Sterile Neutrinos at DUNE

André de Gouvêa – Northwestern University

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{Berryman *et al*, PRD92, 073012 (2015) [arXiv:1507.03986]}

More New Physics In Neutrino Oscillations:
What Else Could We Run Into?

- New neutrino states. In this case, the 3×3 mixing matrix would not be unitary.
- New short-range neutrino interactions. These lead to, for example, new matter effects.
- New, unexpected neutrino properties. Do they have nonzero magnetic moments? Do they decay? The answer is 'yes' to both, but nature might deviate dramatically from νSM expectations.
- Weird stuff. CPT-violation. Decoherence effects (aka "violations of Quantum Mechanics.")
- etc.

Case Study

I will discuss one case-study: the fourth-neutrino hypothesis. First, some general considerations…

- I will discuss, for concreteness, the DUNE setup;
- I don't particularly care about how likely, nice, or contrived the scenario is. It is useful to consider it as a well defined way in which the three-flavor paradigm can be violated. It can be used as a benchmark for comparing different efforts, or, perhaps, as a proxy for other new phenomena.
- I will mostly be interested in three questions:
  - How sensitive are next-generation long-baseline efforts?;
  - How well they can measure the new-physics parameters, including new sources of CP-invariance violation?;
  - Can they tell different new-physics models apart?

A Fourth Neutrino

(Berryman et al, arXiv:1507.03986)

If there are more neutrinos with a well defined mass, it is easy to extend the three-neutrino paradigm:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_? \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{?1} & U_{?2} & U_{?3} & U_{?4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

- New mass eigenstates easy: ν_4 with mass m_4, ν_5 with mass m_5, etc.
- What are these new "flavor" (or weak) eigenstates $\nu_?$? Here, the answer is we don't care. We only assume there are no new accessible interactions associated to these states.

