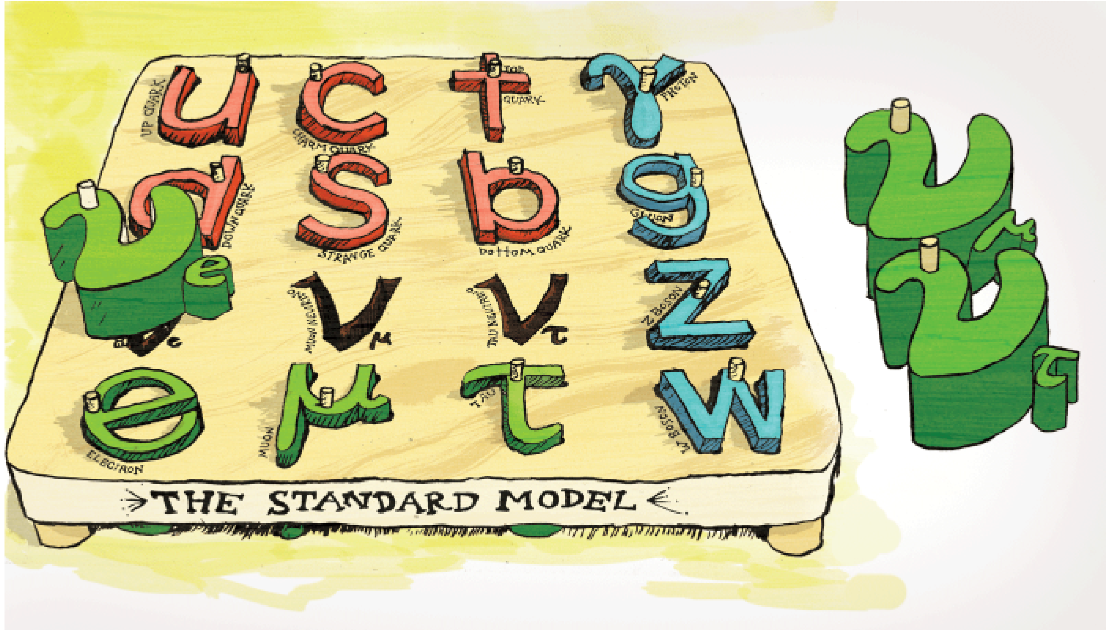
Looking for More New Physics with Long-Baseline Neutrino Experiments



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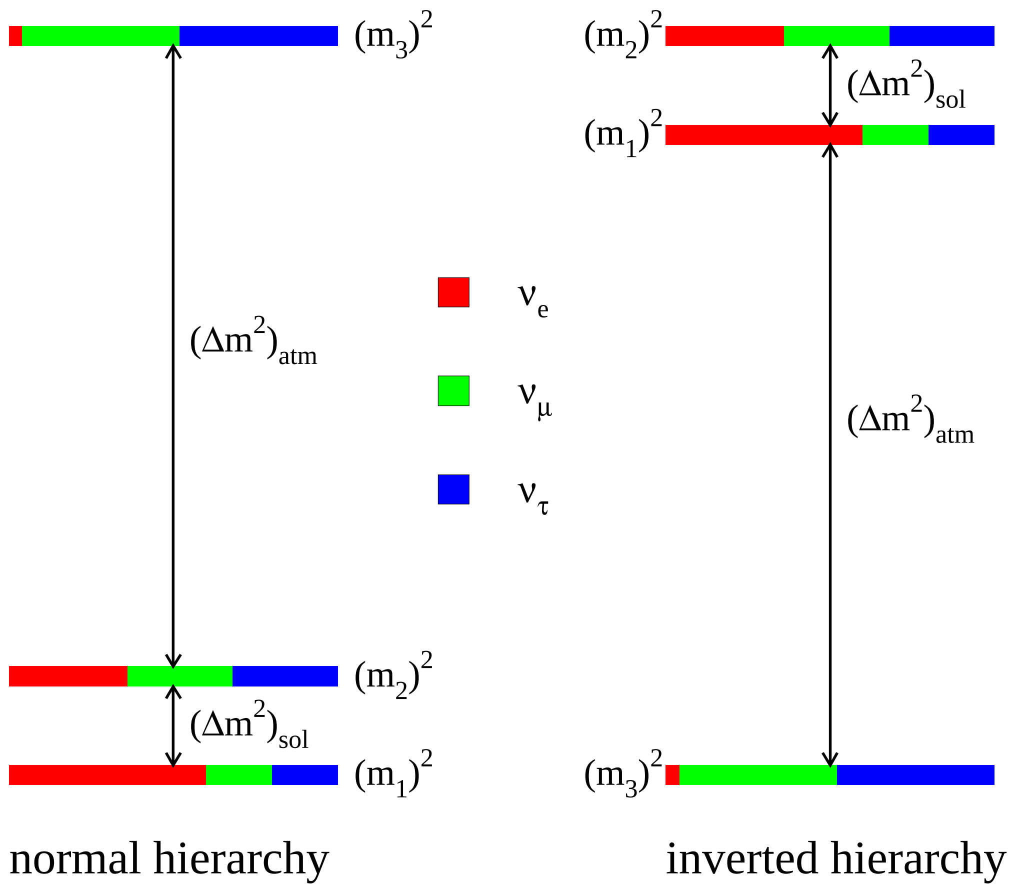
NTN Workshop on Neutrino Non-Standard Interations

Washington University in Saint Louis, May 29–31, 2019

New Neutrino Oscillation Experiments: Missing Oscillation Parameters

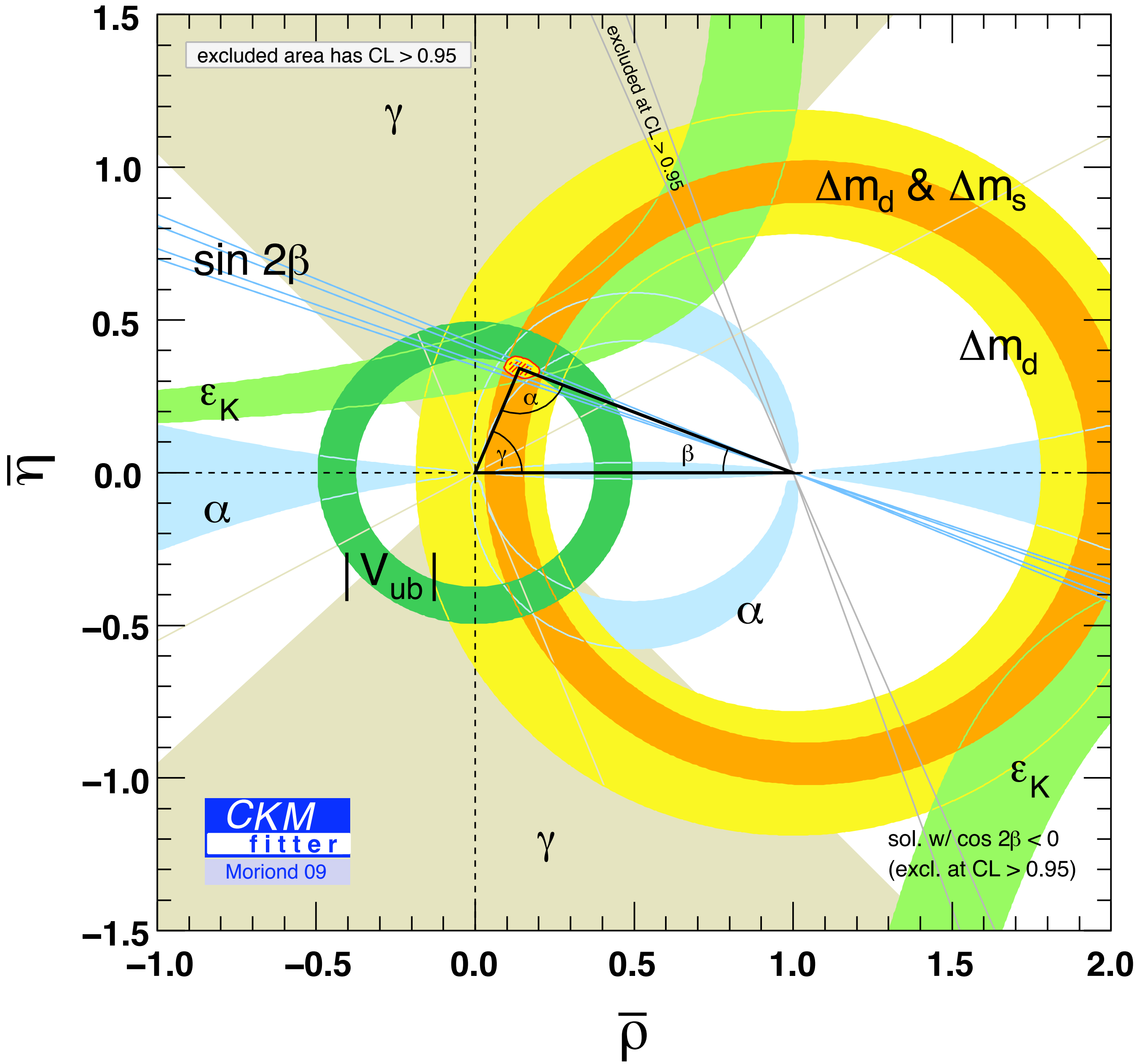


- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

What we ultimately want to achieve:



We need to do this in the lepton sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2 |U_{e1}|^2$ – KamLAND;
- $|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2 (1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2 |U_{\mu 3}|^2$ (upper bound $\to$ evidence) – MINOS, T2K.

We still have a ways to go!

What 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. If we don't take these into account, there is no reason for the three flavor paradigm to "close."
- 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 Studies

I will discuss a few case-studies, especially the fourth-neutrino hypothesis and non-standard neutral-current neutrino–matter interactions. In general

- I will mostly discuss, for concreteness, the DUNE setup;
- I don't particularly care about how likely, nice, or contrived the scenarios are. It is useful to consider them as well-defined ways in which the three-flavor paradigm can be violated. They can be used as benchmarks for comparing different efforts, or, perhaps, as proxies 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 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.

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

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 $\{\phi_{12}, \phi_{13}, \phi_{23}, \eta_1\} \to \{\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}\}$.

