variation of true δ24 and δ34 results in the colored bands which show the minimum and maximum sensitivity that can be obtained for a particular δ13. The black curve corresponds to sensitivity to the hierarchy in 3+0. Left panel: Shows the effect as all the three active-sterile mixings are increased. Right panel: Shows the effect of the 3-4 mixing when the true θ14 and θ24 have been fixed at 12 ◦ and 7 ◦ respectively for all three bands.



All appearance data when combined identify a region in the ~ 1 eV^2 neighbourhood

In tension with disappearance data

Combining everything in a 3+1 scenario gives the following ranges for the new mixings (95% CL)

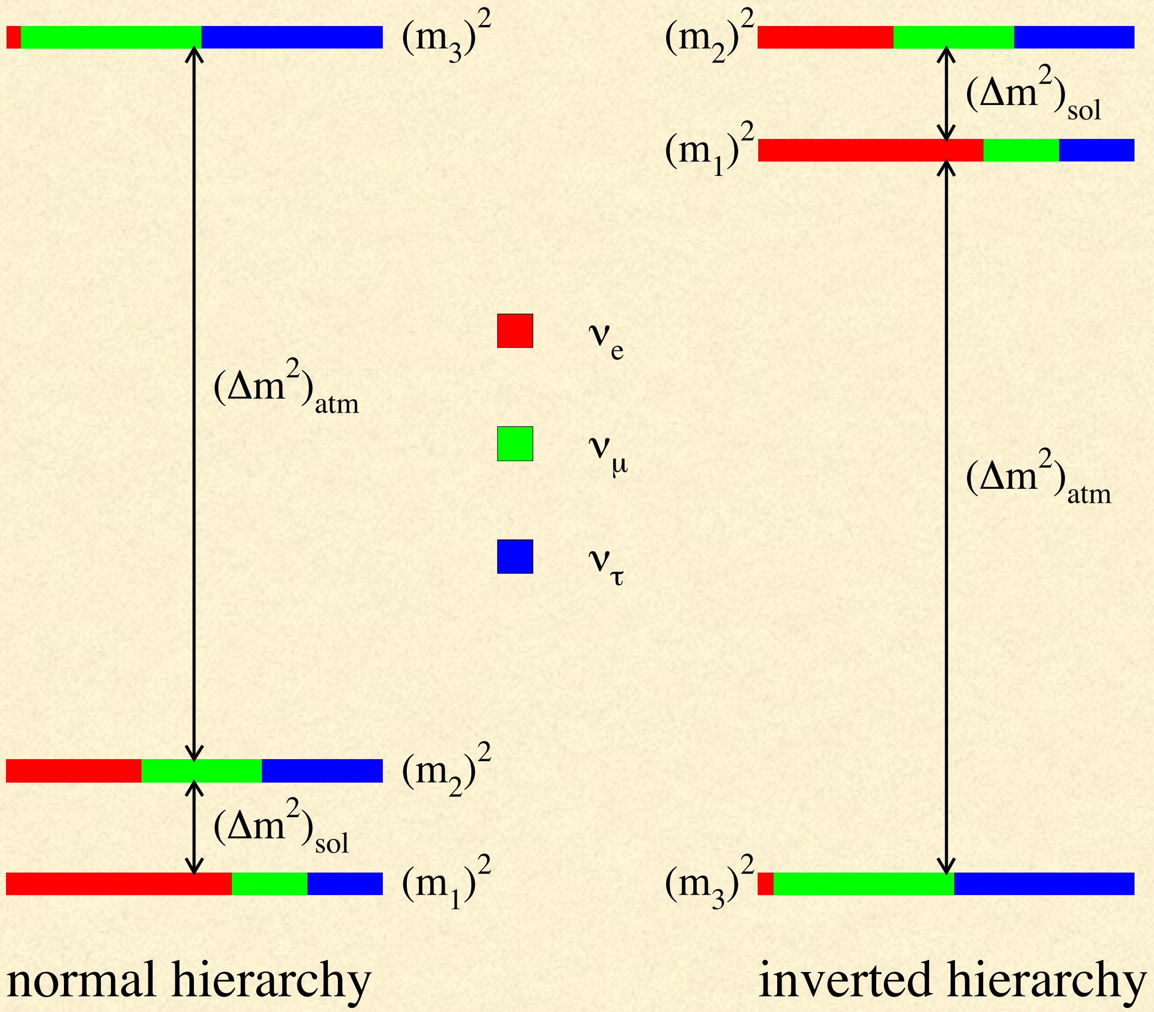
$$\theta_{24} \in [0, 11^o], \theta_{34} \in [0, 31^o]$$

$$\theta_{14} \in [0, 20^o].$$

What remains, and why do we care to push on?.....

