The impact of sterile neutrinos on CP measurements at long baselines

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Introduction

A major goal of the present and future long-baseline neutrino oscillation experiments is to establish that leptons violate CP, or else to place a stringent upper limit on any such violation.

The studies related to these experiments have been done assuming the standard three-neutrino-only paradigm.

Several short-baseline anomalies hint at the possible existence of short-wavelength oscillations driven by one or more $O(1\ eV^2)$ mass-squared splittings.

These oscillations are significant when $L/E \sim 1$ km/GeV but they are also present at the far detector where $L/E \sim 500$ km/GeV.

At $L/E \sim 500$ km/GeV, the rapid oscillations driven by $O(1\ eV^2)$ neutrinos get averaged to a L/E-independent value due to the finite energy resolution of any realistic detector.

Introduction

However, these oscillations can have a major impact on the probability amplitudes over and above that of the standard oscillations.

For simplicity, we restrict ourselves to the scenario where there is only one additional mass eigenstate (3+1).

For 3+N scenarios where N>1, the consequences on measurements made at the far-detector site can be expected to be manifold.

We perform our calculations for the 3+1 scenario as manifested in the proposed Deep Underground Neutrino Experiment (DUNE).

See arXiv:1108.4136, Hamann et. al. for a compatibility study with Cosmological bounds.

See arXiv:1308.6218, Esmaili et. al. for robustness of Θ_{13} in 3+1.

The 3+1 model

We consider a O(1 eV^2) mass sterile neutrino, heavier than the other 3 mass eigenstates => $\Delta m^2_{41} = +1\ eV^2$. Δm^2_{31} can be + or -

The oscillations are now characterised by 6 mixing angles, 3 CP-violating phases and 3 mass-squared differences.

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

$\sin^2\Delta_{4i}$ averages to 0.5

$\sin 2\Delta_{4i}$ averages to 0

$$\begin{aligned} P^{3+1}_{\mu e} &= 4|U_{\mu 4}U_{e4}|^2 \times 0.5 \\ &- 4Re(U_{\mu 1}U^*_{e1}U^*_{\mu 2}U_{e2})\sin^2\Delta_{21} + 2Im(U_{\mu 1}U^*_{e1}U^*_{\mu 2}U_{e2})\sin 2\Delta_{21} \\ &- 4Re(U_{\mu 1}U^*_{e1}U^*_{\mu 3}U_{e3})\sin^2\Delta_{31} + 2Im(U_{\mu 1}U^*_{e1}U^*_{\mu 3}U_{e3})\sin 2\Delta_{31} \\ &- 4Re(U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3})\sin^2\Delta_{32} + 2Im(U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3})\sin 2\Delta_{32} \end{aligned}$$

Appearance probability in 3+1 in vacuum

$$
\begin{aligned}
P_{\mu e}^{3+1} &= \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu} \\
&+ (a^2 \sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu})\Big[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\Big] \\
&+ \cos(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\Big[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\Big] \\
&+ \cos(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\Big[\cos 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} - \sin^2\theta_{13}(\sin^2\Delta_{31} - \sin^2\Delta_{32})\Big] \\
&+ \cos(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[-\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} \\
&+ \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\Big] \\
&- \frac{1}{2}\sin(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\Big[\sin 2\Delta_{21} - \sin 2\Delta_{31} + \sin 2\Delta_{32}\Big] \\
&+ \frac{1}{2}\sin(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\Big[\cos^2\theta_{13}\sin 2\Delta_{21} + \sin^2\theta_{13}(\sin 2\Delta_{31} - \sin 2\Delta_{32})\Big] \\
&+ \frac{1}{2}\sin(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\Big] \\
&+ (b^2 a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{4\nu})\sin^2\Delta_{21}
\end{aligned}
$$

where $\sin 2\theta_{\mu e}^{3\nu} = \sin 2\theta_{13}\sin\theta_{23}$, $b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}$,

$\sin 2\theta_{\mu e}^{4\nu} = \sin 2\theta_{14}\sin\theta_{24}$ and $a = \cos\theta_{14}\cos\theta_{24}$

Appearance probability in 3+1 in vacuum

$$P_{\mu e}^{3+1} = \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu}$$

$$+ \left(a^2 \sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu}\right)\left[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right]$$

$$+ \cos(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\left[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\right]$$

$$+ \cos(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\left[\cos 2\theta_{12}\cos^2\theta\right.$$

$$+ \cos(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\left[\right.$$

$$\left.+ \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\right]$$

$$- \frac{1}{2}\sin(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\left[\sin 2\Delta_{21} - \right.$$

$$+ \frac{1}{2}\sin(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\left[\cos^2\theta_{13}\sin 2\right.$$

$$+ \frac{1}{2}\sin(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\left[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\right]$$

$$+ \left(b^2 a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{4\nu}\right)\sin^2\Delta_{21}$$

Θ_{14} and Θ_{24} come in certain combinations only..

In vacuum, the expression does not depend on Θ_{34} and δ_{34}

where $\sin 2\theta_{\mu e}^{3\nu} = \sin 2\theta_{13}\sin\theta_{23}$, $b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}$,

$\sin 2\theta_{\mu e}^{4\nu} = \sin 2\theta_{14}\sin\theta_{24}$ and $a = \cos\theta_{14}\cos\theta_{24}$