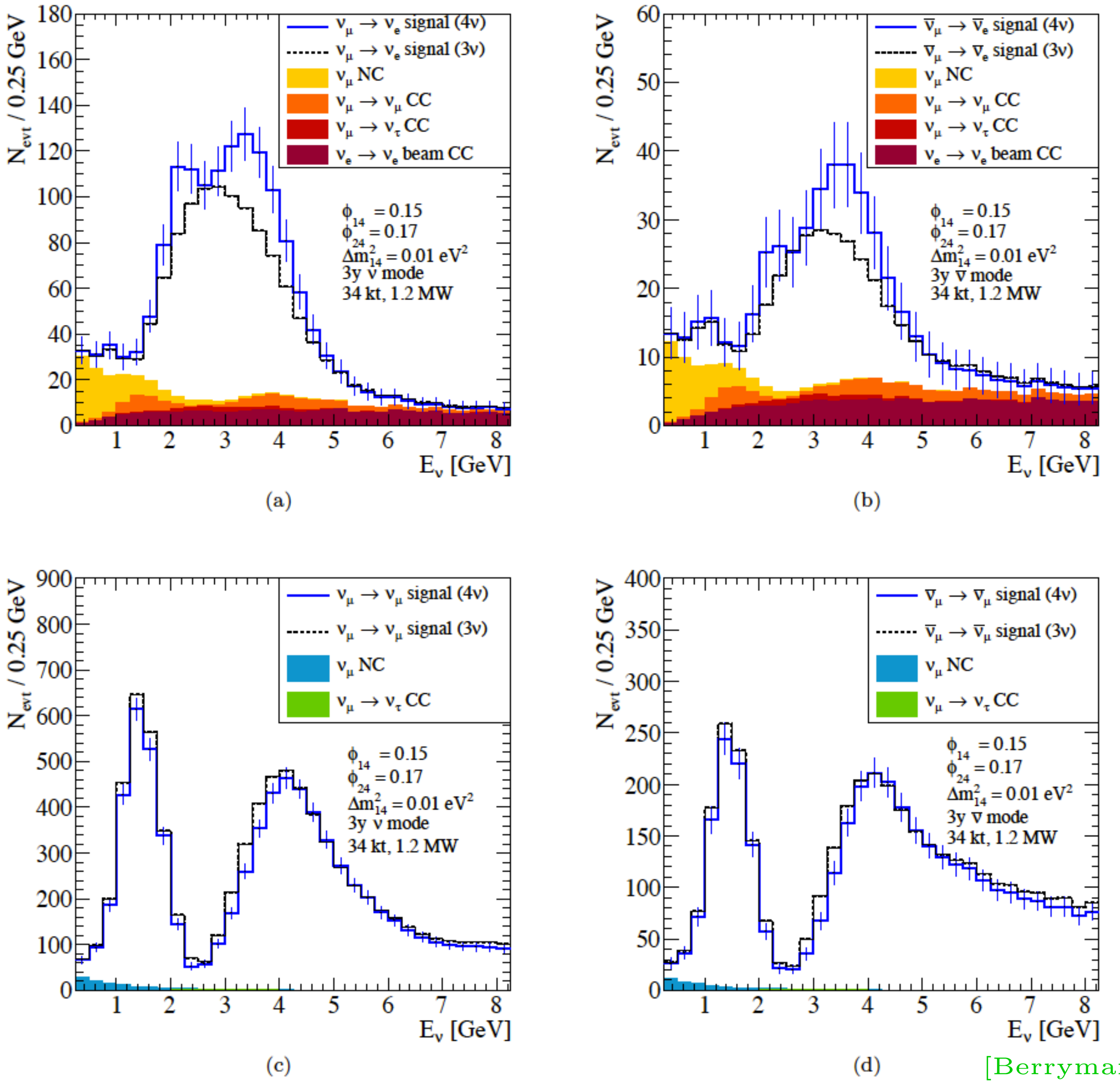
$$
\begin{aligned}
U_{e2} &= s_{12}c_{13}c_{14}, \\
U_{e3} &= e^{-i\eta_1}s_{13}c_{14}, \\
U_{e4} &= e^{-i\eta_2}s_{14}, \\
U_{\mu 2} &= c_{24}\left(c_{12}c_{23} - e^{i\eta_1}s_{12}s_{13}s_{23}\right) - e^{i(\eta_2-\eta_3)}s_{12}s_{14}s_{24}c_{13}, \\
U_{\mu 3} &= s_{23}c_{13}c_{24} - e^{i(\eta_2-\eta_3-\eta_1)}s_{13}s_{14}s_{24}, \\
U_{\mu 4} &= e^{-i\eta_3}s_{24}c_{14}, \\
U_{\tau 2} &= c_{34}\left(-c_{12}s_{23} - e^{i\eta_1}s_{12}s_{13}c_{23}\right) - e^{i\eta_2}c_{13}c_{24}s_{12}s_{14}s_{34} \\
&\quad -e^{i\eta_3}\left(c_{12}c_{23} - e^{i\eta_1}s_{12}s_{13}s_{23}\right)s_{24}s_{34}, \\
U_{\tau 3} &= c_{13}c_{23}c_{34} - e^{i(\eta_2-\eta_1)}s_{13}s_{14}s_{34}c_{24} - e^{i\eta_3}s_{23}s_{24}s_{34}c_{13}, \\
U_{\tau 4} &= s_{34}c_{14}c_{24}.
\end{aligned}
$$

Here c_{ij}, s_{ij} short for $\cos\phi_{ij}, \sin\phi_{ij}$, $i,j = 1,2,3,4$. When the new mixing angles ϕ_{14}, ϕ_{24}, and ϕ_{34} vanish, one encounters oscillations among only three neutrinos, and we can map the remaining parameters $\{\phi_{12},\ \phi_{13},\ \phi_{23},\ \eta_1\} \rightarrow \{\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{CP}\}$.

Also

$$\eta_s \equiv \eta_2 - \eta_3,$$

is the only new CP-odd parameter to which oscillations among ν_e and ν_μ are sensitive.