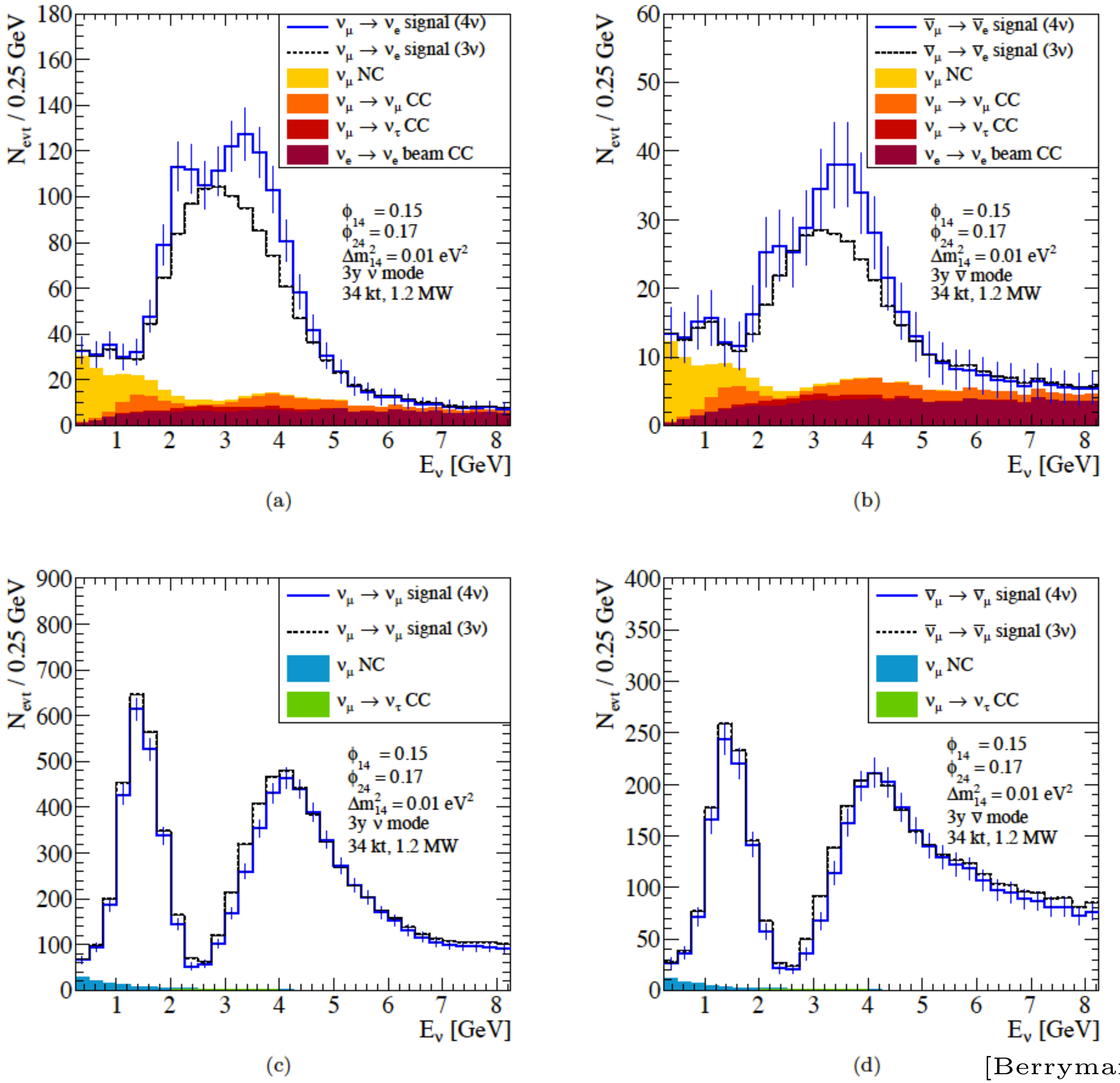
Also

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

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

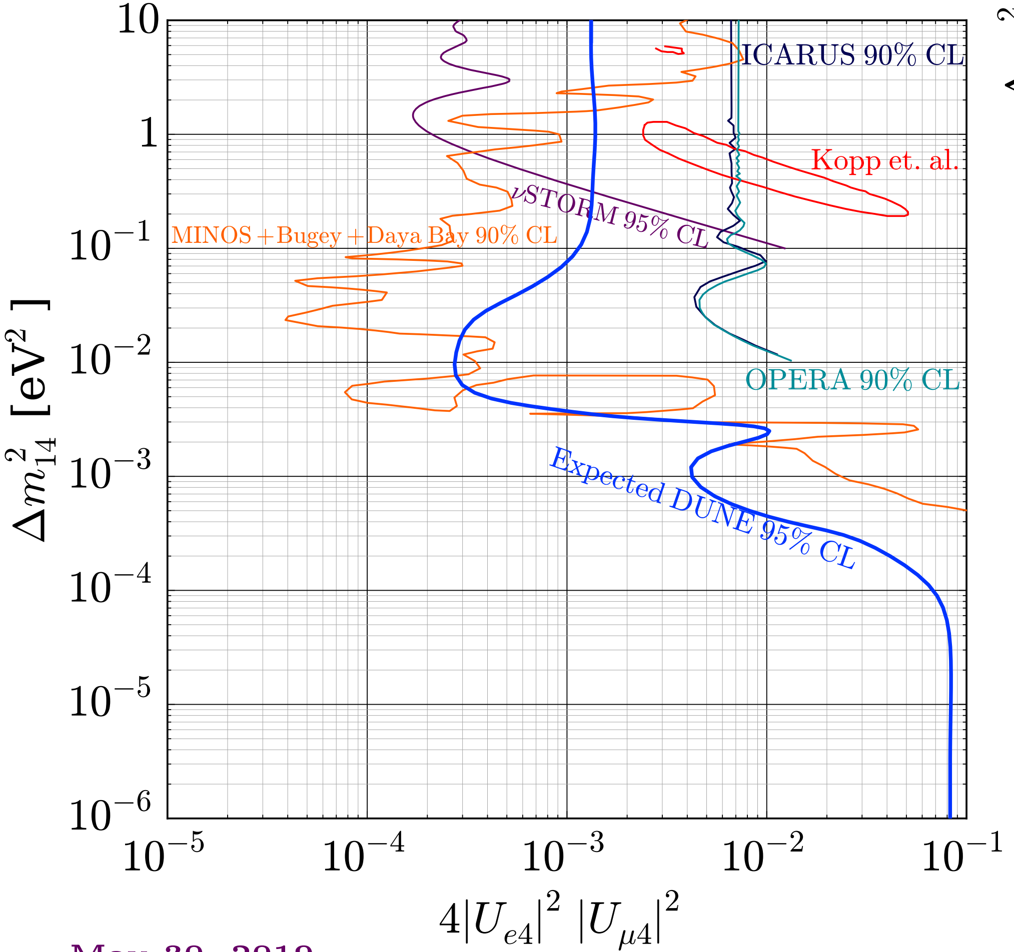
Some technicalities for the aficionados

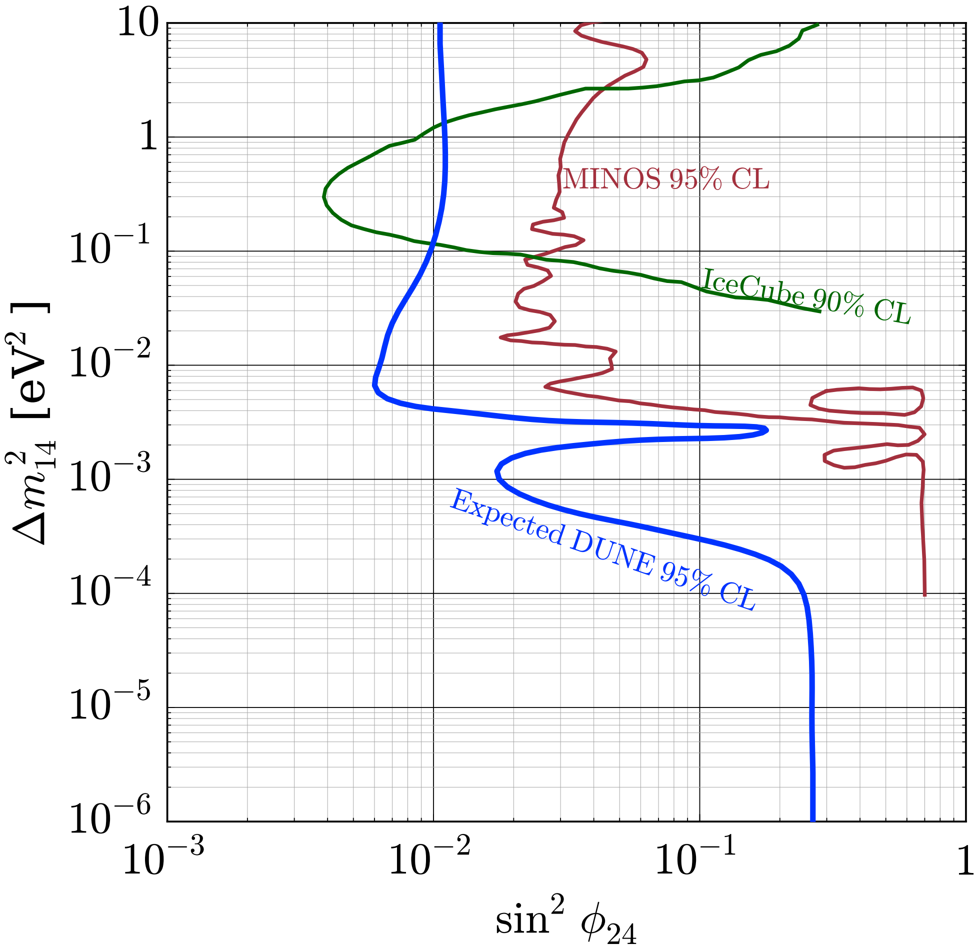
- 34 kiloton liquid argon detector;
- 1.2 MW proton beam on target as the source of the neutrino and antineutrino beams, originating 1300 km upstream at Fermilab;
- 3 years each with the neutrino and antineutrino mode;
- Include standard backgrounds, and assume a 5% normalization uncertainty;
- Whenever 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;
- We do not include information from past experiments. We assume that DUNE will "out measure" all experiments that came before it (except for the solar ones, as mentioned above).



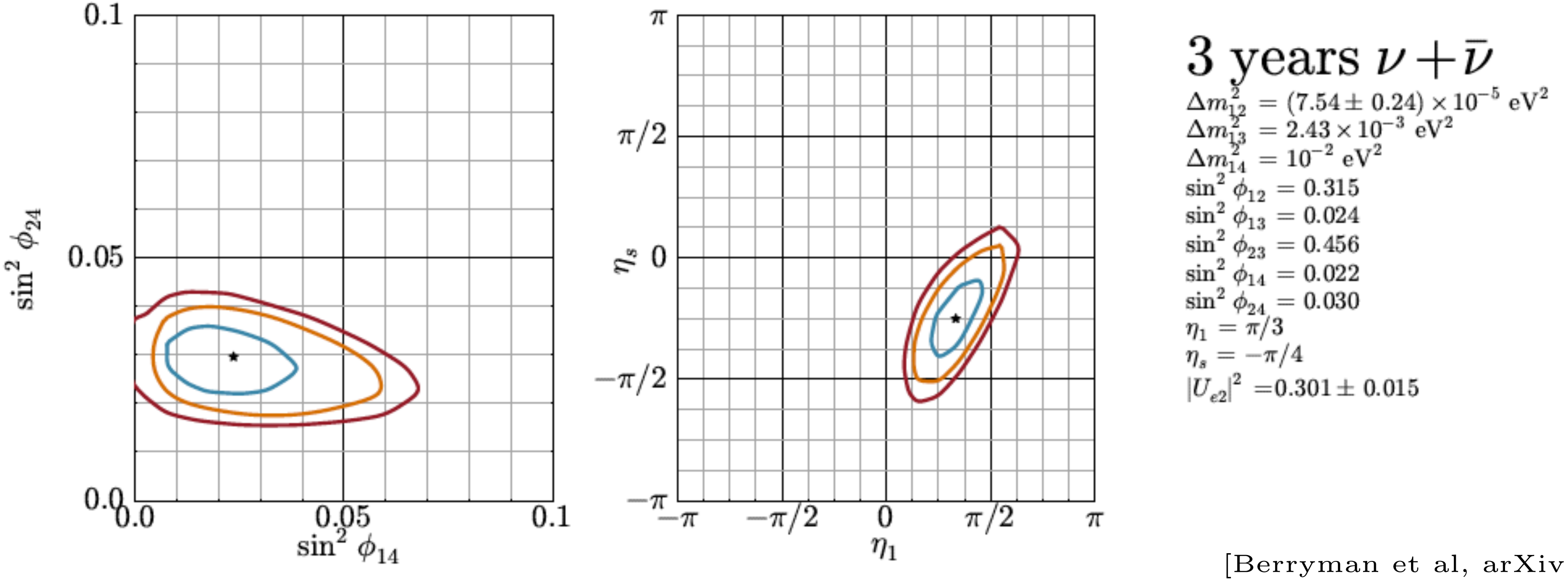
[Berryman et al, arXiv:1507.03986]

FIG. 1: Expected signal and background yields for six years (3y ν + 3y $\bar\nu$) 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.





[Berryman et al, arXiv:1507.03986]

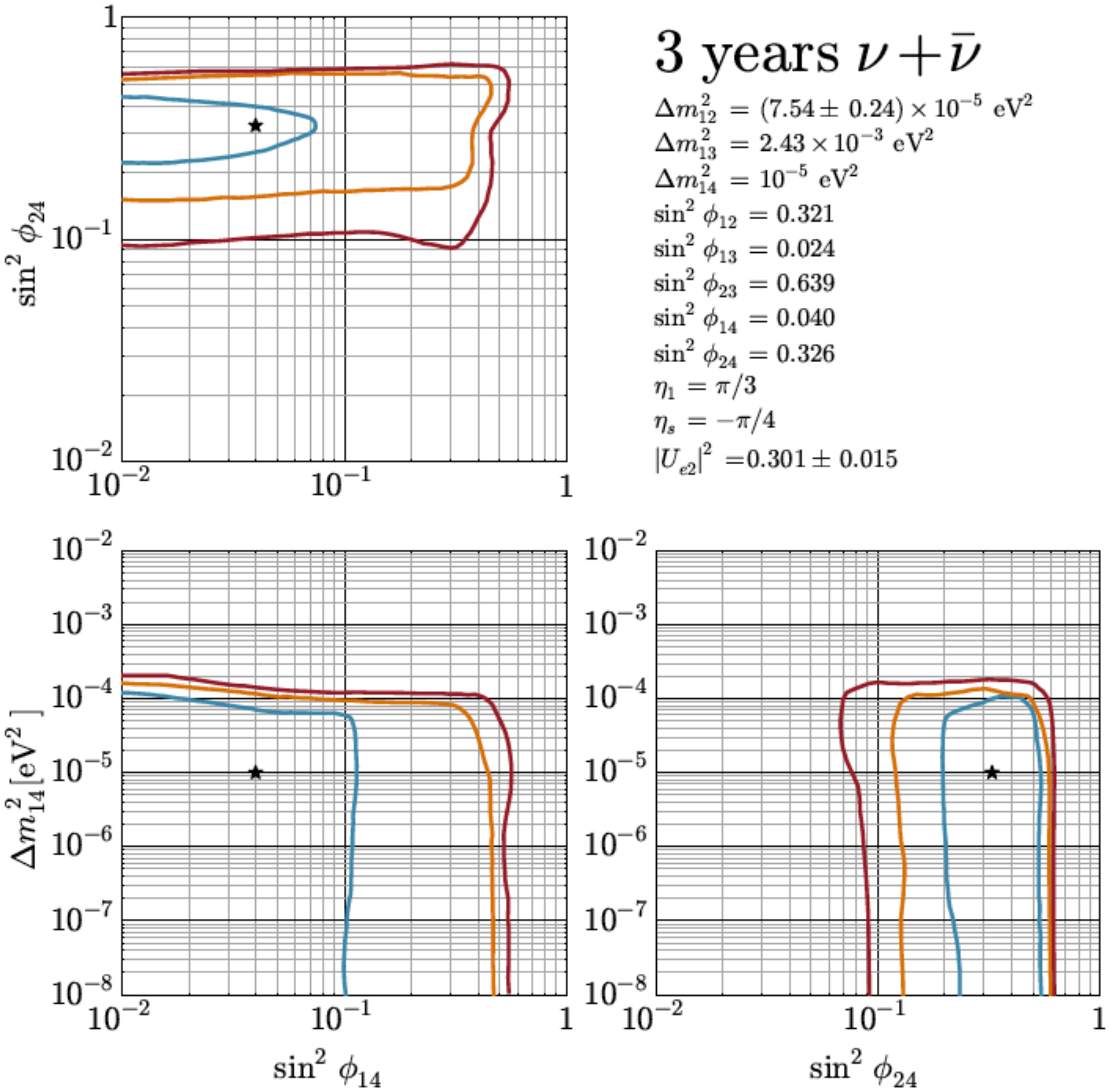


[Berryman et al, arXiv:1507.03986]

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 $\bar{\nu}$), 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 $|U_{\mu3}|^2$, 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., $m_4^2 > m_1^2$.



[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 $\overline{\nu}$), 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].

Non-Standard Neutrino Interactions (NSI)

Effective Lagrangian:

$$\mathcal{L}^{\rm NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)\sum_{f=e,u,d}(\epsilon_{\alpha\beta}^{fL}\overline{f}_L\gamma^\rho f_L + \epsilon_{\alpha\beta}^{fR}\overline{f}_R\gamma^\rho f_R) + h.c.,$$

For oscillations,

$$H_{ij} = \frac{1}{2E_\nu}{\rm diag}\left\{0, \Delta m^2_{12}, \Delta m^2_{13}\right\} + V_{ij},$$

where

$$V_{ij} = U^\dagger_{i\alpha}V_{\alpha\beta}U_{\beta j},$$

$$V_{\alpha\beta} = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix},$$

$A = \sqrt{2}G_F n_e$. $\epsilon_{\alpha\beta}$ are linear combinations of the $\epsilon_{\alpha\beta}^{fL,R}$. Important: I will discuss propagation effects only and ignore NSI effects in production or detection (ϵ versus ϵ^2).

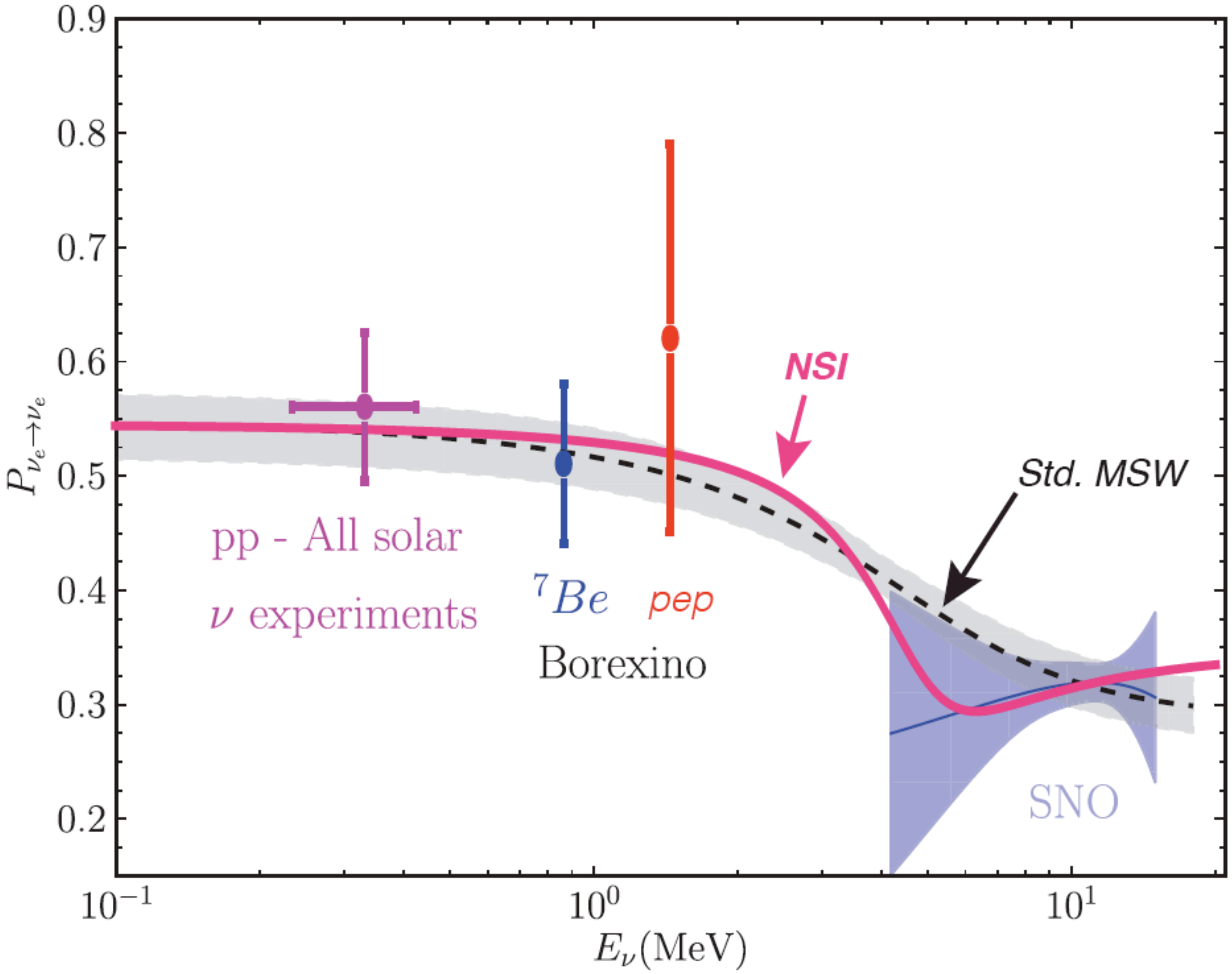


FIG. 1: Recent SNO solar neutrino data [18] on $P(\nu_e \to \nu_e)$ (blue line with 1 σ band). The LMA MSW solution (dashed black curve with gray 1 σ band) appears divergent around a few MeV, whereas for NSI with $\varepsilon_{e\tau} = 0.4$ (thick magenta), the electron neutrino probability appears to fit the data better. The data points come from the recent Borexino paper [19].

Solar Neutrinos

We are not done yet!

- see "vaccum-matter" transition
- probe for new physics: NSI, pseudo-Dirac, ...
- probe of the solar interior! "solar abundance problem" (see e.g. 1104.1639)

'CNO neutrinos may provide information on planet formation!'

[Friedland, Shoemaker 1207.6642]

OSC			+COHERENT		
	LMA	LMA $\oplus$ LMA-D		LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$	ε^u_{ee}	$[-0.008, +0.618]$	$[-0.008, +0.618]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$	$\varepsilon^u_{\mu\mu}$	$[-0.111, +0.402]$	$[-0.111, +0.402]$
			$\varepsilon^u_{\tau\tau}$	$[-0.110, +0.404]$	$[-0.110, +0.404]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$	$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.049]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$	$\varepsilon^u_{e\tau}$	$[-0.248, +0.116]$	$[-0.248, +0.116]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$	$\varepsilon^u_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$	ε^d_{ee}	$[-0.012, +0.565]$	$[-0.012, +0.565]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$	$\varepsilon^d_{\mu\mu}$	$[-0.103, +0.361]$	$[-0.103, +0.361]$
			$\varepsilon^d_{\tau\tau}$	$[-0.102, +0.361]$	$[-0.102, +0.361]$
$\varepsilon^d_{e\mu}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$	$\varepsilon^d_{e\mu}$	$[-0.058, +0.049]$	$[-0.058, +0.049]$
$\varepsilon^d_{e\tau}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$	$\varepsilon^d_{e\tau}$	$[-0.206, +0.110]$	$[-0.206, +0.110]$
$\varepsilon^d_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$	$\varepsilon^d_{\mu\tau}$	$[-0.011, +0.009]$	$[-0.011, +0.009]$
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	$[-0.041, +1.312]$	$\oplus[-3.328, -1.958]$	ε^p_{ee}	$[-0.010, +2.039]$	$[-0.010, +2.039]$
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	$[-0.015, +0.426]$	$[-0.424, +0.426]$	$\varepsilon^p_{\mu\mu}$	$[-0.364, +1.387]$	$[-0.364, +1.387]$
			$\varepsilon^p_{\tau\tau}$	$[-0.350, +1.400]$	$[-0.350, +1.400]$
$\varepsilon^p_{e\mu}$	$[-0.178, +0.147]$	$[-0.178, +0.178]$	$\varepsilon^p_{e\mu}$	$[-0.179, +0.146]$	$[-0.179, +0.146]$
$\varepsilon^p_{e\tau}$	$[-0.954, +0.356]$	$[-0.954, +0.949]$	$\varepsilon^p_{e\tau}$	$[-0.860, +0.350]$	$[-0.860, +0.350]$
$\varepsilon^p_{\mu\tau}$	$[-0.035, +0.027]$	$[-0.035, +0.035]$	$\varepsilon^p_{\mu\tau}$	$[-0.035, +0.028]$	$[-0.035, +0.028]$

Table 1. 2σ allowed ranges for the NSI couplings $\varepsilon^u_{\alpha\beta}$, $\varepsilon^d_{\alpha\beta}$ and $\varepsilon^p_{\alpha\beta}$ as obtained from the global analysis of oscillation data (left column) and also including COHERENT constraints. The results are obtained after marginalizing over oscillation and the other matter potential parameters either within the LMA only and within both LMA and LMA-D subspaces respectively (this second case is denoted as LMA $\oplus$ LMA-D).