Appearance probability in 3+1 in vacuum

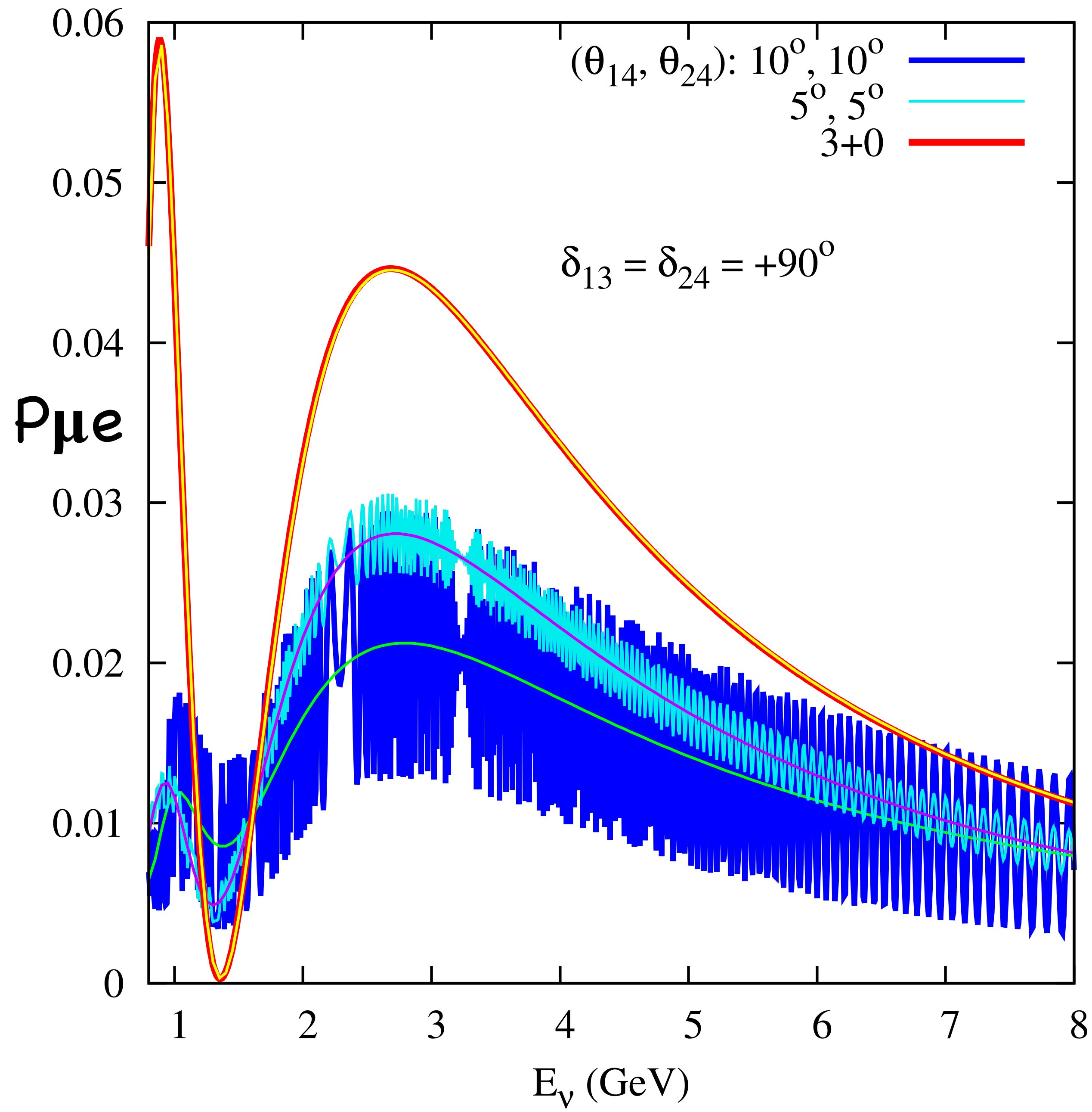
Comparison of analytical expression with GLoBES =>

In the limit that $\Theta_{i4} = 0$, the 3+0 probabilities are reproduced.

When 3+1 effects are switched on, the probabilities match quite well.

The rapid oscillations due to Δm^2_{4i} for a 1 eV^2 sterile neutrino will not be visible in the DUNE far detector.

DUNE, L = 1300 km, vacuum



$\Theta_{12} = 33.48°$, $\Theta_{13} = 8.5°$, $\Theta_{23} = 45°$

$\Delta m^2_{31} = +2.4e{-}3\ eV^2$, $\Delta m^2_{21} = 7.5e{-}5\ eV^2$

Why are the 3+1 effects large?

$$
\begin{aligned}
P_{\mu e}^{3+1} &= \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu} \\
&+ (a^2 \sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu})\Big[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\Big] \\
&+ \cos(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\Big[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\Big] \\
&+ \cos(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\Big[\cos 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} - \sin^2\theta_{13}(\sin^2\Delta_{31} - \sin^2\Delta_{32})\Big] \\
&+ \cos(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[-\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} \\
&+ \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\Big] \\
&- \frac{1}{2}\sin(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\Big[\sin 2\Delta_{21} - \sin 2\Delta_{31} + \sin 2\Delta_{32}\Big] \\
&+ \frac{1}{2}\sin(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\Big[\cos^2\theta_{13}\sin 2\Delta_{21} + \sin^2\theta_{13}(\sin 2\Delta_{31} - \sin 2\Delta_{32})\Big] \\
&+ \frac{1}{2}\sin(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\Big] \\
&+ (b^2 a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{4\nu})\sin^2\Delta_{21}
\end{aligned}
$$

