The Impact of Sterile Neutrinos on the Search for Leptonic CP Violation

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SBN Physics Workshop
January 26, 2016

A major goal of future LBL 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 **SBL** 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.

The Hints of eV^2-Scale Δm^2

Experiment	Possible Oscillation	Comment
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	Interesting
MiniBooNE	$\nu_\mu \to \nu_e$	Somewhat disfavored by ICARUS & OPERA
MiniBooNE	$\bar{\nu}_\mu \to \bar{\nu}_e$	NOT constrained by ICARUS & OPERA
Reactor Exps.	$\bar{\nu}_e \to$ Not $\bar{\nu}_e$	Flux uncertainty ~ 6% size of effect
^{51}Cr and ^{37}Ar Source Exps.	$\nu_e \to$ Not ν_e	Detection efficiency?

Not needed here

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

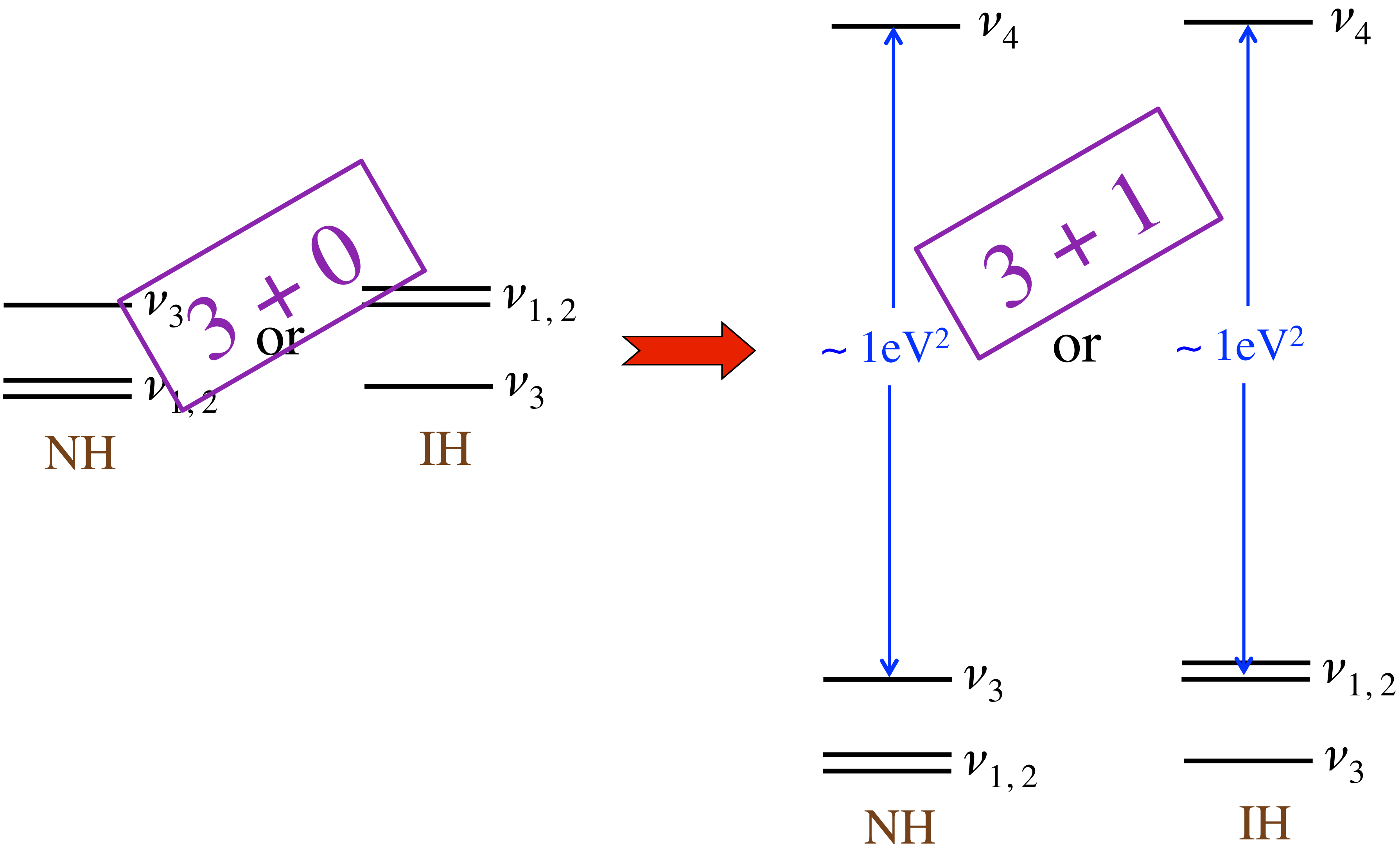
Related work includes studies by—

N. Klop and A. Palazzo

D. Hollander and I. Mocioiu

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

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 $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$.

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

This is impossible when there are only 3 mass eigenstates.

The Freedom a 4th Flavor Gives to CP Violation

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

Assuming CPT invariance, $P\left[\nu_\beta \to \nu_\alpha\right] = P\left[\bar{\nu}_\alpha \to \bar{\nu}_\beta\right]$.

Then $\Delta P_{\beta\alpha} = -\Delta P_{\alpha\beta}$. In particular, $\Delta P_{\alpha\beta} = 0$ when $\beta = \alpha$.

Conservation of probability

⇒ $$\sum_{\text{All } \beta} P\left(\nu_\alpha \to \nu_\beta\right) = \sum_{\text{All } \beta} P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right) = 1 \,.$$

Then $$\boxed{\sum_{\text{All } \beta} \Delta P_{\alpha\beta} = \sum_{\beta \neq \alpha} \Delta P_{\alpha\beta} = 0} \,.$$

When there are only 3 neutrino flavors, there are only 3 independent (potentially) nonzero CP-violating differences $\Delta P_{\alpha\beta}$ to be measured: $\Delta P_{e\mu}$, $\Delta P_{\mu\tau}$, and $\Delta P_{\tau e}$.

$$\sum_{\beta\neq\alpha} \Delta P_{\alpha\beta} = 0 \quad \Longrightarrow$$

$$\Delta P_{e\mu} + \Delta P_{e\tau} = 0 \quad \text{and} \quad \Delta P_{\mu e} + \Delta P_{\mu\tau} = 0 \ .$$

Then $\boxed{\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e}}$.

If CP is not violated in $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$, then it is not violated in ***any*** oscillation channel.

When there are 4 neutrino flavors, assuming CPT invariance, there are 6 independent (potentially) nonzero CP-violating differences $\Delta P_{\alpha\beta}$:

$\Delta P_{e\mu}$, $\Delta P_{\mu\tau}$, $\Delta P_{\tau e}$, ΔP_{es}, $\Delta P_{\mu s}$, and $\Delta P_{\tau s}$.

Sterile flavor

Now $\sum_{\beta\neq\alpha} \Delta P_{\alpha\beta} = 0$ only implies such relations as —

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} + \Delta P_{\mu s}$$

The CP-violating differences $\boldsymbol{\Delta P_{\alpha\beta}}$ in different active-to-active oscillation channels are no longer required to be equal.

Physics At *L* = 1300 km (DUNE)

At L = 1300 km, the finite energy resolution of the far detector will average the rapid oscillations driven by the large $\Delta m^2_{41} \sim 1\ \mathrm{eV}^2$ to an energy-independent, ***but nonzero***, value.

The influence of the rapid oscillations can be <u>quite significant</u> due to their interference with the longer-wavelength oscillations.

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)

Turning to the “new” parameters, we take $\Delta m_{41}^2 = 1\mathrm{eV}^2$.

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 —

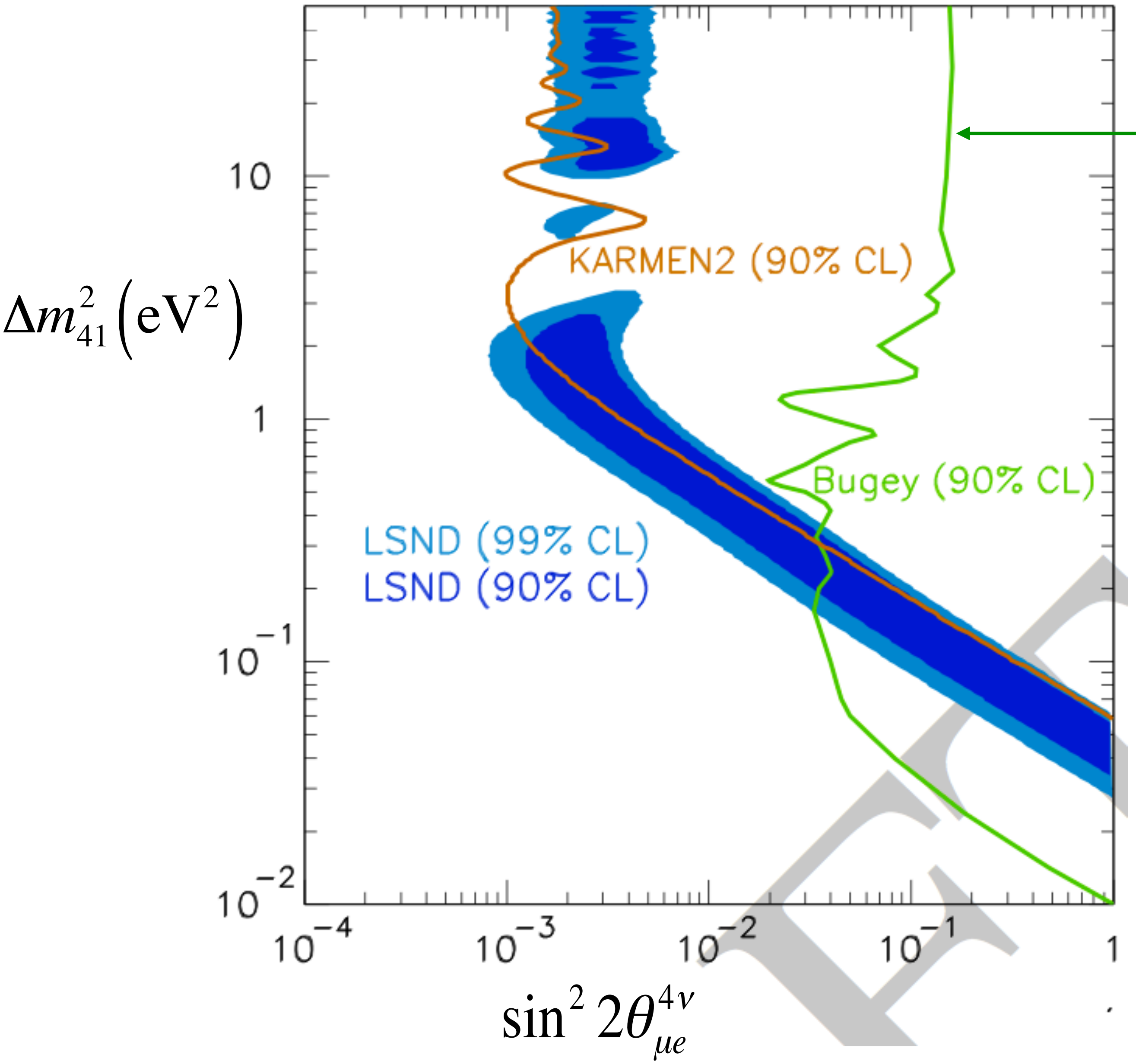
$$0° \leq \theta_{14} \leq 20°, \quad 0° \leq \theta_{24} \leq 10°, \quad 0° \leq \theta_{34} \leq 30°$$

$\left(\begin{array}{c}\text{Disappearance constraints from} \\ \text{Kopp, Machado, Maltoni, and Schwetz}\end{array}\right)$

When all new mixing angles are at the upper limits of these ranges, the effective 3+1 mixing parameter $\sin^2 2\theta_{\mu e}^{4\nu}$ for $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ at short baselines is —

$$\sin^2 2\theta_{\mu e}^{4\nu} = 0.013 \,.$$

The LSND-favored region



Out of date

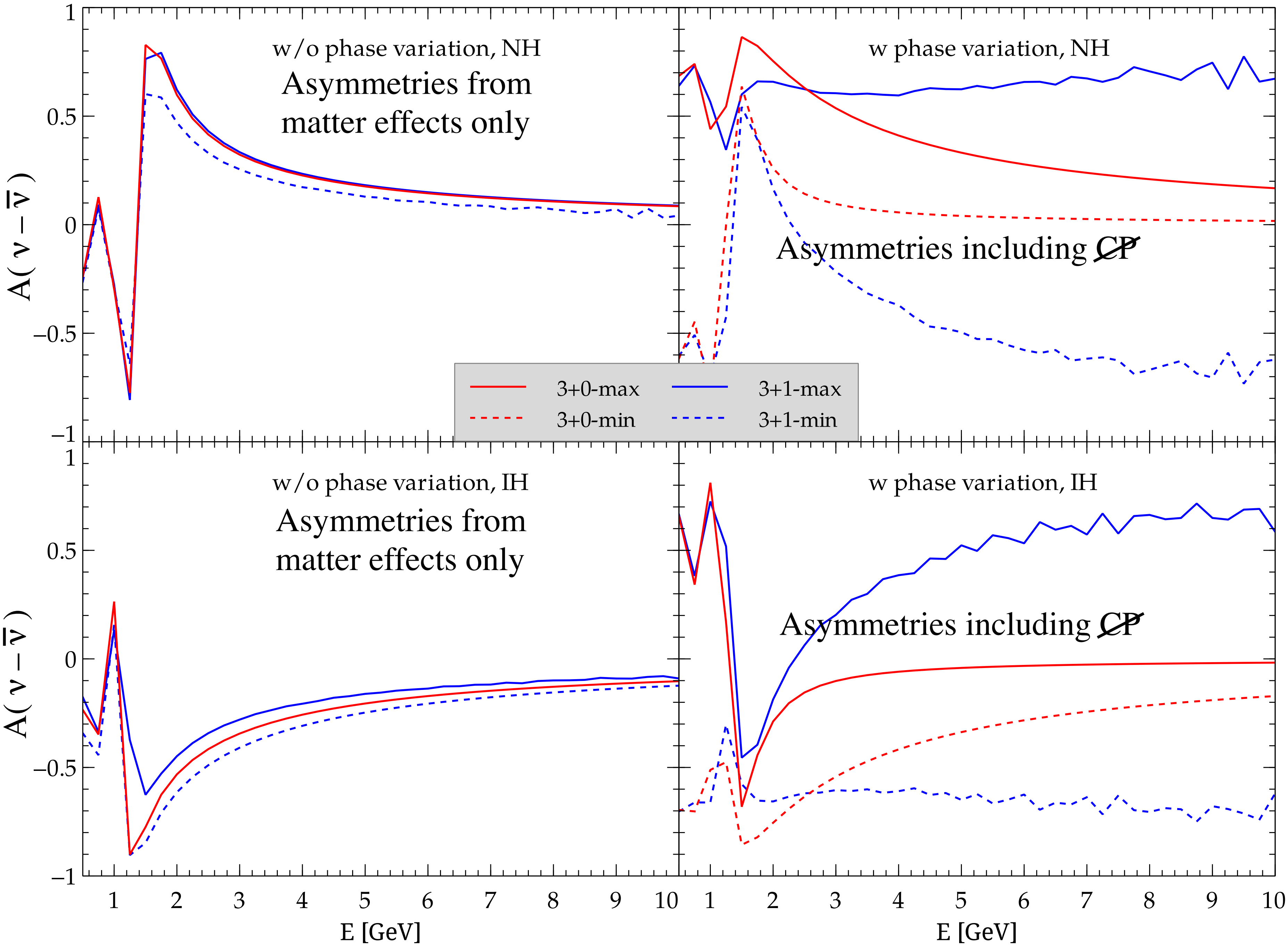
3 + 1
spectrum
assumed.