I. Esteban *et al*, 1805.04530 [hep-ph]

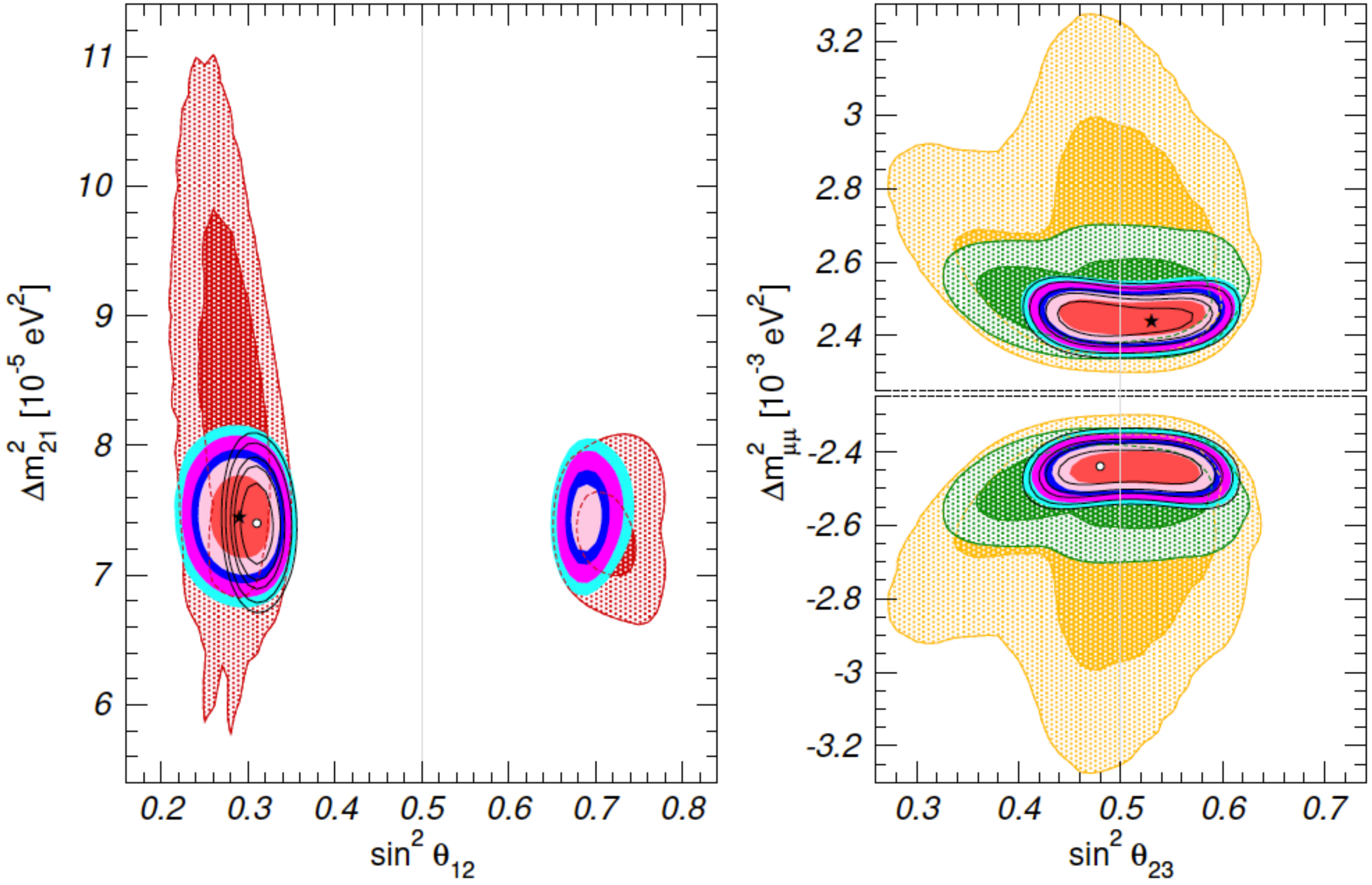
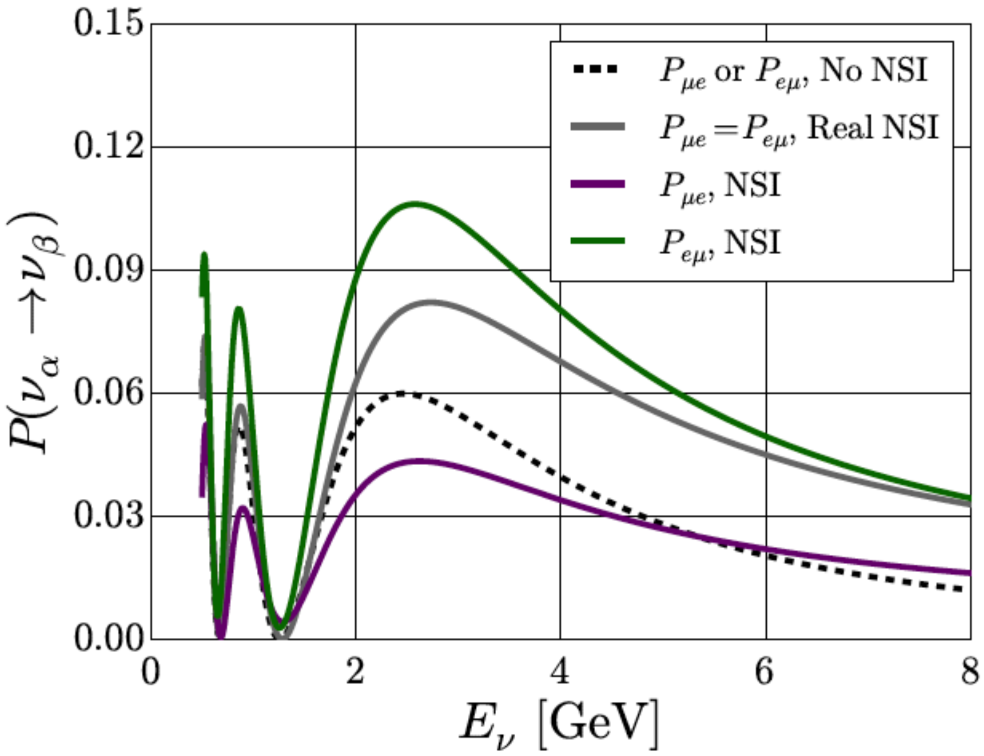


Figure 6. Two-dimensional projections of the allowed regions onto different vacuum parameters after marginalizing over the matter potential parameters (including η) and the undisplayed oscillation parameters. The solid colored regions correspond to the global analysis of all oscillation data, and show the 1σ, 90%, 2σ, 99% and 3σ CL allowed regions; the best-fit point is marked with a star. The black void regions correspond to the analysis with the standard matter potential (*i.e.*, without NSI) and its best-fit point is marked with an empty dot. For comparison, in the left panel we show in red the 90% and 3σ allowed regions including only solar and KamLAND results, while in the right panels we show in green the 90% and 3σ allowed regions excluding solar and KamLAND data, and in yellow the corresponding ones excluding also IceCube and reactor data.

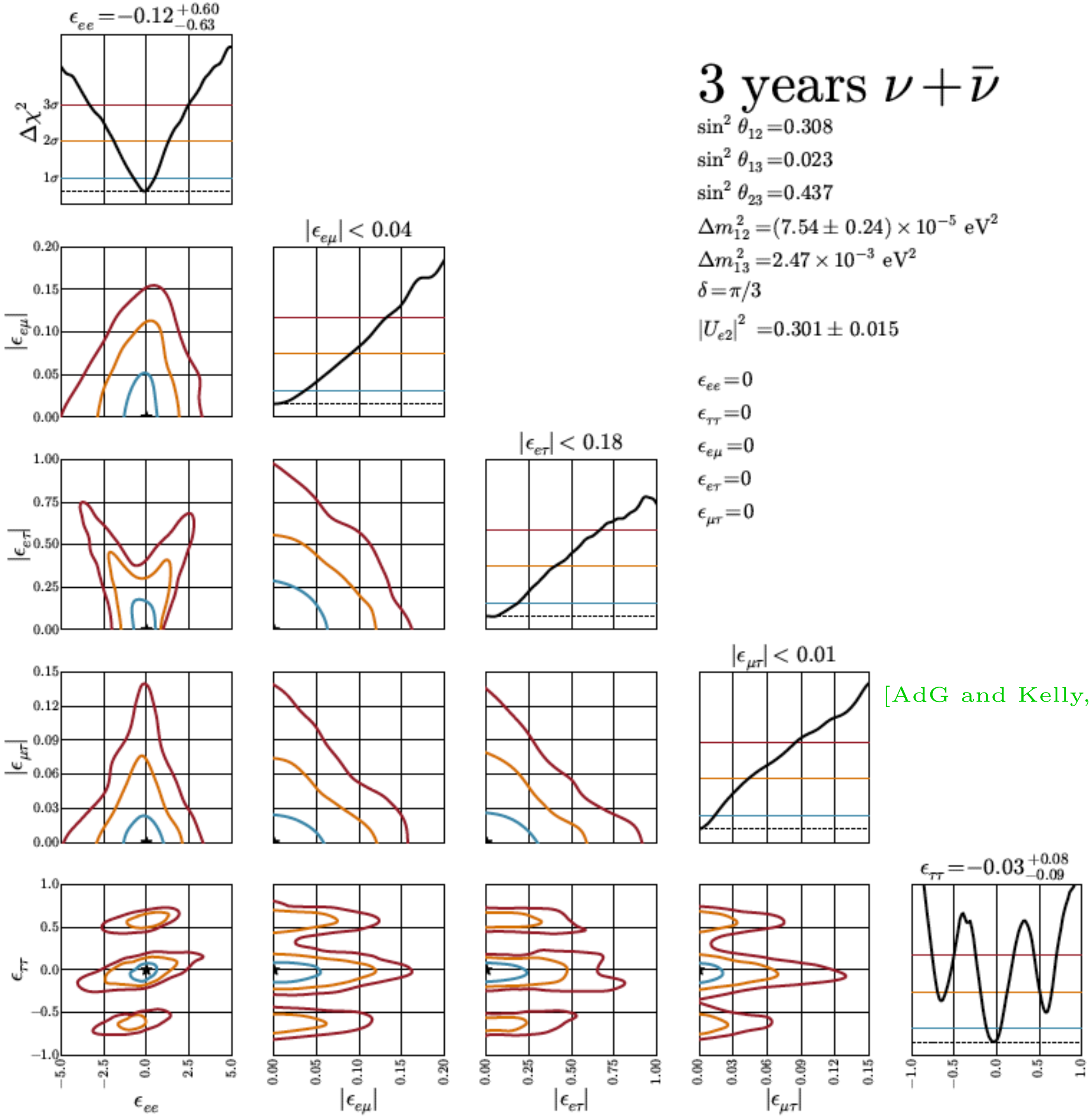
I. Esteban *et al*, 1805.04530 [hep-ph]

There are new sources of CP-invariance violation! [easier to see T-invariance violation]



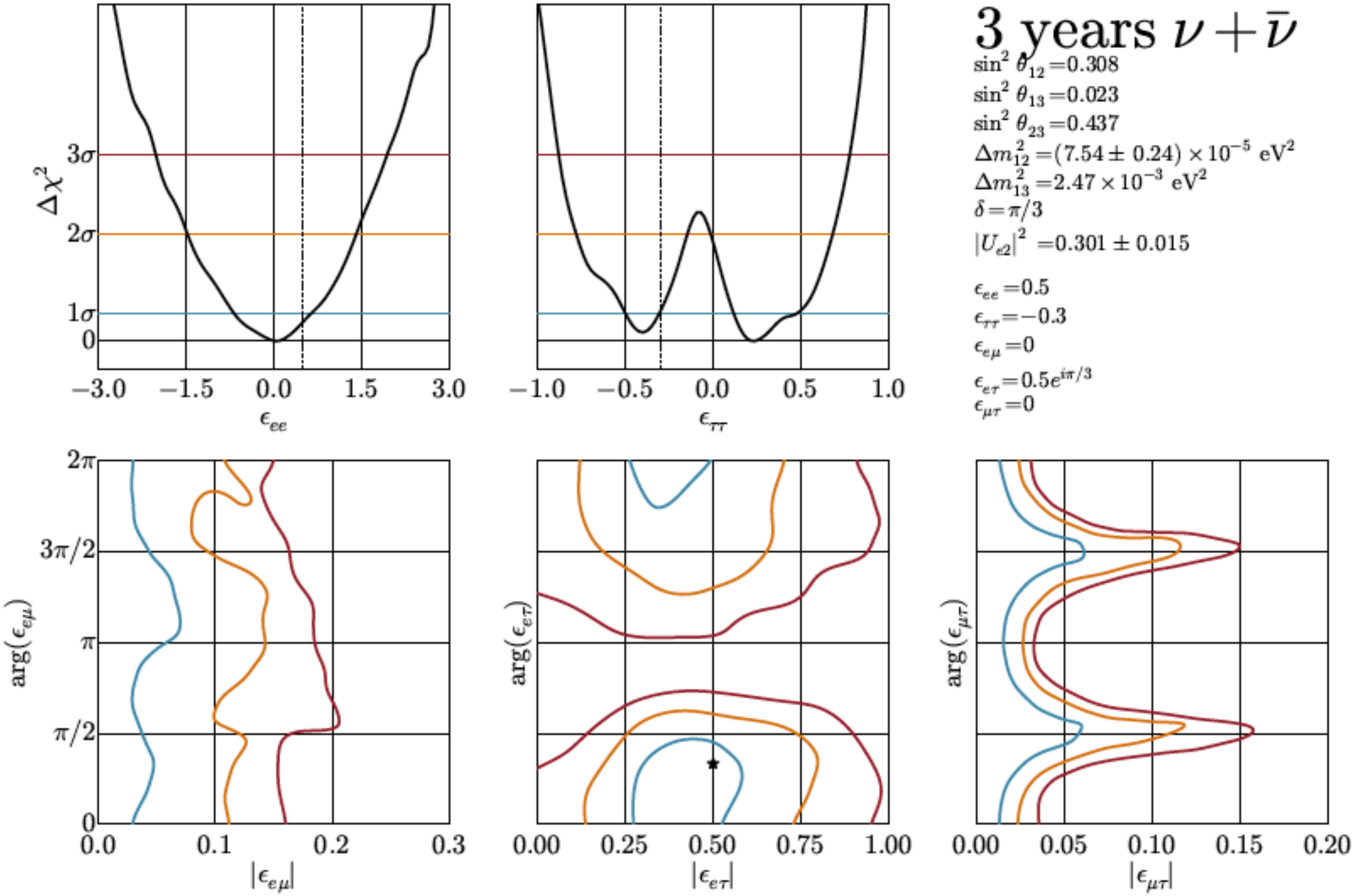
[AdG and Kelly, arXiv:1511.05562]

FIG. 2: T-invariance violating effects of NSI at $L = 1300$ km for $\epsilon_{e\mu} = 0.1e^{i\pi/3}$, $\epsilon_{e\tau} = 0.1e^{-i\pi/4}$, $\epsilon_{\mu\tau} = 0.1$ (all other NSI parameters are set to zero). Here, the three-neutrino oscillation parameters are $\sin^2\theta_{12} = 0.308$, $\sin^2\theta_{13} = 0.0234$, $\sin^2\theta_{23} = 0.437$, $\Delta m^2_{12} = 7.54 \times 10^{-5}$ eV^2, $\Delta m^2_{13} = 2.47 \times 10^{-3}$ eV^2, and $\delta = 0$, i.e., no "standard" T-invariance violation. The green curve corresponds to $P_{e\mu}$ while the purple curve corresponds to $P_{\mu e}$. If, instead, all non-zero NSI are real ($\epsilon_{e\mu} = 0.1$, $\epsilon_{e\tau} = 0.1$, $\epsilon_{\mu\tau} = 0.1$), $P_{e\mu} = P_{\mu e}$, the grey curve. The dashed line corresponds to the pure three-neutrino oscillation probabilities assuming no T-invariance violation (all $\epsilon_{\alpha\beta} = 0$, $\delta = 0$).



