Sterile Neutrinos and LBL CP Violation Measurements

Boris Kayser
MITP
July 27, 2015

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 $\Delta m^2 \sim 1\ \mathrm{eV}^2$.

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

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

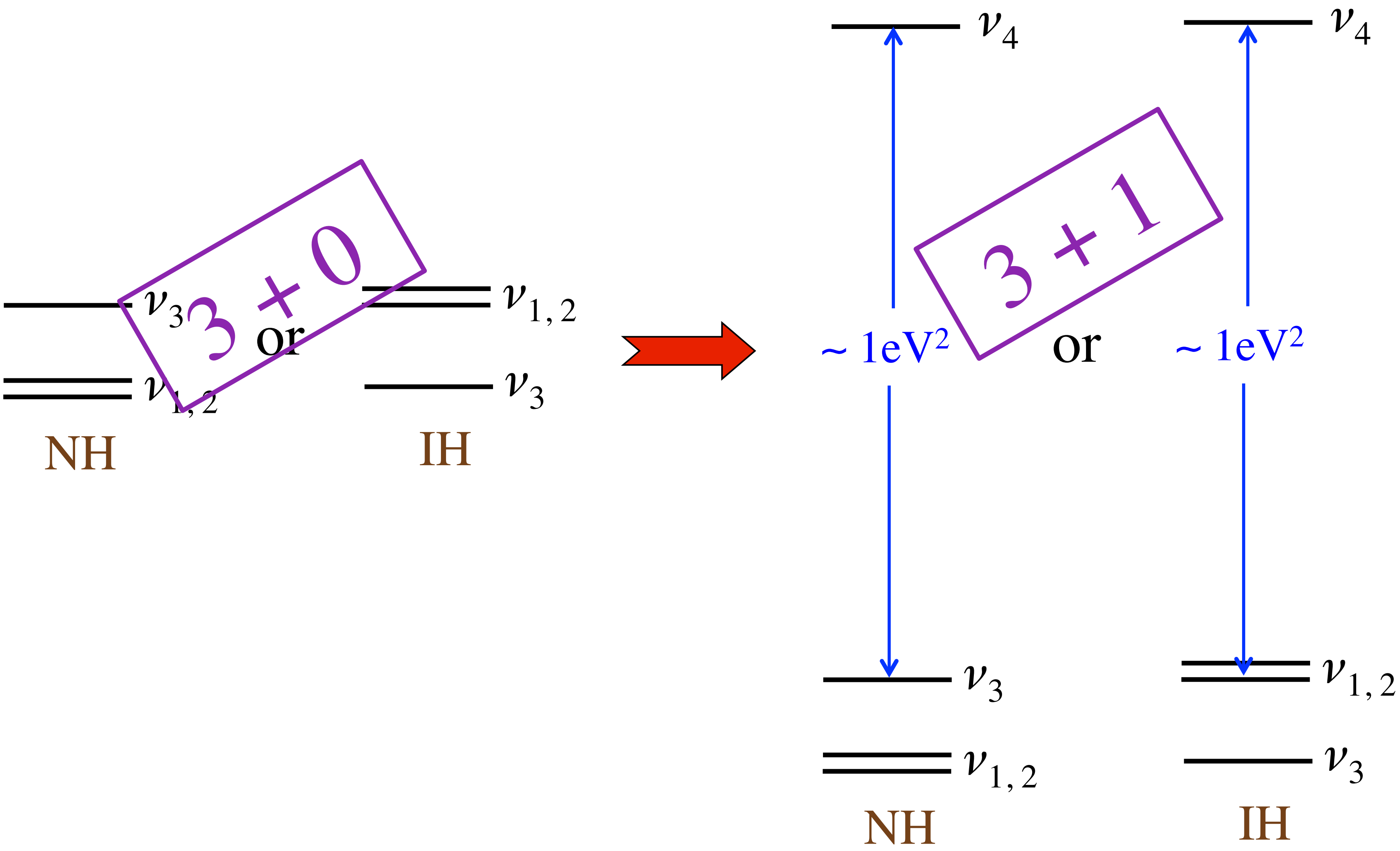
Related work includes studies by —

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 —



ν_3

$\nu_{1,2}$

NH

or

$\nu_{1,2}$

ν_3

IH

3 + 0

ν_4

$\sim 1\text{eV}^2$

ν_3

$\nu_{1,2}$

NH

or

ν_4

$\sim 1\text{eV}^2$

$\nu_{1,2}$

ν_3

IH

3 + 1

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

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

➡ $\Delta_{e\mu} = \Delta_{\mu\tau} = \Delta_{\tau e}$.

