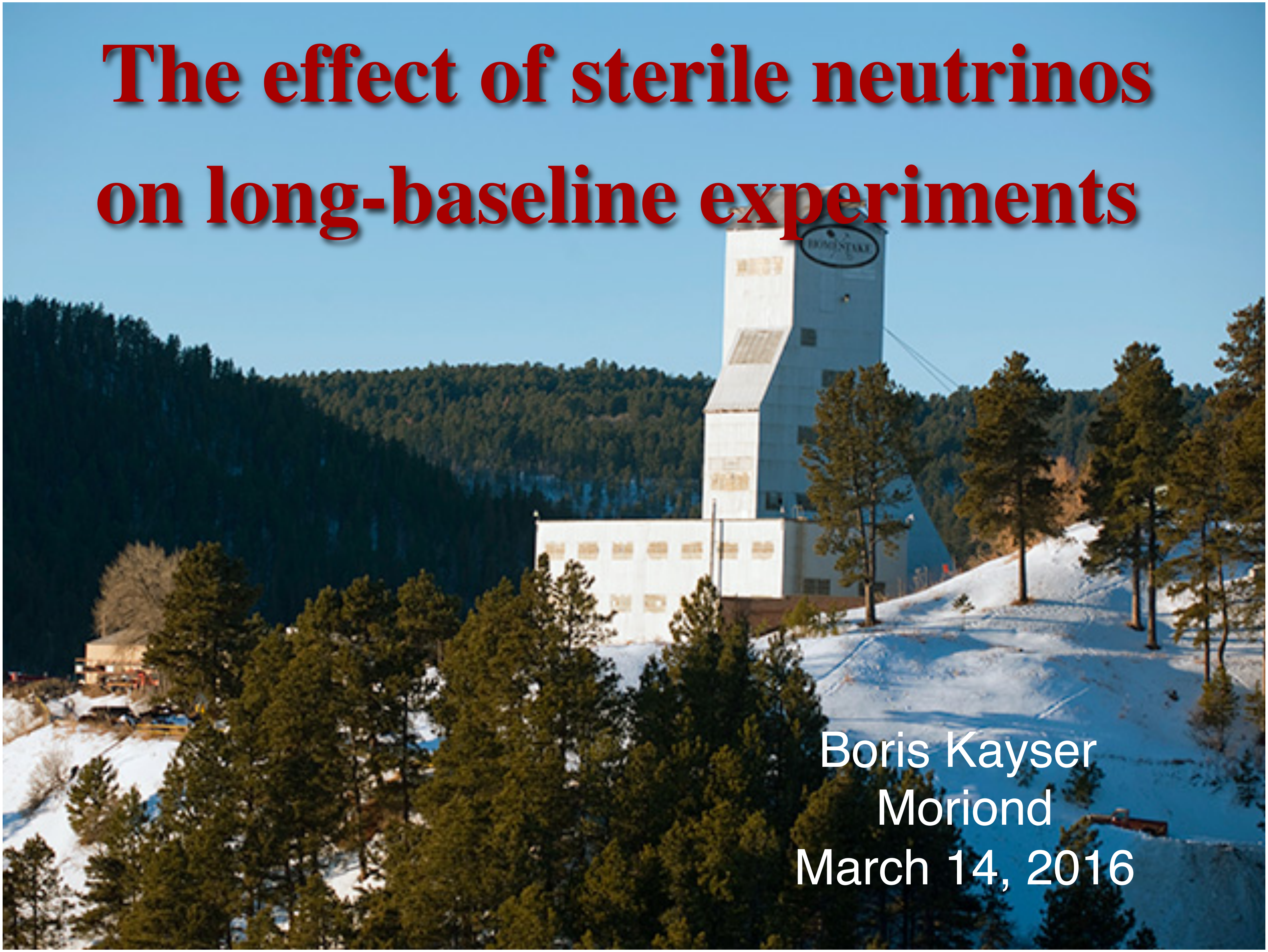
The effect of sterile neutrinos on long-baseline experiments



Boris Kayser
Moriond
March 14, 2016

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

If CP violation is found, one would like to measure the CP-violating phase(s).