[AdG and Kelly, arXiv:1511.05562]

FIG. 4: Expected exclusion limits at 68.3% (red), 95% (orange), and 99% (blue) CL at DUNE assuming data consistent with



[AdG and Kelly, arXiv:1511.05562]

	ϵ_{ee}	$\epsilon_{e\mu}$	$\epsilon_{e\tau}$	$\epsilon^{\star}_{\mu\mu}$	$\epsilon_{\mu\tau}$	$\epsilon_{\tau\tau}$
Case 1	0	$0.15e^{i\pi/3}$	$0.3e^{-i\pi/4}$	0	0.05	0
Case 2	−1.0	0	0	0	0	0.3
Case 3	0.5	0	$0.5e^{i\pi/3}$	0	0	−0.3

TABLE I: Input values of the new physics parameters for the three NSI scenarios under consideration. The star symbol is a reminder that, as discussed in the text, we can choose $\epsilon_{\mu\mu}\equiv 0$ and reinterpret the other diagonal NSI parameters.

Telling Different Scenarios Apart:

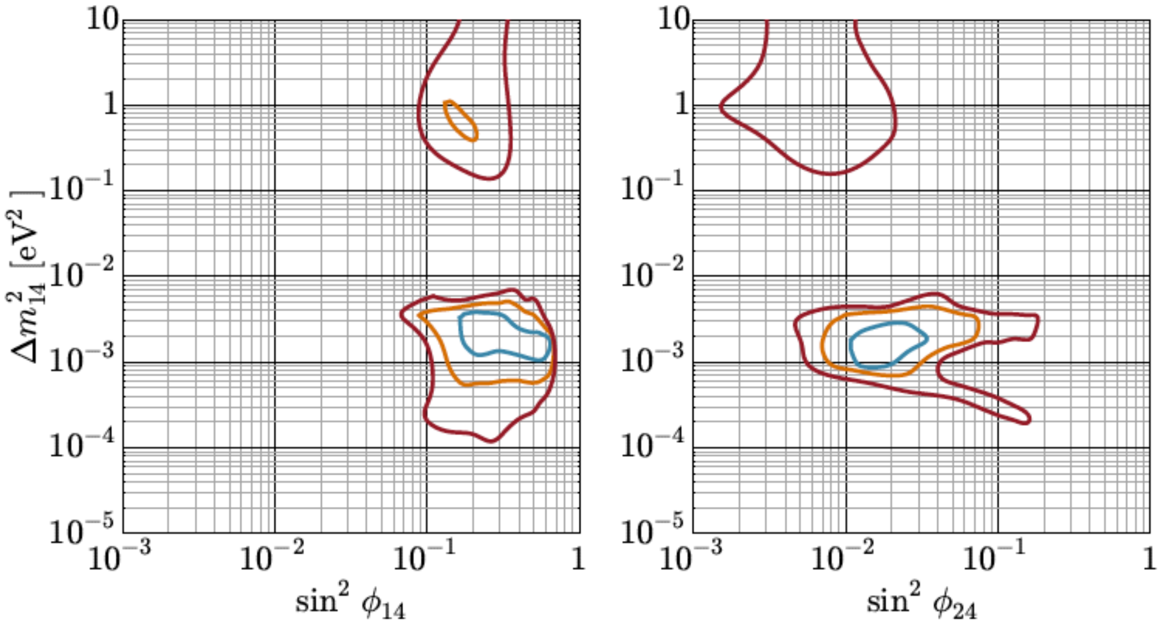


FIG. 8: Sensitivity contours at 68.3% (blue), 95% (orange), and 99% (red) for a four-neutrino fit to data consistent with Case 2 from Table I. All unseen parameters are marginalized over, and Gaussian priors are included on the values of Δm^2_{12} and $|U_{e2}|^2$. See text for details.

[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	$193/110 \simeq 4.8\sigma$	$142/110 \simeq 2.3\sigma$	$153/110 \simeq 2.8\sigma$

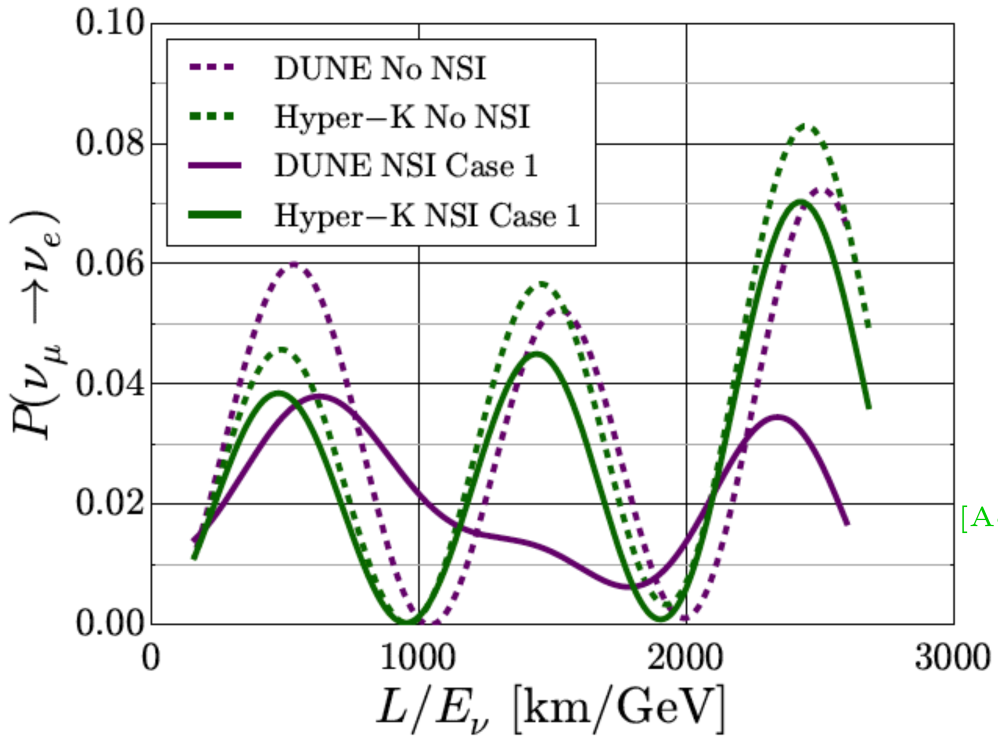
TABLE II: Results of various three- or four-neutrino fits to data generated to be consistent with the cases listed in Table I. Numbers quoted are for $\chi^2_{\rm min}/$ dof and the equivalent discrepancy using a χ^2 distribution.

How Do We Learn More – Different Experiments!

– Different L and E, same L/E (e.g. HyperK versus DUNE);

– Different matter potentials (e.g. atmosphere versus accelerator);

– Different oscillation modes (appearance versus disappearance, e's, μ's and τ's).



[AdG and Kelly, arXiv:1511.05562]

FIG. 9: Oscillation probabilities for three-neutrino (dashed) and NSI (solid) hypotheses as a function of L/E_ν, the baseline length divided by neutrino energy, for the DUNE (purple) and HyperK (green) experiments. Here, $\delta = 0$ and the three-neutrino parameters used are consistent with Ref. [47].

The Physics Behind NSI – Comments and Concerns

There are two main questions associated to NSI's. They are somewhat entwined.

1. What is the new physics that leads to neutrino NSI? or are there models for new physics that lead to large NSIs? Are these models well motivated? Are they related to some of the big questions in particle physics?
2. Are NSIs constrained by observables that have nothing to do with neutrino physics? Are large NSI effects allowed at all?

Effective Lagrangian:

$$\mathcal{L}^{\rm NSI} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)\left(\overline{f}\gamma^\rho f\right).$$

This is not $SU(2)_L$ invariant. Let us fix that:

$$\mathcal{L}^{\rm NSI} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{L}_\alpha\gamma_\rho L_\beta)\left(\overline{f}\gamma^\rho f\right).$$

where $L = (\nu, \ell^-)^T$ is the lepton doublet. This is a big problem. Charged-Lepton flavor violating constraints are really strong (think $\mu \to e^+e^-e^+$, $\mu \to e$-conversion, $\tau \to \mu$+hadrons, etc), and so are most of the flavor diagonal charged-lepton effects.

There are a couple of ways to circumvent this…

1. Dimension-Eight Effective Operator

$$\mathcal{L}^{\rm NSI} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)\left(\overline{f}\gamma^\rho f\right).$$

This is not $SU(2)_L$ invariant. Let us fix that **in a different way**

$$\mathcal{L}^{\rm NSI} = -2\sqrt{2}G_F\frac{\epsilon^{\alpha\beta}}{v^2}((HL)^\dagger_\alpha\gamma_\rho(HL)_\beta)\left(\overline{f}\gamma^\rho f\right).$$

where $HL \propto H^+\ell^- - H^0\nu$. After electroweak symmetry breaking $H^0 \to v + h^0$ and we only get new neutrino interactions.

Sadly, it is not that simple. At the one-loop level, the dimension-8 operator will contribute to the dimension-6 operator in the last page, as discussed in detail in [Gavela *et al*, arXiv:0809.3451 [hep-ph]]. One can, however, fine-tune away the charged-lepton effects.

2. Light Mediator

(Recent overview: Y. Farzan and M. Tórtola, arXiv:1710.09360 [hep-ph])

$$\mathcal{L}^{\rm NSI} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)\left(\bar{f}\gamma^\rho f\right).$$

This may turn out to be a good effective theory for neutrino propagation but a bad effective theory for most charged-lepton processes. I.e.

$$\mathcal{L}^{\rm NSI} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{L}_\alpha\gamma_\rho L_\beta)\left(\bar{f}\gamma^\rho f\right).$$

might be inappropriate for describing charged-lepton processes if the particle we are integrating out is light (as in lighter than the muon).

Charged-lepton processes are "watered down." Very roughly

$$\epsilon \to \epsilon\left(\frac{m_{Z'}}{m_\ell}\right)^2$$

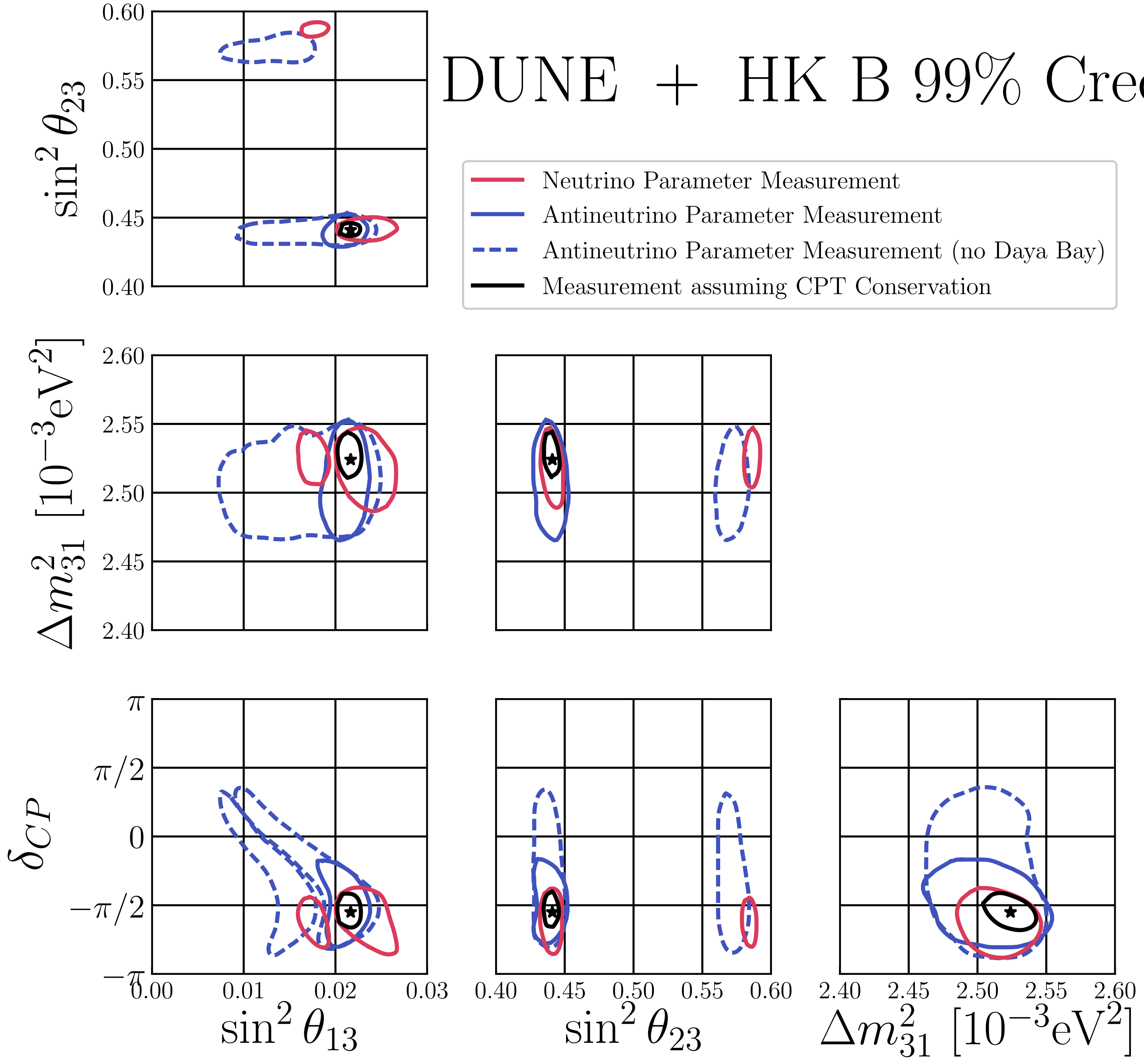
where $m_{Z'}$ is the mass of the particle mediating the new interaction, and m_ℓ is the mass associated to the charged-lepton process of interest.

Different Oscillation Parameters for Neutrinos and Antineutrinos?

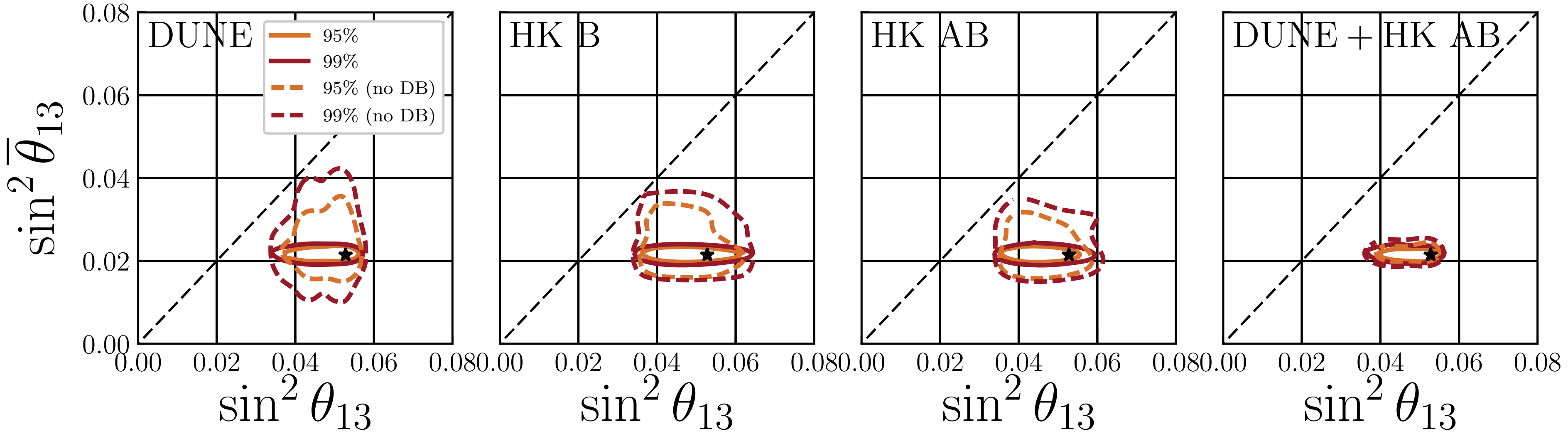
[AdG, Kelly, arXiv:1709.06090]

- How much do we know, independently, about neutrino and antineutrino oscillations?
- What happens if the parameters disagree?

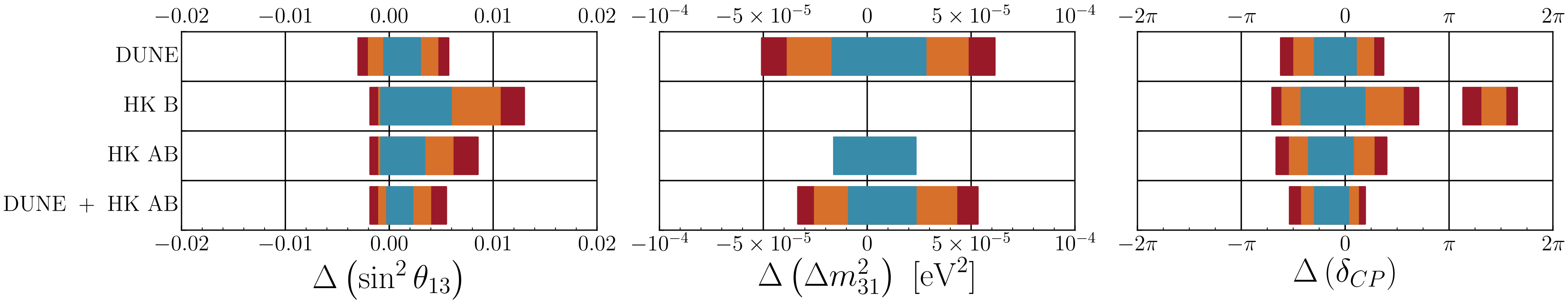
DUNE + HK B 99% Cred.



