Sterile Neutrinos Introduction and Long Baseline Impact

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Sterile Neutrino

One that does not experience any of the known forces of nature except gravity.

There could be sterile neutrinos at any mass scale.

The most straightforward version of ***Leptogenesis***, an outgrowth of the See-Saw mechanism, explains the baryon asymmetry of the universe in terms of the early-universe decays of very heavy sterile neutrinos ***N***.

This see-saw model leads to $M_\nu \sim \dfrac{v^2 y^2}{M_N}$.

(SM Higgs vev → v; Yukawa coupling → y; Light neutrino → M_ν)

This relation, the light ν masses, and the $y^2 \sim 10^{-5}$ called for by the observed cosmic baryon asymmetry,

⇒ $M_N \gtrsim 10^{(9-10)}$ GeV.

So how do we prove that the heavy sterile neutrinos N exist?

Leptogenesis with sterile neutrinos light enough to be experimentally accessible, say at CERN, has been explored. For example —

Baryogenesis via Neutrino Oscillations

(Akhmedov, Rubakov, Smirnov)

So, are there GeV-scale sterile neutrinos?

One can seek such neutrinos at the SPS with ***SHiP***.

The physics of these ***GeV-scale sterile neutrinos*** will be discussed by Jordi Salvado.

(Hernandez, Kekic, Lopez-Pavon, Racker, Rius, Salvado)

Are there MeV-scale sterile neutrinos?

MeV-scale sterile neutrinos would not lead to observable oscillations. At the nearest detector of the Short Baseline Neutrino program (SBN) at Fermilab, a 1 MeV neutrino would lead to —

$$\sin^2\left[\underbrace{1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}}_{10^{11}}\right]$$

But MeV-scale sterile neutrinos N light enough to be produced in pion and kaon decays can be sought by looking for their decays, such as $N \to \ell^{\mp}\pi^{\pm}$ and $N \to \nu\gamma$.

This will be discussed by Peter Ballett.

(Ballett, Pascoli, Ross-Lonergan)

Are there keV-scale sterile neutrinos?

These are candidates for the Dark Matter. A possible 3.5 keV X-ray emission line could be from their EM decays.
(Dodelson, Widrow; Cappelluti et. al.)

Are there eV-scale sterile neutrinos?

The anomalies suggesting that they may exist have been discussed by Carlo Giunti.

Their consequences, should they be real, for Long-Baseline (LBL) experiments will be discussed in this talk.

Are there meV-scale sterile neutrinos?

DUNE's ability to exclude them has been analyzed by Berryman, de Gouvea, Kelly, Kobach.

Sterile Neutrinos and the Long Baseline Experiments

Major goals of the long-baseline neutrino experiments

- ***Establish, or bound, CP violation in neutrino oscillation***
- ***Determine the neutrino mass ordering***

If the eV-scale sterile neutrinos hinted at by the short-baseline anomalies are real, how is the pursuit of these goals at long-baseline affected?

What can the LBL experiments tell us about the sterile neutrinos?