When considering the standard 3 + 0 (no sterile neutrinos) model, we vary the sole CP-violating phase δ_{13} from – π to + π, and when considering the 3 + 1 model, we do the same for all three CP-violating phases, δ_{13} , δ_{24} , and δ_{34} .

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

Can we tell whether CP is violated or not? That is, whether CP violation is substantial or at most very small? Can we be fooled into thinking CP violation is ~ zero when it is large?

To explore such questions, let us look at the neutrino – antineutrino ***asymmetries***.



Asymmetries from matter effects only

Asymmetries including $\not{CP}$

Asymmetries from matter effects only

Asymmetries including $\not{CP}$

When there is ***no*** ~~CP~~, the (matter-induced) asymmetries in 3+0 and 3+1 are quite similar.

But when there ***is*** ~~CP~~, the asymmetries in 3+0 and 3+1 can be quite different.

Why is the difference between 3+0 and 3+1 potentially quite large?

$\cancel{CP}$ 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.

N. Klop and A. Palazzo

What Could Measurements Tell Us?

An asymmetry ***different*** from the similar ones for 3+0 and 3+1 with no $\cancel{CP}$ would imply that, if either 3+0 or 3+1 describes the physics, CP is violated.

The implications of an asymmetry ***consistent with*** the similar ones for 3+0 and 3+1 with no $\cancel{CP}$ are not yet obvious.

In 3+1, there can be $\cancel{CP}$ in, say, $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau$,
even if there is none in $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$.

An asymmetry implying $\cancel{CP}$ if either 3+0 or 3+1 is true, but consistent with both, leaves its origin among the underlying phases ambiguous.

A Quantitative Question

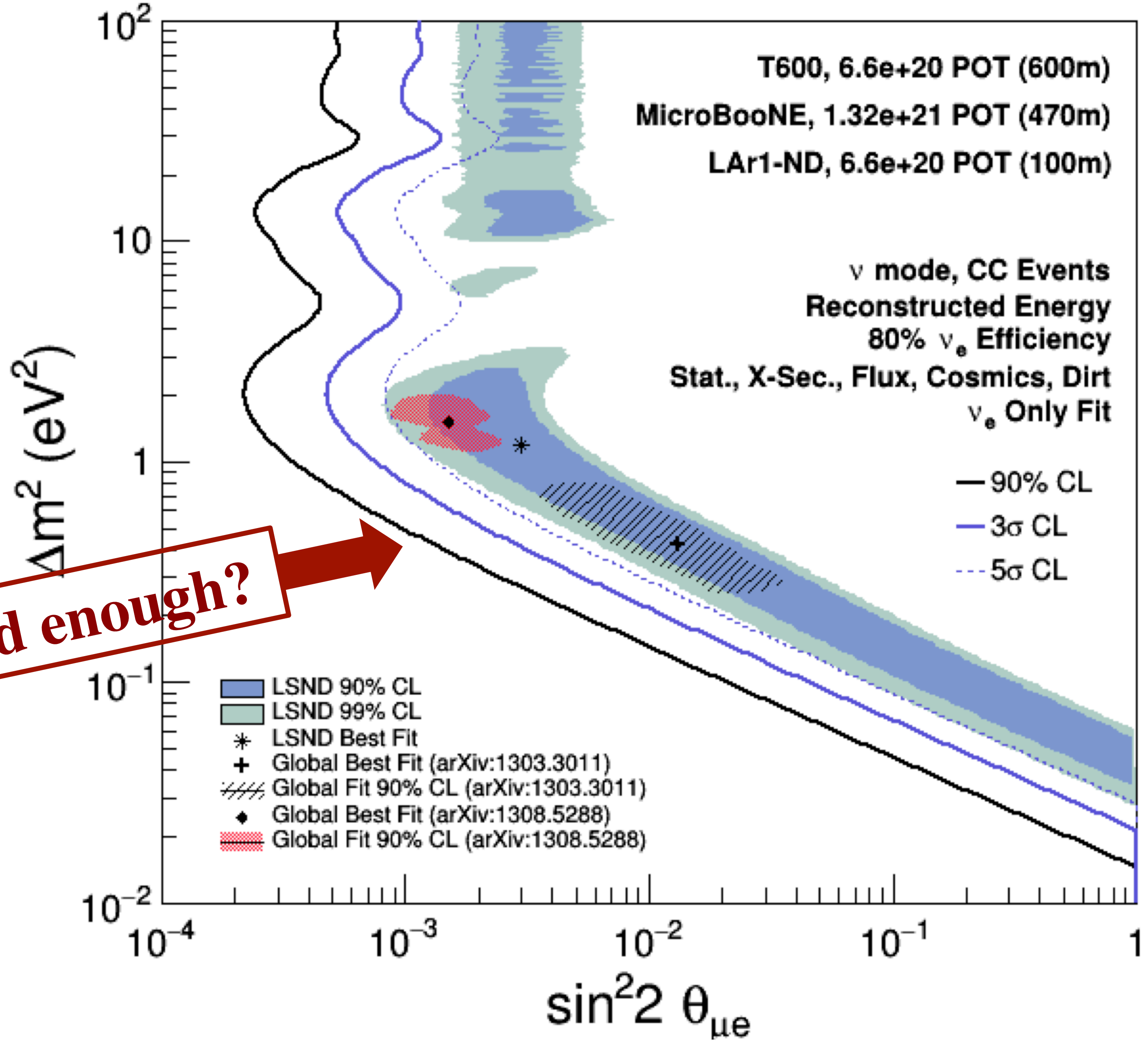
Clearly, we need to find out whether eV-scale sterile neutrinos exist or not.

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?

With thanks to Bryce Littlejohn

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



Is this good enough?

And similar questions about the sterile-active mixing angles probed by short-baseline disappearance of accelerator ν_μ and $\overline{\nu}_\mu$, source ν_e, and reactor and source $\overline{\nu}_e$, and processes more challenging to study.

We are exploring this issue.

— Some preliminary results —

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

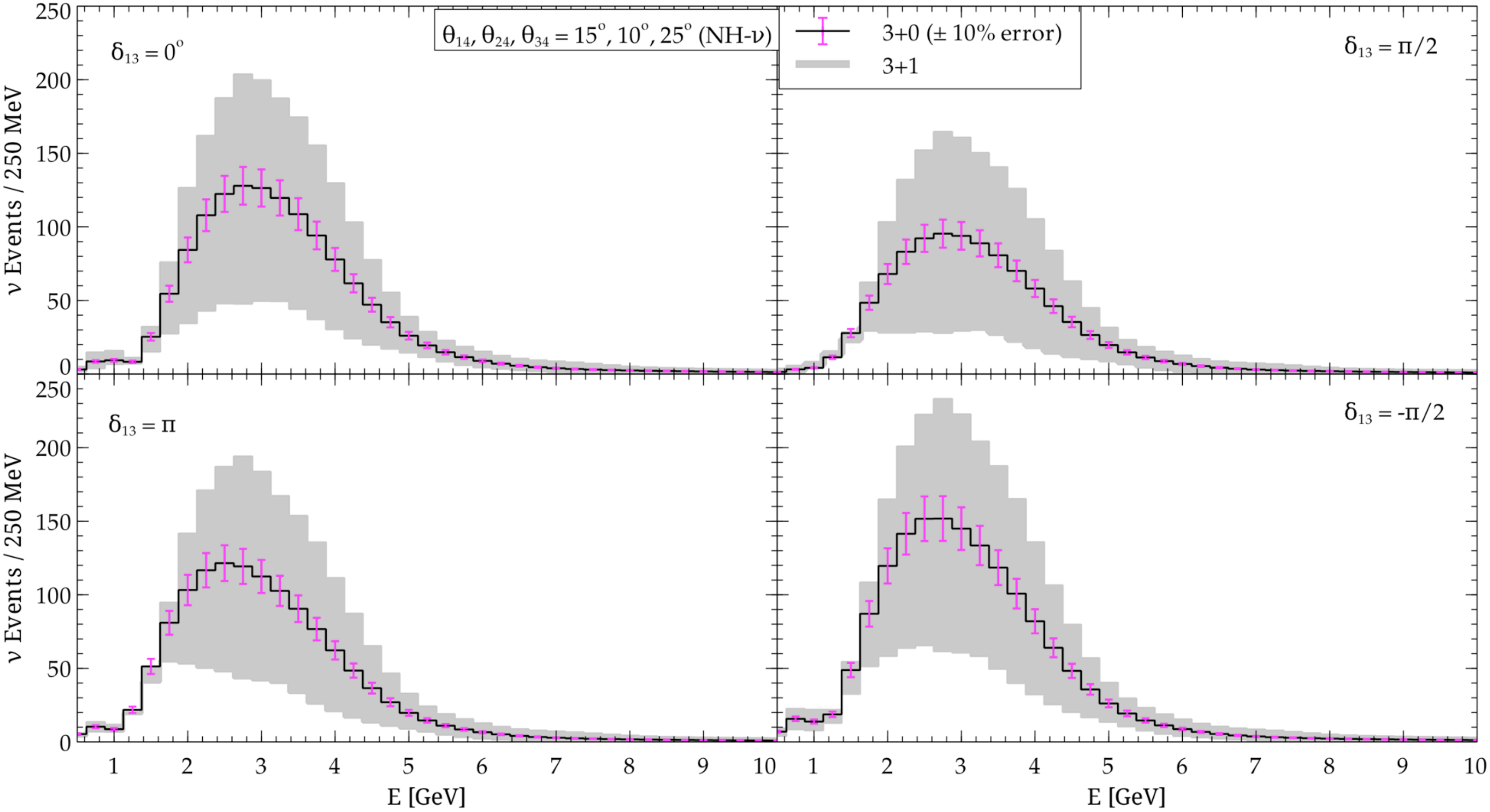
We use the **General Long Baseline Experiment Simulator GLoBES** to generate simulated long-baseline event rates.

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 x 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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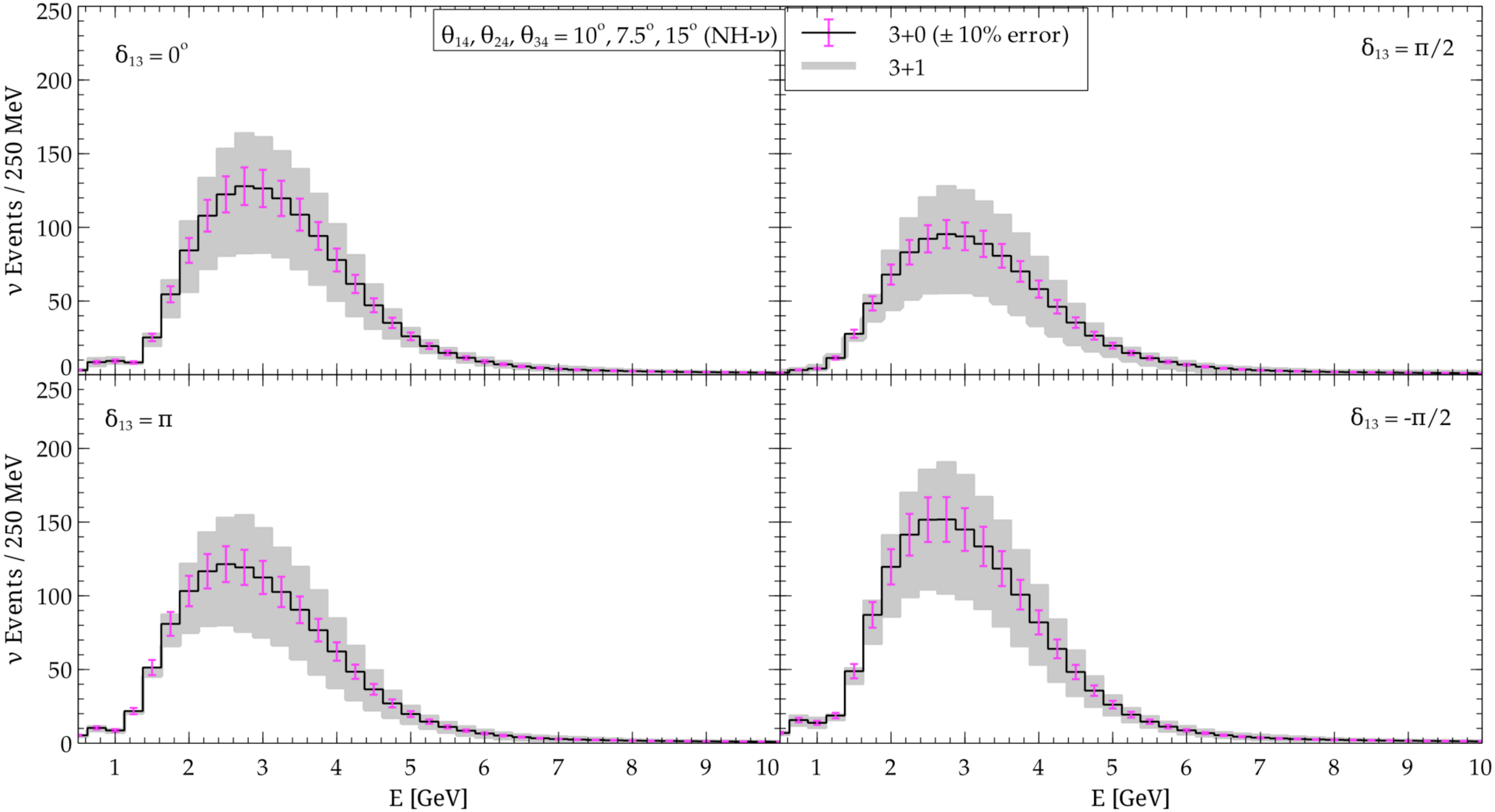