[AdG and Kelly, arXiv:1709.06090]



[AdG and Kelly, arXiv:1709.06090]



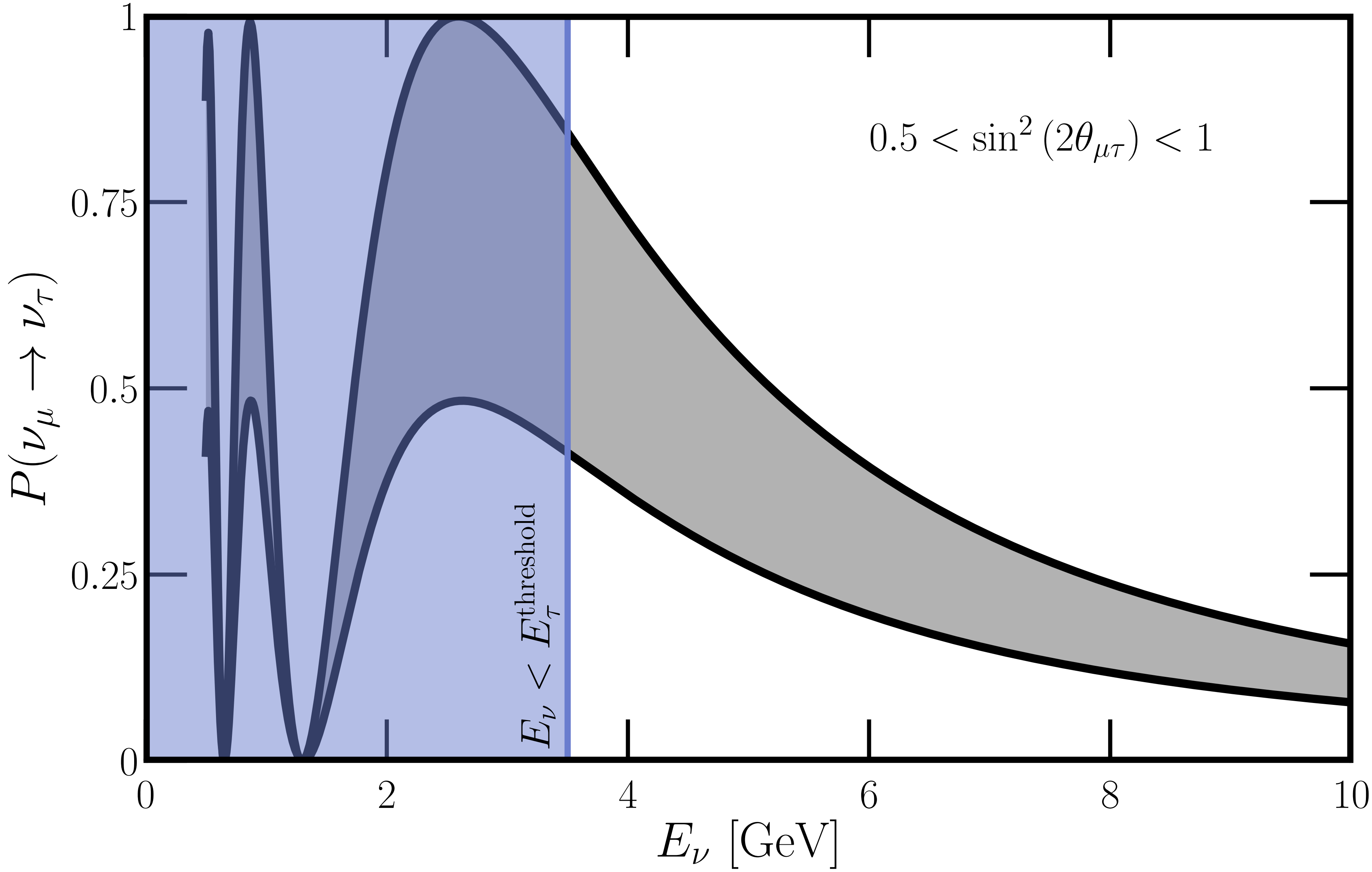
Physics with Beam ν_τ's at the DUNE Far Detector Site

André de Gouvêa, Kevin Kelly, Pedro Pasquini, Gabriela Stenico, arXiv:1904.07265

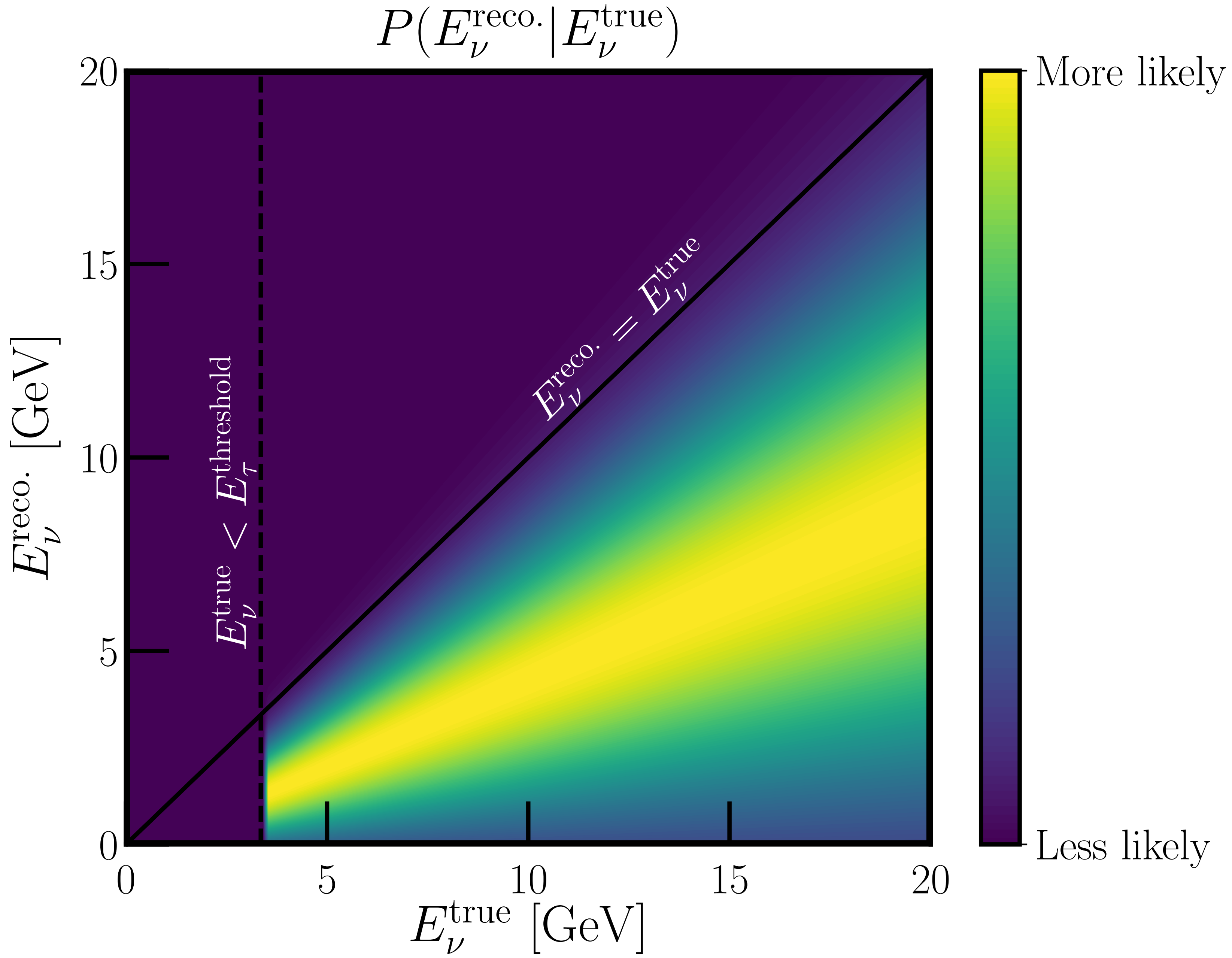
- ν_τ sample: what is it good for?
- ν_τ sample: how many? how clean? how well can we reconstruct the ν_τ energy?
- options? High energy beam?
- others: ν_τ in the near detector? Atmospheric ν_τ? $\Rightarrow$ for the future...

ν_τ sample: what is it good for?

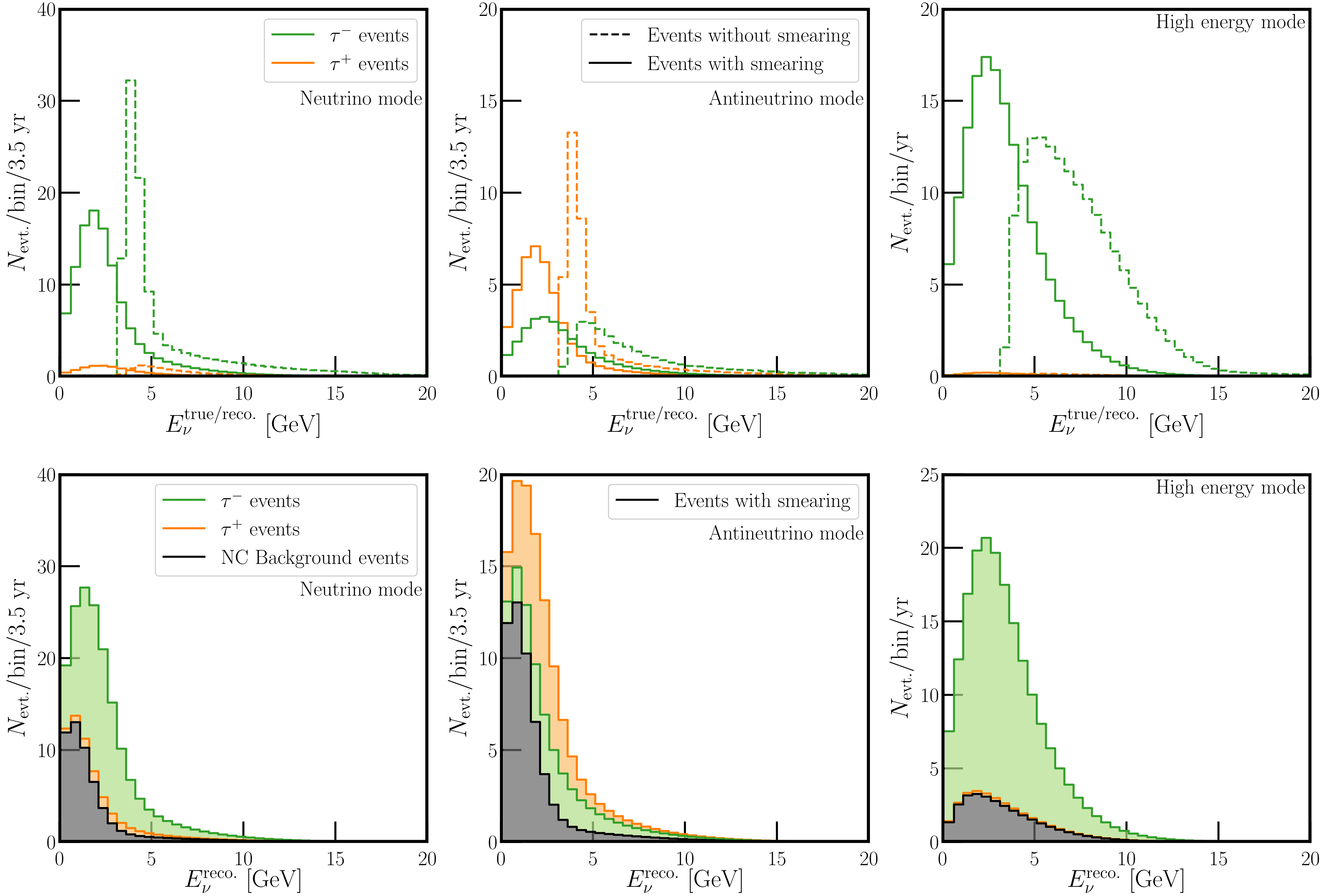
- Model independent checks.
  - Establishing the existence of ν_τ in the beam;
  - Is it consistent with the oscillation interpretation $\nu_\mu \to \nu_\tau$?
  - Measuring the oscillation parameters.
  - Comparison to OPERA, atmospheric samples.
- Cross-section measurements.
  - Comparison to OPERA, atmospheric samples.
- Testing the 3-neutrinos paradigm.
  - Independent measurement of the oscillation parameters.
  - More concretely: "unitarity triangle"-like test.
  - Is there anything the ν_τ sample brings to the table given the ν_μ, ν_e, and neutral current samples? [model-dependent]



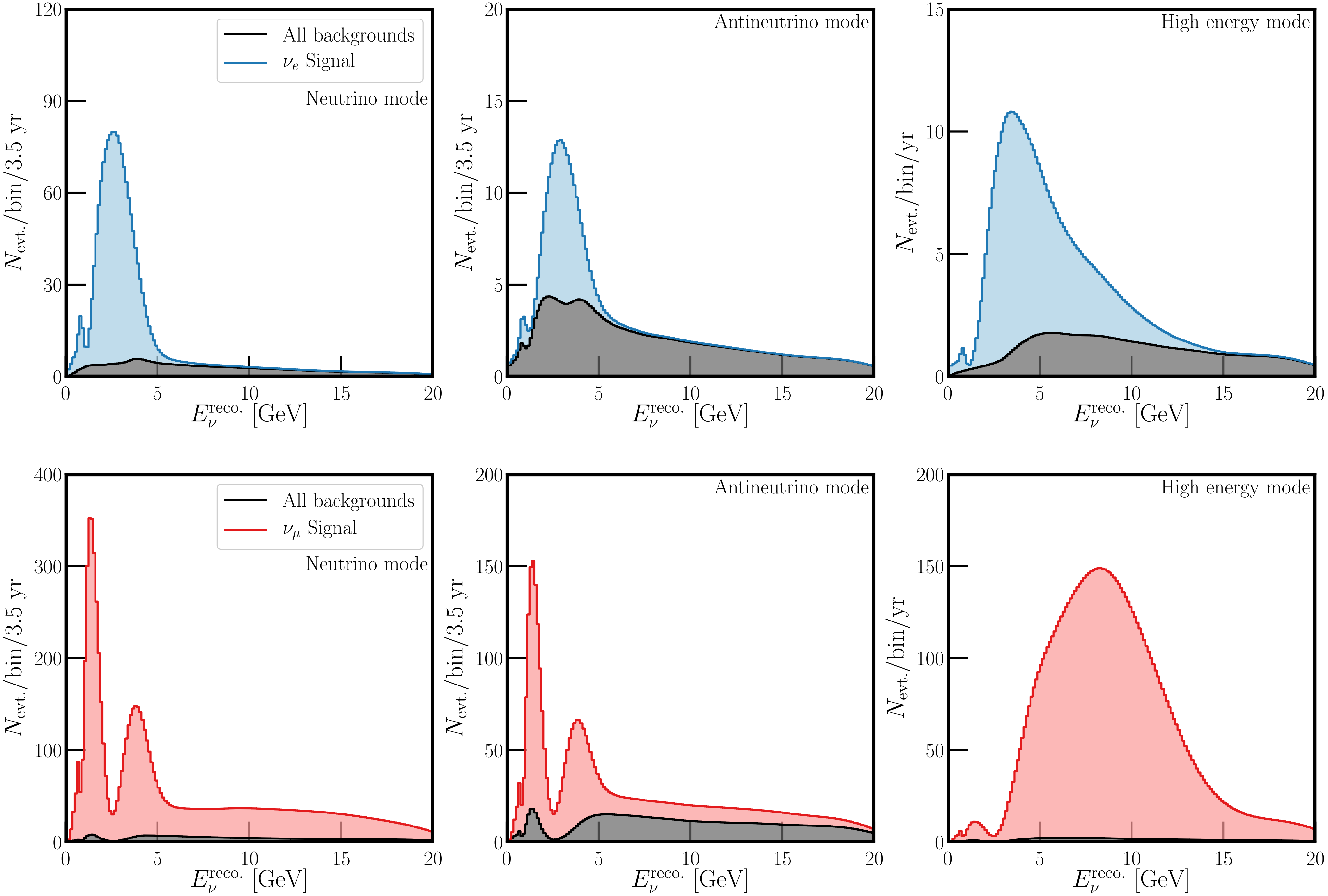
$0.5 < \sin^2(2\theta_{\mu\tau}) < 1$
$E_\nu < E_\tau^{\rm threshold}$
$P(\nu_\mu \to \nu_\tau)$
E_ν [GeV]
1
0.75
0.5
0.25
0
0
2
4
6
8
10



$P(E_\nu^{\rm reco.}|E_\nu^{\rm true})$
$E_\nu^{\rm true} < E_\tau^{\rm threshold}$
$E_\nu^{\rm reco.} = E_\nu^{\rm true}$
More likely
Less likely
$E_\nu^{\rm reco.}$ [GeV]
$E_\nu^{\rm true}$ [GeV]
0
5
10
15
20