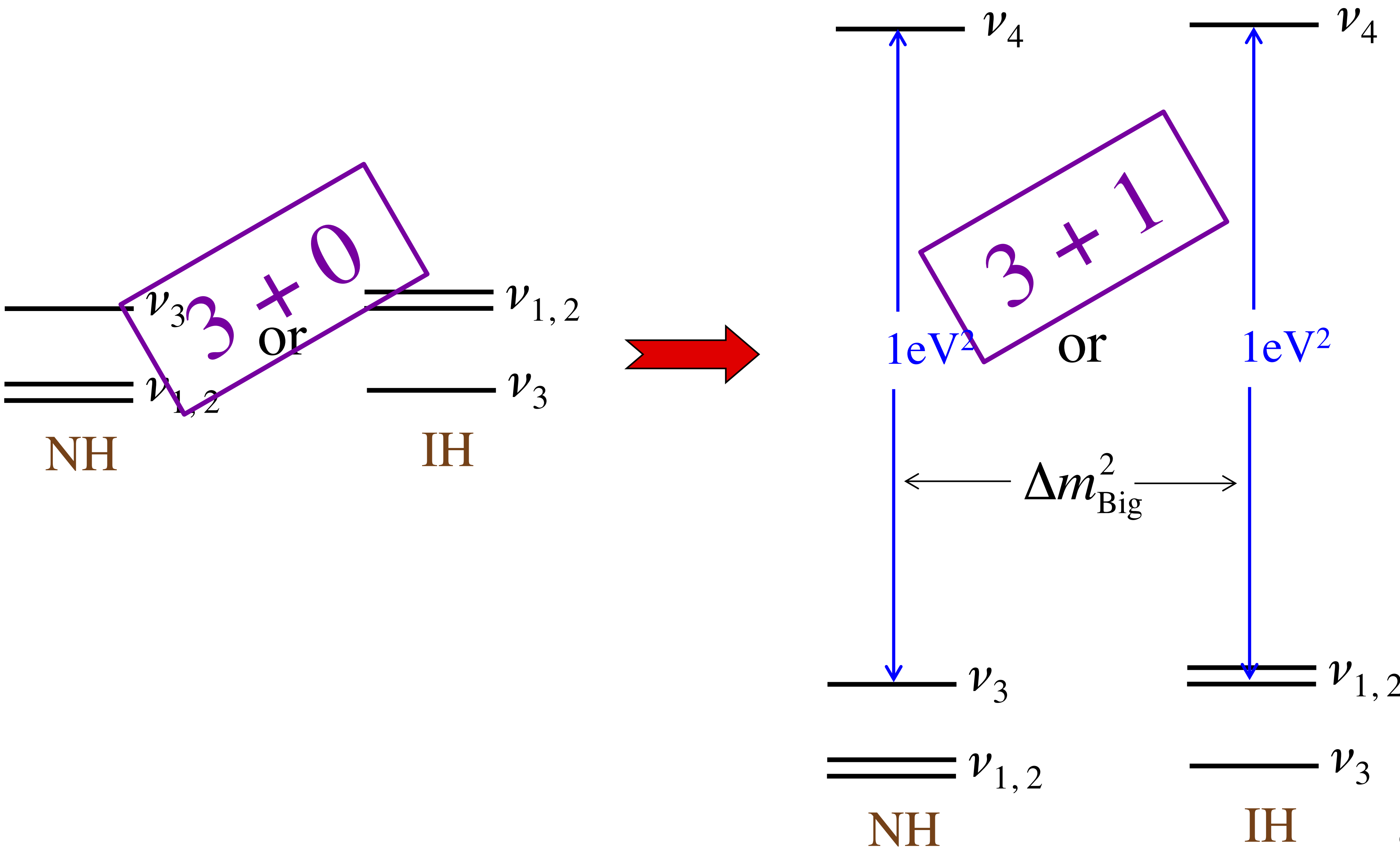
Focus owing to familiarity on work by —

Gandhi, B. K., Masud, Prakash	1508.06275
Dutta, Gandhi, B. K., Masud, Prakash	1607.02152

Related work —

Hollander, Mocioiu	1408.1749
Klop, Palazzo	1412.7524
Berryman, de Gouvêa, Kelly, Kobach	1507.03986
Agarwalla, Chatterjee, Dasgupta, Palazzo	1601.05995
Agarwalla, Chatterjee, Palazzo	1603.03759
Capozzi, Giunti, Laveder, Palazzo	1612.07764

To get a feeling for the LBL consequences of extra, mostly sterile, neutrino mass eigenstates, we assume that there is just 1 of them, so that —



In the 3 + 1 model, the mixing matrix U^{3+1} is a 4 x 4 unitary matrix. It contains 6 mixing angles, and **3** oscillation-relevant CP-violating phases.

Possible Effect of the Extra Degrees of Freedom

If there are more than 3 neutrino mass eigenstates, it is possible for CP to be violated in ***some*** oscillations, even if not violated in $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$.

The only channel to be studied for some time to come.

This is impossible when there are only 3 mass eigenstates.

CP Violation When There Are Only Three Neutrinos

Let $P\left[\nu_\alpha \rightarrow \nu_\beta\right] - P\left[\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta\right] \equiv \Delta_{\alpha\beta}$ be a CP-violating $\nu - \bar{\nu}$ difference in vacuum.

Assuming CPT invariance, when there are only 3 neutrino flavors, there are only 3 independent CP-violating differences $\Delta_{\alpha\beta}$ to be measured: $\Delta_{e\mu}$, $\Delta_{\mu\tau}$, and $\Delta_{\tau e}$.

Probability conservation and CPT invariance

$$\Rightarrow \quad \Delta_{e\mu} = \Delta_{\mu\tau} = \Delta_{\tau e} \ .$$

CP Violation When There Are Four Neutrinos

Assuming CPT invariance, when there are 4 neutrino flavors, there are 6 independent CP-violating differences $\Delta_{\alpha\beta}$:

$\Delta_{e\mu}$, $\Delta_{\mu\tau}$, $\Delta_{\tau e}$, Δ_{es}, $\Delta_{\mu s}$, and $\Delta_{\tau s}$.

Sterile flavor

Probability conservation and CPT invariance

$$\Rightarrow \quad \Delta_{e\mu} = \Delta_{\mu\tau} + \Delta_{\mu s} \text{ , etc.}$$

The CP-violating differences $\Delta_{\alpha\beta}$ in different active-to-active oscillations can now differ.