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

⇒ $\Delta_{e\mu} = \Delta_{\mu\tau} + \Delta_{\mu s}$, etc.

Good luck

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 $\Delta m^2_{41} \sim 1 \text{ eV}^2$ to an energy-independent, ***but nonzero***, value.

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

We use the **General Long Baseline Experiment Simulator GLoBES** to assess the Long Baseline consequences of these large-Δm^2 oscillations, the additional mixing angles, and the additional CP-violating phases.

The “established” parameters are taken 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 —

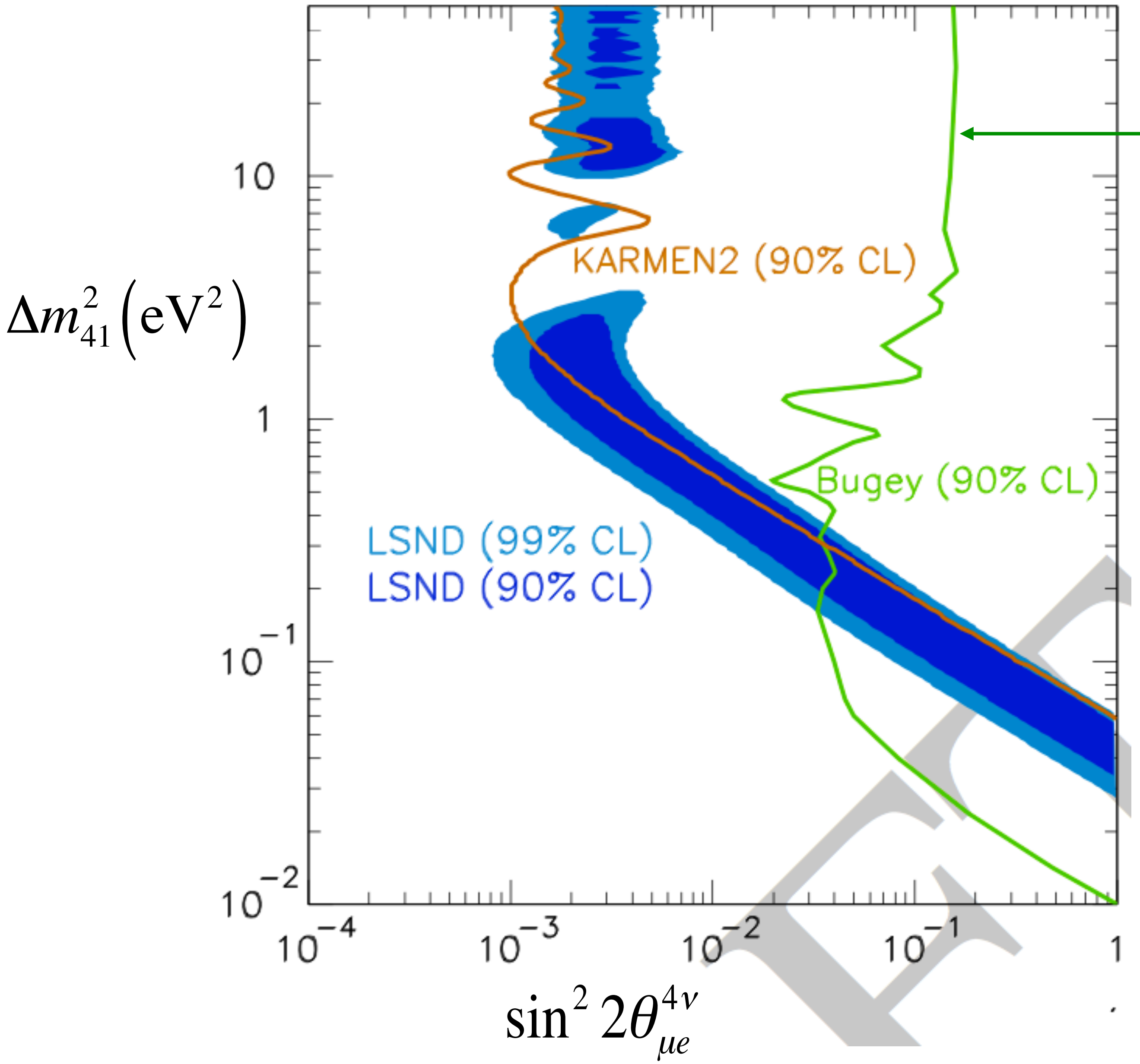
$$0^\circ \leq \theta_{14} \leq 20^\circ, \quad 0^\circ \leq \theta_{24} \leq 10^\circ, \quad 0^\circ \leq \theta_{34} \leq 30^\circ$$