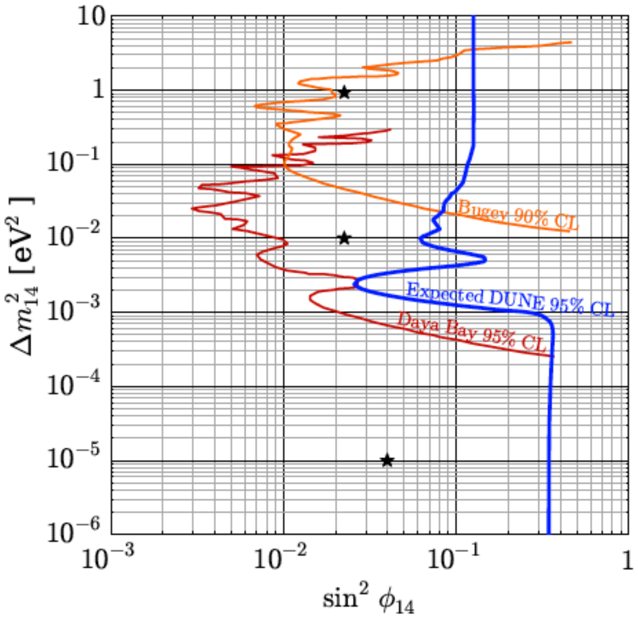


[Berryman et al, arXiv:1507.03986]

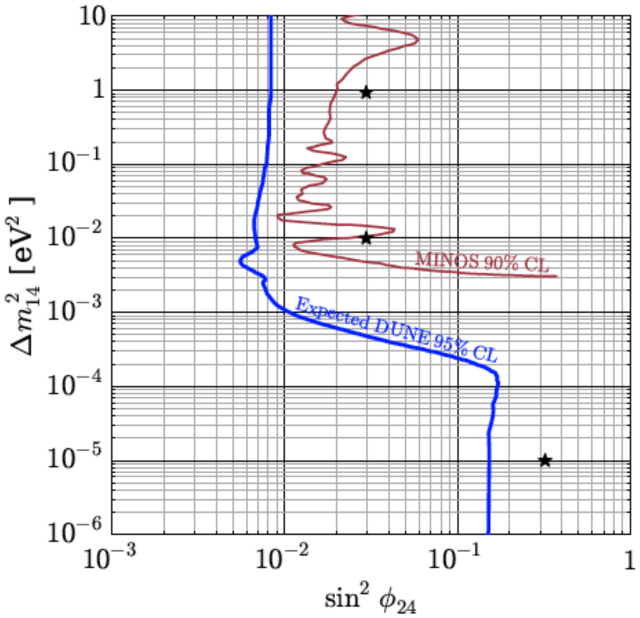
FIG. 1: Expected signal and background yields for six years (3y ν + 3y $\overline{\nu}$) of data collection at DUNE, using fluxes projected by Ref. [1], for a 34 kiloton detector, and a 1.2 MW beam. (a) and (b) show appearance channel yields for neutrino and antineutrino beams, respectively, while (c) and (d) show disappearance channel yields. The 3ν signal corresponds to the standard three-neutrino hypothesis, where $\sin^2\theta_{12} = 0.308$, $\sin^2\theta_{13} = 0.0235$, $\sin^2\theta_{23} = 0.437$, $\Delta m^2_{12} = 7.54 \times 10^{-5}$ eV^2, $\Delta m^2_{13} = 2.43 \times 10^{-3}$ eV^2, $\delta_{CP} = 0$, while the 4ν signal corresponds to $\sin^2\phi_{12} = 0.315$, $\sin^2\phi_{13} = 0.024$, $\sin^2\phi_{23} = 0.456$, $\sin^2\phi_{14} = 0.023$, $\sin^2\phi_{24} = 0.030$, $\Delta m^2_{14} = 10^{-2}$ eV^2, $\eta_1 = 0$, and $\eta_s = 0$. Statistical uncertainties are shown as vertical bars in each bin. Backgrounds are defined in the text and are assumed to be identical for the three- and four-neutrino scenarios: any discrepancy is negligible after accounting for a 5% normalization uncertainty.