DUNE (L = 1300 km) As An Illustration Of Possible Impacts On LBL Experiments

We consider the processes DUNE will compare to seek CP violation: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

Can we tell whether CP is violated or not?
That is, whether CP violation in $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ is substantial or at most very small?

To explore this question, we look at the ***asymmetry***

$$A(\nu - \bar{\nu}) \equiv \frac{\left[P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\right]}{\left[P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\right]}$$

We write the 4 x 4 mixing matrix U^{3+1} in the form —

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

Here, $O(\theta_{34},\delta_{34})$ is a 2-dimensional rotation in the 34 subspace through an angle θ_{34}, and with a phase δ_{34}.

The new mixing angles are taken to be in the ranges —

$$0^\circ \le \theta_{14} \le 20^\circ, \quad 0^\circ \le \theta_{24} \le 10^\circ, \quad 0^\circ \le \theta_{34} \le 30^\circ$$

(Disappearance constraints from Kopp, Machado, Maltoni, and Schwetz)

{We update, tighten the constraints later.}

We vary the CP-violating phases δ_{13}, δ_{24}, and δ_{34} from $-\pi$ to $+\pi$.

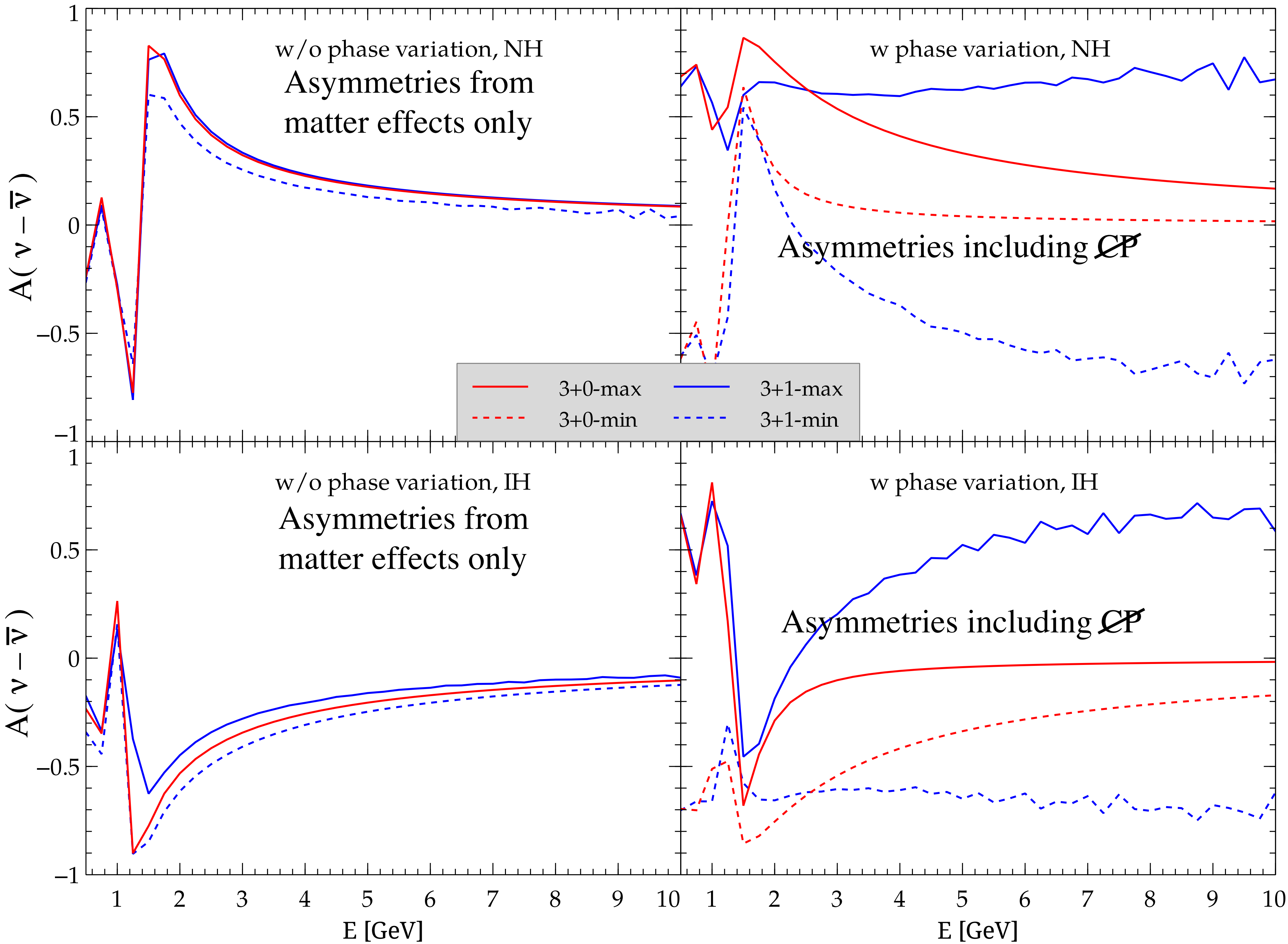
We take the "established" parameters to be —