Our thinking usually assumes the standard neutrino paradigm, which contains just 3 neutrino mass eigenstates, and just 1 (oscillation-relevant) CP-violating phase.

But a variety of short-baseline anomalies hint at the existence of short-wavelength ($L/E \sim 1$ km/GeV) oscillations, driven by splittings $\Delta m^2 \sim 1$ eV^2.

These large splittings imply additional neutrino mass eigenstates, beyond 3, that are largely sterile.

Sterile Neutrino

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

What are the consequences of the additional mass eigenstates and associated new degrees of freedom, if genuine, for CP-violation studies at long baselines, especially by the DUNE experiment?

R. Gandhi, B. K., M. Masud, and S. Prakash
arXiv:1508.06275; JHEP 1511(2015)039

The above plus Debajyoti Dutta: Work in progress

Related work focusing on sensitivity to sterile states—

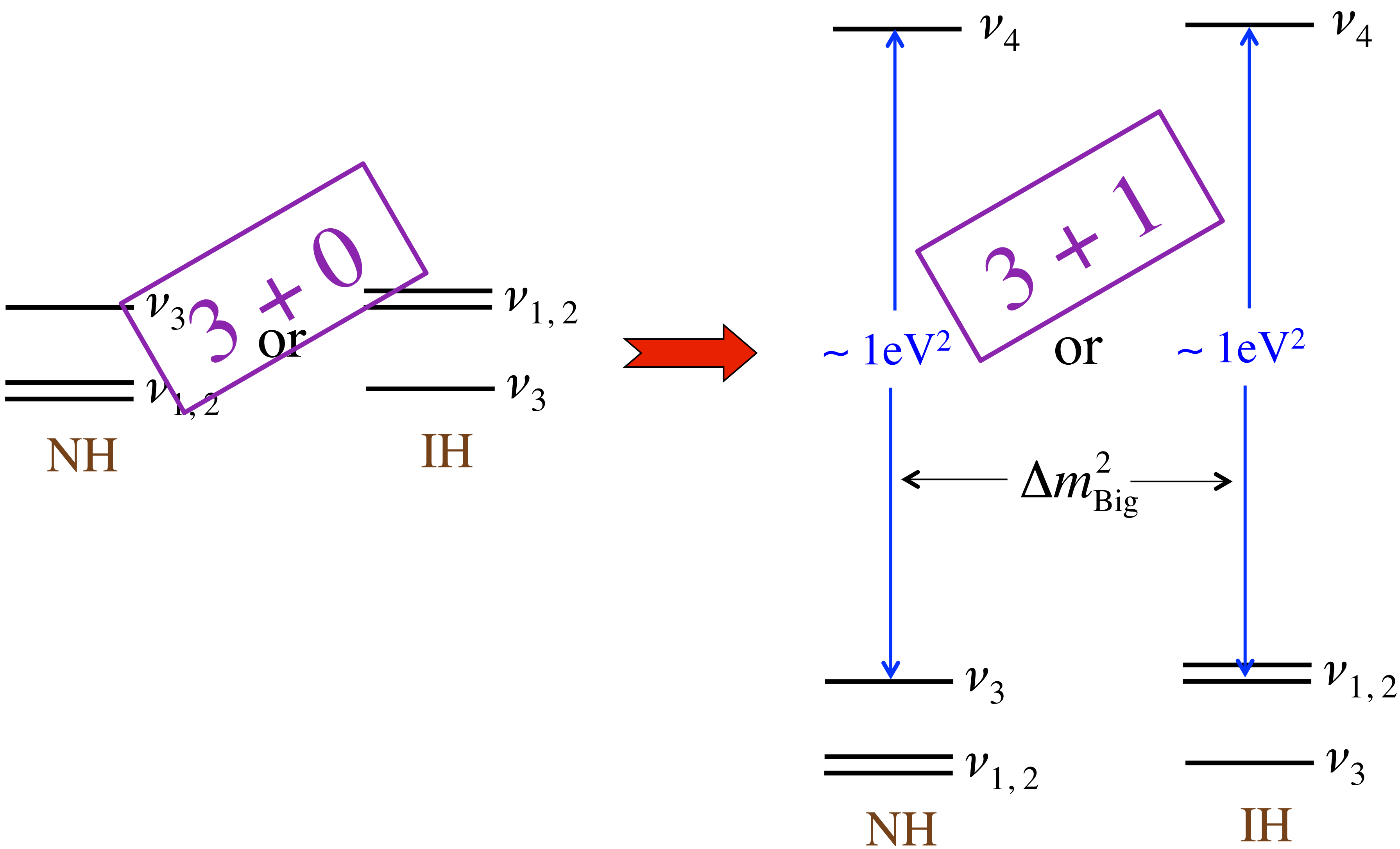
N. Klop and A. Palazzo

D. Hollander and I. Mocioiu

J. Berryman, A. de Gouvêa, K. Kelly, and A. Kobach

S. Agarwalla, S. Chatterjee, A. Dasgupta, and A. Palazzo

To get a feeling for the consequences, we assume that there is just 1 extra mass eigenstate, 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 $\Delta_{\alpha\beta}$:

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

Physics At L = 1300 km (DUNE)

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 $\overset{(-)}{\nu}_\mu \longrightarrow \overset{(-)}{\nu}_e$