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

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 —

$$\sin^2 2\theta_{\mu e}^{4\nu} = 0.012\,.$$

The LSND-favored region



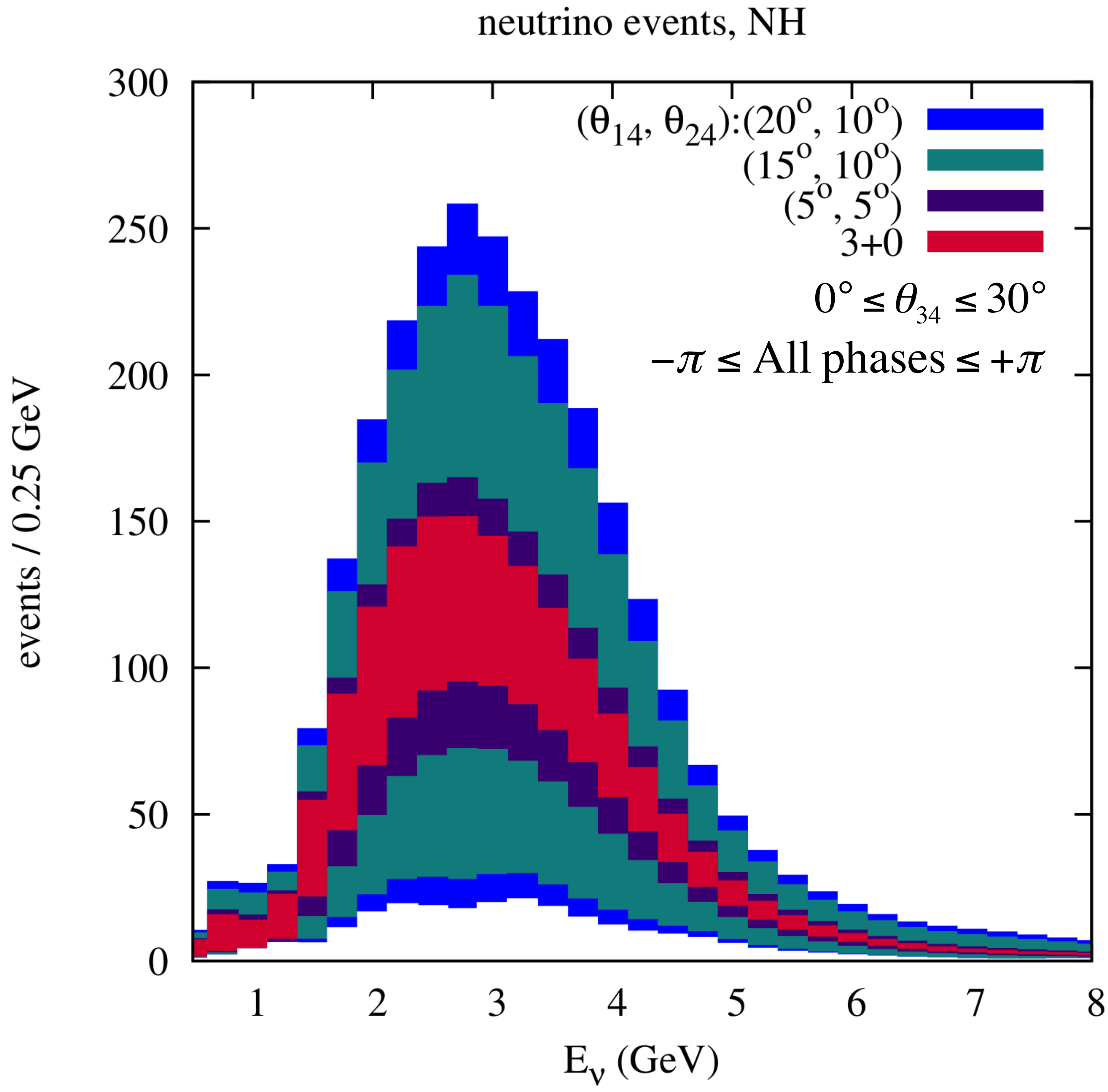
Out of date

3 + 1
spectrum
assumed.