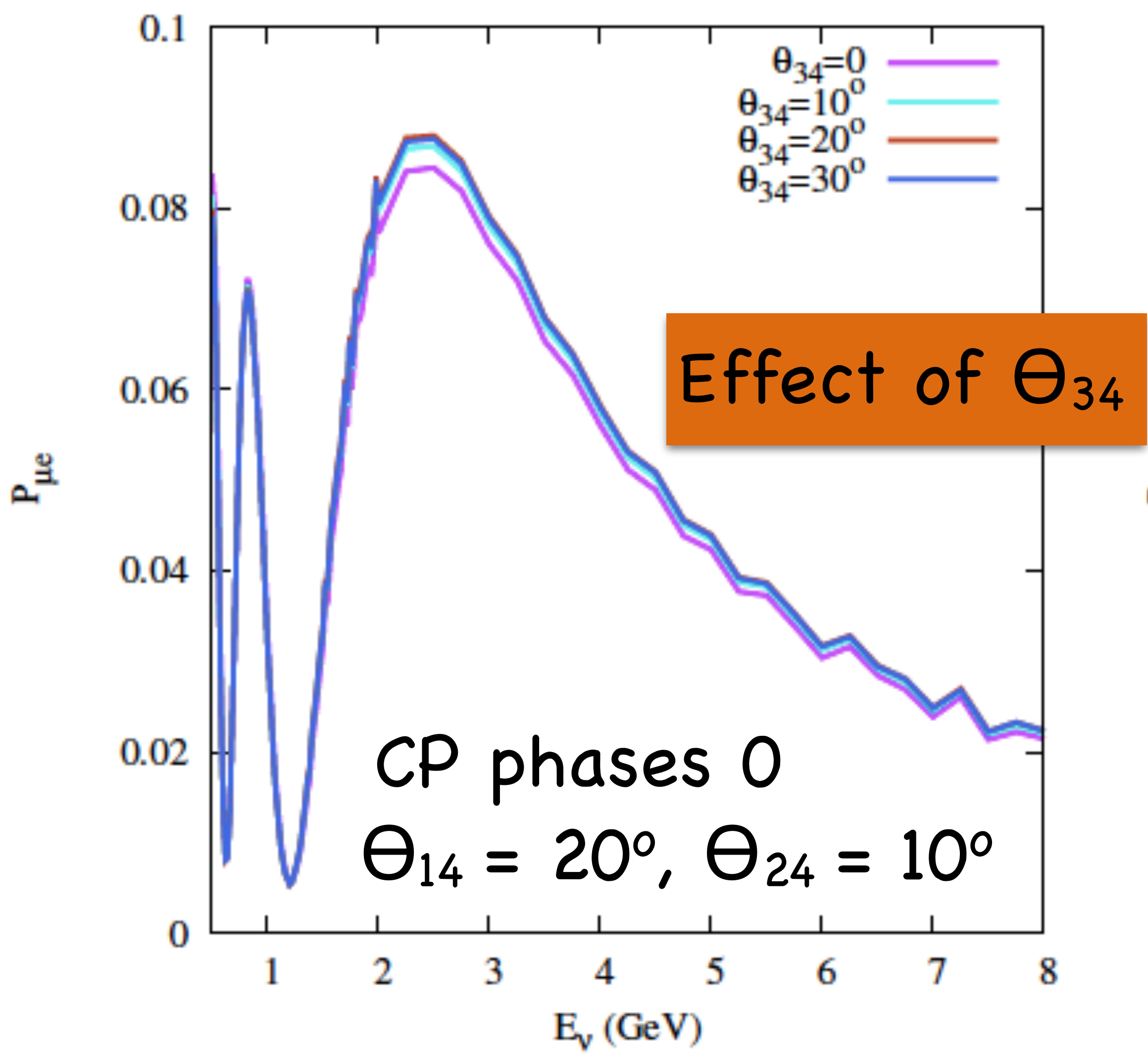
where $\sin 2\theta_{\mu e}^{3\nu} = \sin 2\theta_{13}\sin\theta_{23}$, $b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}$,
$\sin 2\theta_{\mu e}^{4\nu} = \sin 2\theta_{14}\sin\theta_{24}$ and $a = \cos\theta_{14}\cos\theta_{24}$