Some technicalities for the aficionados

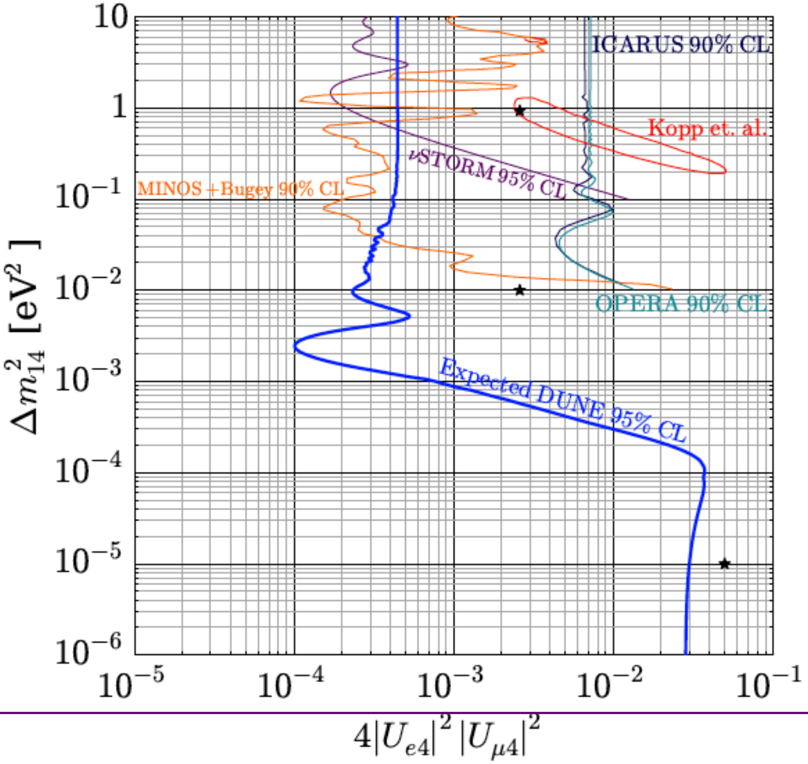
- 34 kiloton liquid argon detector;
- 1.2 MW proton beam on target as the source of the neutrino and antineutrino beams, originating 1300 km upstream at Fermilab;
- 3 years each with the neutrino and antineutrino mode;
- Include standard backgrounds, and assume a 5% normalization uncertainty;
- Whenever quoting bounds or measurements of anything, we marginalize over all parameters not under consideration;
- We include priors on Δm^2_{12} and $|U_{e2}|^2$ in order to take into account information from solar experiments and KamLAND. Unless otherwise noted, **we assume the mass ordering is normal**;
- Except for the solar parameters, as discussed above, do not include information from other experiments. We assume that DUNE will "out measure" all experiments that come before it. This is not entirely true, but is not a bad approximation.



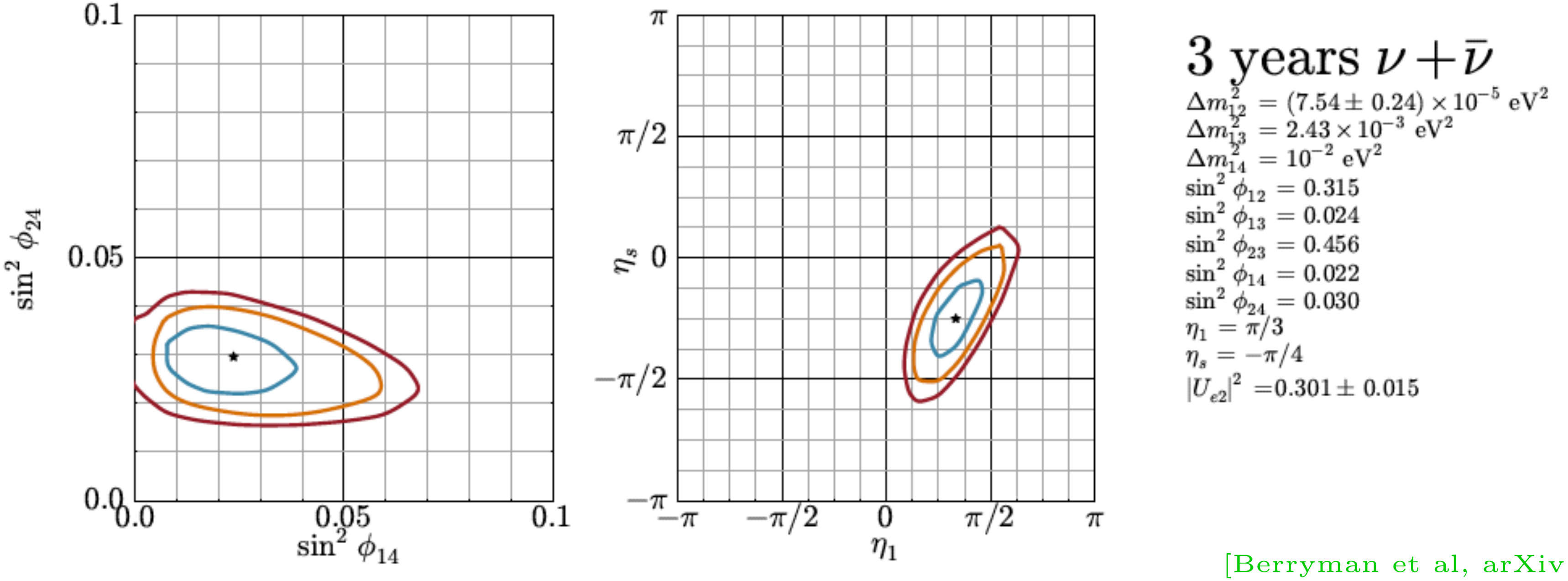
(a)