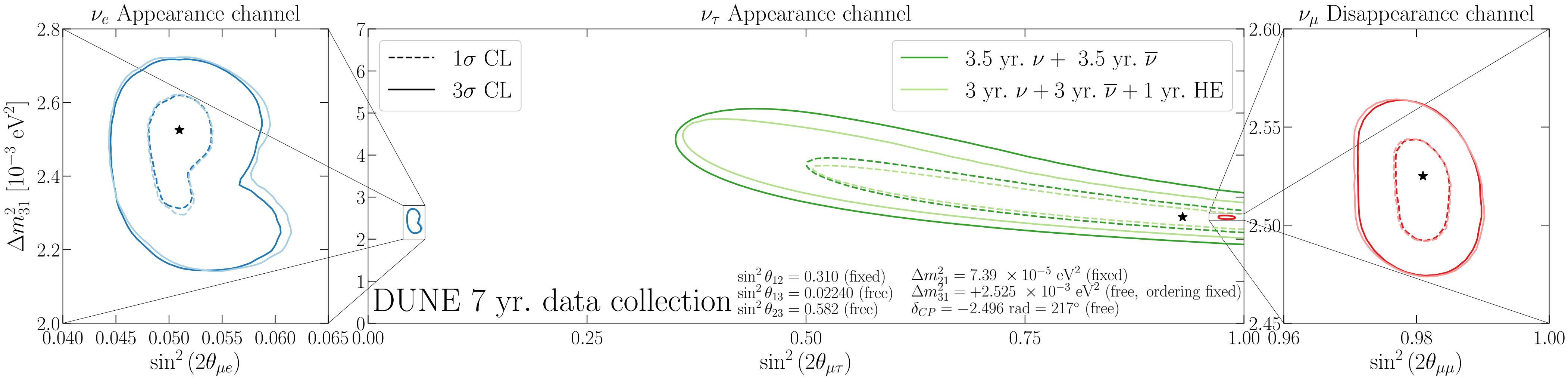


τ^- events
τ^+ events
Neutrino mode
$N_{\mathrm{evt.}}$/bin/3.5 yr
$E_\nu^{\mathrm{true/reco.}}$ [GeV]
Events without smearing
Events with smearing
Antineutrino mode
$N_{\mathrm{evt.}}$/bin/3.5 yr
$E_\nu^{\mathrm{true/reco.}}$ [GeV]
High energy mode
$N_{\mathrm{evt.}}$/bin/yr
$E_\nu^{\mathrm{true/reco.}}$ [GeV]
τ^- events
τ^+ events
NC Background events
Neutrino mode
$N_{\mathrm{evt.}}$/bin/3.5 yr
$E_\nu^{\mathrm{reco.}}$ [GeV]
Events with smearing
Antineutrino mode
$N_{\mathrm{evt.}}$/bin/3.5 yr
$E_\nu^{\mathrm{reco.}}$ [GeV]
High energy mode
$N_{\mathrm{evt.}}$/bin/yr
$E_\nu^{\mathrm{reco.}}$ [GeV]



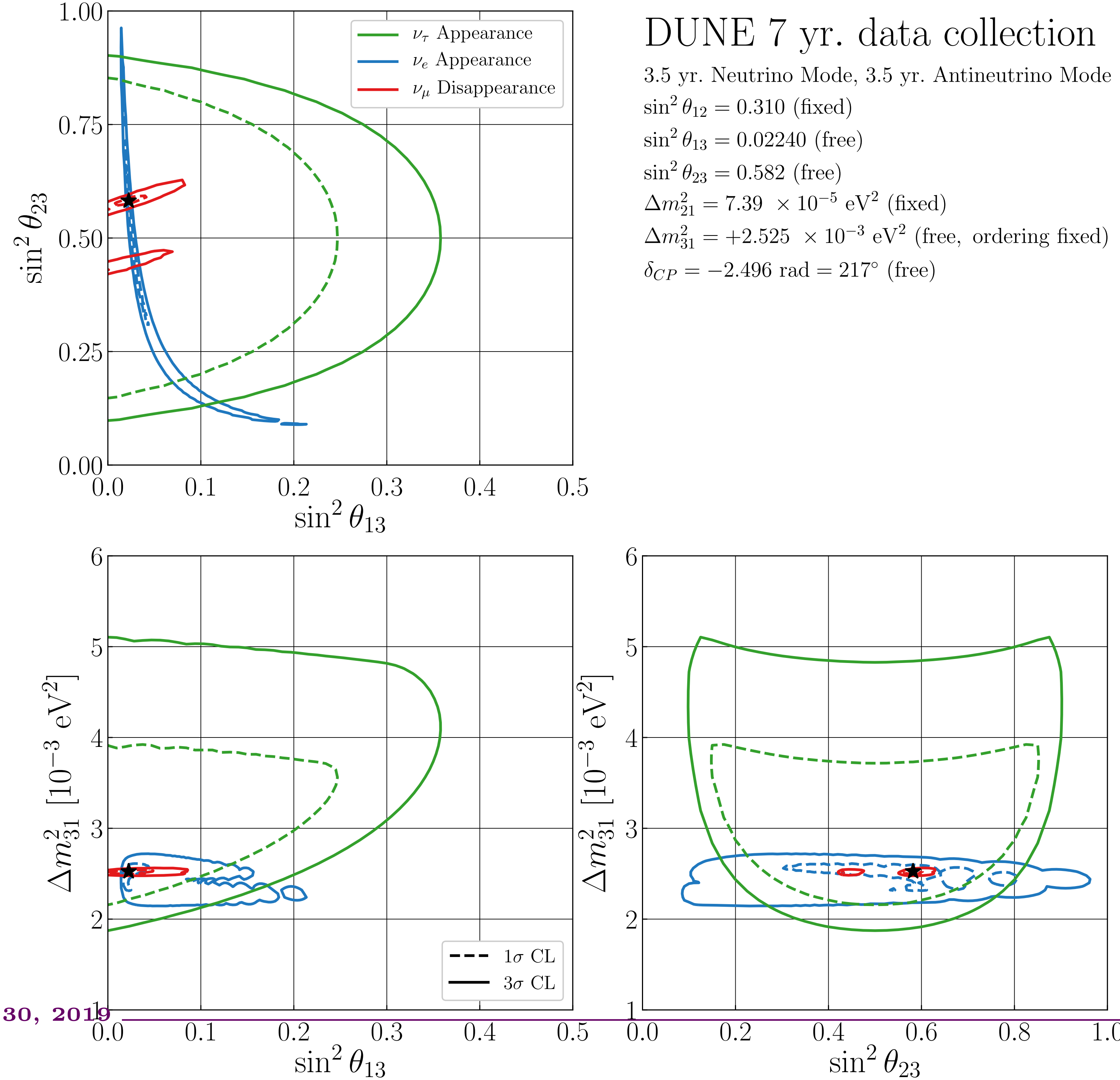
All backgrounds
ν_e Signal
Neutrino mode
Antineutrino mode
High energy mode
ν_μ Signal
$N_{\mathrm{evt.}}$/bin/3.5 yr
$N_{\mathrm{evt.}}$/bin/yr
$E_\nu^{\mathrm{reco.}}$ [GeV]

Testing the Three-Massive-Neutrinos Paradigm

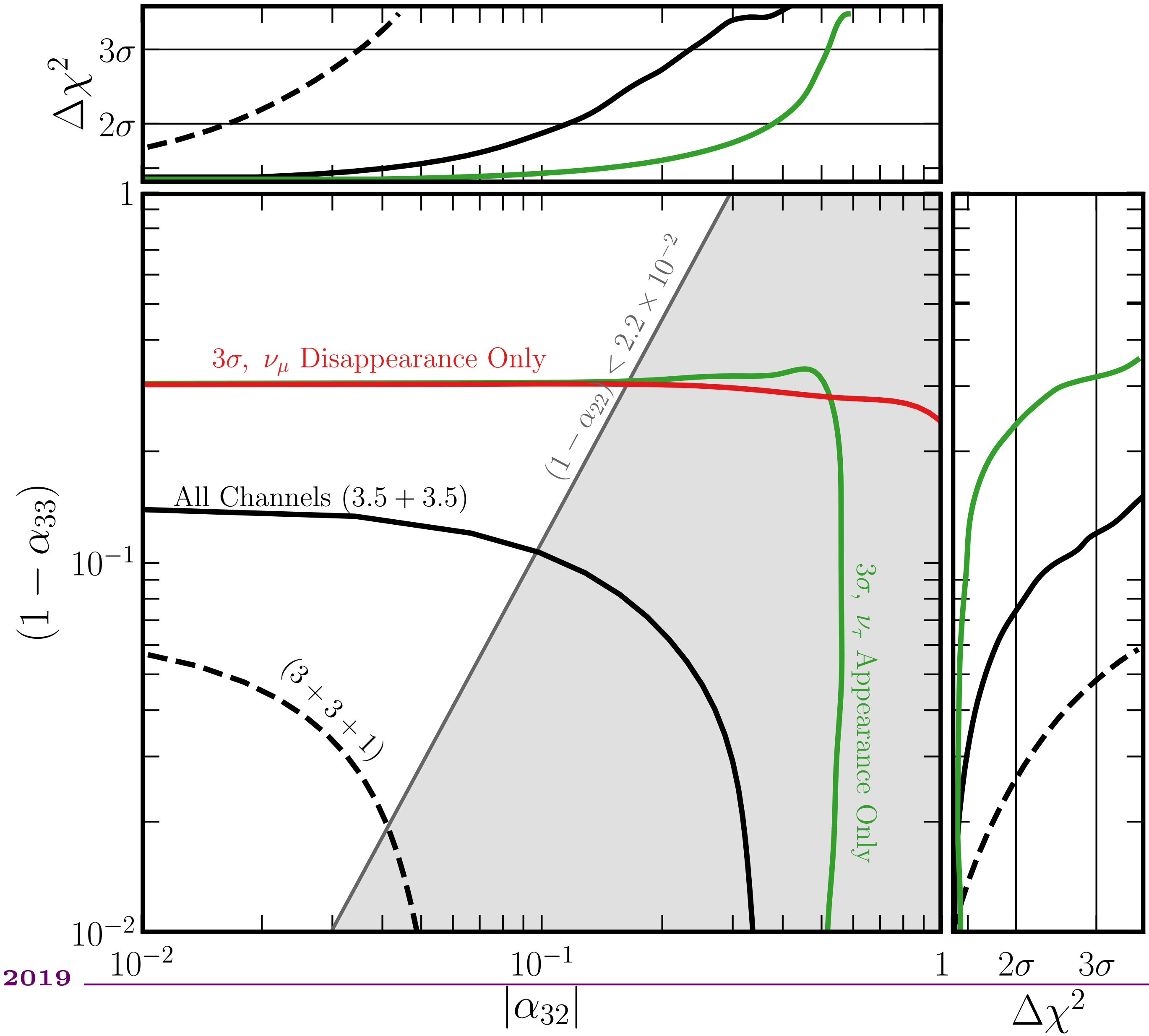


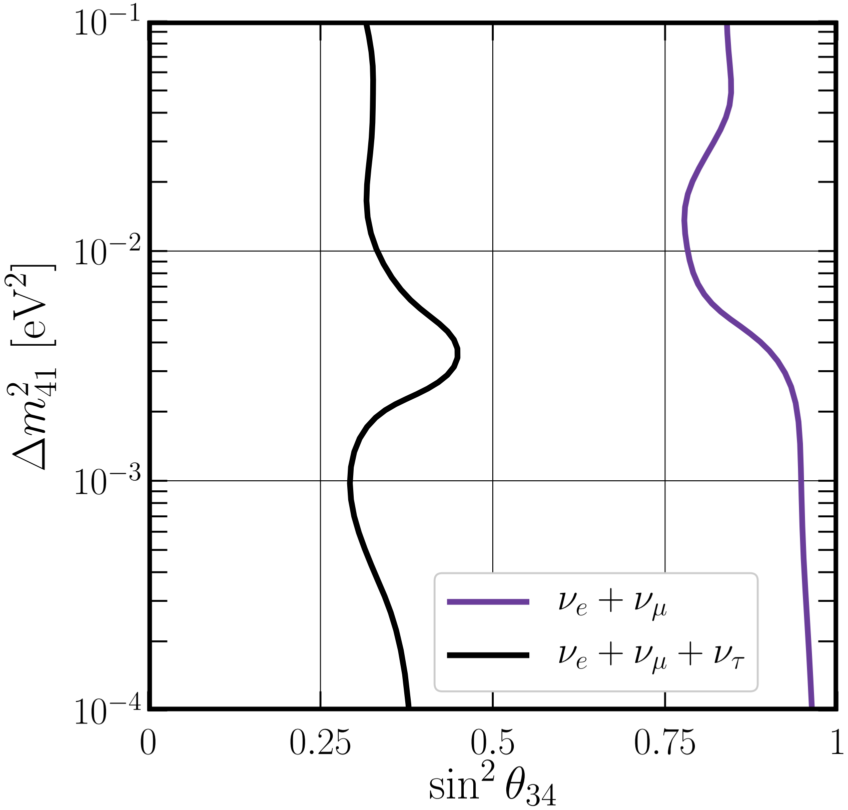
$$\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu3}|^2|U_{e3}|^2, \qquad \sin^2 2\theta_{\mu\tau} \equiv 4|U_{\mu3}|^2|U_{\tau3}|^2, \qquad \sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu3}|^2(1-|U^2_{\mu3}|)$$

Unitarity Test: $|U_{e3}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2 = 1^{+0.05}_{-0.06}$ [one sigma] $(1^{+0.13}_{-0.17}$ [three sigma])

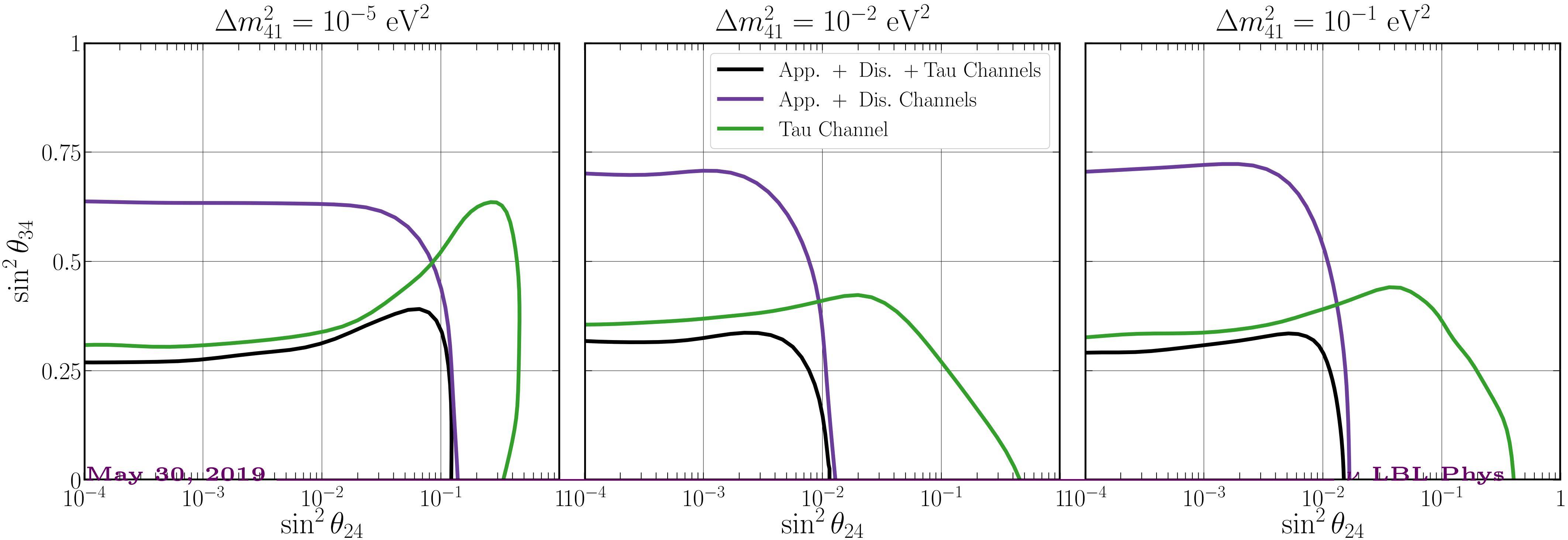

DUNE 7 yr. data collection
3.5 yr. Neutrino Mode, 3.5 yr. Antineutrino Mode
$\sin^2\theta_{12} = 0.310$ (fixed)
$\sin^2\theta_{13} = 0.02240$ (free)
$\sin^2\theta_{23} = 0.582$ (free)
$\Delta m^2_{21} = 7.39 \times 10^{-5}$ eV^2 (fixed)
$\Delta m^2_{31} = +2.525 \times 10^{-3}$ eV^2 (free, ordering fixed)
$\delta_{CP} = -2.496$ rad $= 217°$ (free)
ν_τ Appearance
ν_e Appearance
ν_μ Disappearance
1σ CL
3σ CL
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
Δm^2_{31} [10^{-3} eV^2]