(Are we a community that just likes to know numbers more and more precisely?)

What is the ordering of neutrino masses? (hierarchy)



$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm sol}^2}$$
$$m_3 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2 - \Delta m_{\rm sol}^2}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

Is there CP violation in the lepton sector?

i.e Is δ_{CP} different from 0 or π ?

Possible in next decade or so

More Difficult to answer soon

Are neutrinos their own anti-particles ? (Dirac or Majorana ?)

What are their absolute masses ?

CP Violation and a long baseline: some general features.....

The determination of CP violation depends on the appearance probability , and certain important and nice conclusions follow from an examination of the basic expression :

Marciano hep-ph 0108181 , Marciano and Parsa, hep-ph 0610258

$O(\alpha^2)$

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e) + \text{matter} + \text{smaller terms}$$

not necessarily small, depending on L

"atmospheric" term, large

$$P_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)$$

$$P_{II}(\nu_\mu \to \nu_e) = \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$
$$\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right)\times\left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right.$$
$$\left.+\cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right]$$

"interference" term, CP dependent

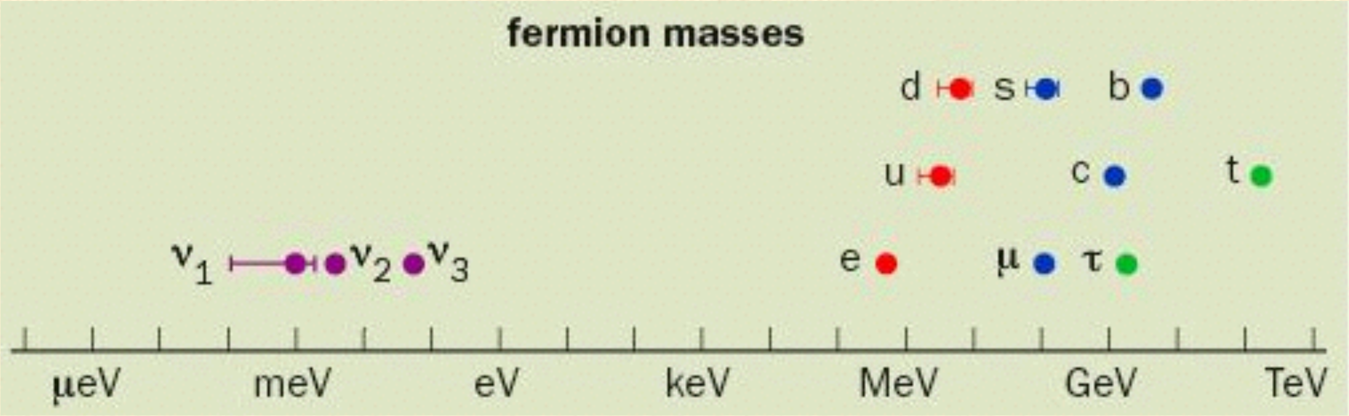
$$P_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

"solar" term, small

What remains, and why do we care to push on?.....

(Are we a community that just like to know numbers more and more precisely?)

A. Neutrino masses appear to be special



$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}.$$

quark mixing

Neutrino mixings are quite different from quark mixings

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0.178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

neutrino mixing

- Neutrino mass may have a different origin from the masses of quarks and charged leptons

The difference between the mixing patterns of quarks and leptons may be a clue to the flavour problem

Both of these are signposts of physics beyond the Standard Model

Precise measurements put us in a position to properly explore underlying connections and symmetries

Types of Experiments and their scope ....

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta} & c_{23}\,c_{13} \end{pmatrix} =$$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{probed by LBL accelerator and atmospheric expts}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{probed by LBL accelerator and SBL reactor expts}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{probed by solar \& LBL reactor expts}}$$

probed by LBL accelerator and atmospheric expts

probed by LBL accelerator and SBL reactor expts

probed by solar & LBL reactor expts

LBL accelerator experiments thus have the capability of measuring hierarchy, CP violation and the octant. The first and last of these depend strongly on matter effects which accrue with baseline length.