is substantial or at most very small?

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

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

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

We take the "established" parameters to be —

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

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

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

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

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

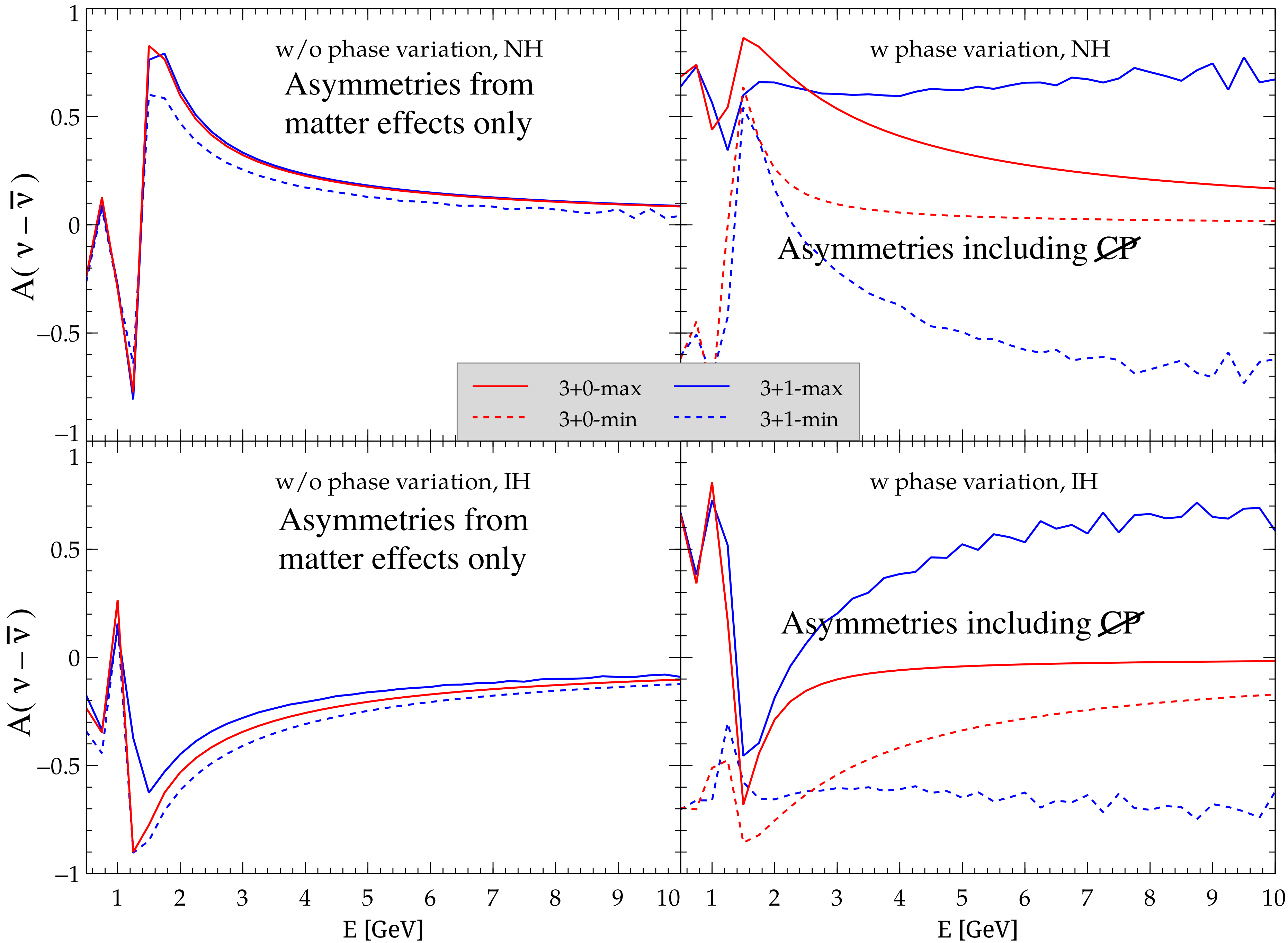
$$U^{3+1} = O(\theta_{34},\delta_{34})O(\theta_{24},\delta_{24})O(\theta_{14})O(\theta_{23})O(\theta_{13},\delta_{13})O(\theta_{12})$$