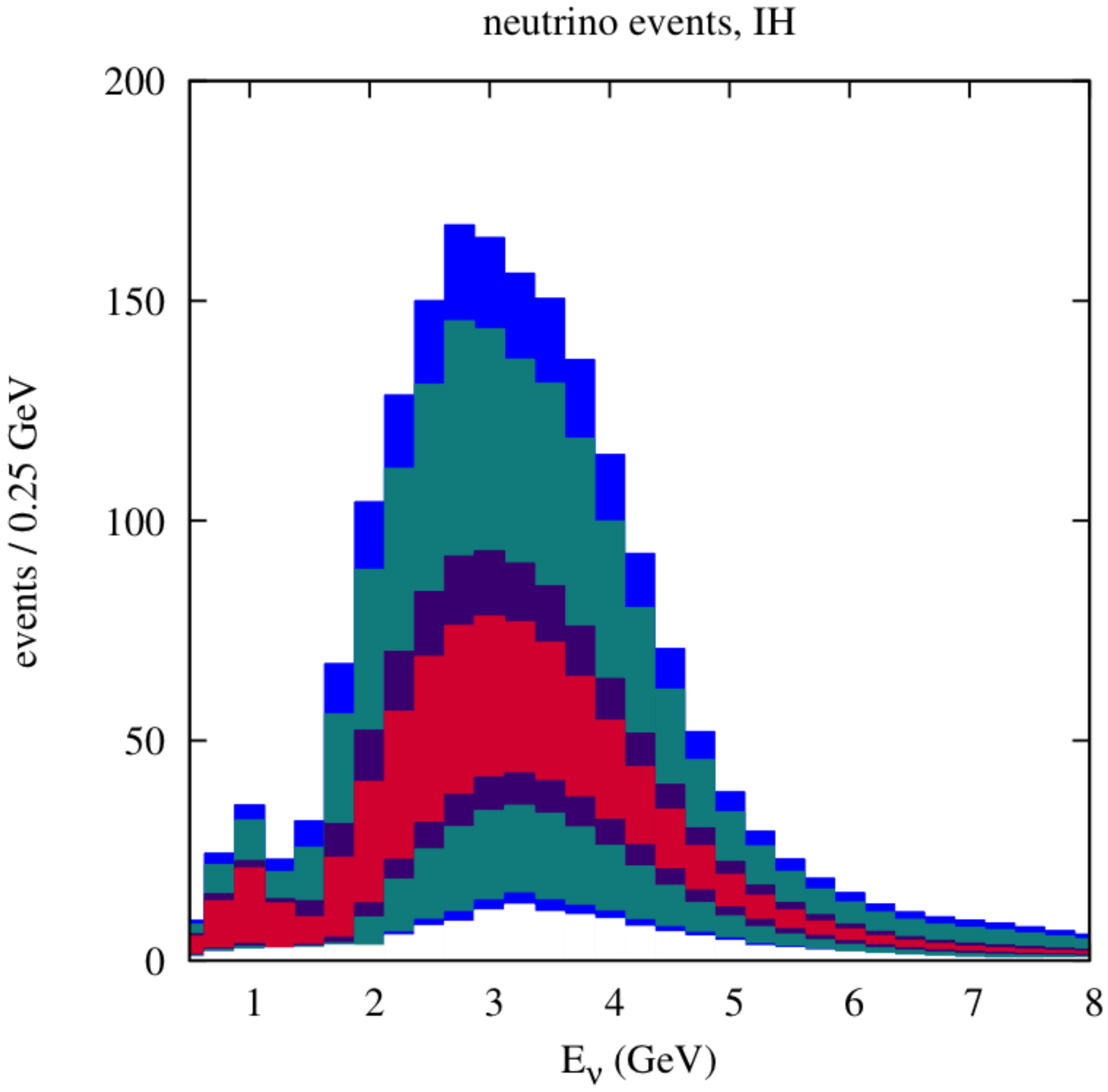
When considering the standard 3 + 0 (no sterile neutrinos) model, we vary the sole CP-violating phase δ_{13} from $-\pi$ to $+\pi$, and when considering the 3 + 1 model, we do the same for all three CP-violating phases, δ_{13}, δ_{24}, and δ_{34}.