Testing the Unitarity of the Mixing Matrix

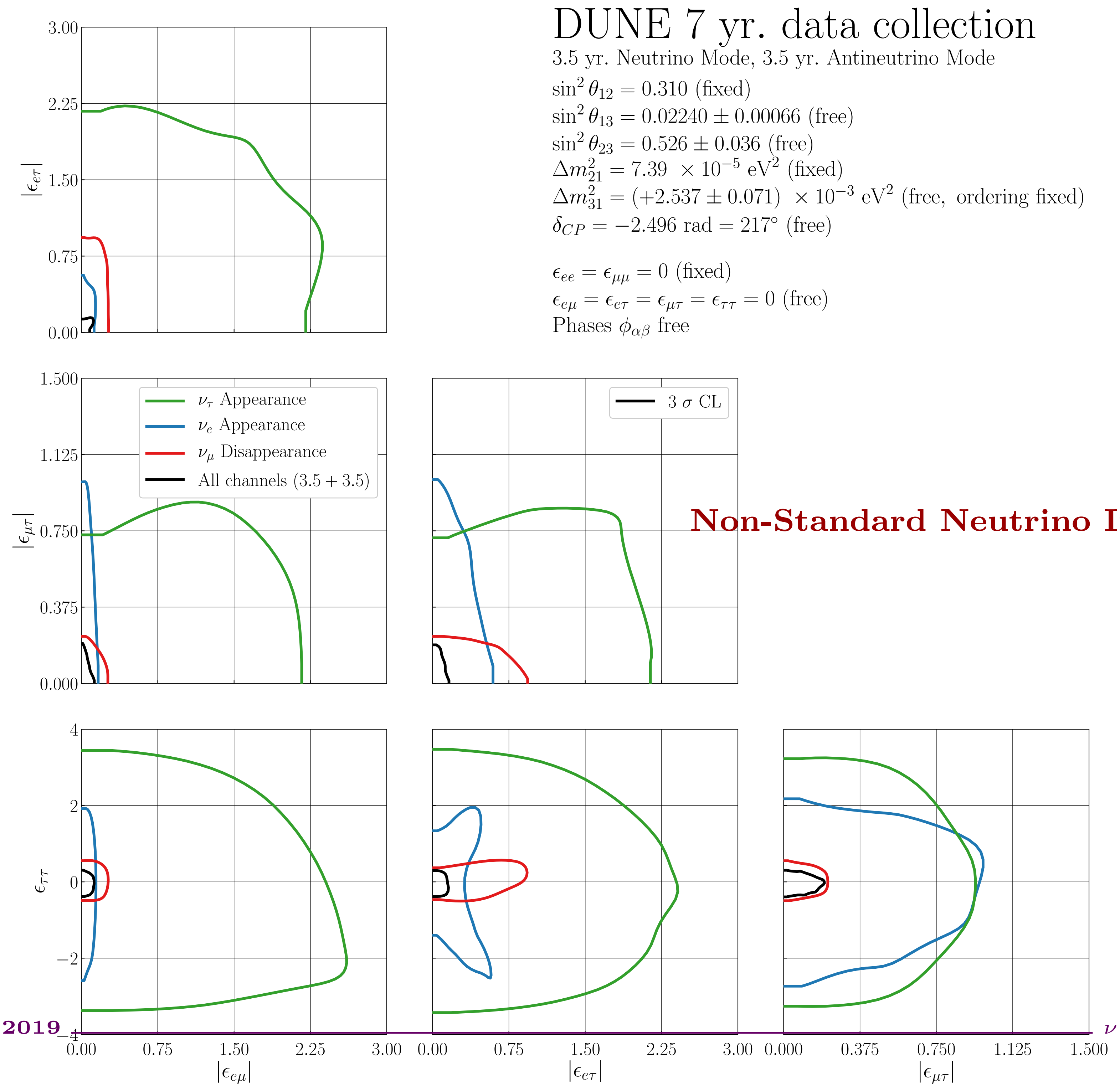




Fourth Neutrino Hypothesis



Non-Standard Neutrino Interactions



In Conclusion

The venerable Standard Model sprung a leak in the end of the last century (and we are still trying to patch it): neutrinos are not massless!

1. We still **know very little** about the new physics uncovered by neutrino oscillations.

2. **neutrino masses are very small** – we don't know why, but we think it means something important.

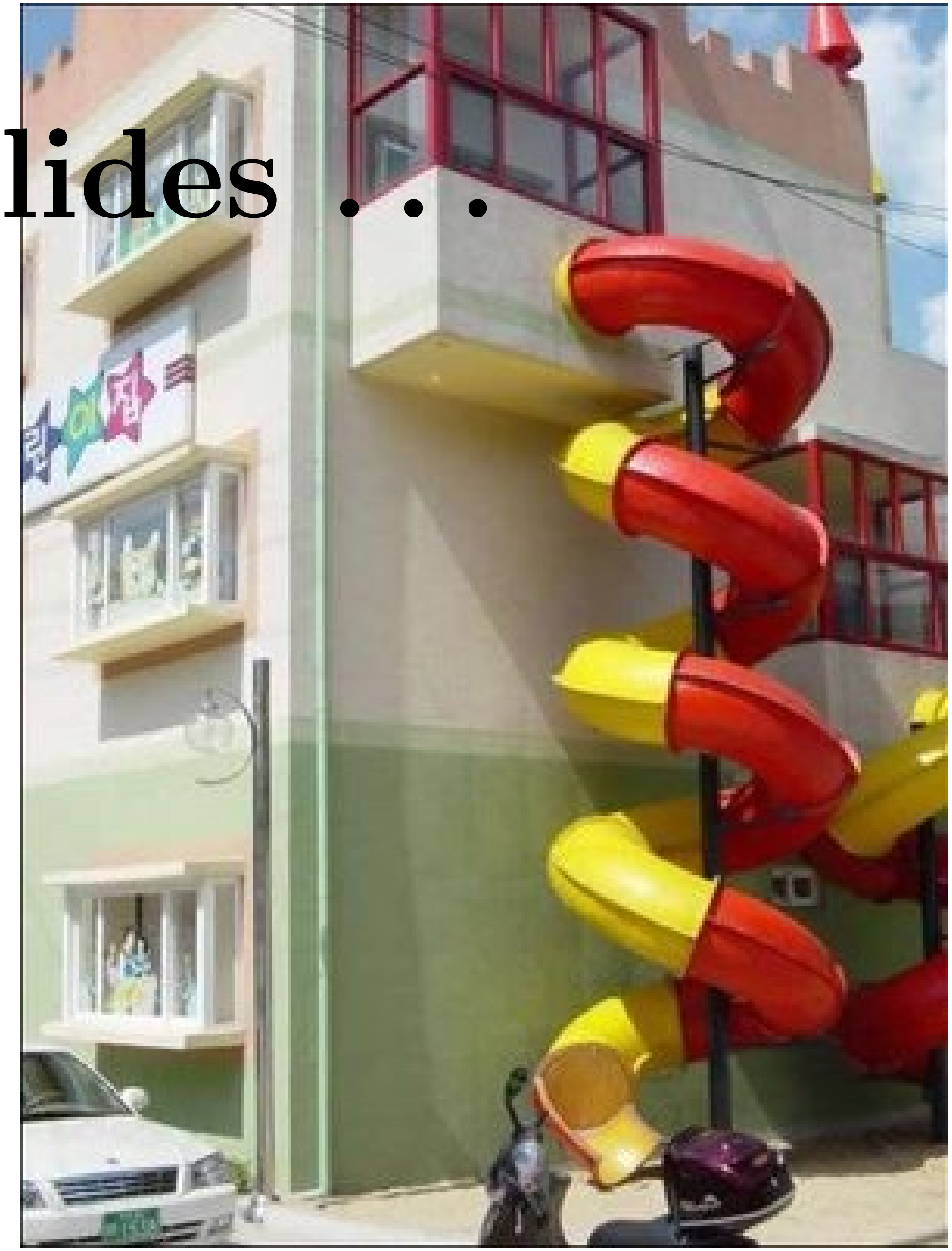
3. **neutrino mixing is "weird"** – we don't know why, but we think it means something important.

4. We **need more experimental input** These will come from a rich, diverse experimental program which relies heavily on the existence of underground facilities capable of hosting large detectors (**double-beta decay, precision neutrino oscillations, supernova neutrinos, proton decay, etc**).

5. **Precision measurements of neutrino oscillations are sensitive to several new phenomena, including new neutrino properties, the existence of new states, or the existence of new interactions. There is a lot of work to be done when it comes to understanding which new phenomena can be probed in long-baseline oscillation experiments (and how well) and what are the other questions one can ask – related and unrelated to neutrinos – of these unique particle physics experiments.**

6. There is plenty of **room for surprises**, as neutrinos are potentially very deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are "quantum interference devices" – potentially very sensitive to whatever else may be out there (e.g., $\Lambda \simeq 10^{14}$ GeV).

Backup Slides . . .



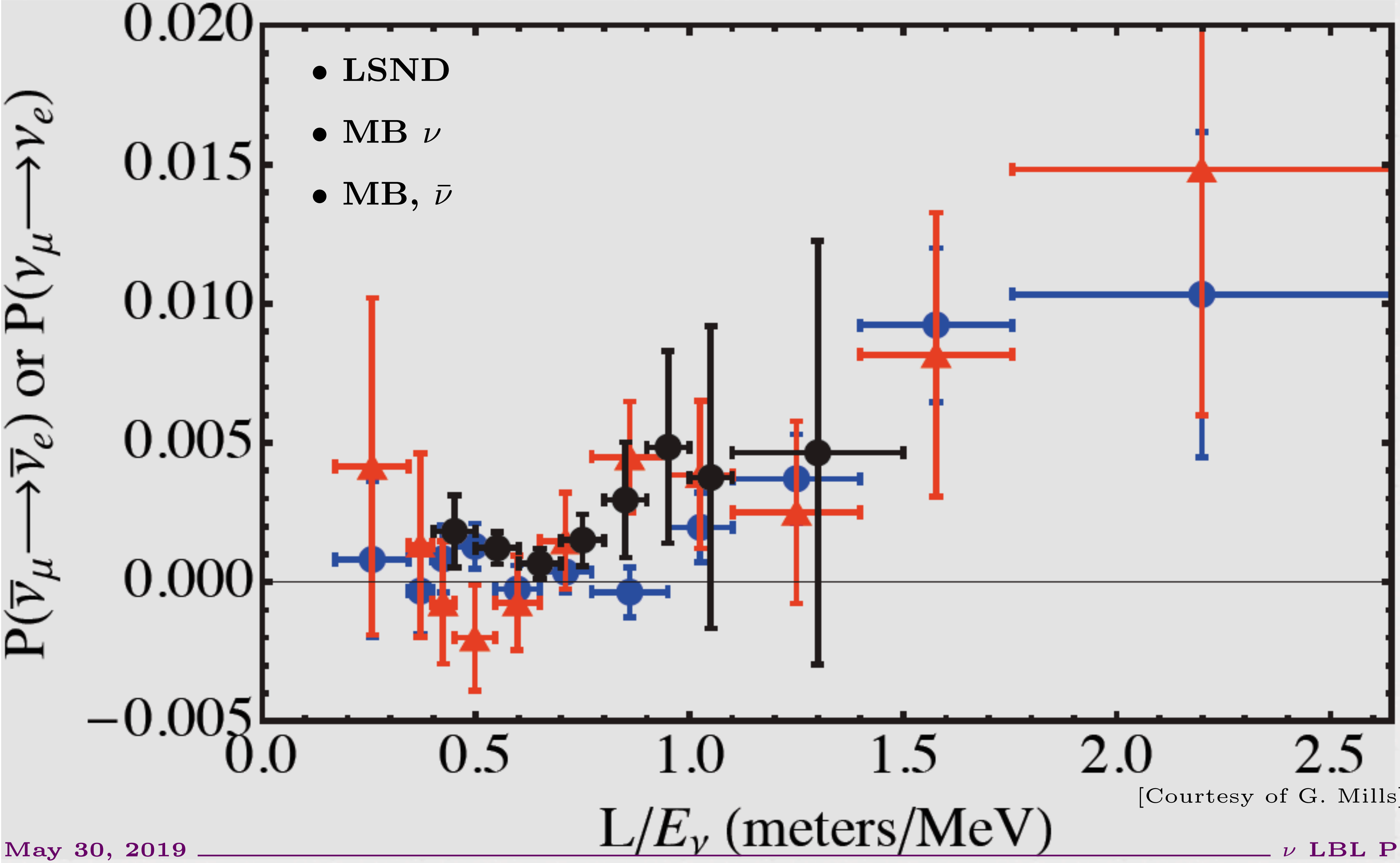
Not all is well(?): The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have "time" to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \to \nu_{\rm other}$ disappearance — radioactive sources;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ disappearance — reactor experiments.

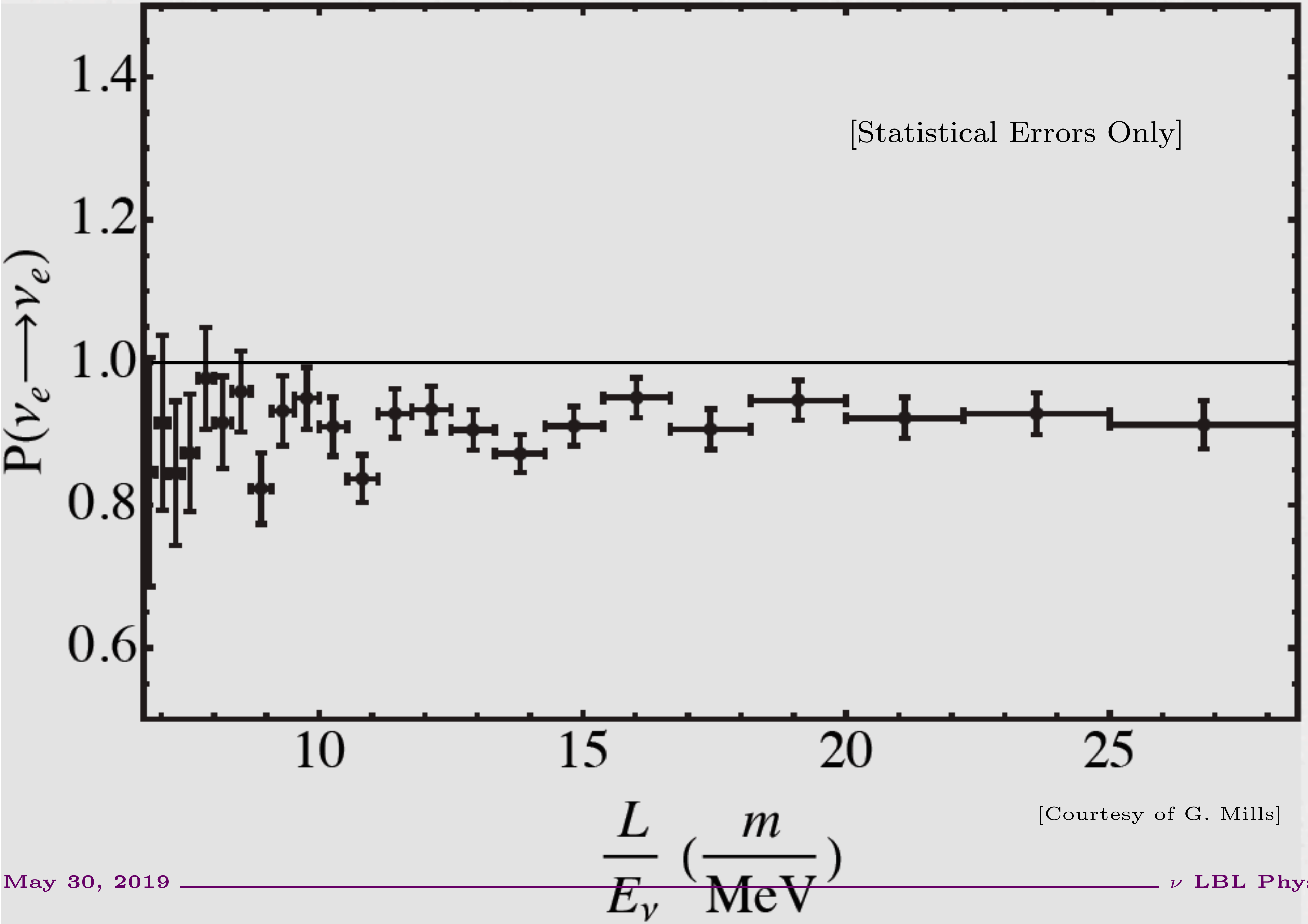
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND