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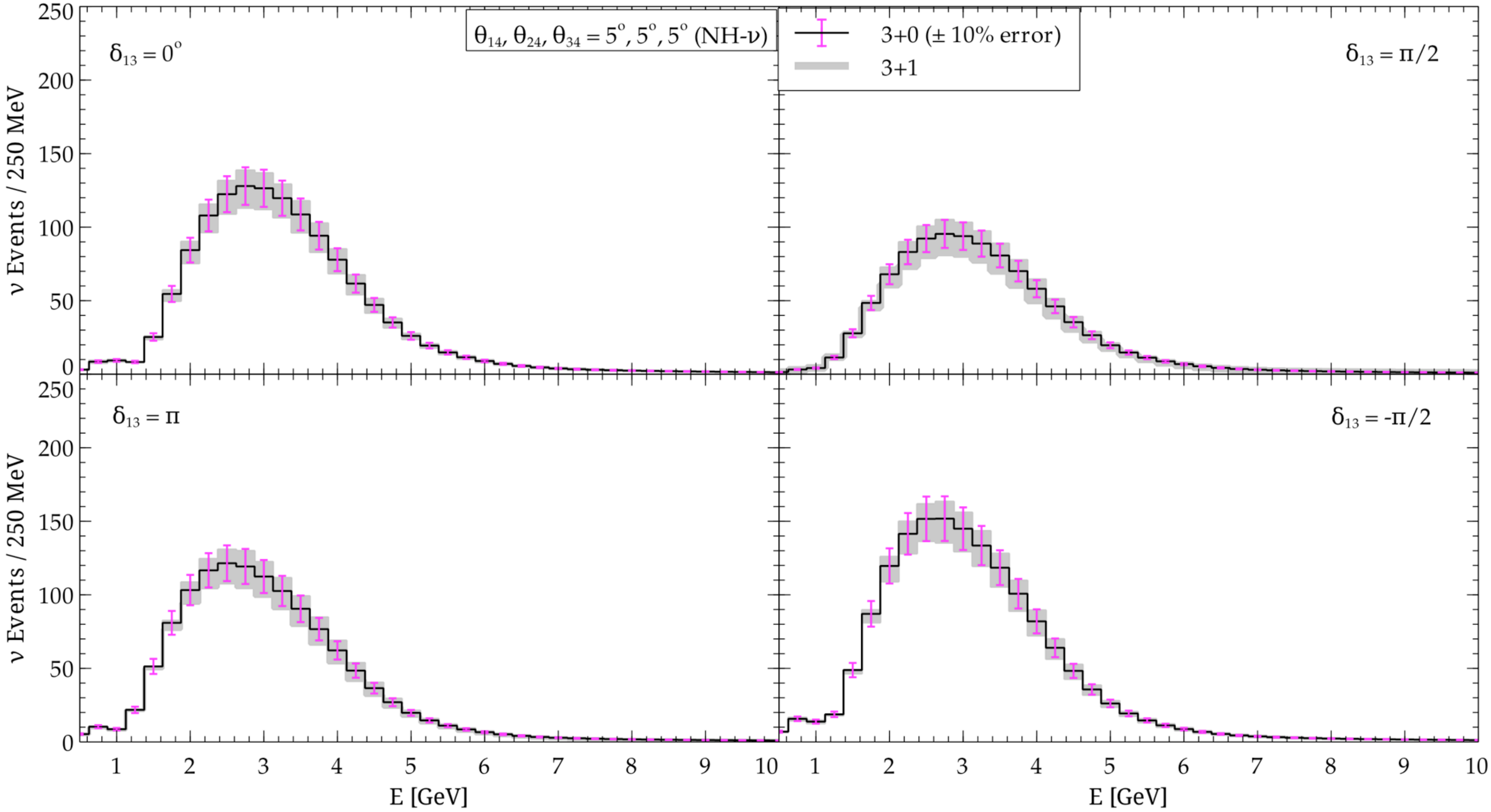

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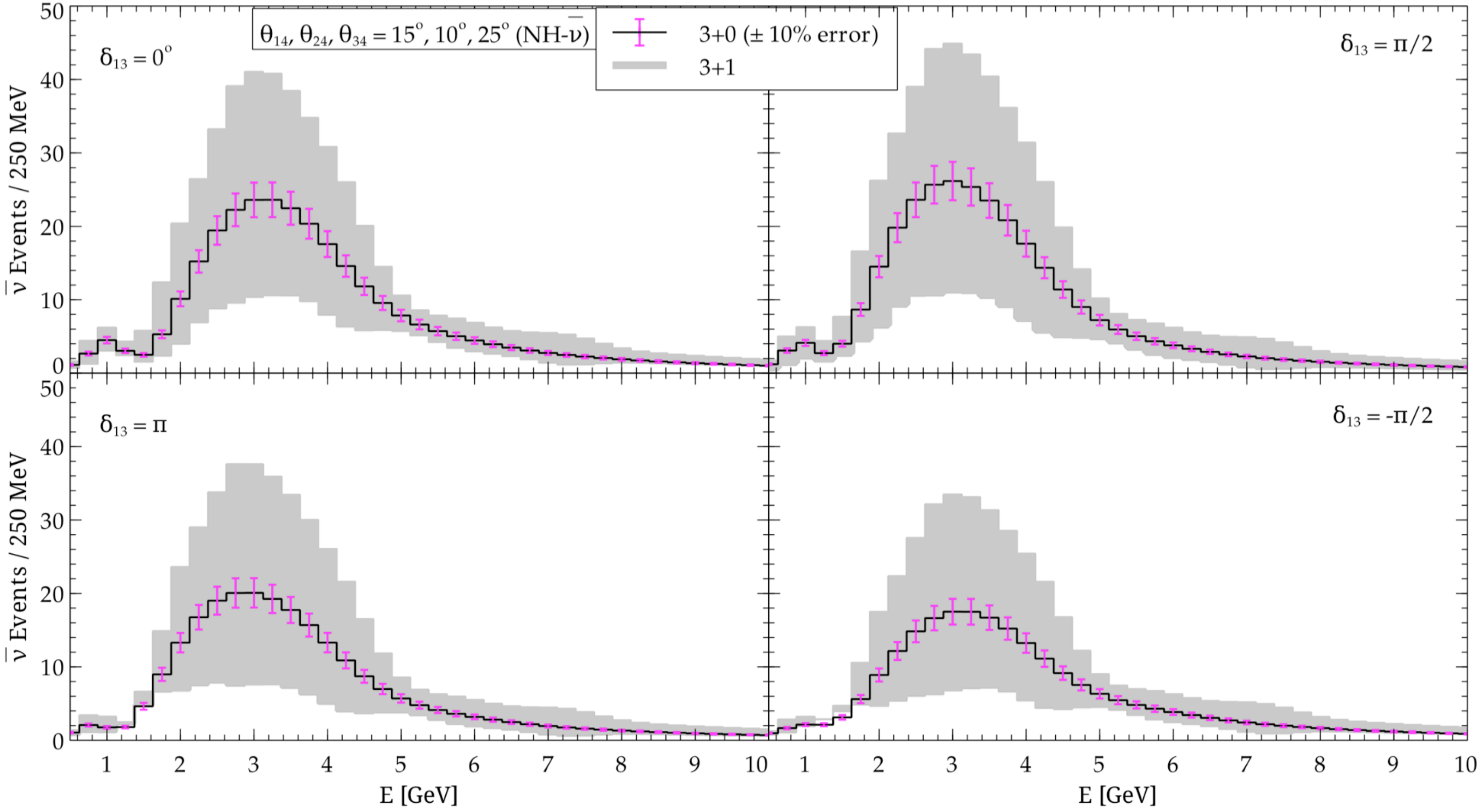

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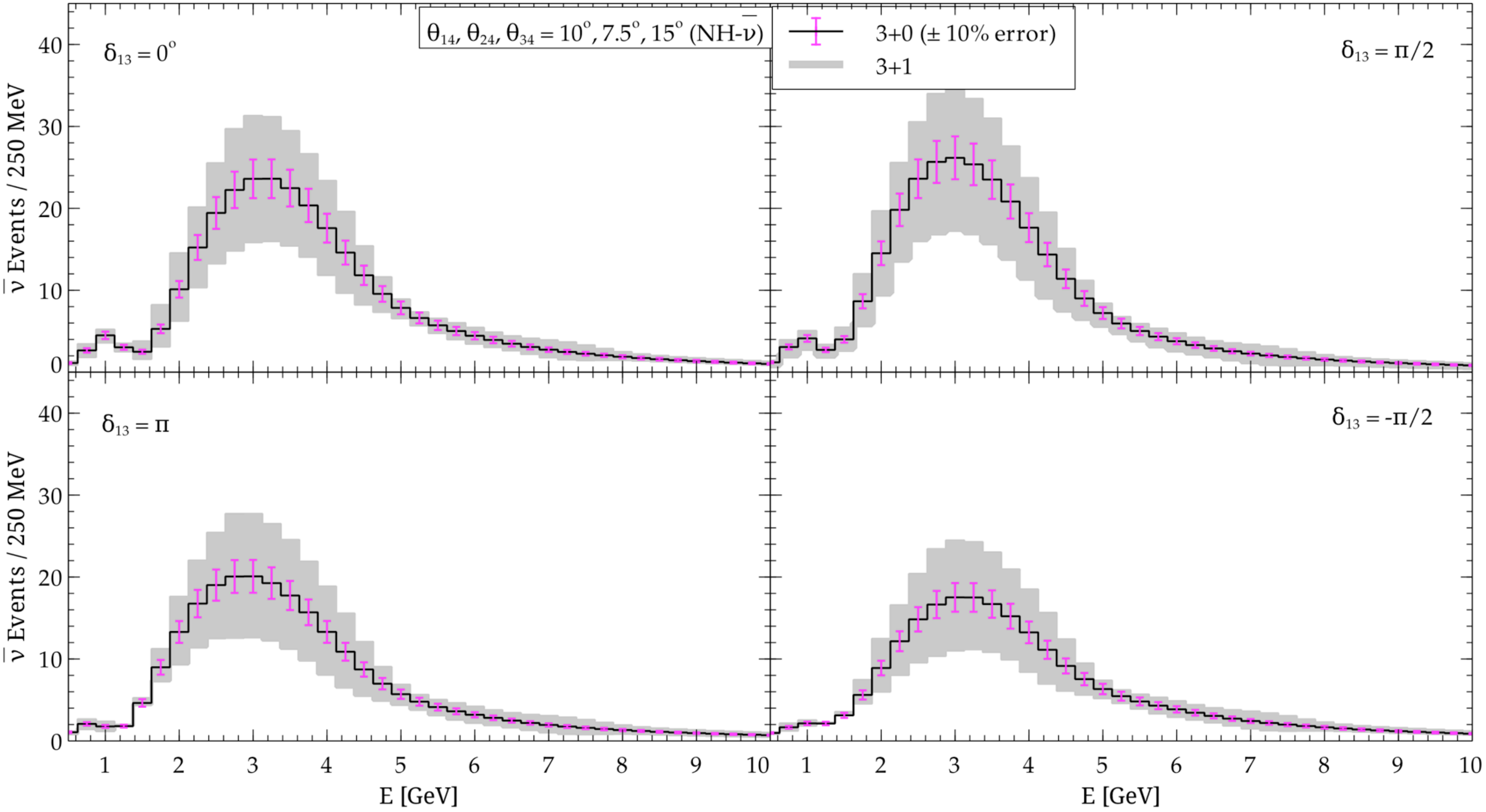

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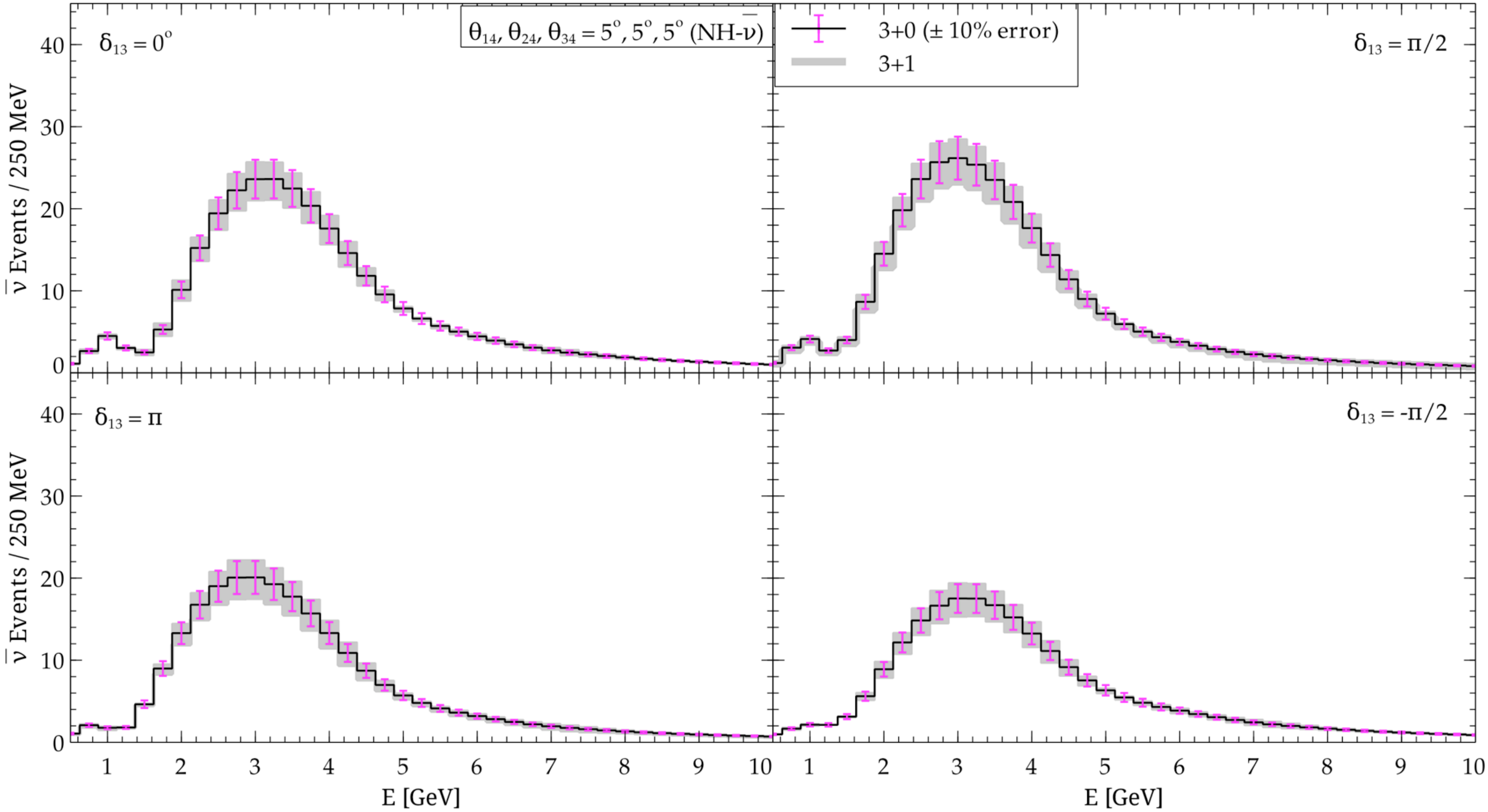