Our event rates are based on —

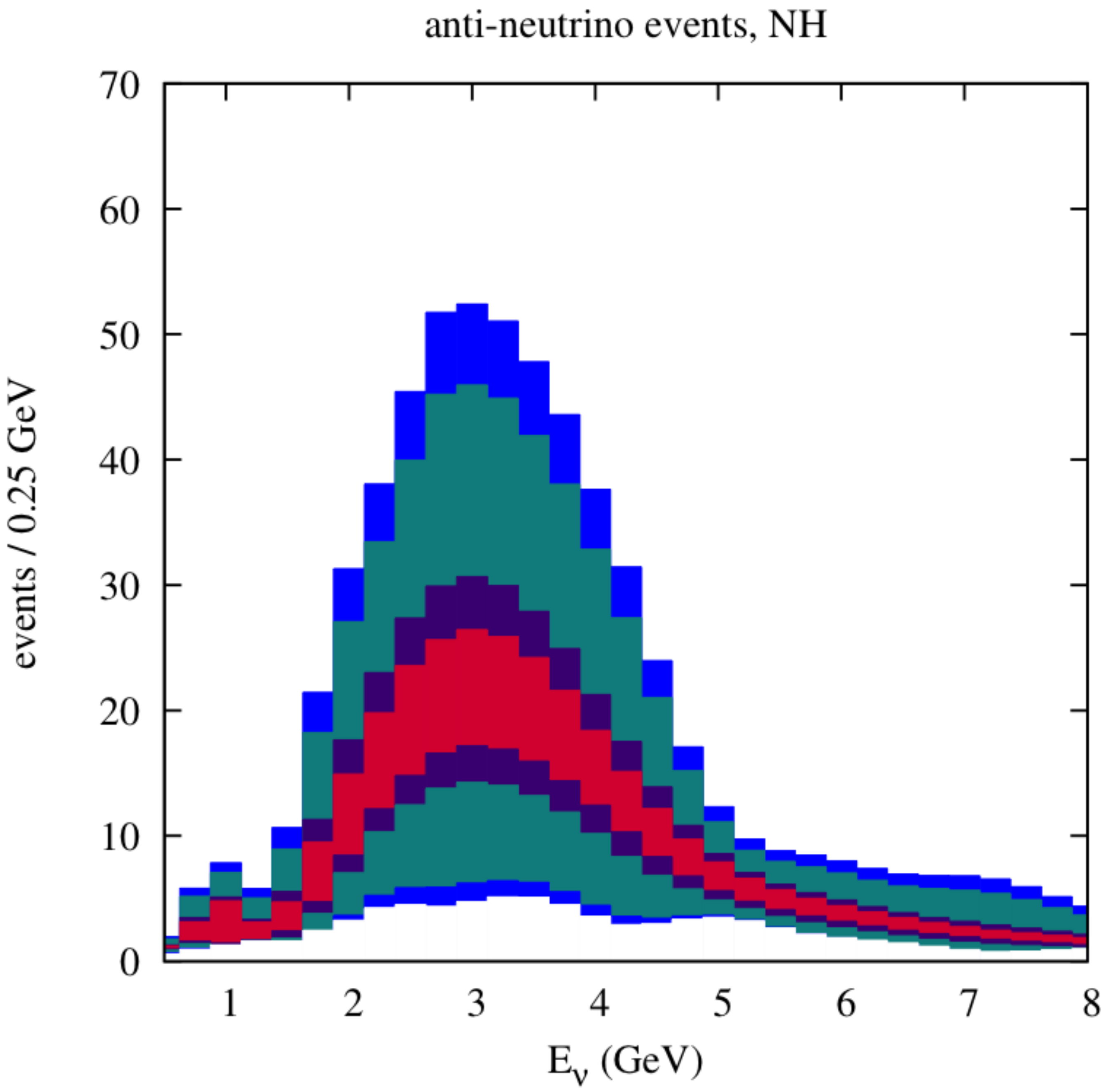
L = 1300 km, a 35 kton far detector, 10^{21} POT/yr, and 10 years of running (35 x 10^{22} kton-POT-yr), divided evenly between neutrinos and antineutrinos.