$$\left|\Delta m_{31}^2\right| \cong 2.4 \times 10^{-3}\,\mathrm{eV}^2 \qquad \Delta m_{21}^2 = 7.5 \times 10^{-5}\,\mathrm{eV}^2$$

$$\theta_{12} = 33.5^\circ, \theta_{13} = 8.5^\circ, \theta_{23} = 45^\circ$$

(Guided by Gonzalez-Garcia, Maltoni, and Schwetz)

For purposes of illustration, we take $\Delta m_{\mathrm{Big}}^2 = 1\,\mathrm{eV}^2$.


w/o phase variation, NH
Asymmetries from matter effects only
w phase variation, NH
Asymmetries including CP̸
3+0-max
3+1-max
3+0-min
3+1-min
w/o phase variation, IH
Asymmetries from matter effects only
w phase variation, IH
Asymmetries including CP̸
A(ν − ν̄)
E [GeV]

Why 3+0 and 3+1 lead to potentially very different ~~CP~~

~~CP~~ phases occur in interference terms.

Around the first atmospheric oscillation maximum, where the LBL experiments work, the (very short wavelength oscillation) – (atmospheric wavelength oscillation) interference, and the (atmospheric wavelength oscillation – solar wavelength oscillation) interference can easily be comparable in size.

Then if the phases are right,
3+1 can be quite different from 3+0.

(Klop and Palazzo)

Exploration of What DUNE Can Do

The tightened mixing angles are taken to be in the ranges —

$$0° \leq \theta_{14} \leq 13°, \quad 0° \leq \theta_{24} \leq 7°, \quad 0° \leq \theta_{34} \leq 26°$$

(Constraints from Daya Bay, IceCube, and MINOS)

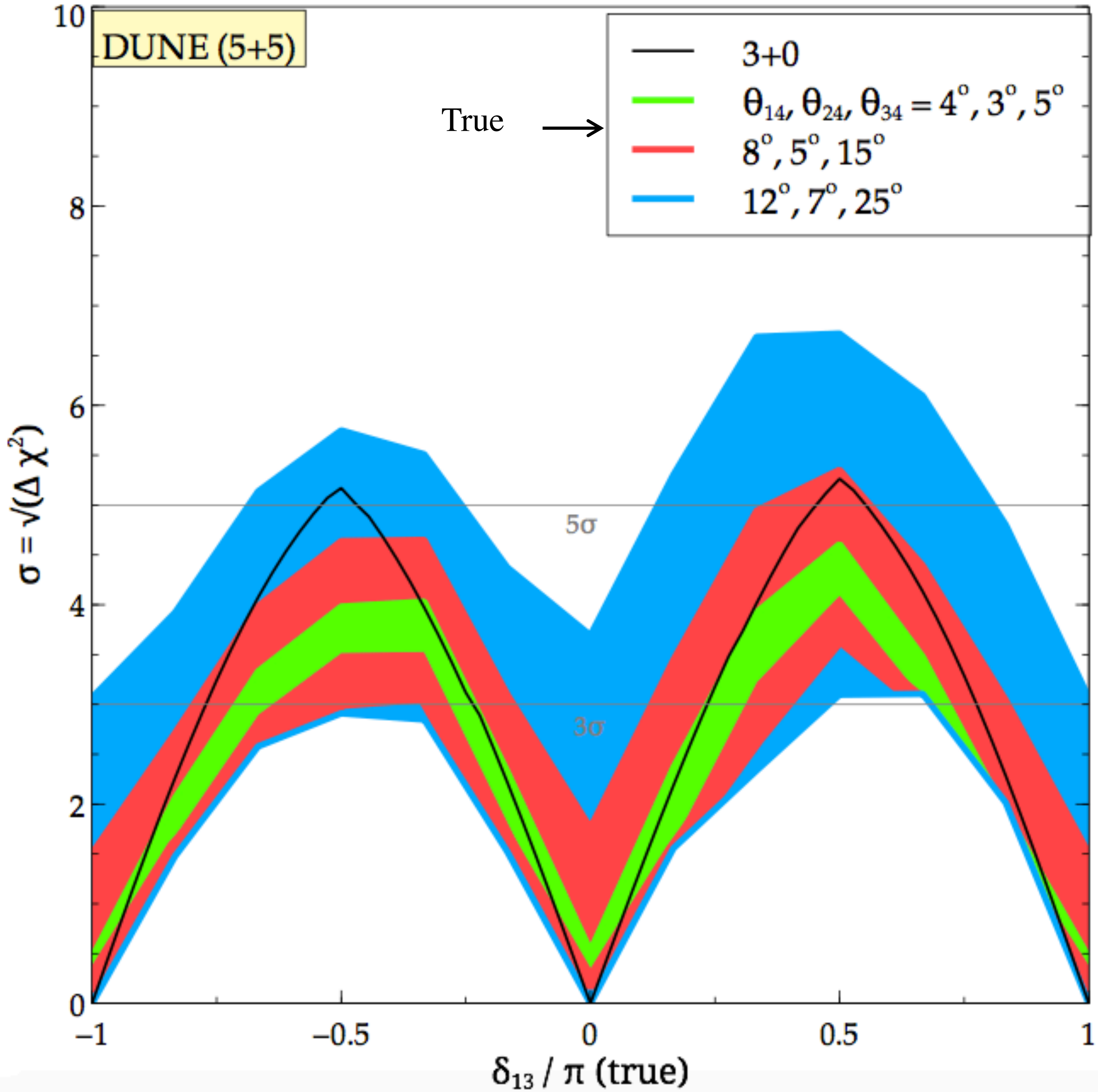
We use the **General Long Baseline Experiment Simulator GLoBES** to generate simulated long-baseline event rates.