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 —

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

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


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

A Quantitative Question

Clearly, we need to find out whether eV-scale sterile neutrinos exist or not.

But suppose future short-baseline experiments do not see anything anomalous.

How tightly must the sterile-active mixing angles be constrained to ensure that analyses of DUNE data can safely disregard the possibility of sterile neutrinos?

Thanks for discussions to Bryce Littlejohn, Lisa Whitehead, Dan Cherdack, and Elizabeth Worcester

Event Rates At DUNE In the 3 + 0 and 3 + 1 Scenarios

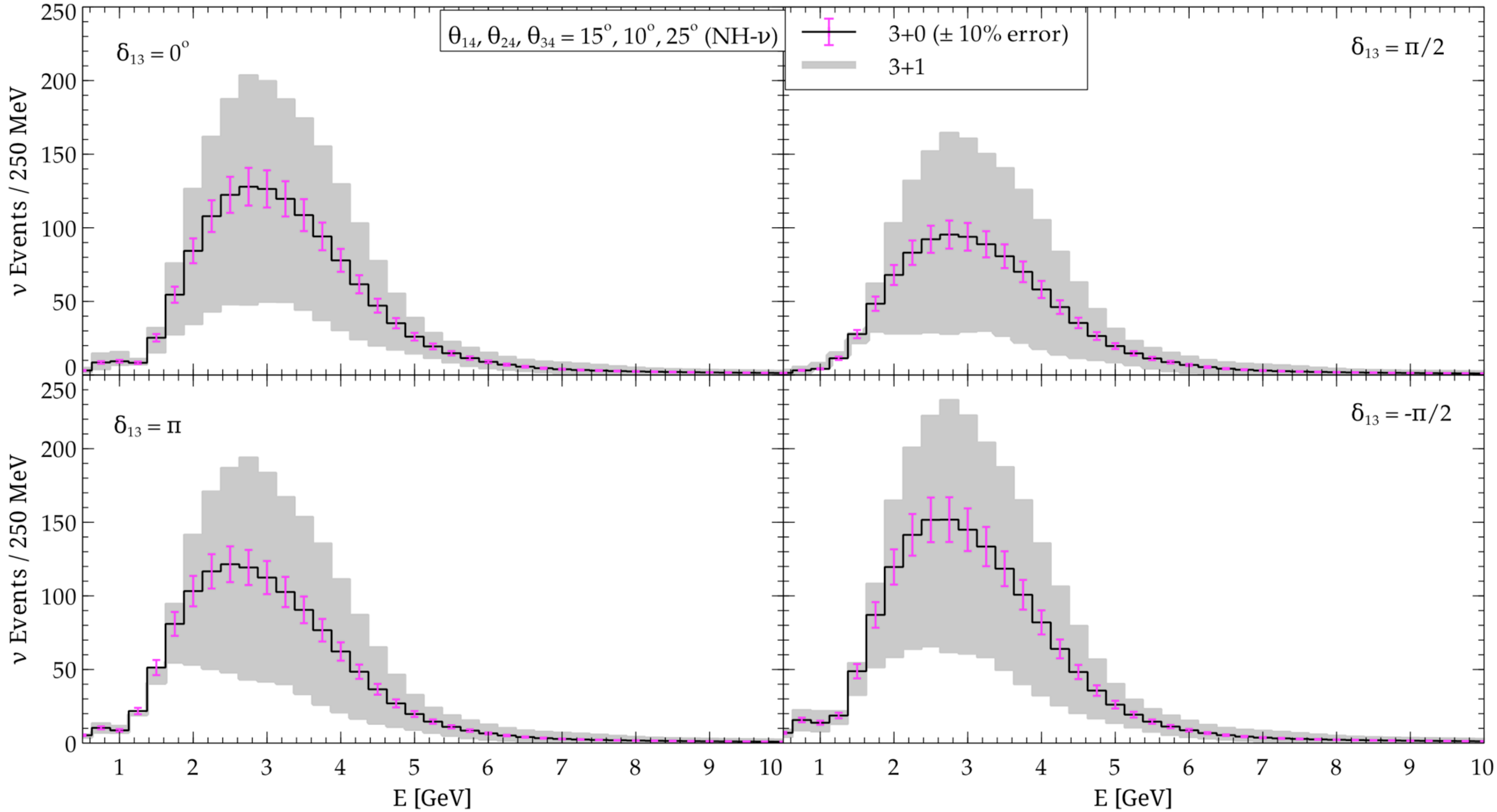
We use the **General Long Baseline Experiment Simulator GLoBES** to generate simulated long-baseline event rates.

Our $\overset{(-)}{\nu}_e$ event rates are based on —

L = 1300 km, a 35 kton far detector, 10^{21} POT/yr, and 10 years of running (35×10^{22} kton-POT-yr), divided evenly between neutrinos and antineutrinos.

For now, we assume an uncertainty of ±10% in the event rate at any energy.

3 + 0 event rates (±10%) for selected values of δ_{13}, and 3 + 1 event rates for all possible δ_{24} and δ_{34}