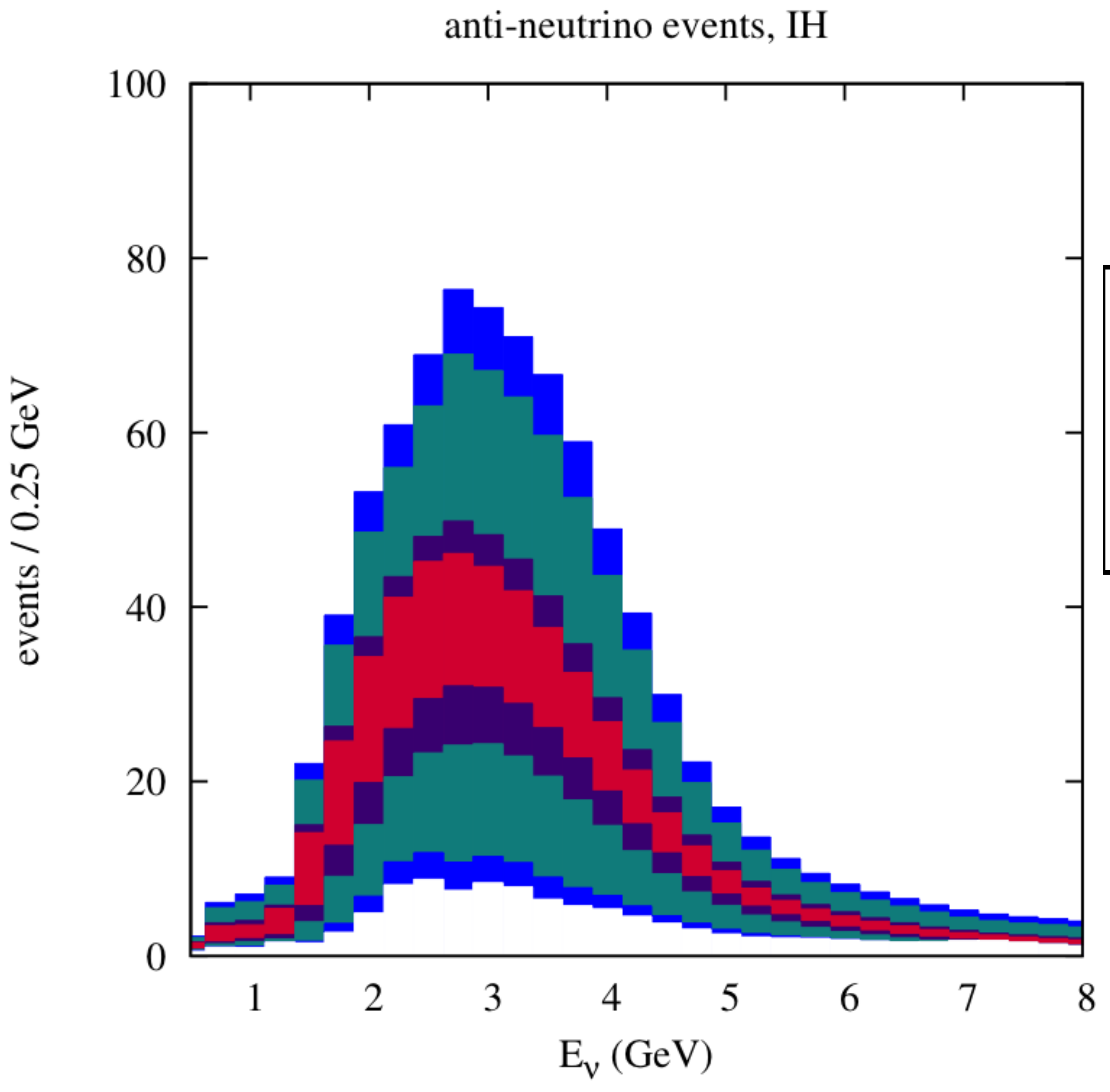
Event rate vs. reconstructed neutrino energy.



Event rate vs. reconstructed neutrino energy.



Event rate vs. reconstructed neutrino energy.