We assume a 35 x 10^{22} kton-POT-yr total exposure, divided evenly between neutrinos and antineutrinos, a 5% signal normalization error, and other features of the experiment from Bass et al., 1311.0212.

DUNE sensitivity to ~~CP~~

Mass hierachy assumed known to be normal.

$\theta_{14}, \theta_{24}, \theta_{34}$ assumed unknown.

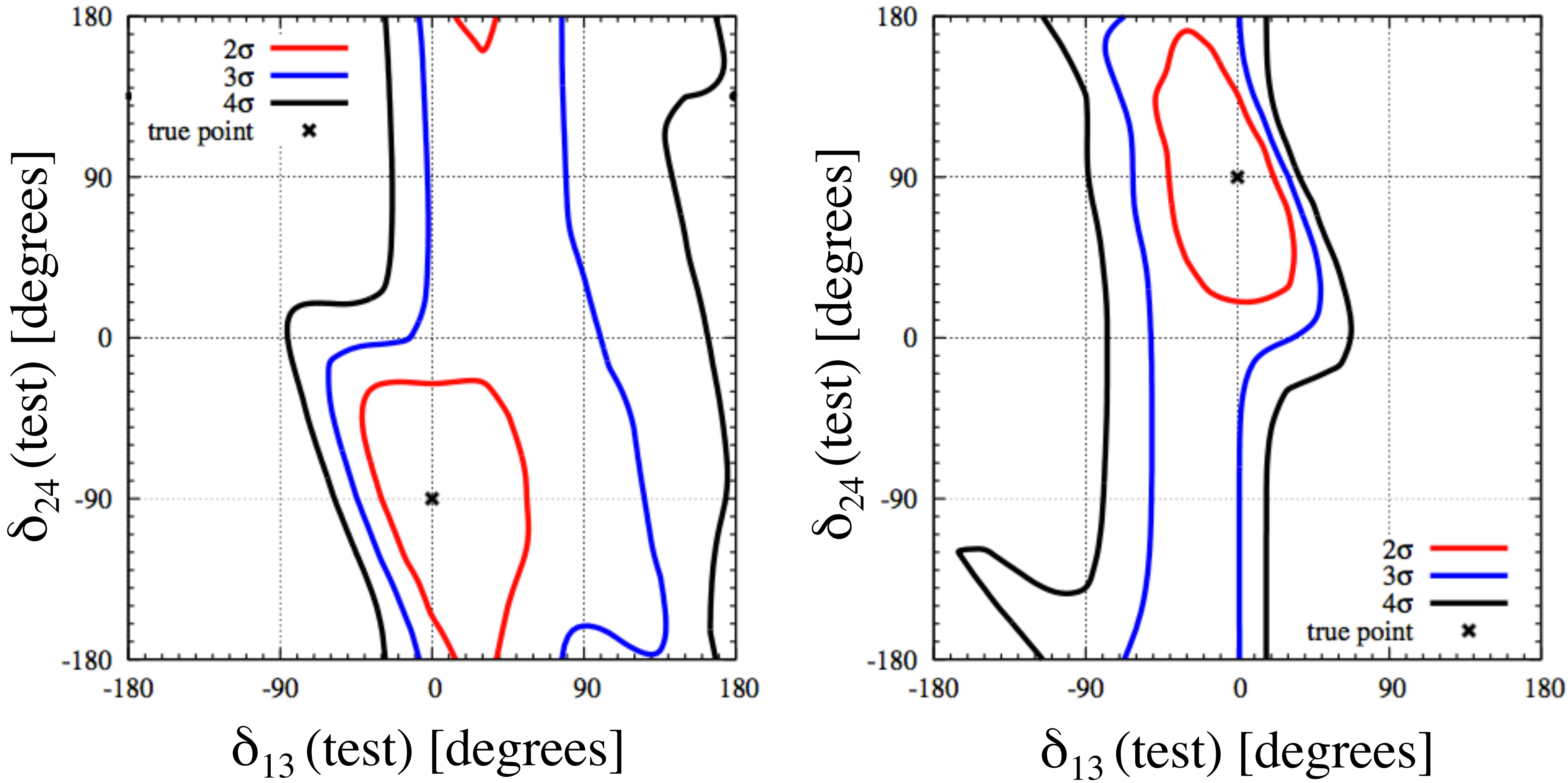