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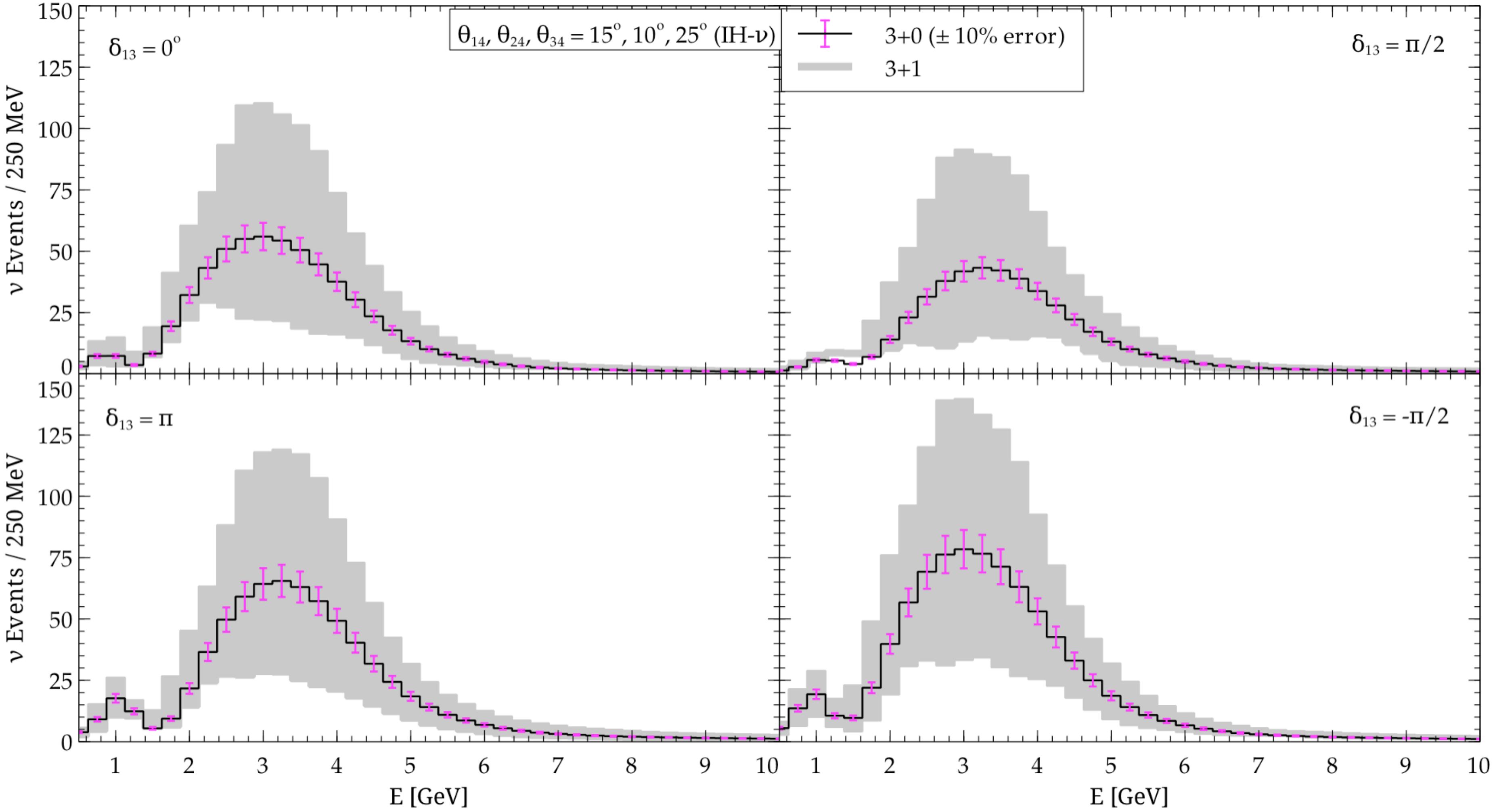

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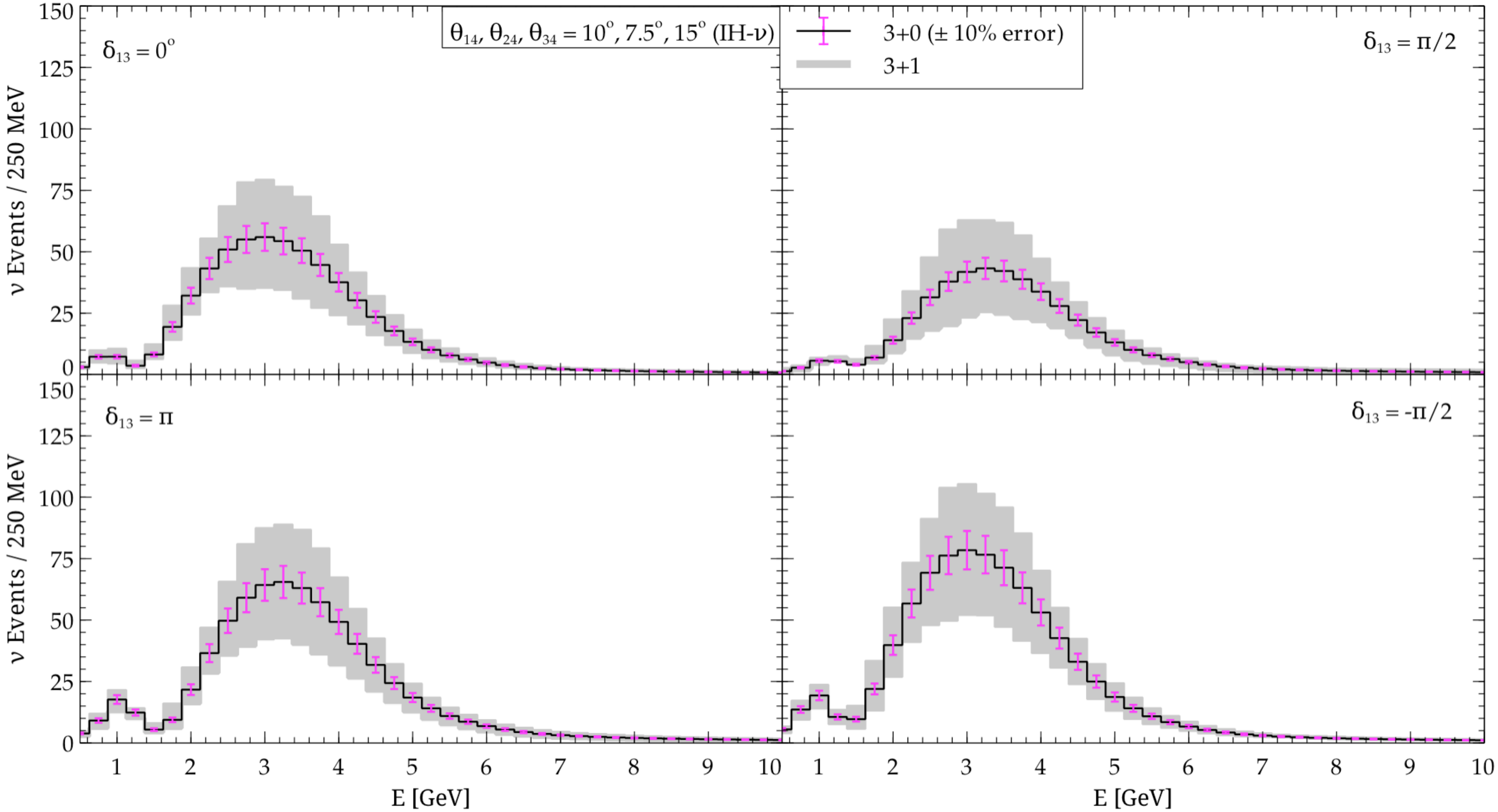

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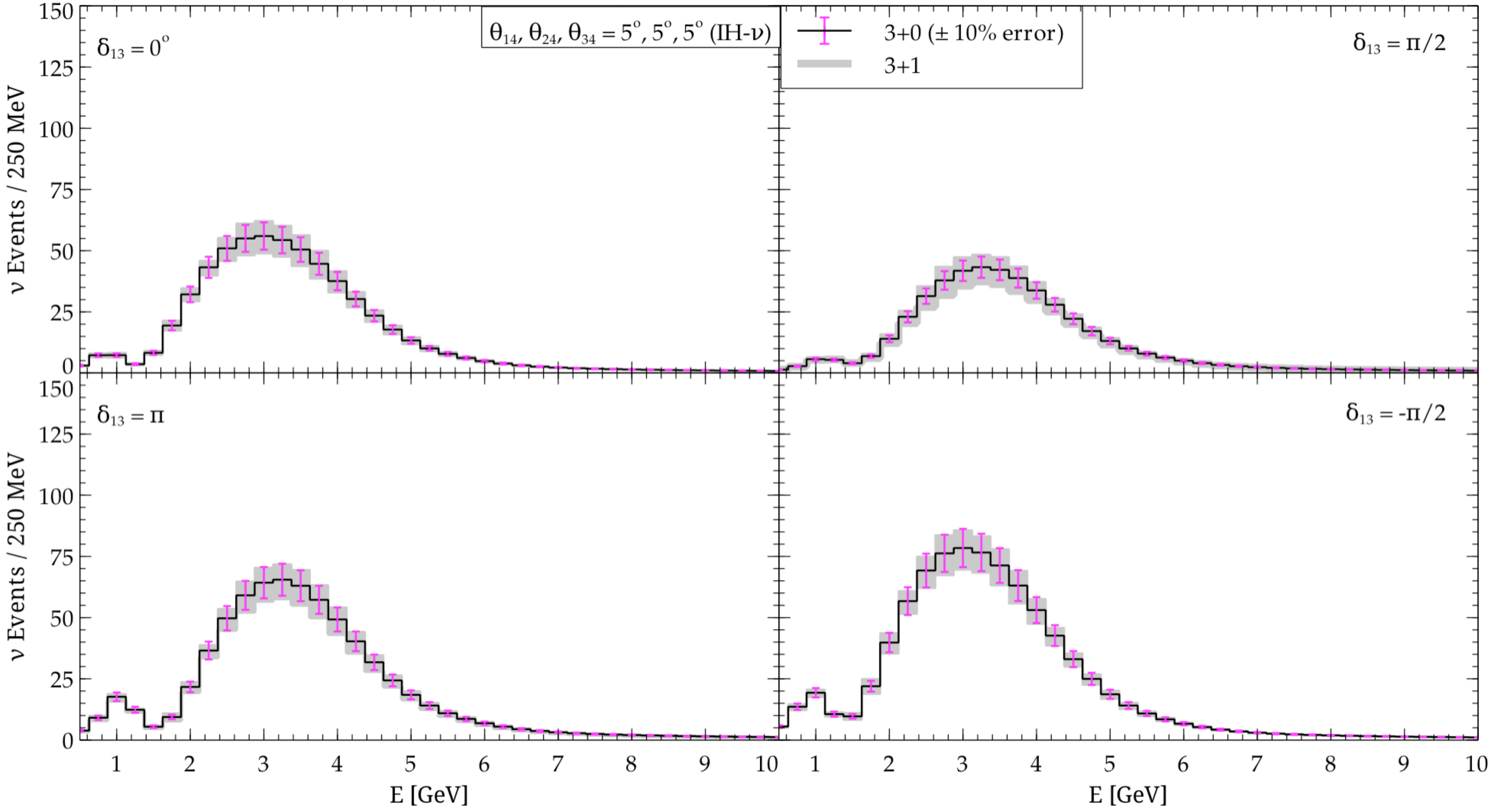

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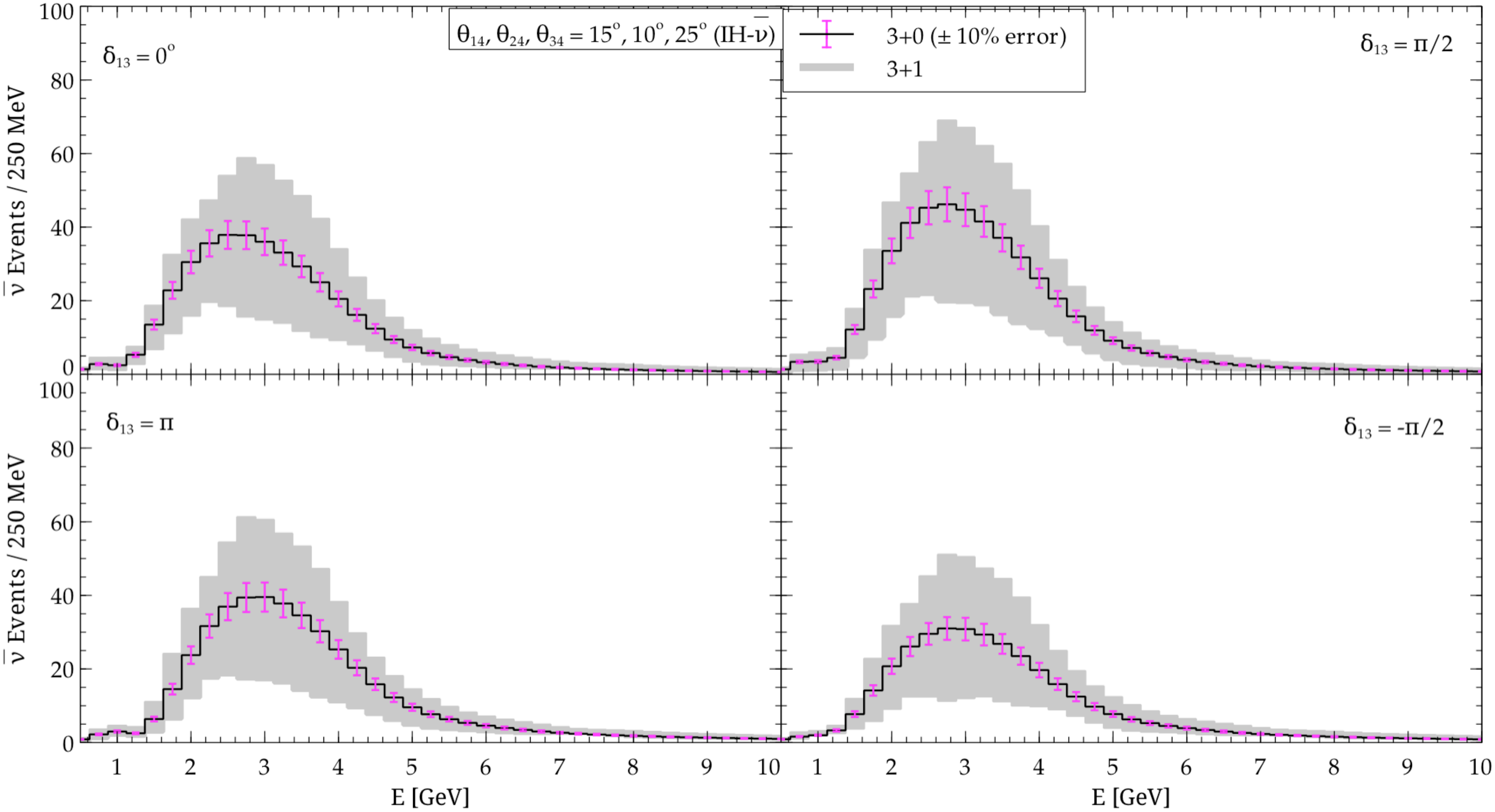