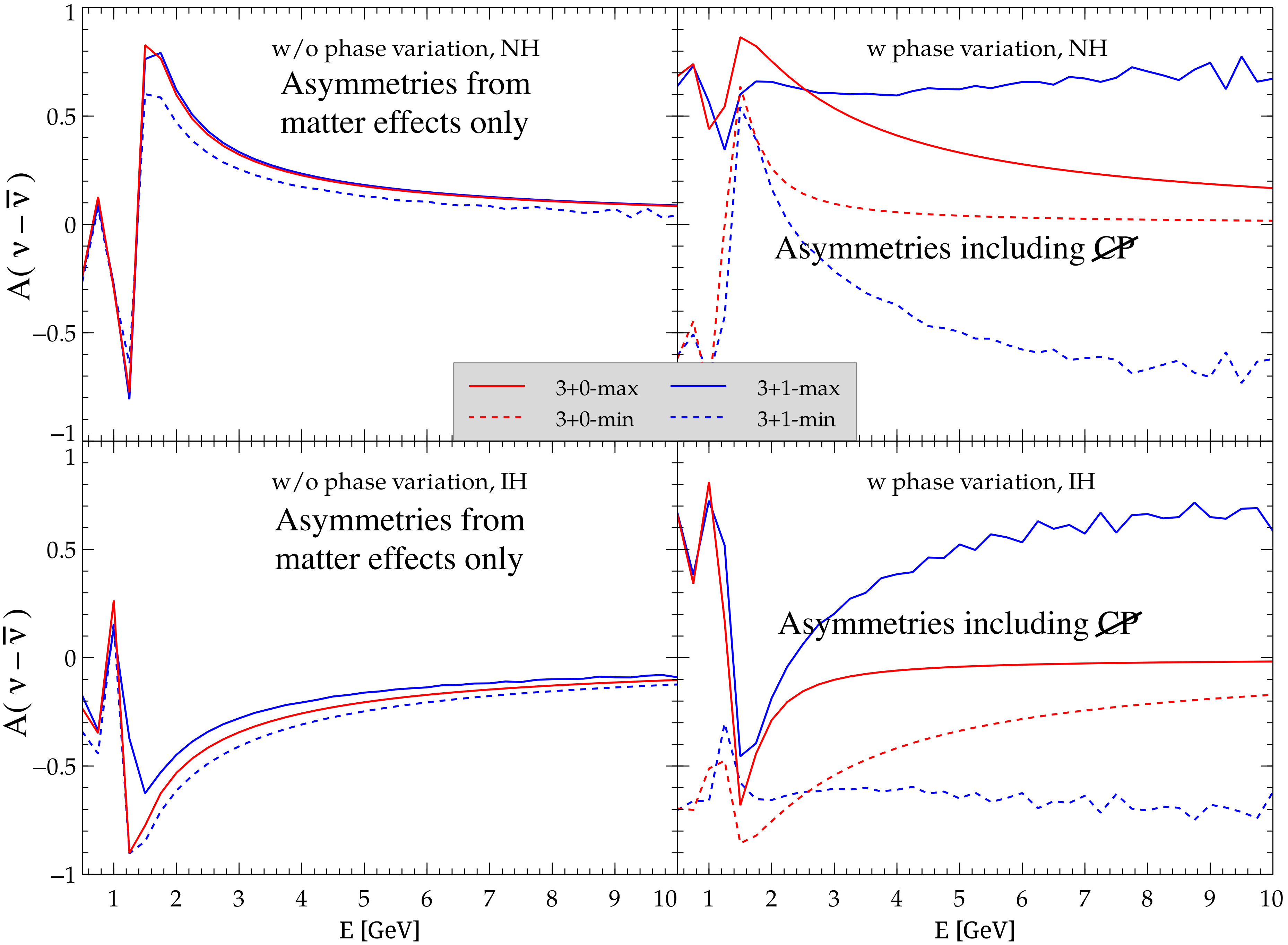
Event rate vs. reconstructed neutrino energy.

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.

***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***.



w/o phase variation, NH
Asymmetries from matter effects only
w phase variation, NH
Asymmetries including $\cancel{CP}$
w/o phase variation, IH
Asymmetries from matter effects only
w phase variation, IH
Asymmetries including $\cancel{CP}$
3+0-max
3+0-min
3+1-max
3+1-min
$A(\nu - \overline{\nu})$
1
0.5
0
−0.5
−1
1
2
3
4
5
6
7
8
9
10
E [GeV]

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, $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\tau$,
even if there is none in $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$.

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 tells us definitively whether
1 eV scale sterile neutrinos actually exist.