When the true sterile-active mixing angles are nonzero but small, the ability to establish $\not{CP}$ is reduced, because one has more unknown parameters with which to fit any data.

When the true sterile-active mixing angles are larger, the extra $\not{CP}$ phases can lead to more $\not{CP}$, and hence more ability to establish $\not{CP}$.

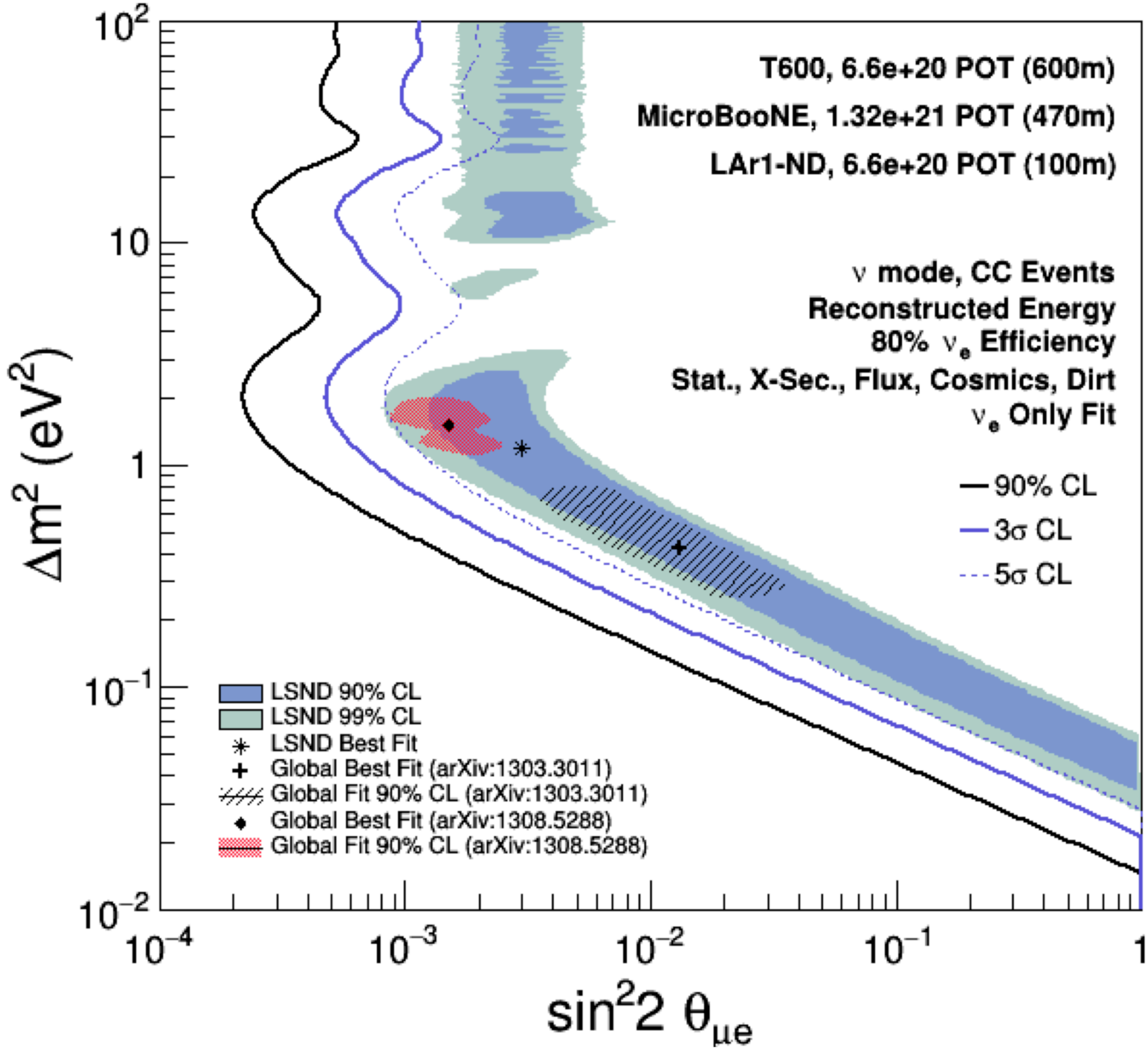
In 3+1, there can be $\not{CP}$ even when the 3+0 phase $\delta_{13} = 0$.