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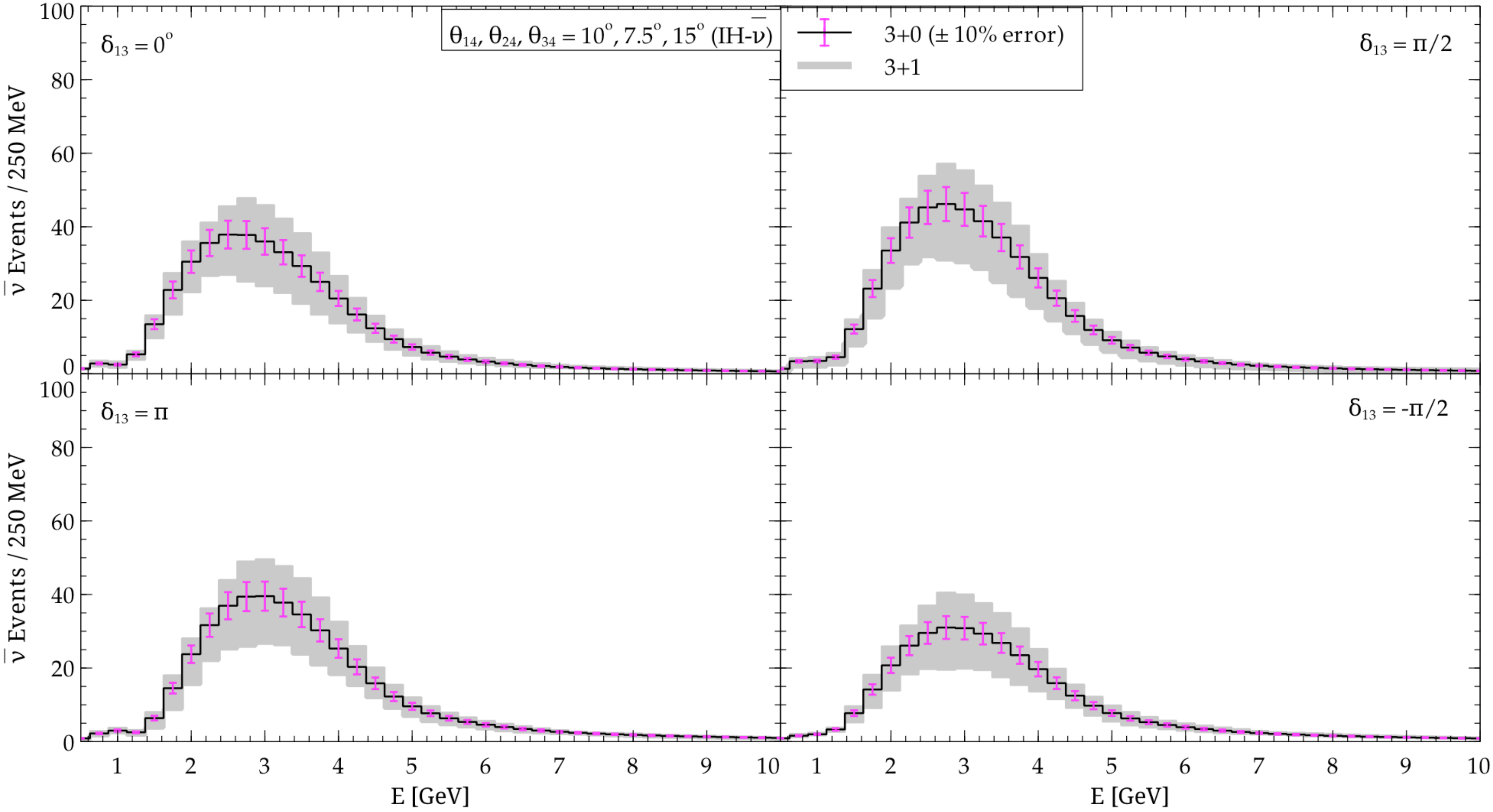

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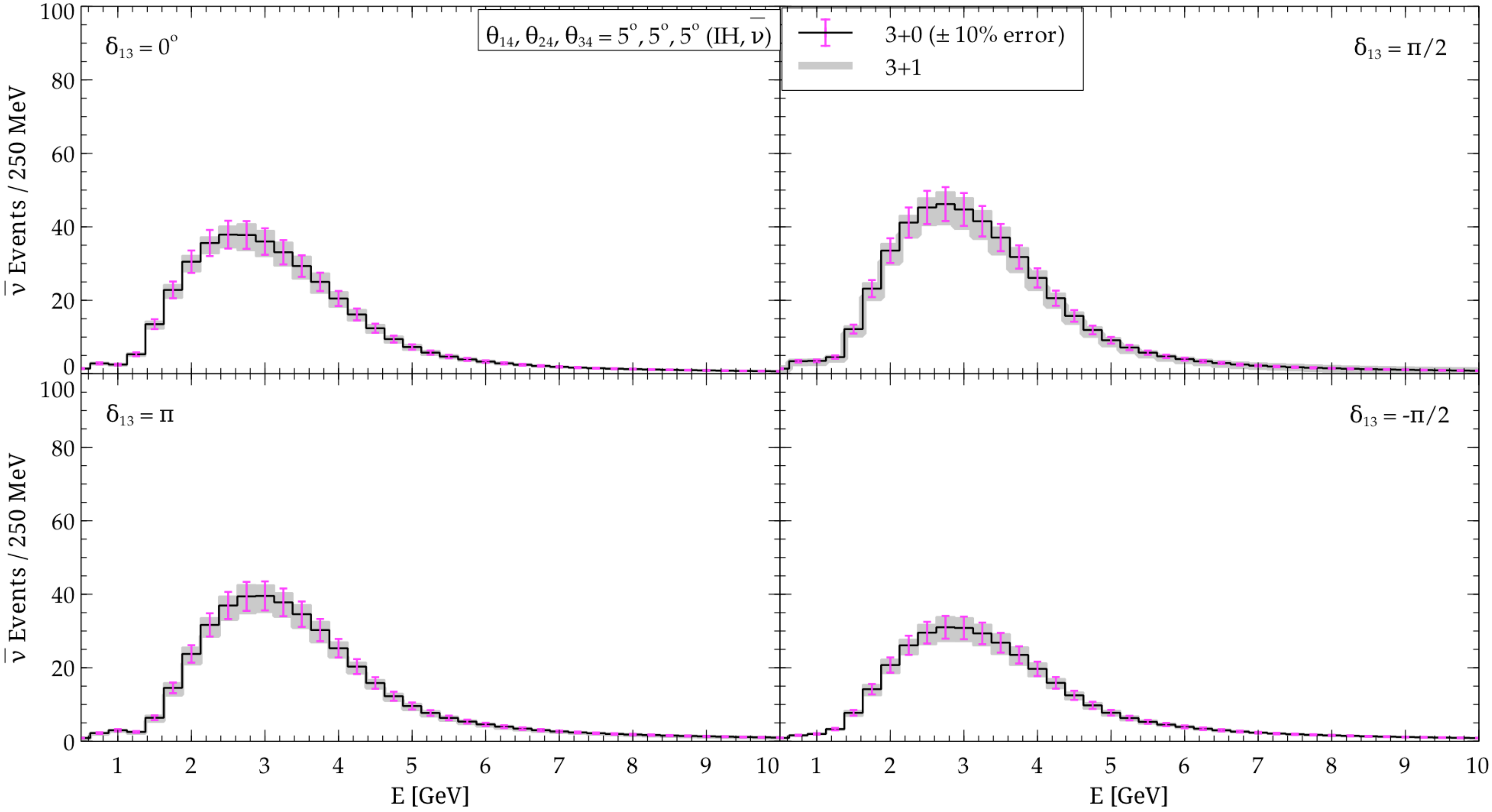


3+1 allows a ***significantly*** larger range of possible event rate spectra than 3+0.

Some spectra consistent with 3+1 would be inconsistent with 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 —

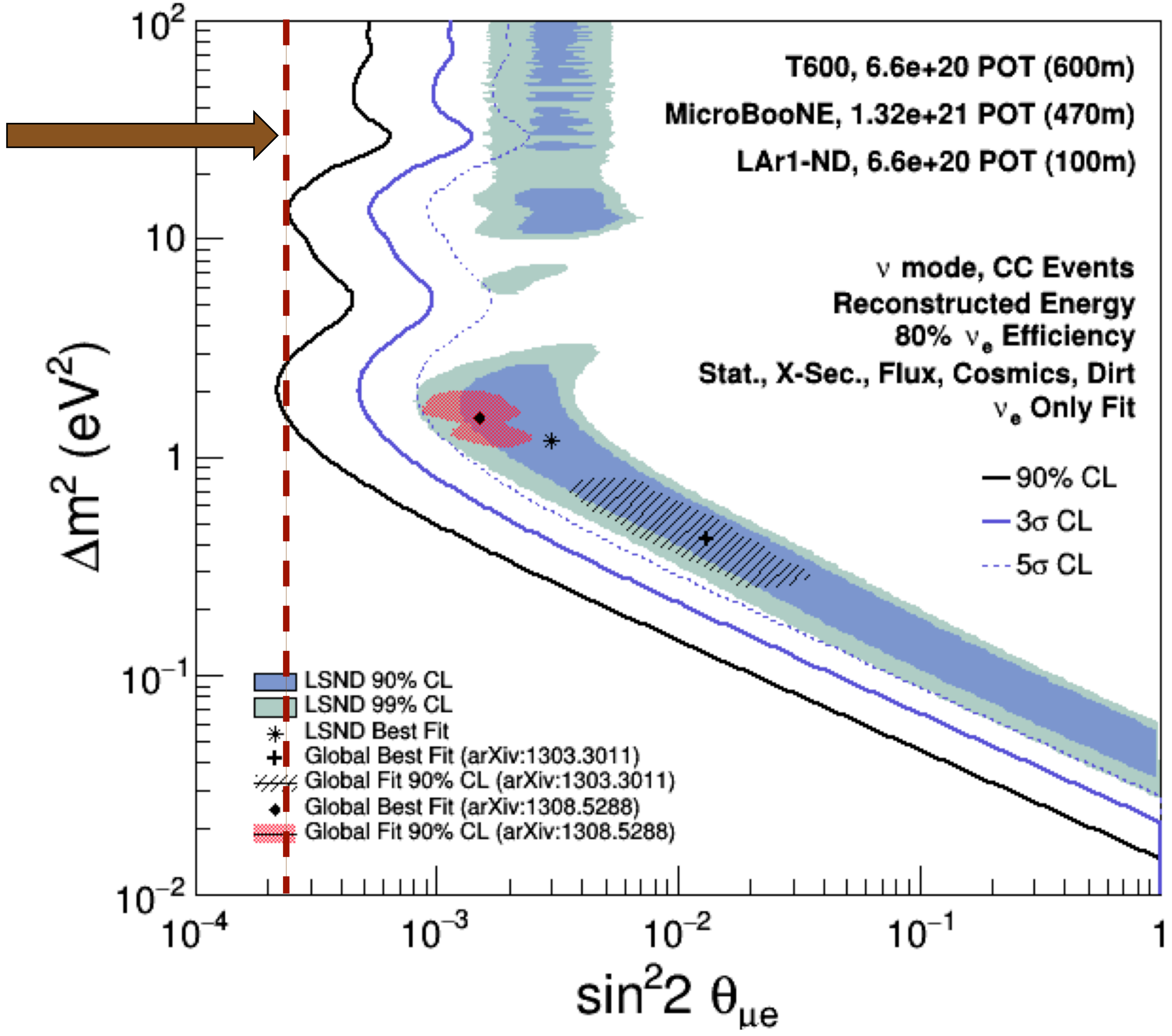
$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24} = 2.3 \times 10^{-4}$$