(b)



[Berryman et al, arXiv:1507.03986]

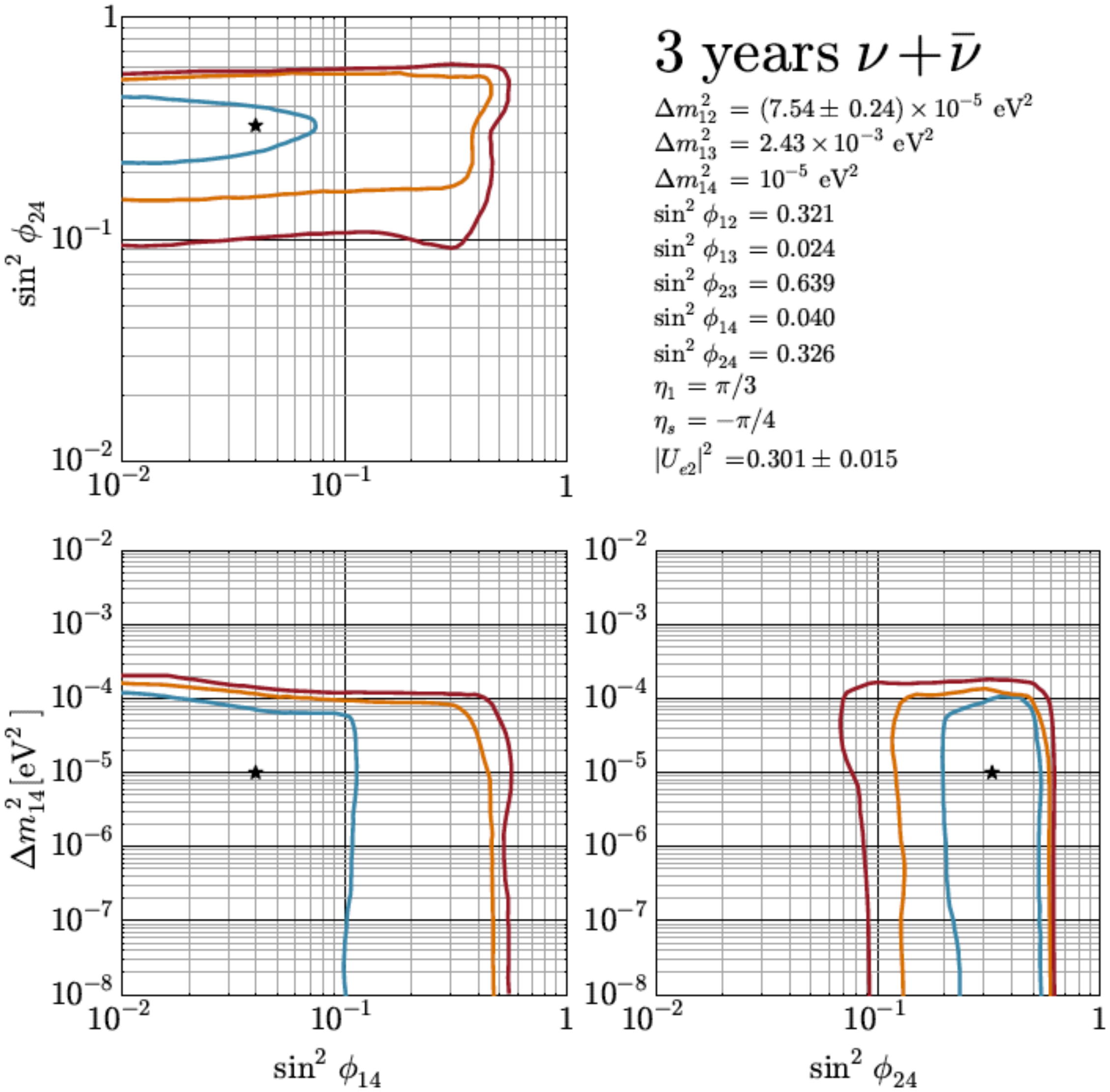


[Berryman et al, arXiv:1507.03986]

FIG. 5: Expected sensitivity contours at 68.3% (blue), 95% (orange), and 99% (red) CL at DUNE with six years of data collection (3y ν + 3y $\overline{\nu}$), a 34 kiloton detector, and a 1.2 MW beam given the existence of a fourth neutrino with parameters from Case 2 in Table I. Results from solar neutrino experiments are included here as Gaussian priors for the values of $|U_{e2}|^2 = 0.301 \pm 0.015$ and $\Delta m^2_{12} = 7.54 \pm 0.24 \times 10^{-5}$ eV^2 [22].

	$\sin^2\phi_{14}$	$\sin^2\phi_{24}$	Δm^2_{14} (eV^2)	η_s	$\sin^2\phi_{12}$	$\sin^2\phi_{13}$	$\sin^2\phi_{23}$	Δm^2_{12} (eV^2)	Δm^2_{13} (eV^2)	η_1
Case 1	0.023	0.030	0.93	$-\pi/4$	0.315	0.0238	0.456	7.54×10^{-5}	2.43×10^{-3}	$\pi/3$
Case 2	0.023	0.030	1.0×10^{-2}	$-\pi/4$	0.315	0.0238	0.456	7.54×10^{-5}	2.43×10^{-3}	$\pi/3$
Case 3	0.040	0.320	1.0×10^{-5}	$-\pi/4$	0.321	0.0244	0.639	7.54×10^{-5}	2.43×10^{-3}	$\pi/3$