DUNE May Not Be Able To Tell Which Phase(s) Cause An Observed ~~CP~~

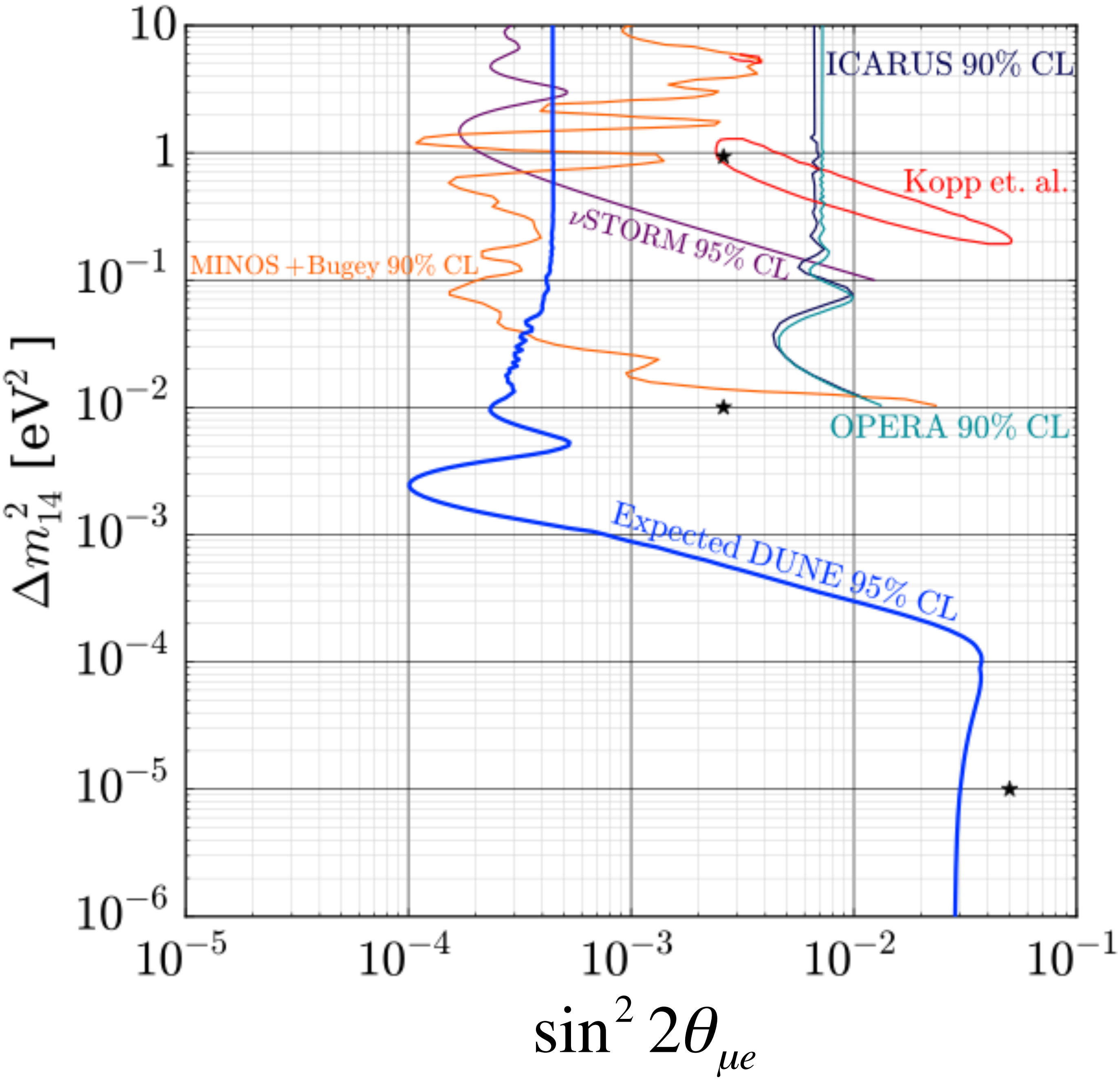


True $(\theta_{14}, \theta_{24}, \theta_{34}, \delta_{34}) = (12^\circ, 7^\circ, 25^\circ, 0^\circ)$