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

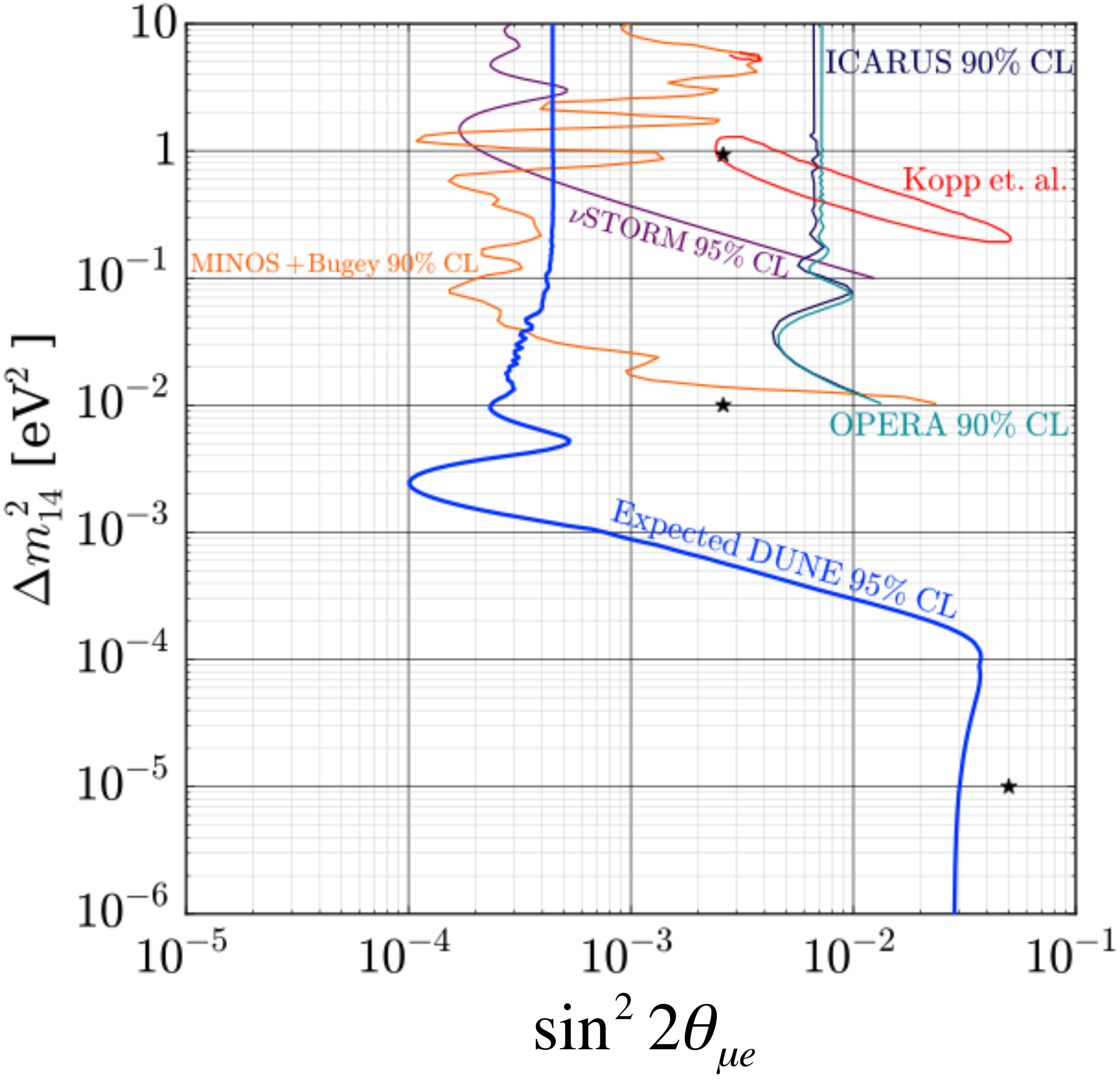
$$\sin^2 2\theta_{ee} = \sin^2 2\theta_{14} = 3.0 \times 10^{-2}$$

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

$2.3{\times}10^{-4}$



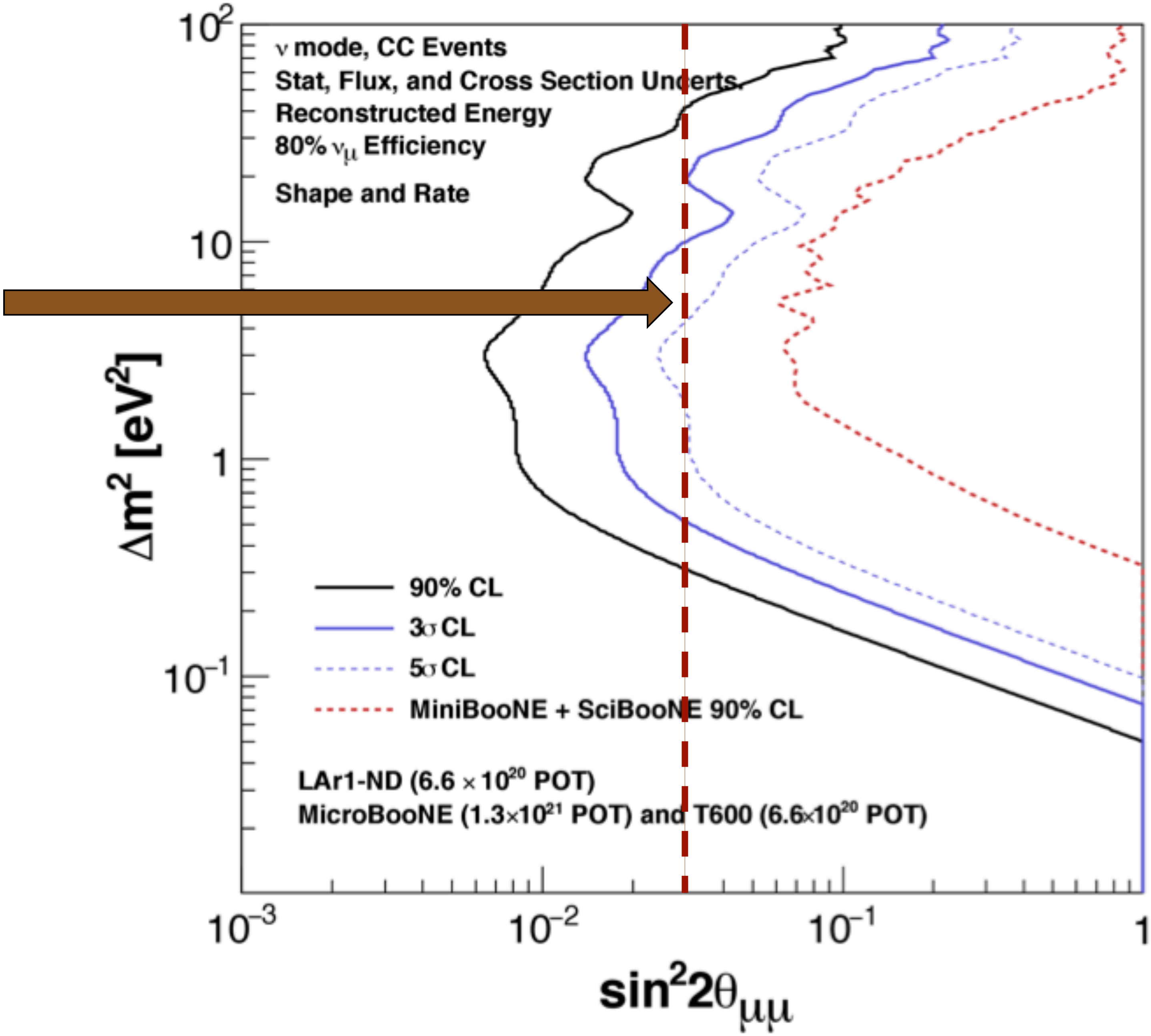
What DUNE Can Do To Exclude 3 + 1



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

Berryman,
de Gouvêa,
Kelly,
Kobach

$\nu_\mu \rightarrow \cancel{\nu_\mu}$ Sensitivity of the SBN Program



3.0×10^{-2}

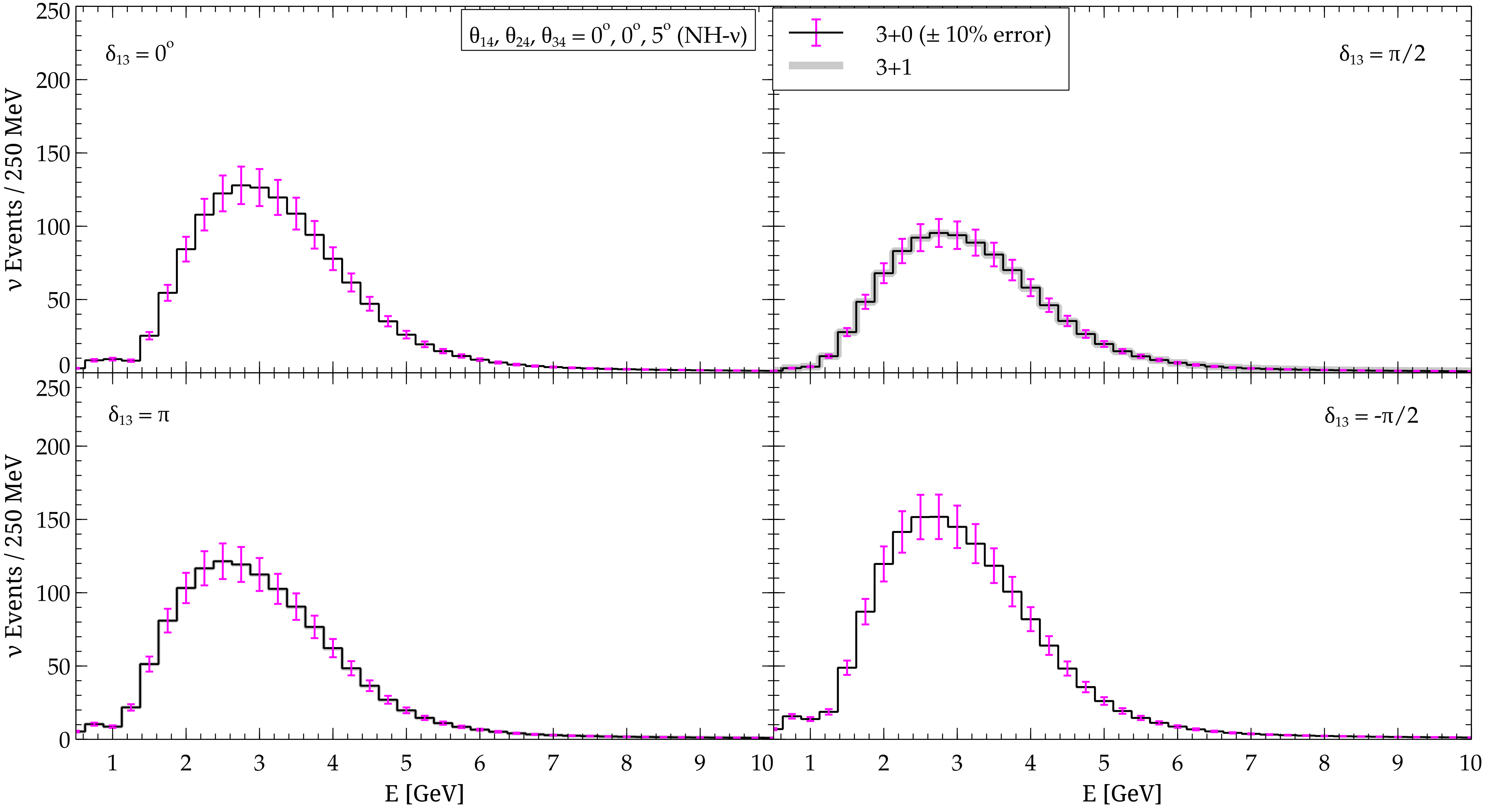
If 6% of reactor $\bar{\nu}_e$ disappear,

$$\sin^2 2\theta_{ee} = 4\times\left(3.0\times10^{-2}\right)$$

Short-baseline $\nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \cancel{\nu_\mu}$, and $\bar{\nu}_e \rightarrow \cancel{\bar{\nu}_e}$ measurements probe θ_{14} and θ_{24} . θ_{34} is hard to probe.

How big an effect can θ_{34} have on long-baseline behavior?

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



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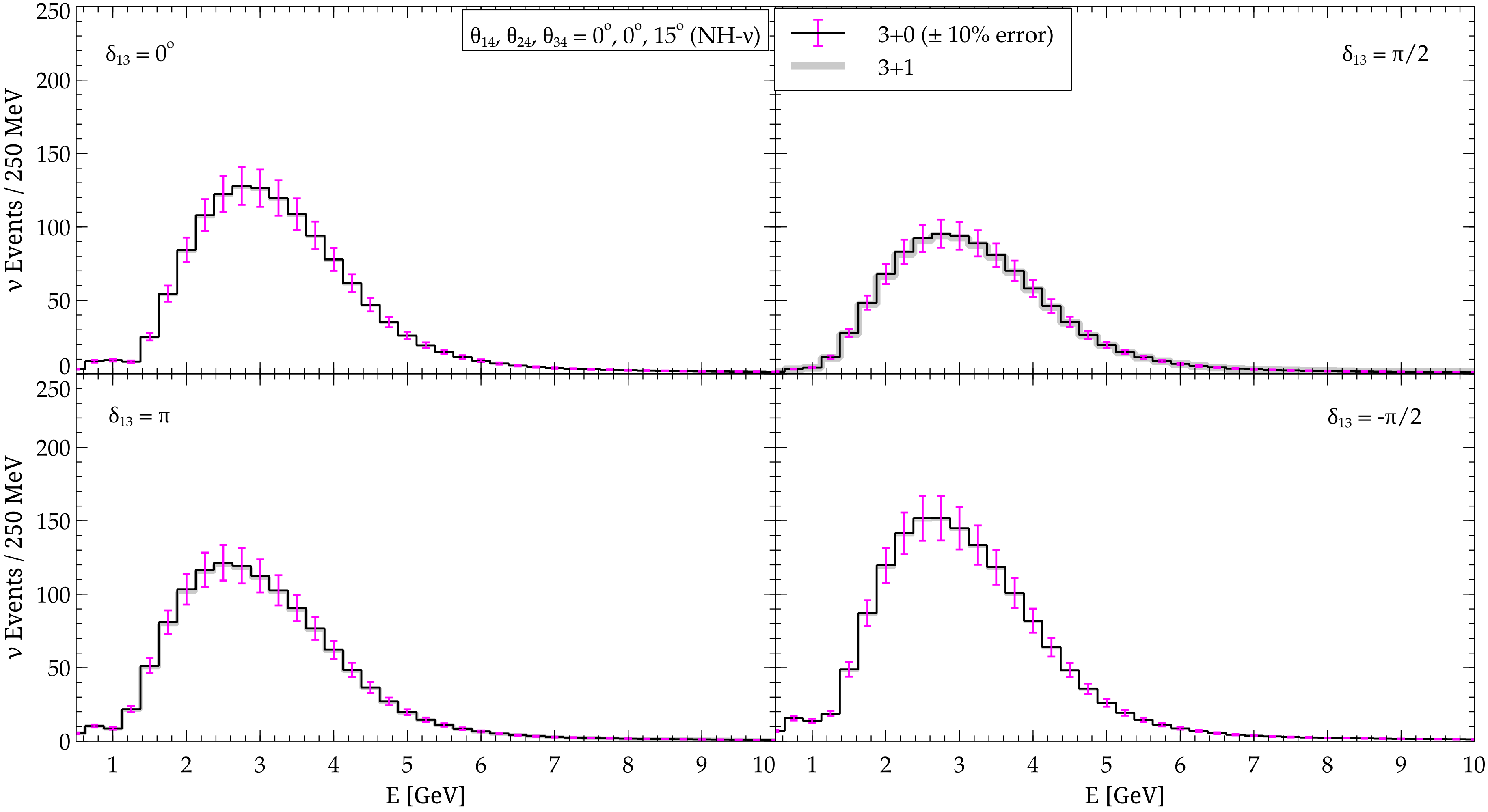