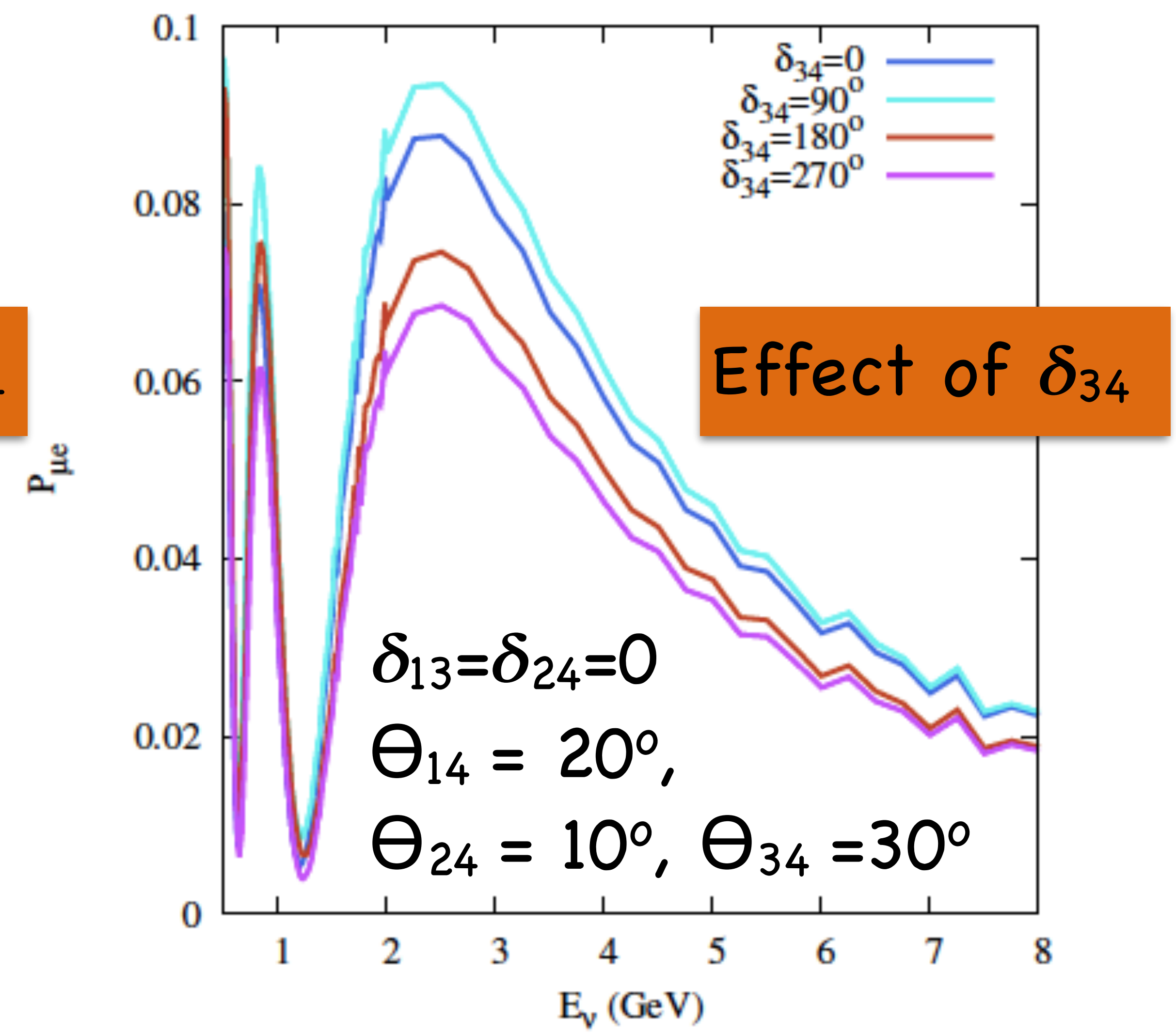
Appearance probability in 3+1 in matter

θ_{34} and δ_{34} which were irrelevant for 3+1 electron appearance in vacuum, play significant roles in the presence of matter.

In producing these plots, we have averaged over the Δm^2_{4i} induced oscillations.

DUNE, L = 1300 km, matter



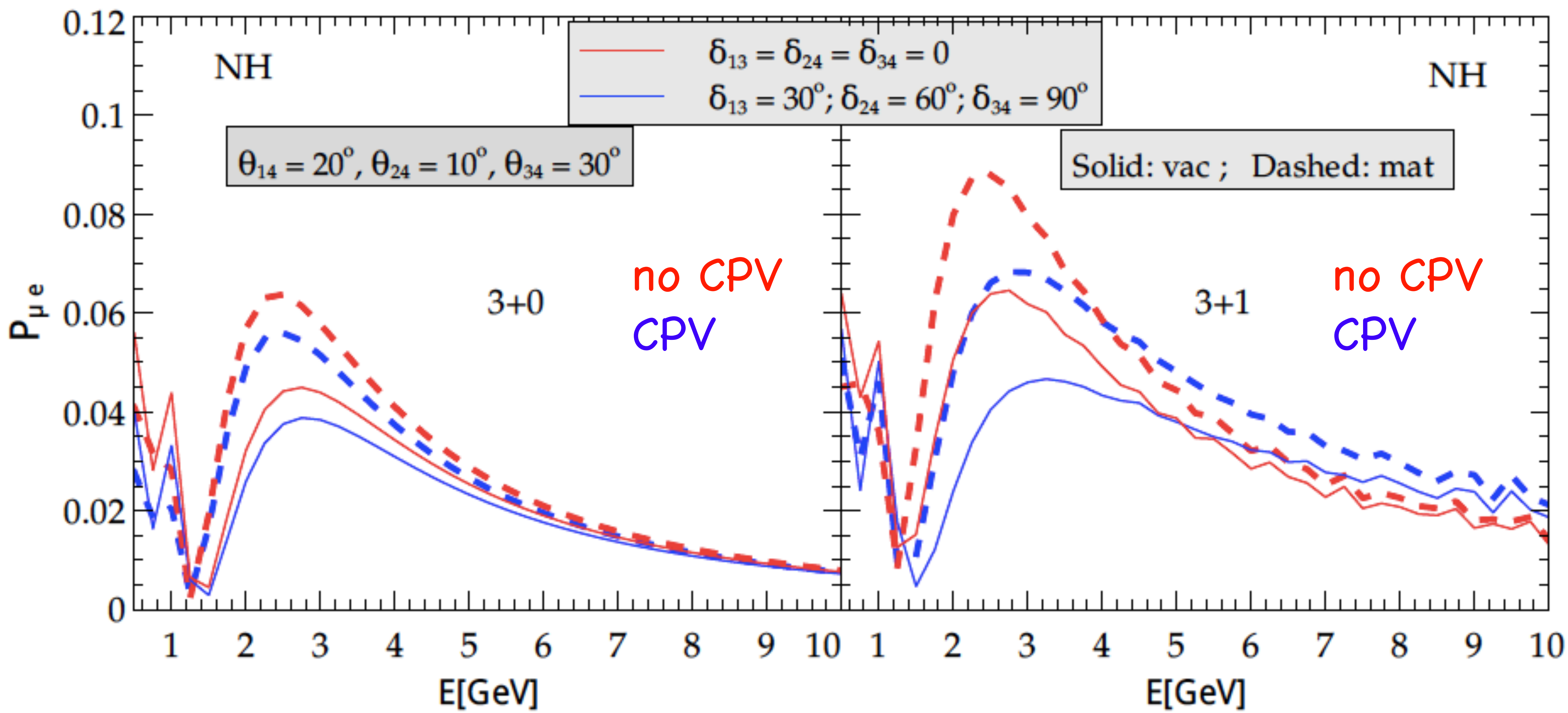


Appearance probability in 3+1 in matter

Left vs. Right - Even at far detector, sterile neutrinos have large effects.

Red vs. Blue - Phases play an important role, more so in 3+1.

Solid vs. Dashed - Matter effects are important, more in 3+1.



Constraints on the active-sterile mixings

We have referred to arXiv:1303.3011, Kopp et. al. to derive constraints on the active-sterile mixings.

We draw constraints on Θ_{14}, Θ_{24}, and Θ_{34} at 95% C.L. sticking to disappearance data only.

We assume the lower limits on the active-sterile mixings to be 0.

ν_e and anti-ν_e disappearance searches probe $|U_{e4}| = \sin\Theta_{14}$.