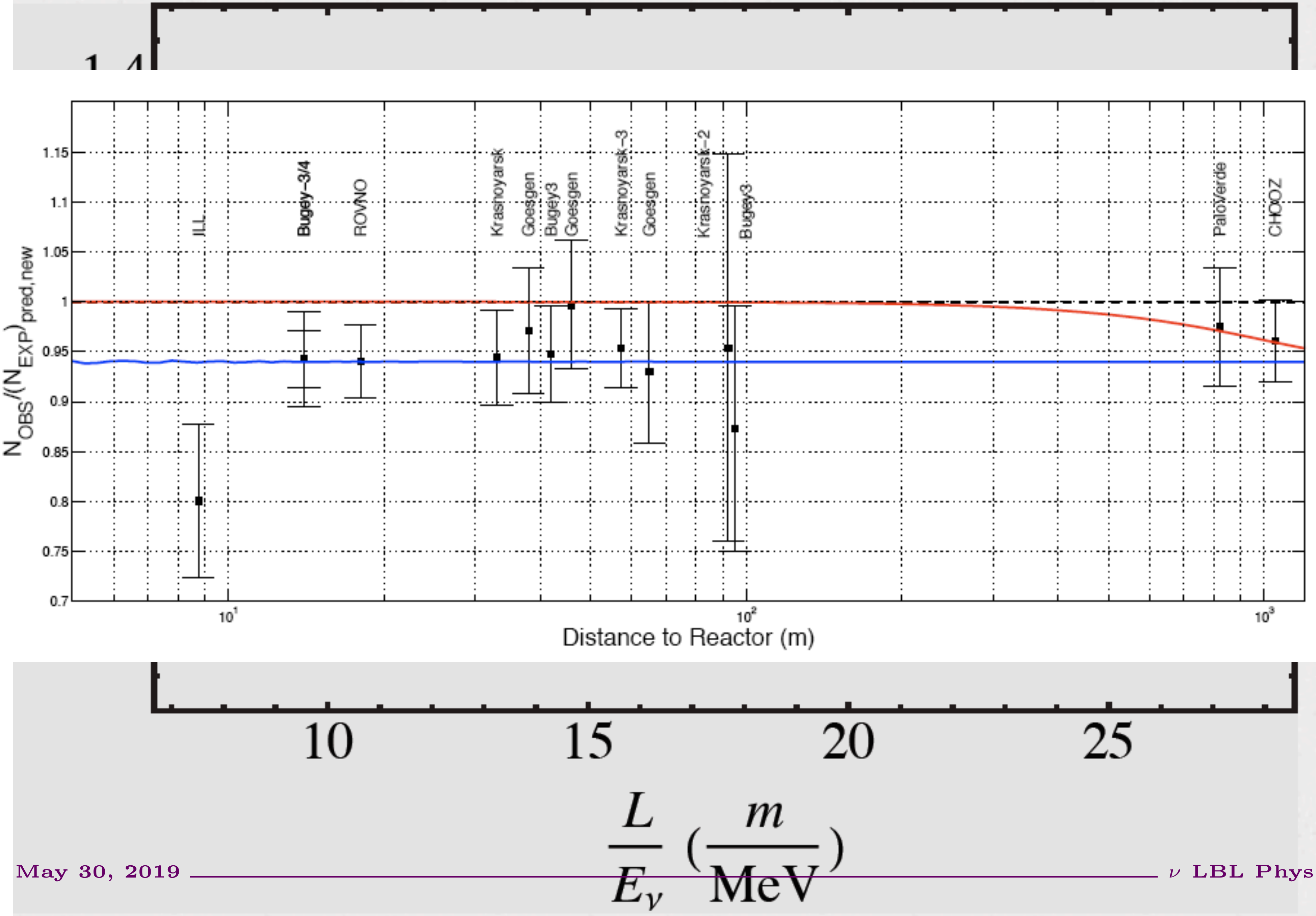
[Courtesy of G. Mills]

Bugey 40 m



[Courtesy of G. Mills]

Bugey 40 m



1.4
$N_{OBS}/(N_{EXP})_{pred,new}$
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
ILL
Bugey-3/4
ROVNO
Krasnoyarsk
Goesgen
Bugey3
Goesgen
Krasnoyarsk-3
Goesgen
Krasnoyarsk-2
Bugey3
PaloVerde
CHOOZ
10^1
10^2
10^3
Distance to Reactor (m)
10
15
20
25
$\frac{L}{E_\nu}$ $(\frac{m}{\text{MeV}})$

What is Going on Here?

- Are these "anomalies" related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type!

Observable wish list:

- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \to \nu_\tau$ appearance.

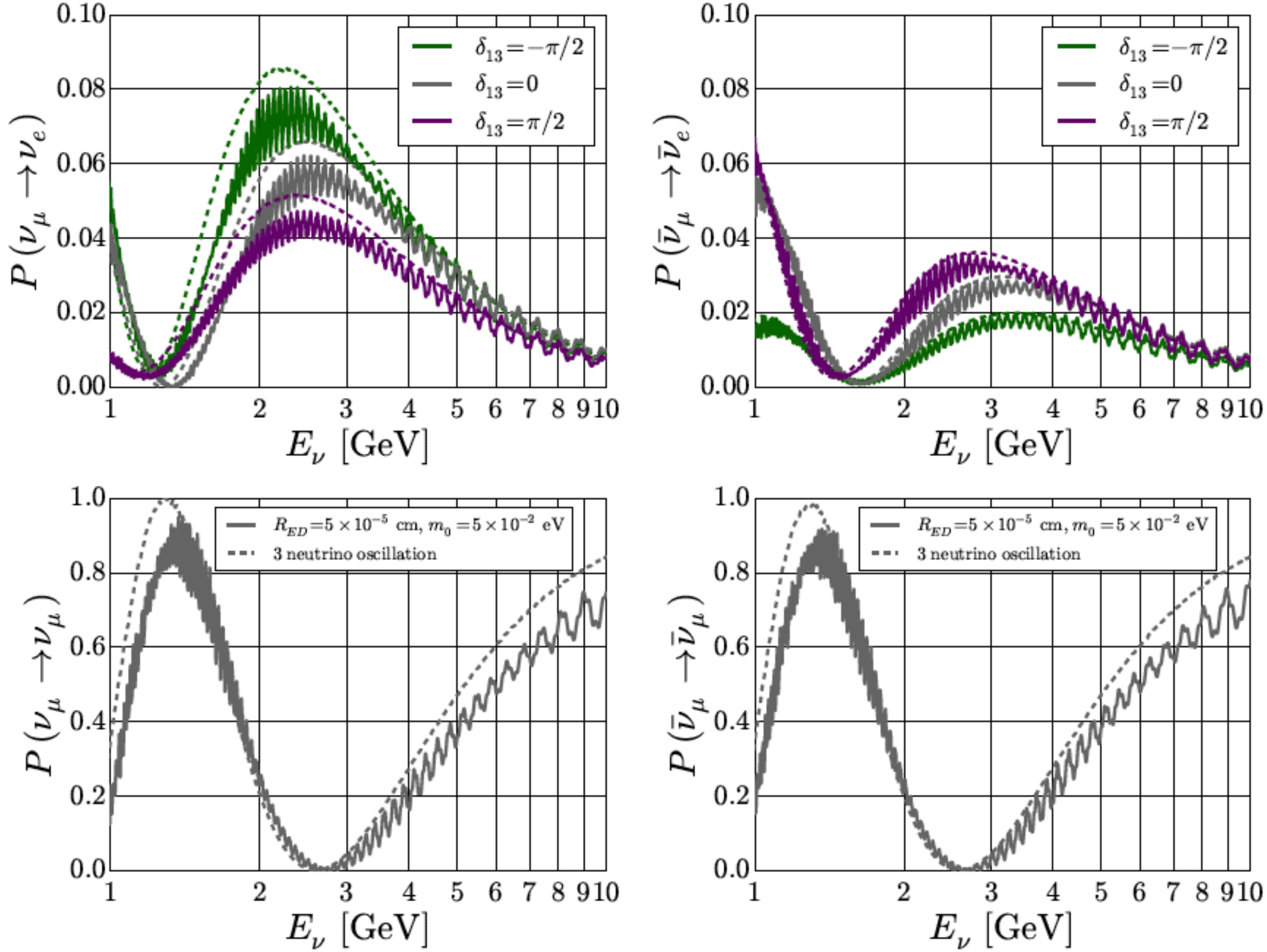


FIG. 1: Oscillation probabilities assuming a three-neutrino framework (dashed) and an LED hypothesis with $m_0 = 5\times10^{-2}$ eV and $R_{\rm ED}^{-1} = 0.38$ eV ($R_{\rm ED} = 5\times10^{-5}$ cm), for the normal neutrino mass hierarchy, $\Delta m^2_{13} > 0$. The values of the other oscillation parameters are tabulated in Table I, see text for details. The top row displays appearance probabilities $P(\nu_\mu \to \nu_e)$ (left) and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ (right), and has curves shown for $\delta_{13} = -\pi/2$ (green), $\delta_{13} = 0$ (gray), and $\delta_{13} = \pi/2$ (purple). The bottom row displays disappearance probabilities $P(\nu_\mu \to \nu_\mu)$ (left) and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ (right).

[Berryman et al, arXiv:1603.00018]

Another Model: Can Neutrino Oscillation Experiments Discover A Fifth Dimension?

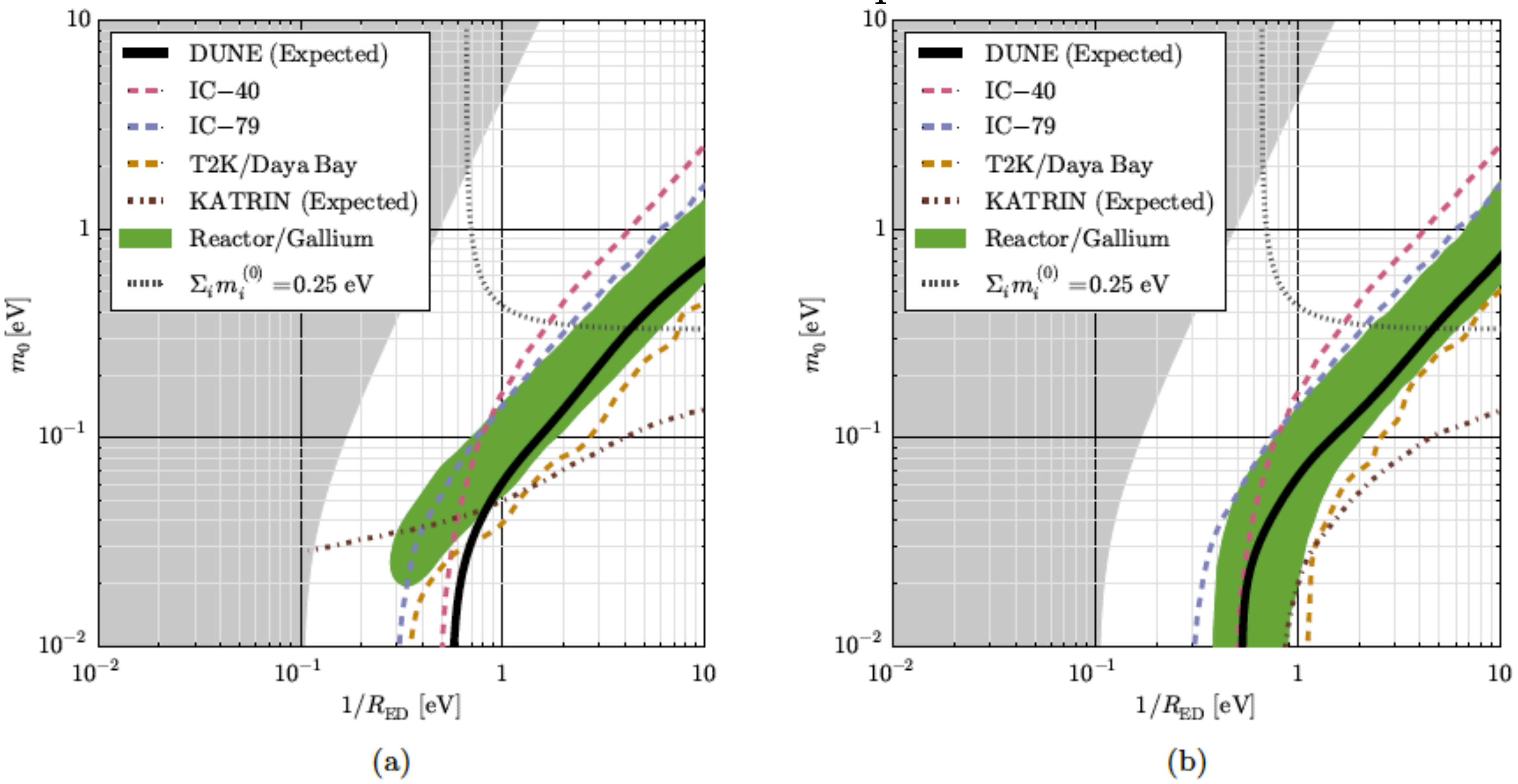


FIG. 3: Exclusion limits in the $R_{\rm ED}^{-1}$–m_0 plane, assuming either (a) a normal hierarchy or (b) an inverted hierarchy of neutrino masses. The exclusion regions are to the top-left of the relevant curves. Shown are the 95% CL lines from DUNE (black), IceCube-40 (mauve) and Ice-Cube79 (blue) [20], and a combined analysis of T2K and Daya Bay (gold) [18]. We also include the 90% CL line from sensitivity analysis of KATRIN (burgundy) [16]. The shaded green regions are preferred at 95% CL by the reactor anomaly seen in reactor and Gallium experiments [19]. The gray shaded regions are excluded by the measurements of Δm_{i1}^2, as explained in the text. The dotted gray lines are curves along which $\sum_i m_i^{(0)} = 0.25$ eV. Higher values of $\sum_i m_i^{(0)}$ correspond to the regions above and to the right of the dotted gray lines.

[Berryman et al, arXiv:1603.00018]

Another Model: Can Neutrino Oscillation Experiments Discover A Fifth Dimension?

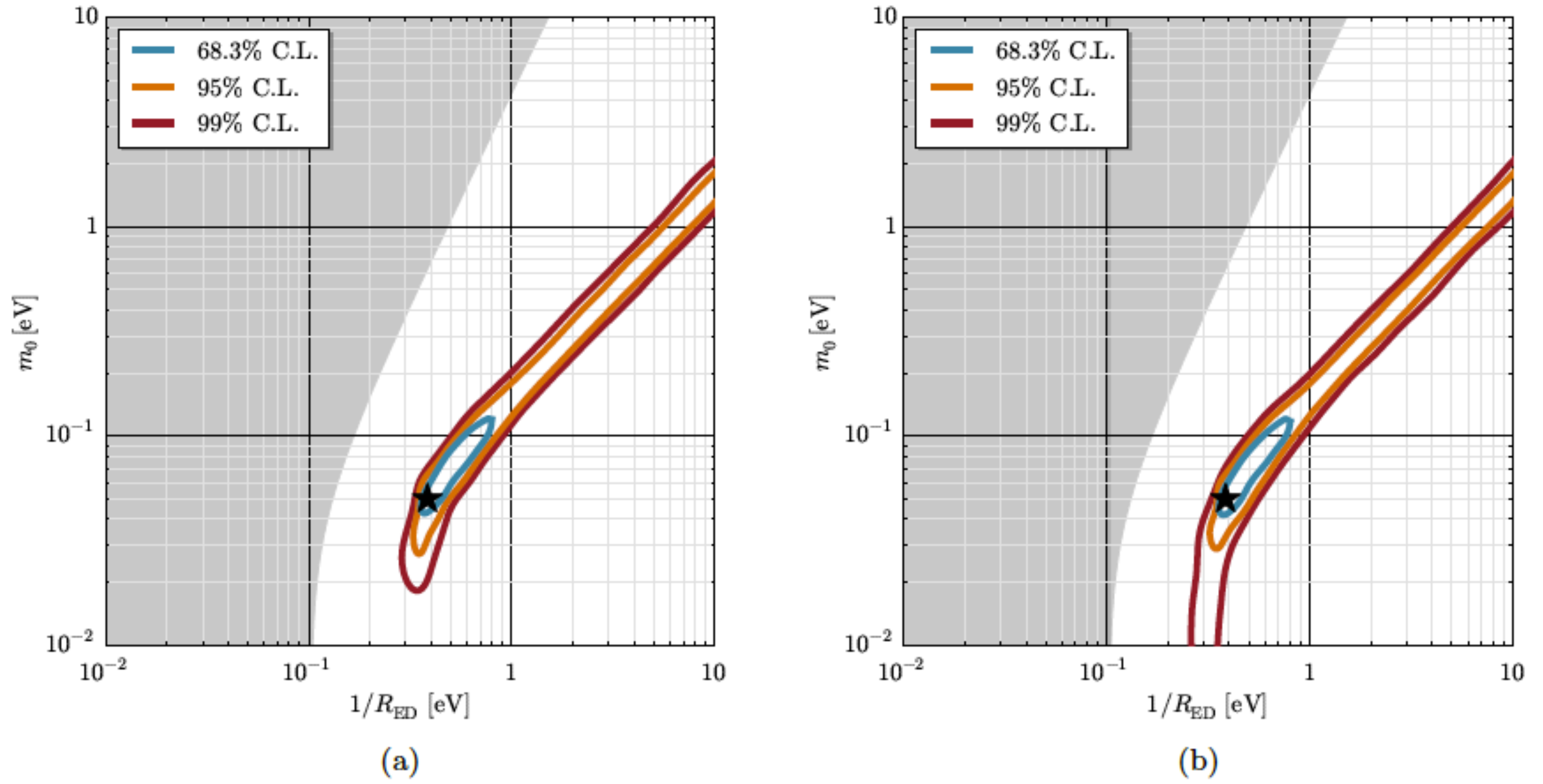


FIG. 4: Expected sensitivity to a non-zero set of LED parameters as measured by DUNE, assuming three years each of neutrino and antineutrino data collection. Fig. 4(a) assumes the normal mass hierarchy (NH) and Fig. 4(b) assumes the inverted mass hierachy (IH). The LED parameters assumed here are $m_0 = 5\times10^{-2}$ eV and $R_{\rm ED}^{-1} = 0.38$ eV, while $\delta_{13} = \pi/3$. The input values of Δm^2_{i1}, $i = 1, 2$ are in Table I. The input values for the mixing angles are, for the NH, $\sin^2\theta_{12} = 0.322$, $\sin^2\theta_{13} = 0.0247$, $\sin^2\theta_{23} = 0.581$, and, for the IH, $\sin^2\theta_{12} = 0.343$, $\sin^2\theta_{13} = 0.0231$, $\sin^2\theta_{23} = 0.541$.

[Berryman et al, arXiv:1603.00018]