What SBN Can Do To Exclude 3 + 1



What DUNE Can Do To Exclude 3 + 1

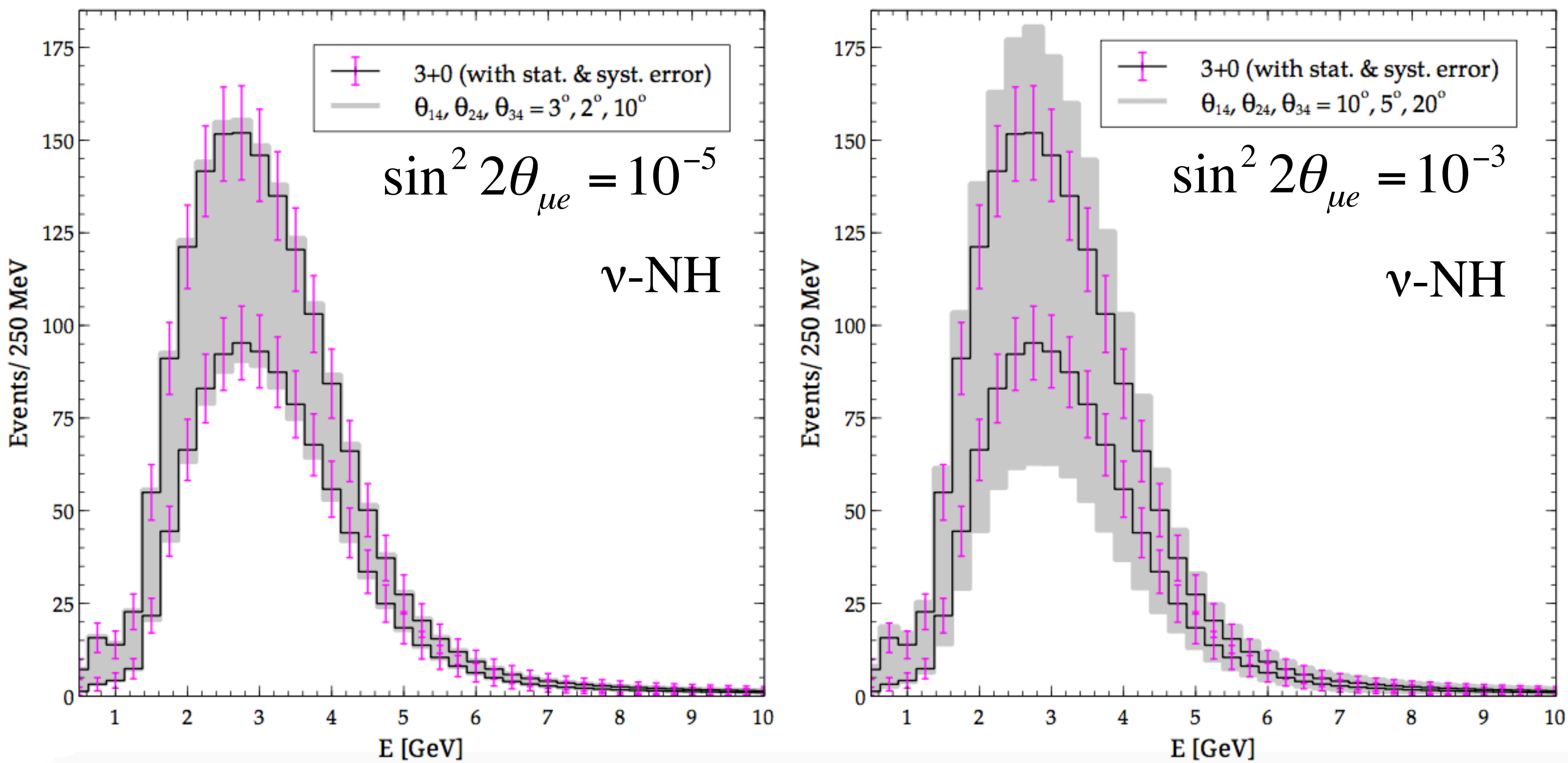


Assumes
3 yrs ν + 3 yrs $\bar{\nu}$
running

Berryman,
de Gouvêa,
Kelly,
Kobach

Event-Rate Probe Of DUNE Sensitivity To 3+1

Error bars include statistical and estimated 2% systematic error



Summary

Sterile neutrinos should be sought at a great variety of mass scales.

1 eV scale sterile neutrinos could play a significant role in LBL experiments.

Questions For Discussion

What is the theoretical motivation for sterile neutrinos at the various mass scales?

If the SBL program sees no evidence for sterile neutrinos, how stringently should/must it constrain their possible existence, and why?

What are good/best ways to probe the existence and properties of sterile neutrinos at SBL and LBL?
Different LBL baselines and energies?
Different flavor channels?
Roles for reactor and naturally-produced neutrinos?