ν_μ, anti-ν_μ and NC disappearance searches probe $|U_{\mu 4}| = \cos\Theta_{14}\sin\Theta_{24}$ and $|U_{\tau 4}| = \cos\Theta_{14}\cos\Theta_{24}\sin\Theta_{34}$.

We get $\Theta_{14} \in [0,20^o]$, $\Theta_{24} \in [0,10^o]$ and $\Theta_{34} \in [0,30^o]$ => $\sin^2 2\Theta_{\mu e} < 0.012$

(LSND: $\sin^2 2\Theta_{\mu e} < 0.008$)

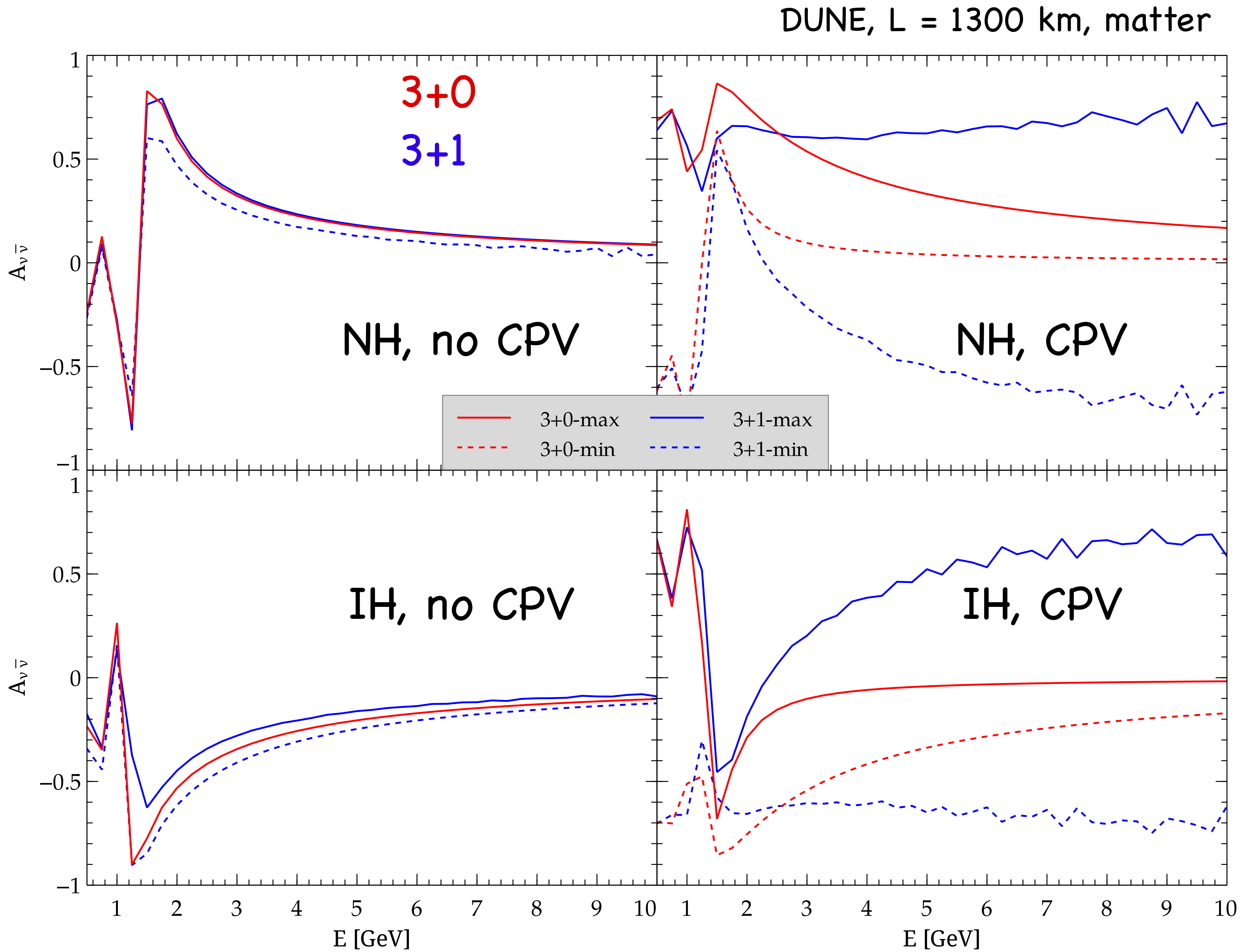
The CP phases remain unconstrained.

CP asymmetries in 3+0 and 3+1

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

If an experiment were to measure asymmetries which consistently lie outside these two bands it would provide evidence of CP violation in either the 3+0 or the 3+1 case.

Asymmetry values measured within these two bands in the left panels do not unambiguously signal a CP conserving situation.