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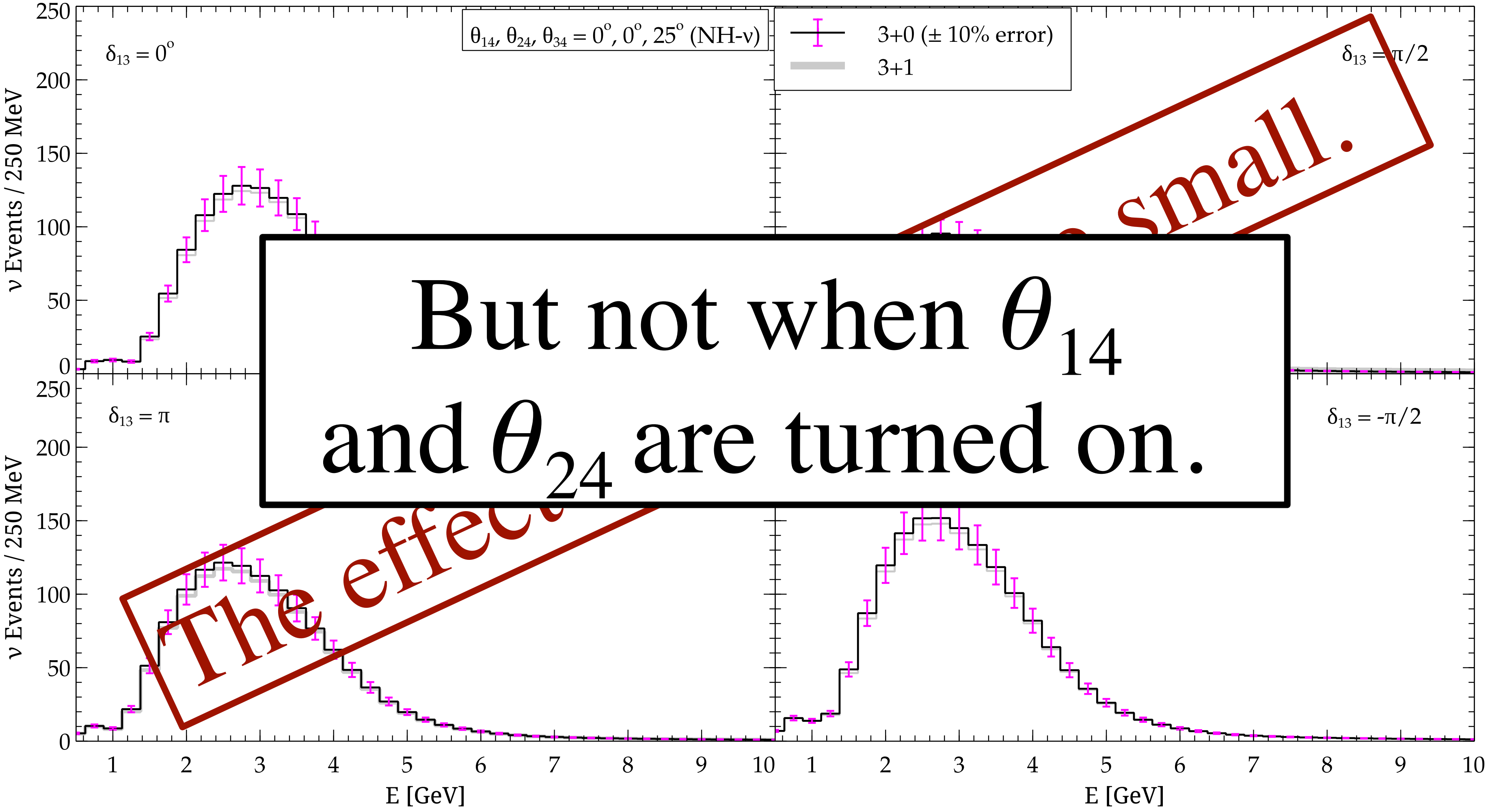


But not when θ_{14} and θ_{24} are turned on.

The Flip Side — Ability To Exclude 3 + 0 When the True Physics Is 3 + 1

To explore this question, we fix $\theta_{34} = 10°$,
and consider $\delta_{34} = -180°, -90°, 0°$, and $+90°$.

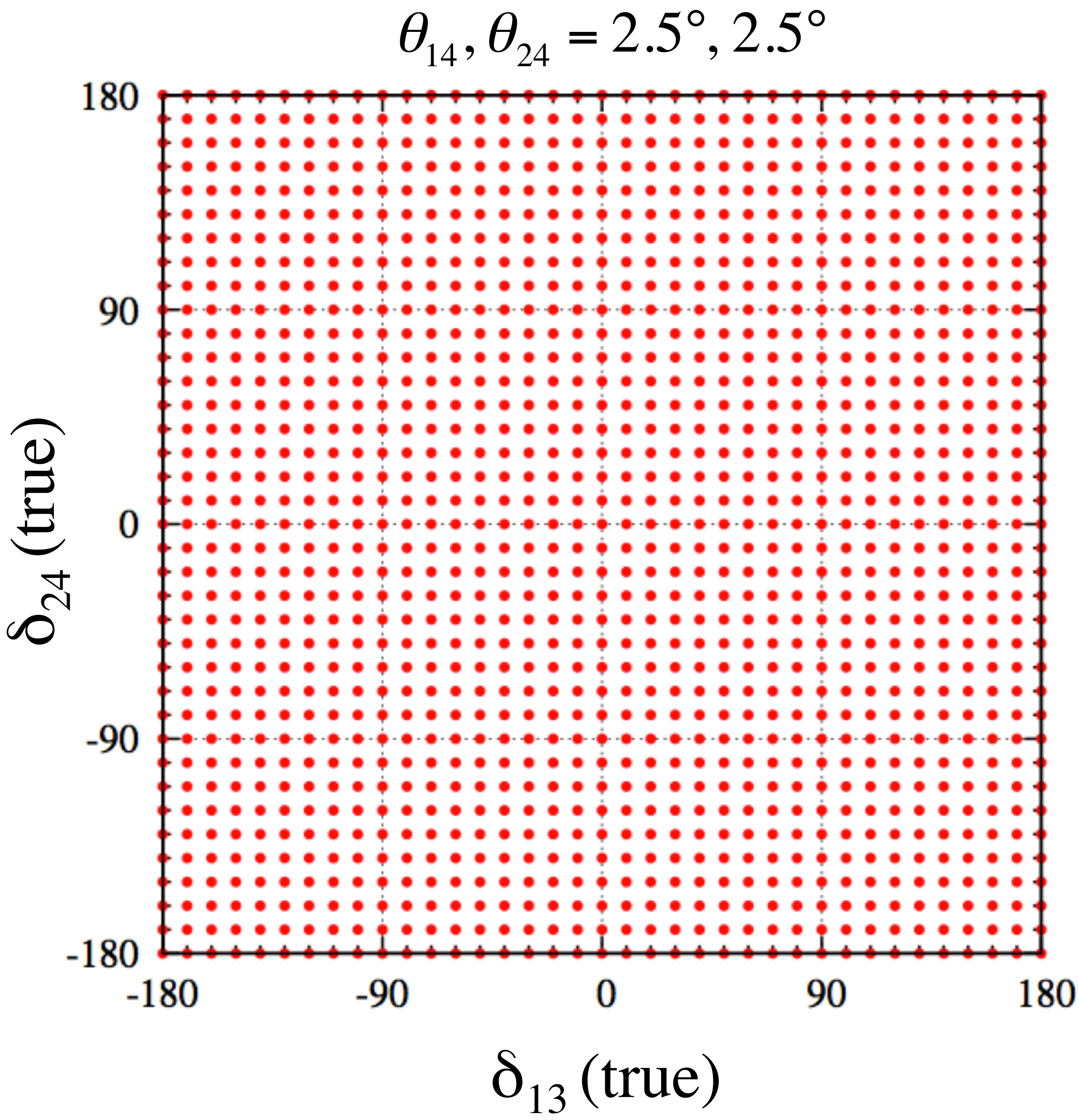
For each value of δ_{34}, we consider
gradually increasing values of θ_{14} and θ_{24} .

We show the results for $\delta_{34} = -90°$.

Red dots:
Cannot exclude
3 + 0, even
at 3σ

Blue dots:
Can exclude
3 + 0 at 3σ
but not 5σ

No dots:
Can exclude
3 + 0 at 5σ



Red dots:
Cannot exclude
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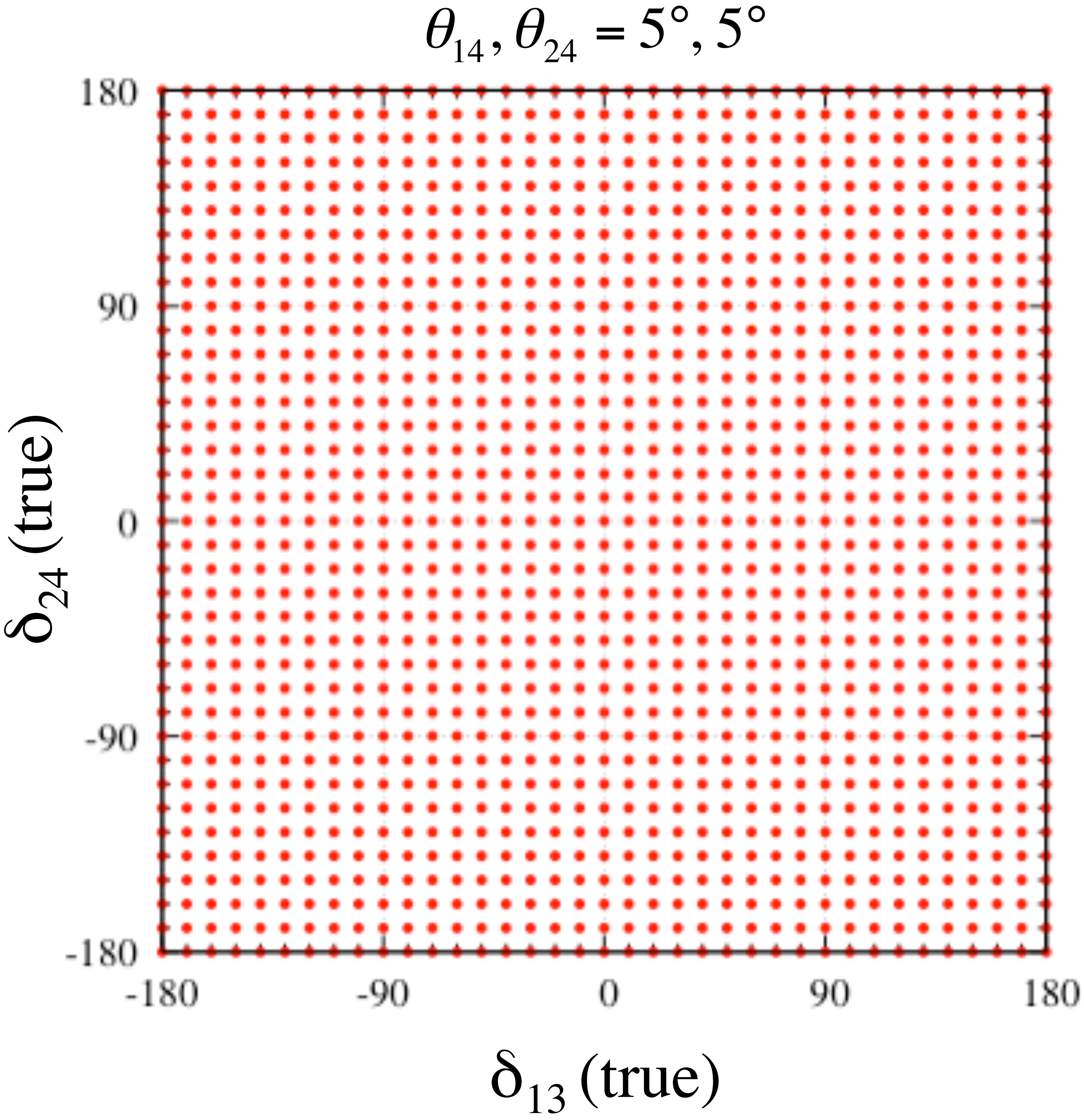
No dots:
Can exclude
3 + 0 at 5σ