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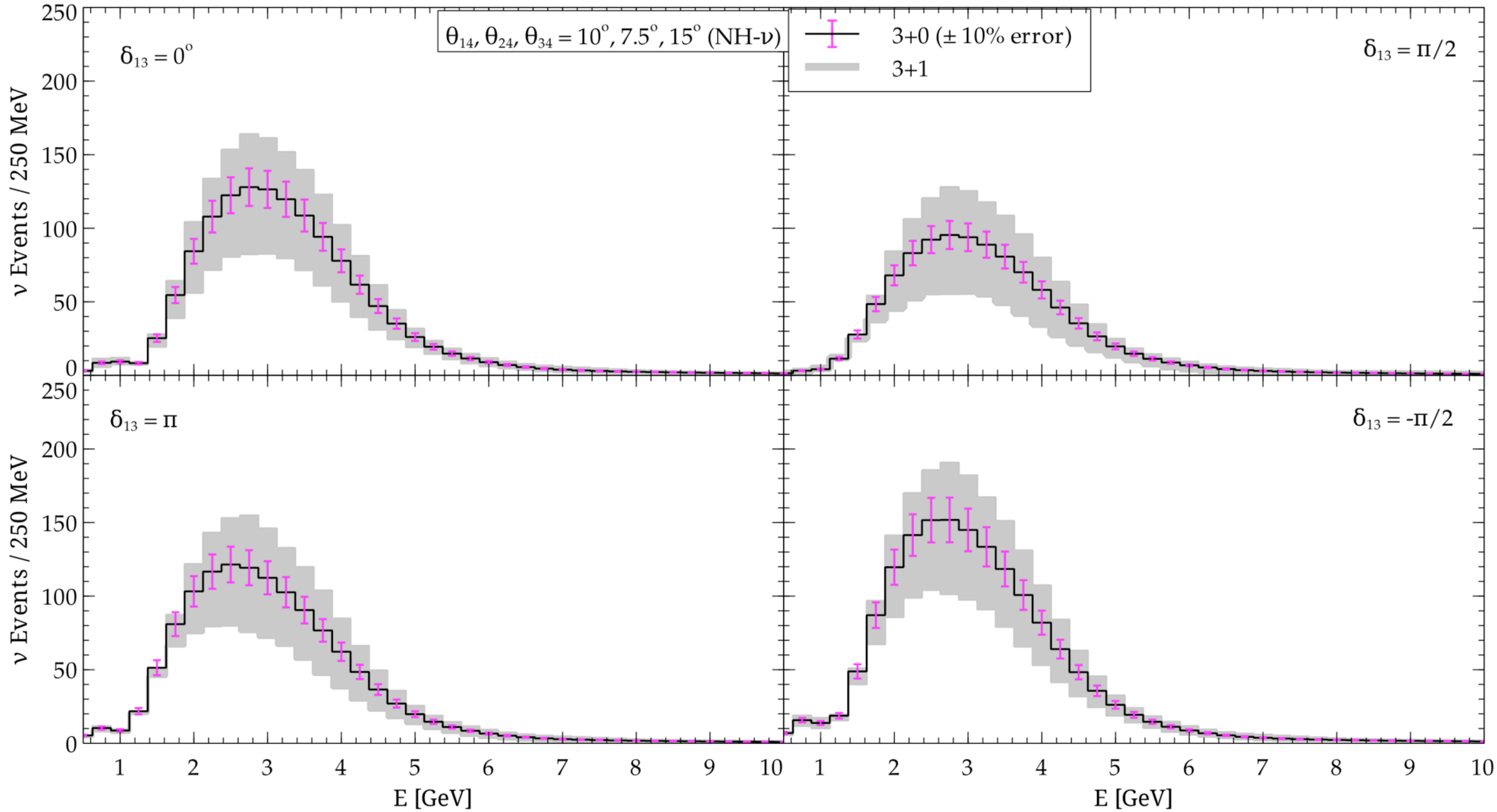
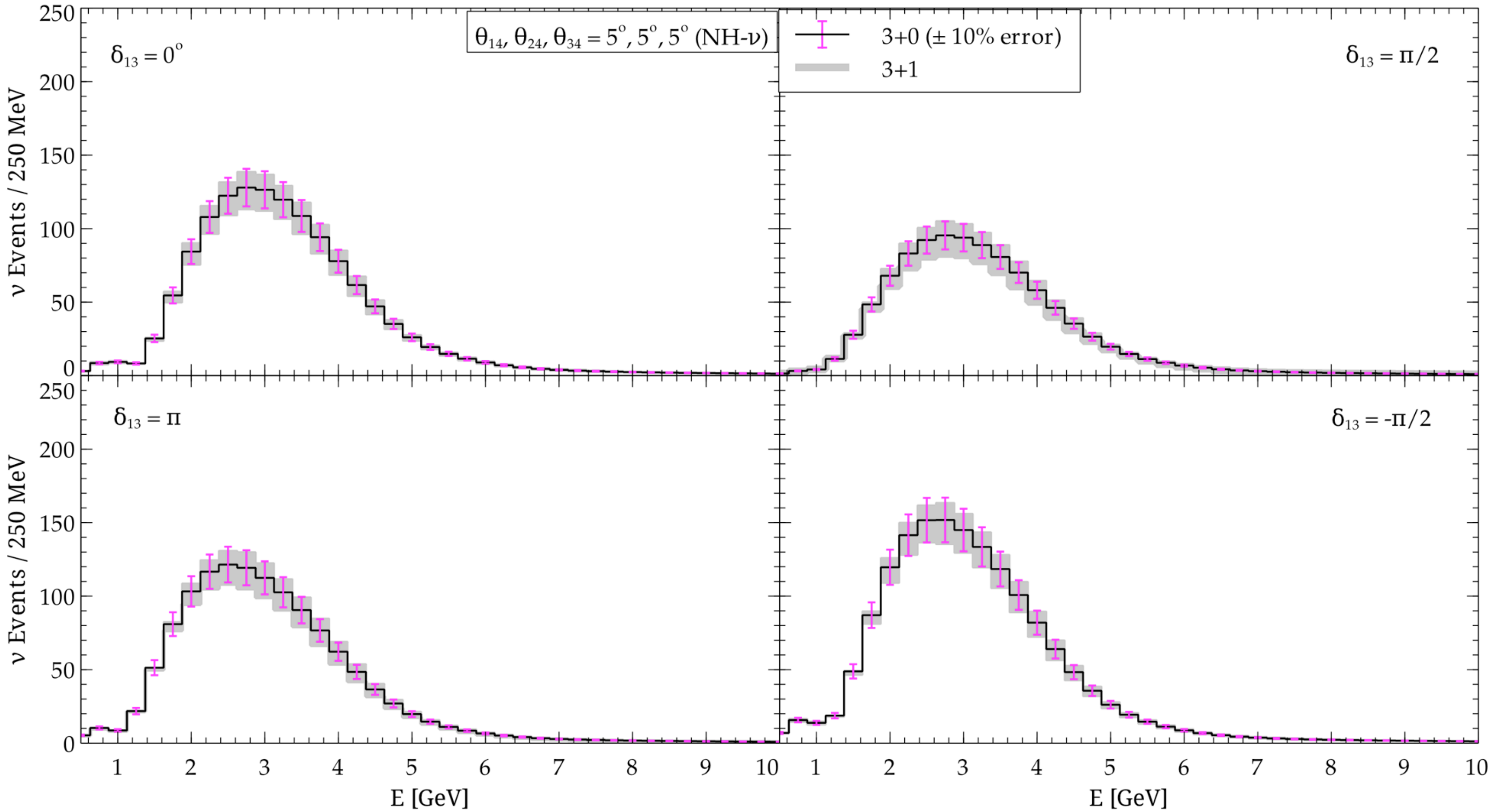