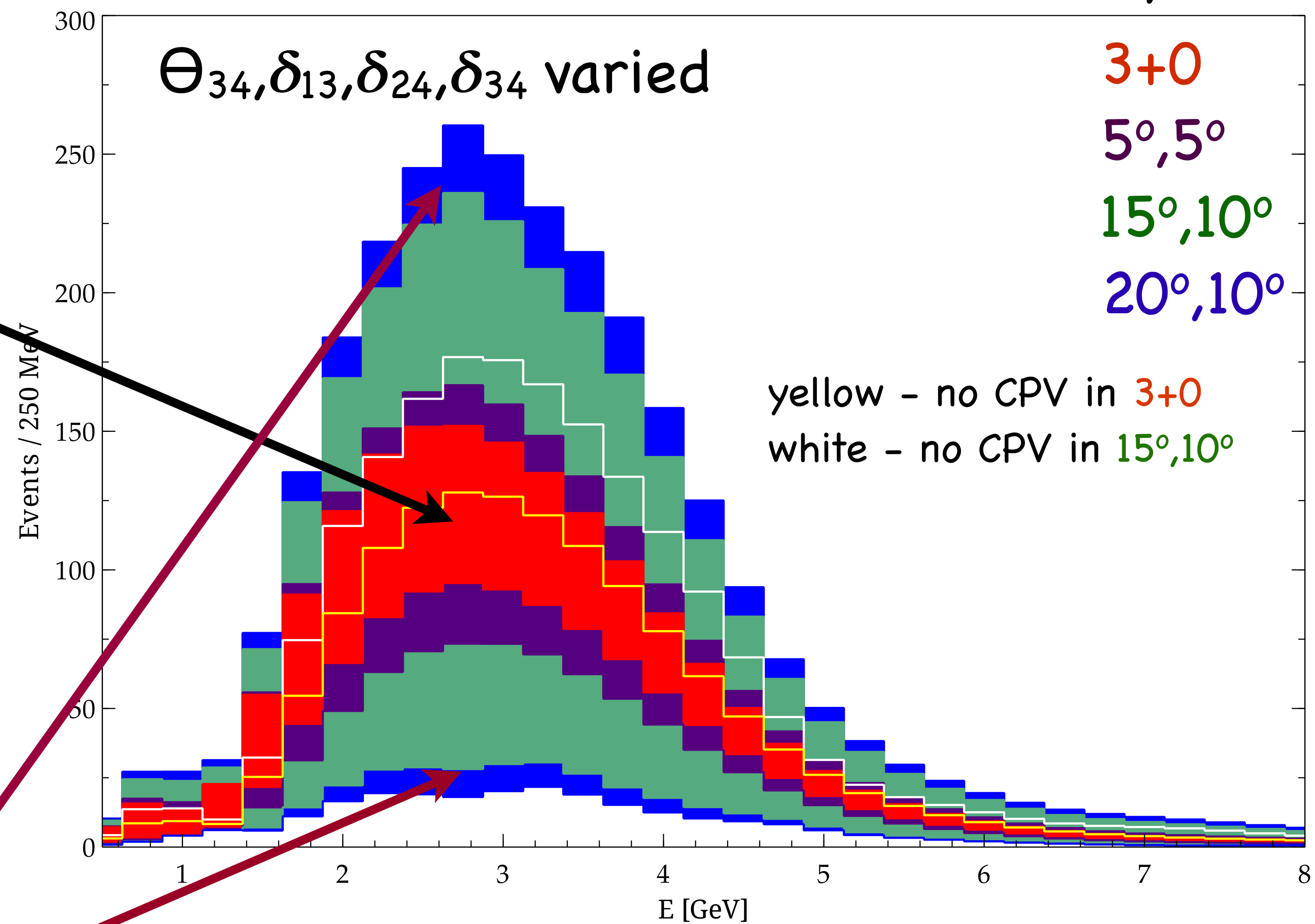


Events rates plots for DUNE

The 3+1 band can potentially encompass the 3+0 band, leading to substantial degeneracy.

For large active-sterile mixings, an excess or shortage of events, esp. at osc. max. will be pointers to the existence of new physics.

DUNE, 1300 km, 35 kt, 5 yrs ν



θ_{12} = 33.48°, θ_{13} = 8.5°, θ_{23} = 45°

Δm^2_{31} = +2.457e-3 eV^2, Δm^2_{21} = 7.5e-5 eV^2

Similar features are observed in the case of IH / anti-nu events

Reassessing CP sensitivities

We assume the standard DUNE setup (arXiv:1311.0212, Bass et. al.) and use GLoBES for carrying out simulations.

We compare CP sensitivities of the DUNE experiment for the 3+0 and 3+1 case.

For 3+1, we simulate data for 4 set of active sterile-mixings and show results as a function of δ_{13}, δ_{24} and δ_{34}. In the fit, we marginalise over the allowed ranges of all sterile oscillation parameters. The standard oscillation parameters were held fixed.

For 3+0, its a question of exclusion of CP-conserving values. For 3+1, its asking whether the experiment will be able to reject δ_{13} = 0, 180^o for a given true δ_{13}.