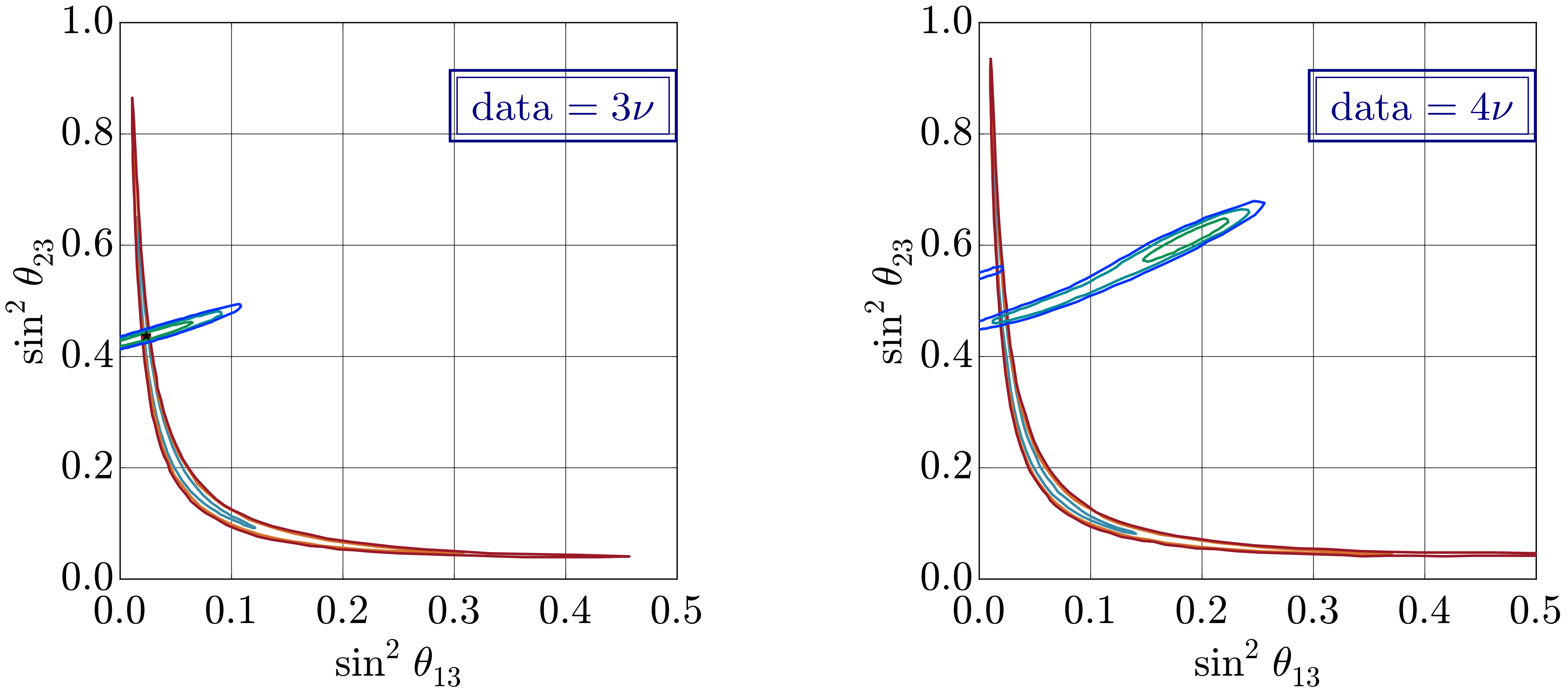
TABLE I: Input values of the parameters for the three scenarios considered for the four-neutrino hypothesis. Values of ϕ_{12}, ϕ_{13}, and ϕ_{23} are chosen to be consistent with the best-fit values of $|U_{e2}|^2$, $|U_{e3}|^2$, and $|U_{\mu 3}|^2$, given choices of ϕ_{14} and ϕ_{24}. Here, $\eta_s \equiv \eta_2 - \eta_3$. Note that Δm^2_{14} is explicitly assumed to be positive, i.e., $m^2_4 > m^2_1$.



[Berryman et al, arXiv:1507.03986]

FIG. 6: Expected sensitivity contours at 68.3% (blue), 95% (orange), and 99% (red) CL at DUNE with six years of data collection (3y ν + 3y $\bar{\nu}$), a 34 kiloton detector, and a 1.2 MW beam given the existence of a fourth neutrino with parameters from Case 3 in Table I. Results from solar neutrino experiments are included here as Gaussian priors for the values of $|U_{e2}|^2 = 0.301 \pm 0.015$ and $\Delta m^2_{12} = 7.54 \pm 0.24 \times 10^{-5}$ eV^2 [22].

[Case 2] Three-flavor paradigm ruled out at the 4 sigma level. How does it fail?



Appearance ("red–blue") versus disappearance ("blue–green"). Both data sets analyzed assuming there are three neutrinos.