3 + 0 event rates (±10%) for selected values of δ_{13}, and 3 + 1 event rates for all possible δ_{24} and δ_{34}



The pattern is the same for both neutrino and antineutrino running, and for both hierarchies.

3+1 allows a ***significantly*** larger range of possible event rate spectra than 3+0.

3 + 1 with $\theta_{14}, \theta_{24}, \theta_{34} = 5°, 5°, 5°$ is fairly consistent with 3 + 0 within the assumed 10% uncertainties.

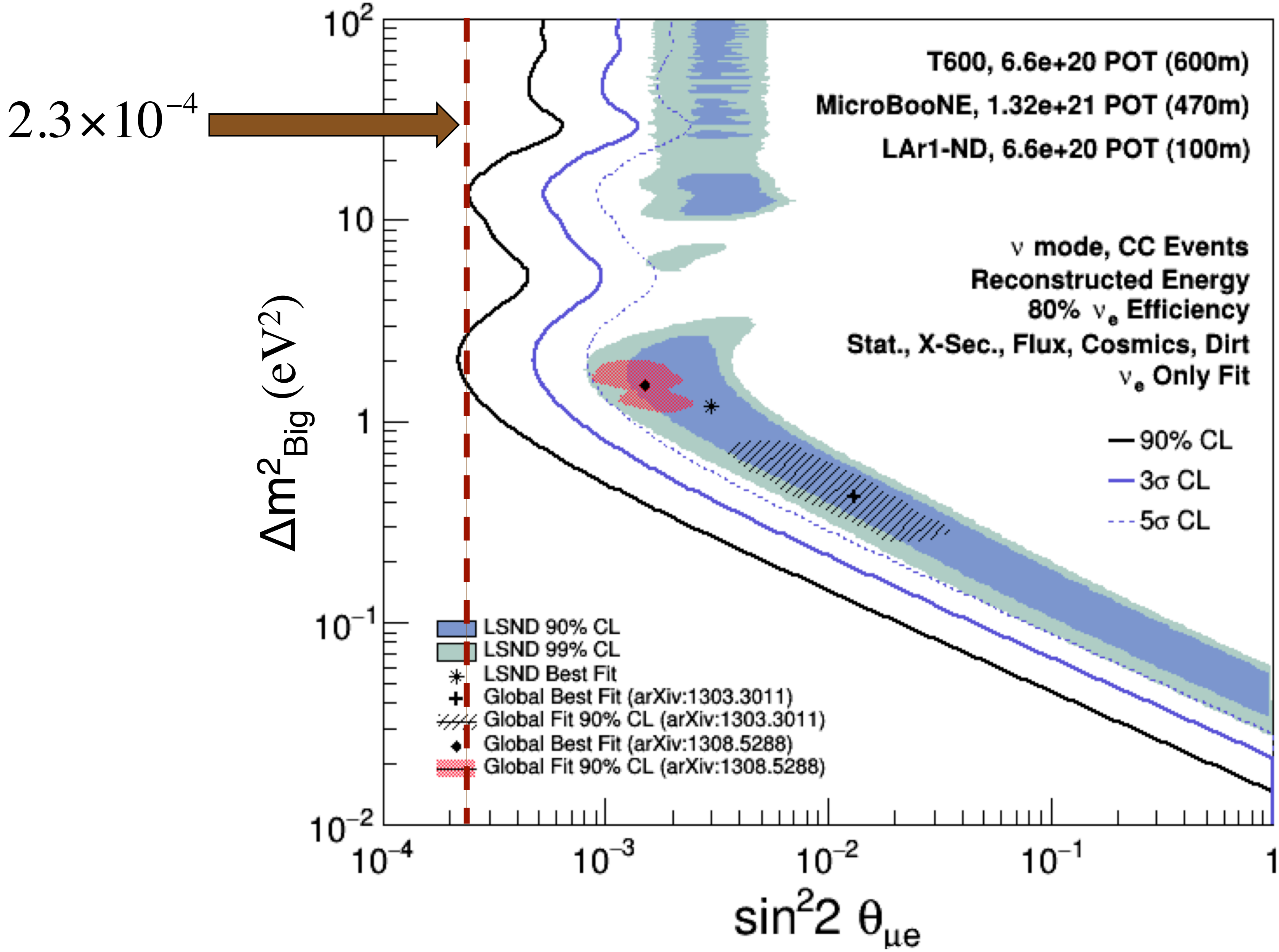
$\theta_{14}, \theta_{24}, \theta_{34} = 5°, 5°, 5°$ corresponds to —

$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24} = 2.3 \times 10^{-4}$$

$$\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14} \sin^2\theta_{24} \left(1 - \cos^2\theta_{14} \sin^2\theta_{24}\right) = 3.0 \times 10^{-2}$$

$$\sin^2 2\theta_{ee} = \sin^2 2\theta_{14} = 3.0 \times 10^{-2}$$

$\nu_\mu \rightarrow \nu_e$ Sensitivity of the SBN Program



Summary

1 eV scale sterile neutrinos, if real, could have a substantial effect on LBL experiments.

Such neutrinos could significantly affect the effort to study neutrino CP violation.

We are continuing to explore the possible ways to probe the physics.

It is very important to have an SBL program that definitively confirms 1 eV-scale sterile neutrinos, or tightly constrains their possible effects.