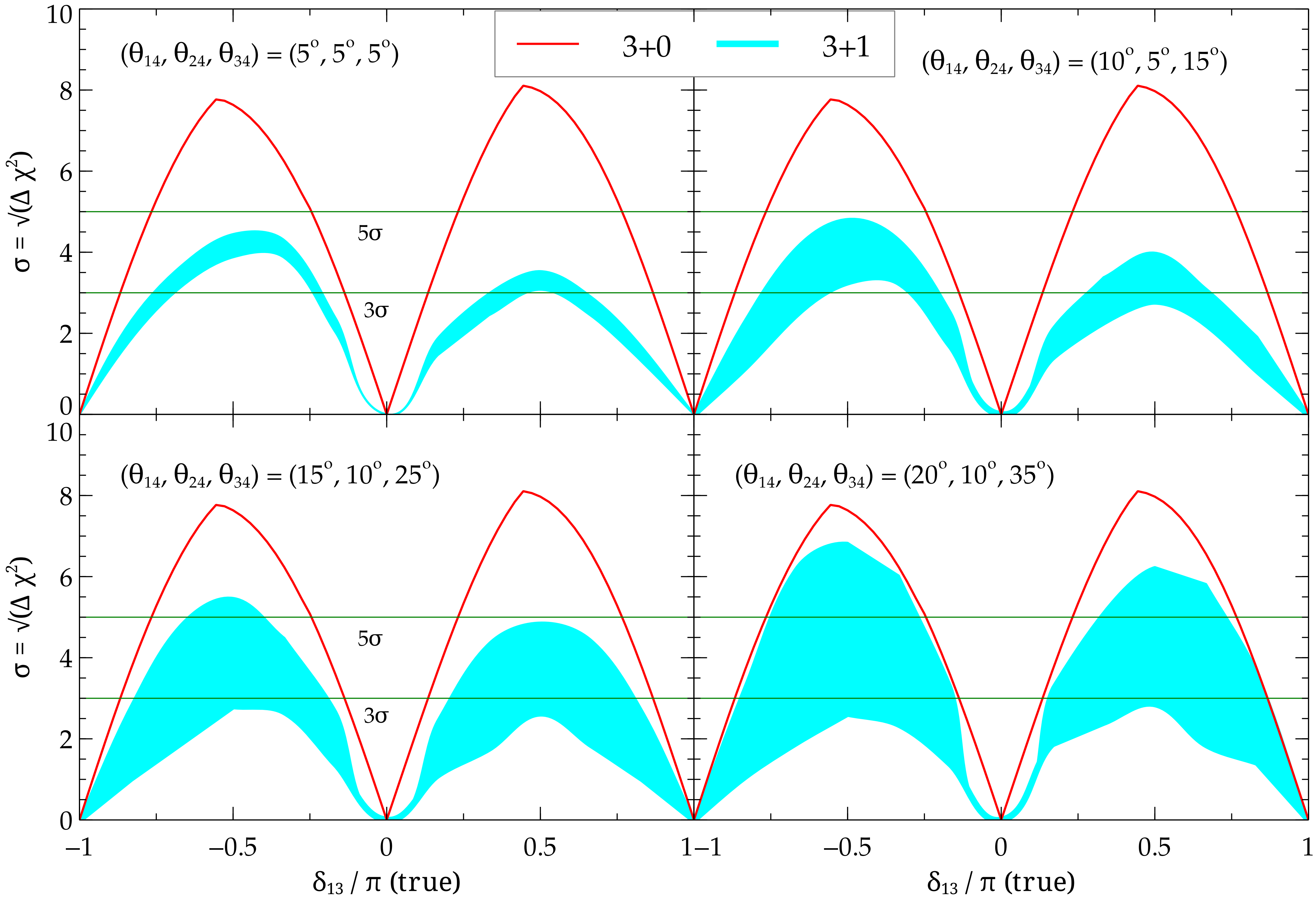
Note that, in 3+0, $\Delta P_{\alpha\beta}$ is the same across all channels. This is not the case in 3+1.

Reassessing CP sensitivities PRELIMINARY

Cyan band - variation of true δ_{24} and δ_{34}

DUNE, 1300 km, 35 kt, 5+5

1% signal norm. error & 5% back norm. error



$\Theta_{12} = 33.48^o$, $\Theta_{13} = 8.5^o$, $\Theta_{23} = 45^o$

$\Delta m^2_{31} = +2.457e\text{-}3\ eV^2$, $\Delta m^2_{21} = 7.5e\text{-}5\ eV^2$