[Berryman et al, arXiv:1507.03986]

Telling Different Scenarios Apart: (Steriles versus NSI)

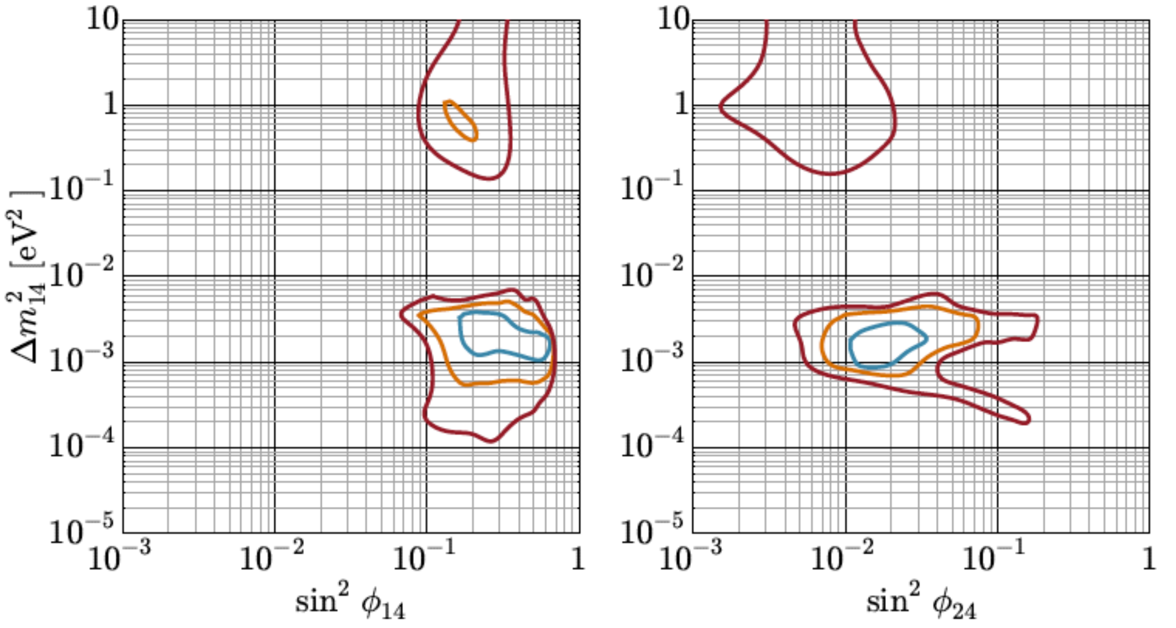


FIG. 8: Sensitivity contours at 68.3% (blue), 95% (orange), and 99% (red) for a four-neutrino fit to data consistent with Case 2 from Table I. All unseen parameters are marginalized over, and Gaussian priors are included on the values of Δm^2_{12} and $|U_{e2}|^2$. See text for details.

[See AdG and Kelly, arXiv:1511.05562]

Fit	Case 1	Case 2	Case 3
3ν with Solar Priors	$217/114 \simeq 5.4\sigma$	$186/114 \simeq 4.2\sigma$	$118/114 \simeq 4.3\sigma$
3ν without Priors	$172/114 \simeq 3.4\sigma$	$134/114 \simeq 1.6\sigma$	$154/114 \simeq 2.7\sigma$
4ν with Solar Priors	$193/110 \simeq 4.8\sigma$	$142/110 \simeq 2.3\sigma$	$153/110 \simeq 2.8\sigma$

TABLE II: Results of various three- or four-neutrino fits to data generated to be consistent with the cases listed in Table I. Numbers quoted are for $\chi^2_{\rm min}/$ dof and the equivalent discrepancy using a χ^2 distribution.

Concluding Thoughts

- The main goals of next-generation long-baseline experiments are to
  - test CP-invariance in the lepton sector. Do neutrinos and antineutrinos oscillate in the same way?
  - test the standard three-flavor paradigm – three massive neutrinos plus the standard model electroweak interactions. Is there more new physics in the neutrino sector, and can we "see" it in oscillation experiments?;
- We don't know what new phenomena we might run into. But there is plenty of room. We have only just started to over-constrain the three-flavor paradigm;

- I discussed the hypothesis that there is a fourth neutrino mass eigenstate. New neutrinos affect oscillations in a well-defined way, and the new physics effects are governed by only a few new parameters. And there are new sources of CP-invariance violation!
- There is still a lot of work to do!
  - What are other new phenomena one can constrain best (only?) with long-baseline neutrino oscillations?
  - How do we quantify "testing the standard paradigm" in a clever way?
- This is important! Necessary frame-of-mind to understand what types experiments we should be pursuing. E.g., in the example discussed here, τ-appearance would provide qualitative help.