Red dots:
Cannot exclude
3 + 0, even
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Blue dots:
Can exclude
3 + 0 at 3σ
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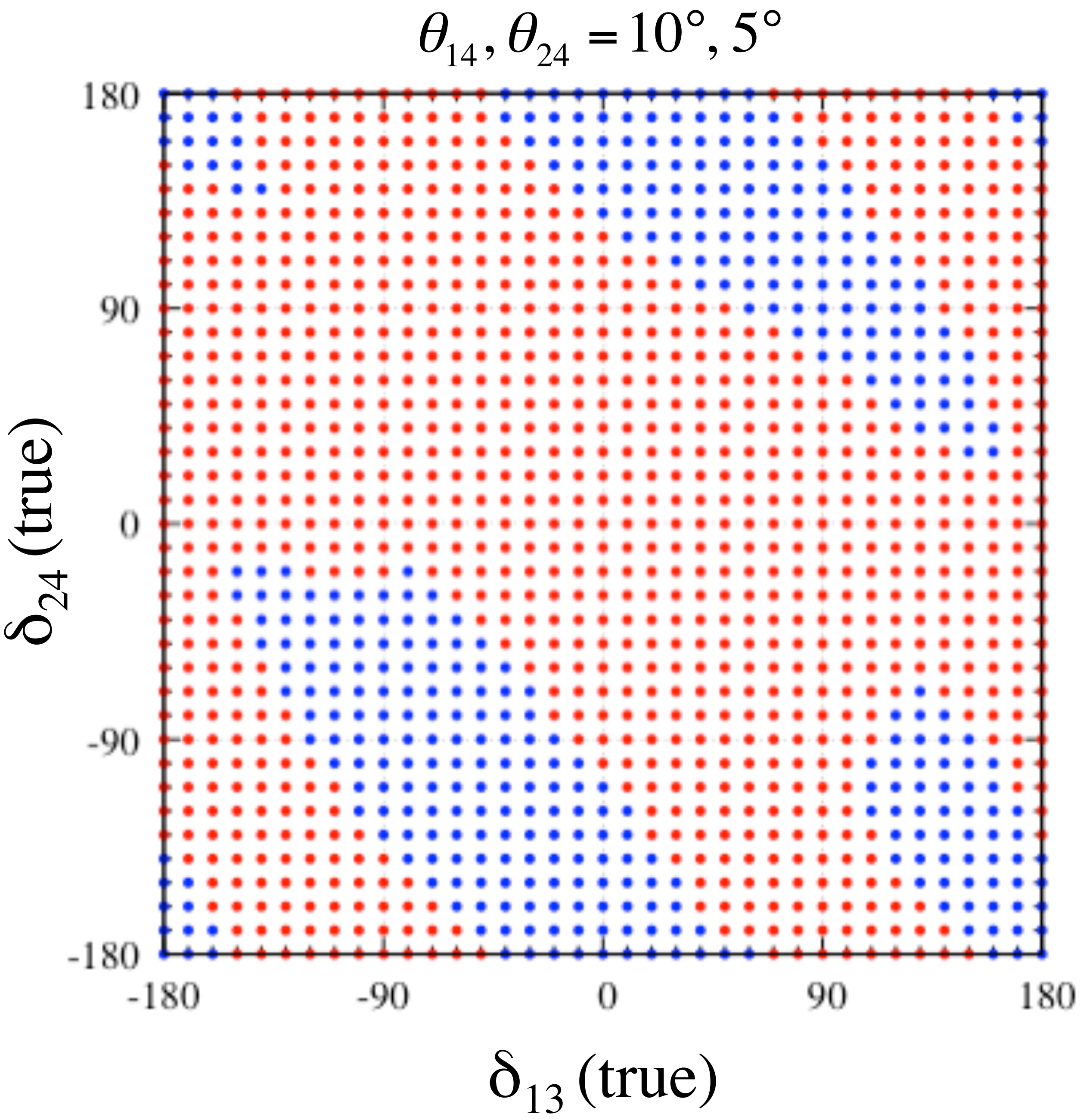
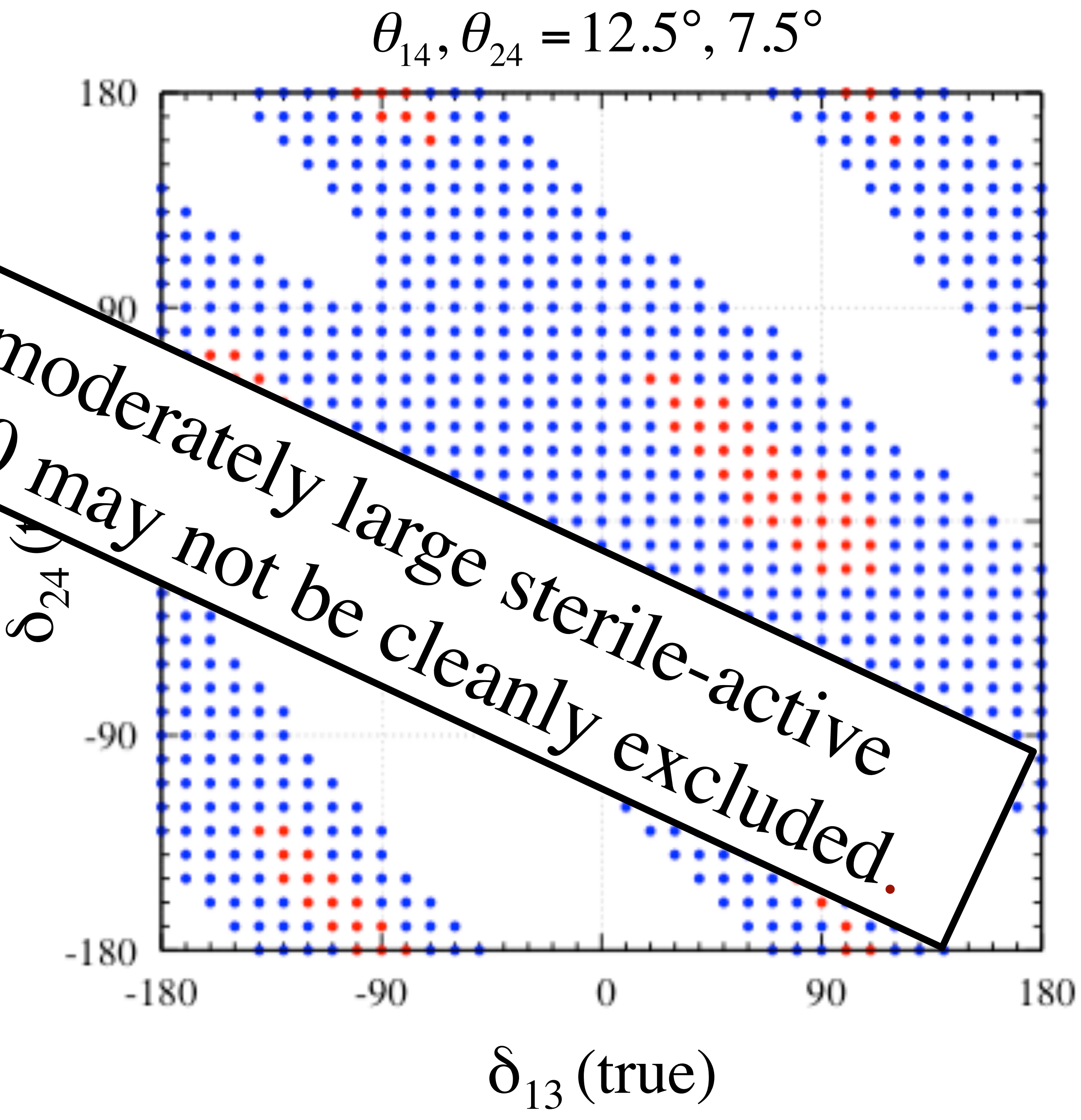
No dots:
Can exclude
3 + 0 at 5σ



Red dots:
Ca xclude

Blue dots:
Can exclude
3 + 0 at 3σ
but not 5σ

No dots:
Can exclude
3 + 0 at 5σ

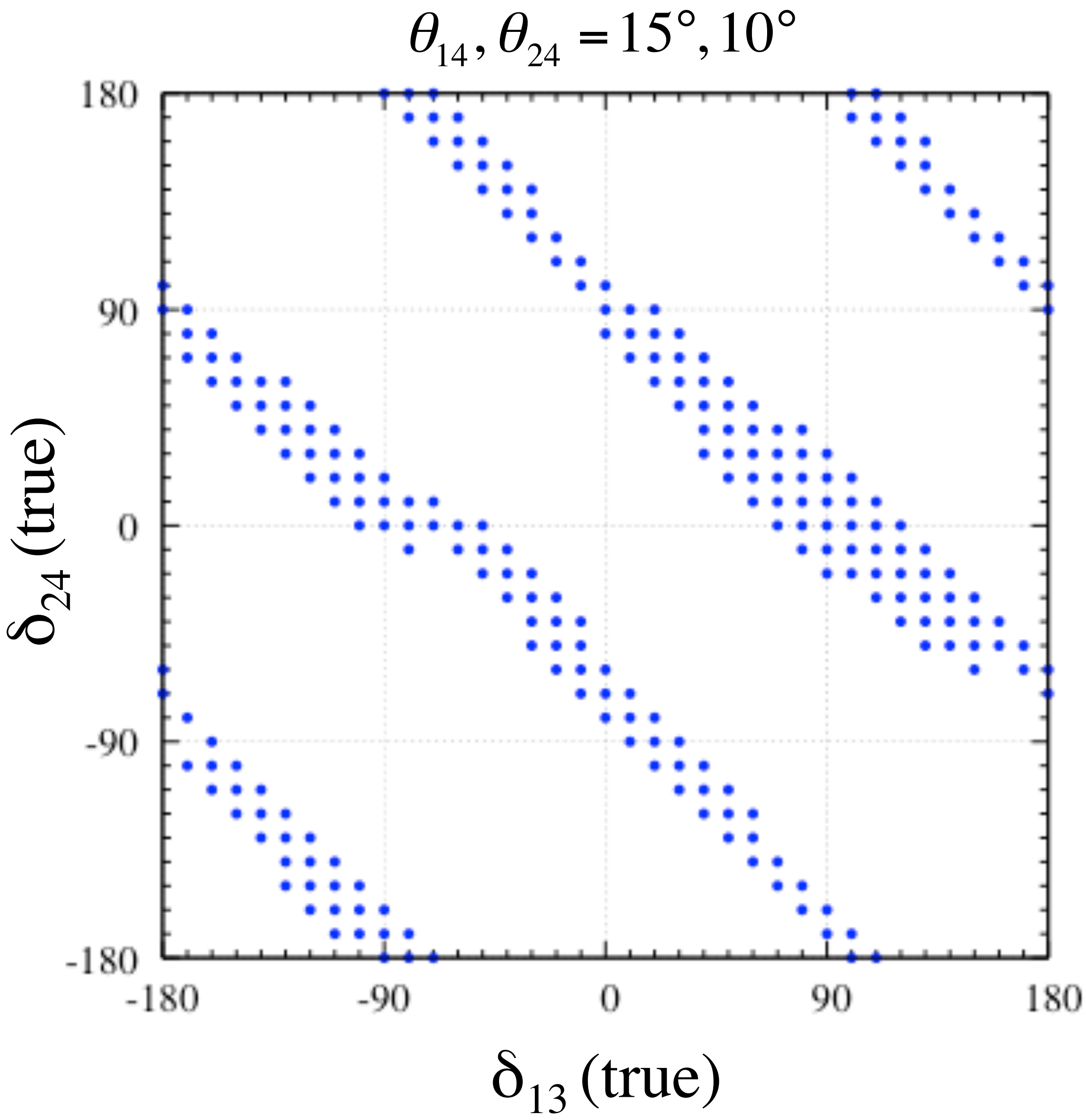


Even for moderately large sterile-active mixing, 3 + 0 may not be cleanly excluded.

Red dots:
Cannot exclude
3 + 0, even
at 3σ

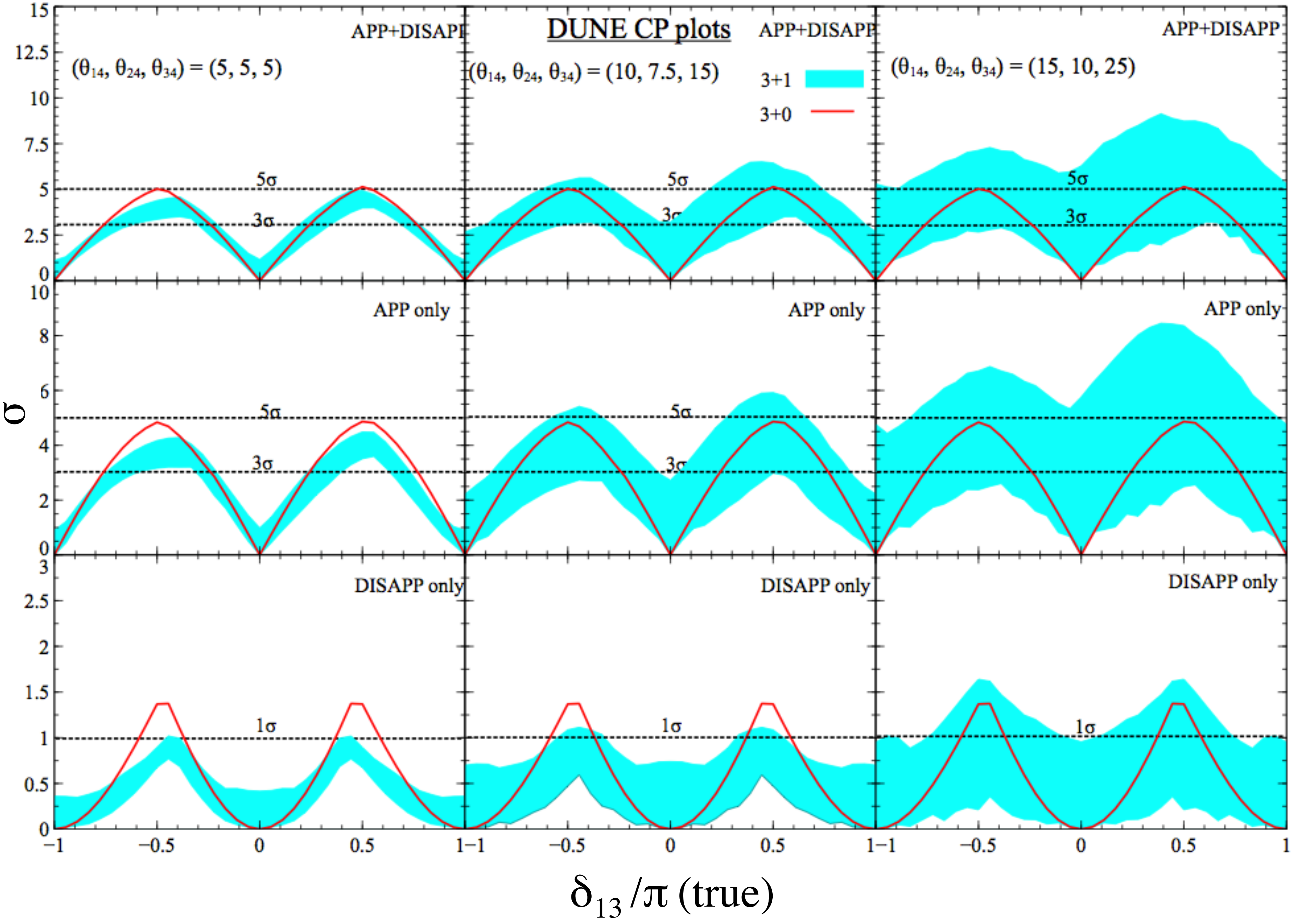
Blue dots:
Can exclude
3 + 0 at 3σ
but not 5σ

No dots:
Can exclude
3 + 0 at 5σ


$\theta_{14}, \theta_{24} = 15°, 10°$

Long-Baseline Sensitivity To the Key Phenomenon — CP Violation

We show the ability of DUNE to exclude
CP invariance, if the physics is known to be 3 + 1,
and the 3 + 0 hierarchy is known to be normal.


DUNE CP plots
APP+DISAPP
APP only
DISAPP only
(θ14, θ24, θ34) = (5, 5, 5)
(θ14, θ24, θ34) = (10, 7.5, 15)
(θ14, θ24, θ34) = (15, 10, 25)
3+1
3+0
5σ
3σ
1σ
σ
δ13 /π (true)
15
12.5
10
7.5
5
2.5
0
10
8
6
4
2
0
3
2.5
2
1.5
1
0.5
0
−1
−0.5
0
0.5
1

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.