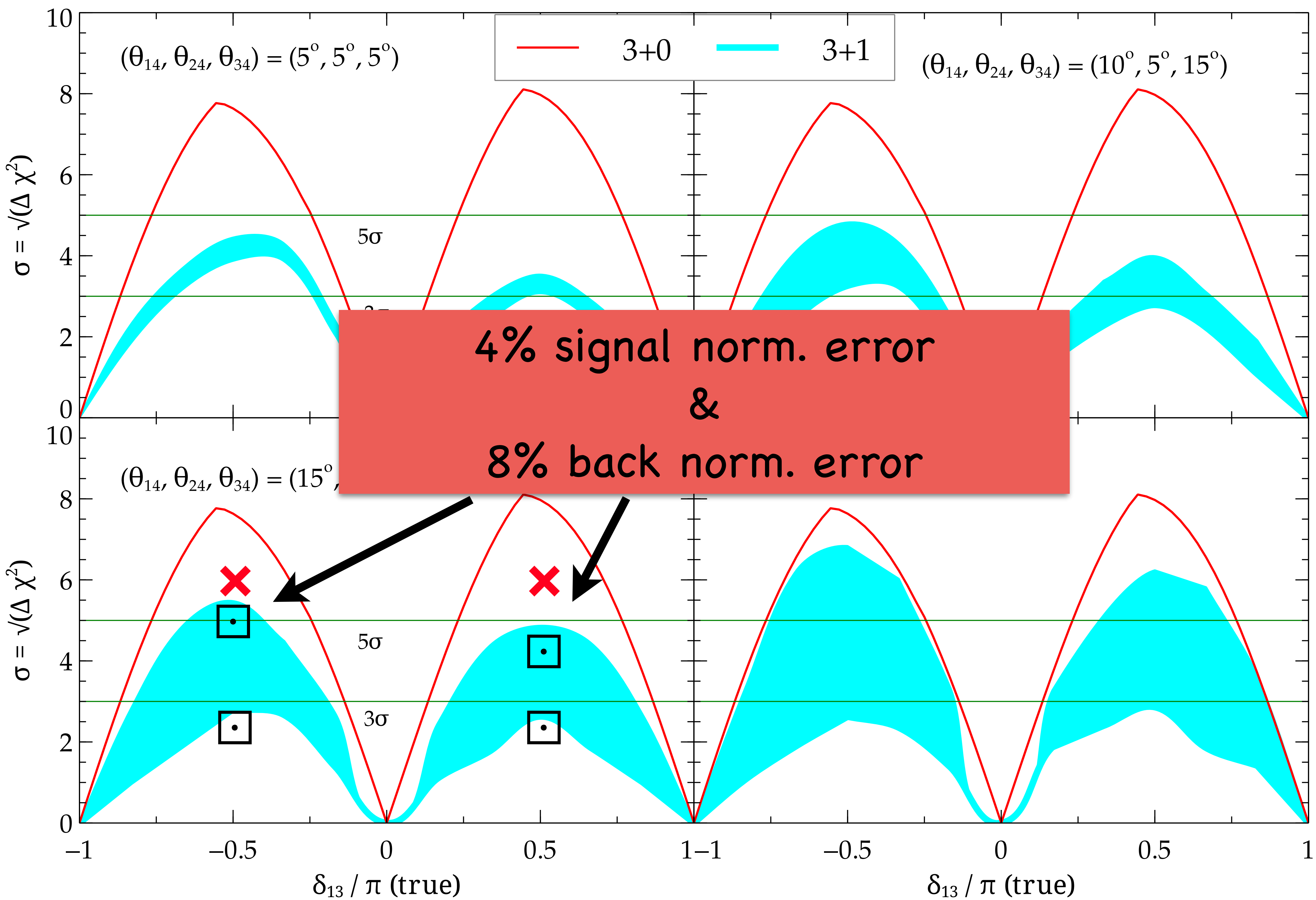
Reassessing CP sensitivities

PRELIMINARY

Cyan band - variation of true δ_{24} and δ_{34}

DUNE, 1300 km, 35 kt, 5+5

1% signal norm. error & 5% back norm. error



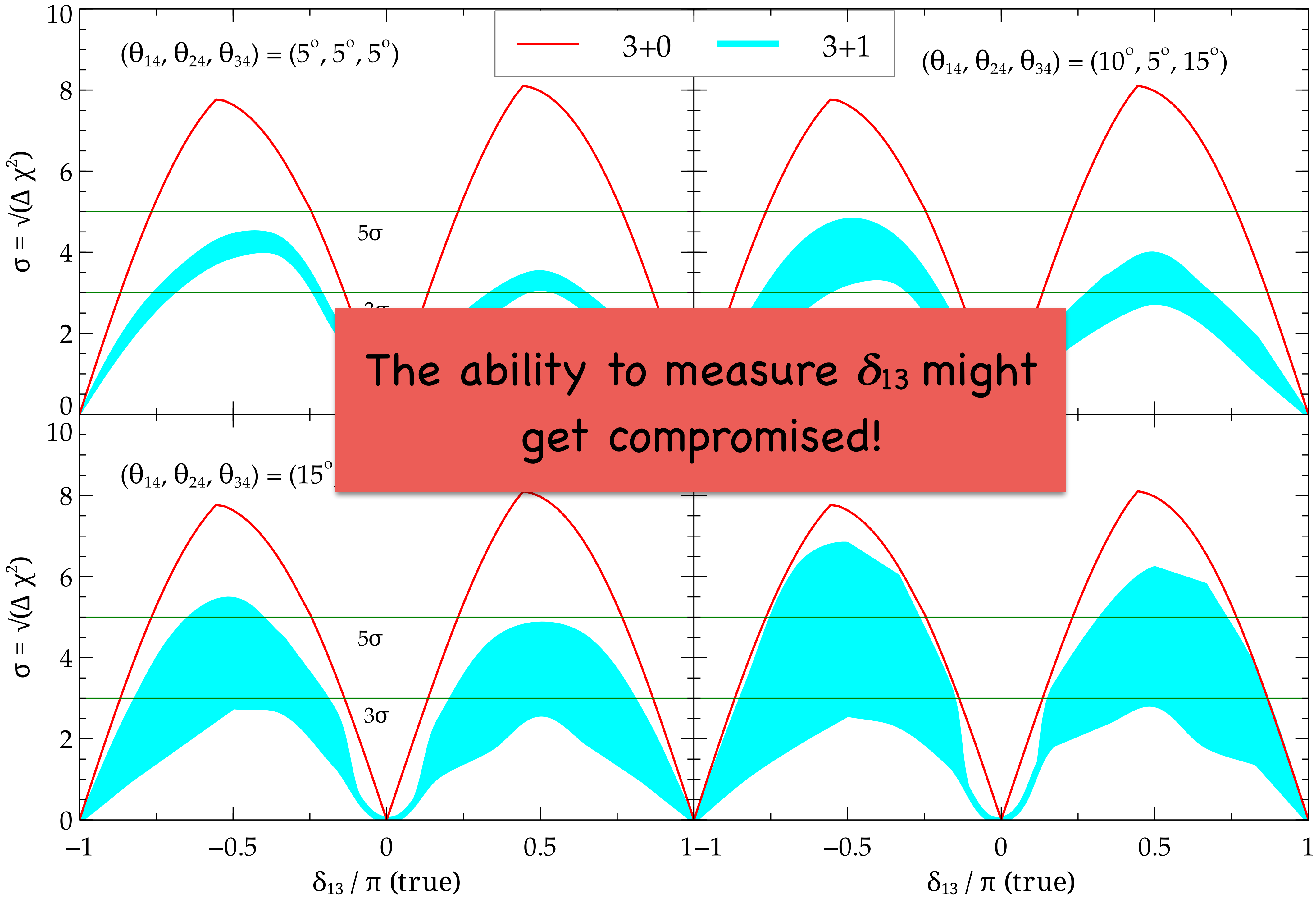
Θ_{12} = 33.48°, Θ_{13} = 8.5°, Θ_{23} = 45° Δm^2_{31} = +2.457e-3 eV^2, Δm^2_{21} = 7.5e-5 eV^2

Reassessing CP sensitivities PRELIMINARY

Cyan band - variation of true δ_{24} and δ_{34}

DUNE, 1300 km, 35 kt, 5+5

1% signal norm. error & 5% back norm. error



The ability to measure δ_{13} might get compromised!

Θ_{12} = 33.48°, Θ_{13} = 8.5°, Θ_{23} = 45° Δm^2_{31} = +2.457e-3 eV², Δm^2_{21} = 7.5e-5 eV²

Implications & Conclusions

From a probability analysis, we show that the effects of the sterile oscillation parameters can be large at the chosen baseline of 1300 km.

From event rate calculations, we show that the presence of a sterile sector manifests itself in measurably altered rates in energy bins across the spectrum.

We have noted above that in the presence of even a single sterile neutrino, conclusions such as a) CP is conserved or violated, or, 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.

A precise knowledge of the source fluxes, relevant cross-sections and the reduction of systematic errors by a near detector assumes an even more crucial role than it did before.

Synergistic linkage between global LBL and SBL efforts.

Thank you!