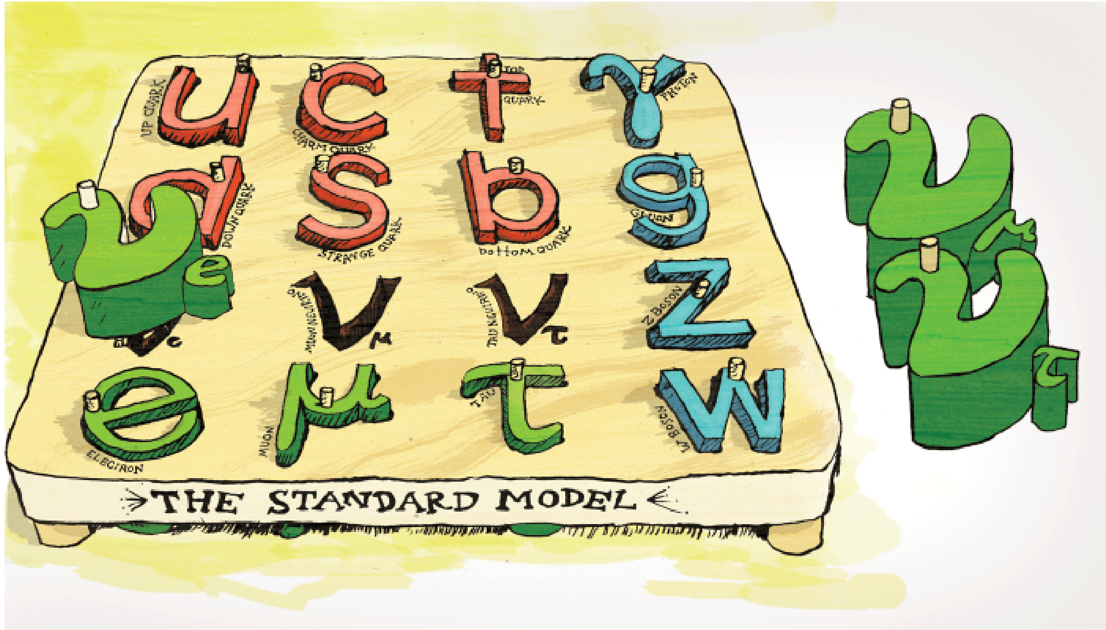
Topics in Neutrino Physics



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6th ComHEP – (Remote)

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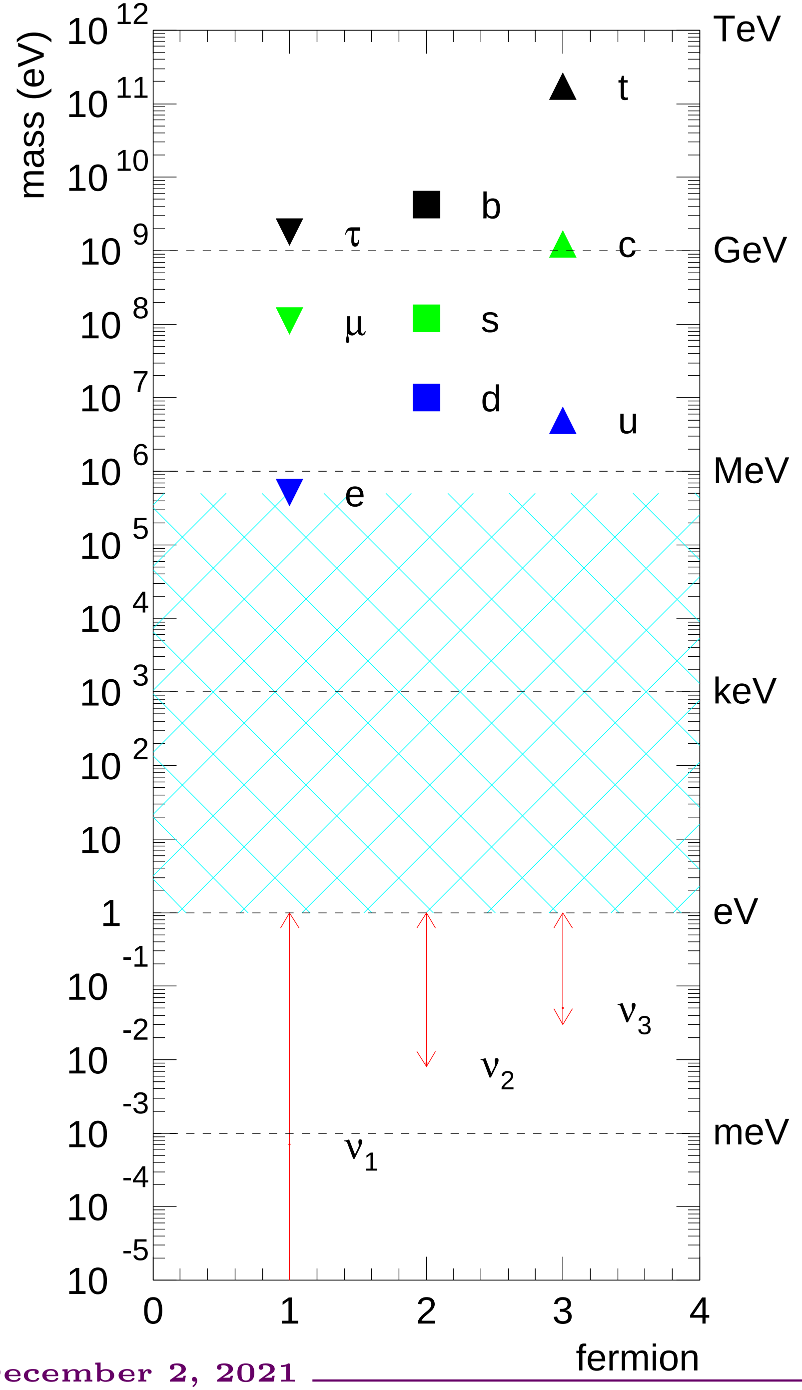
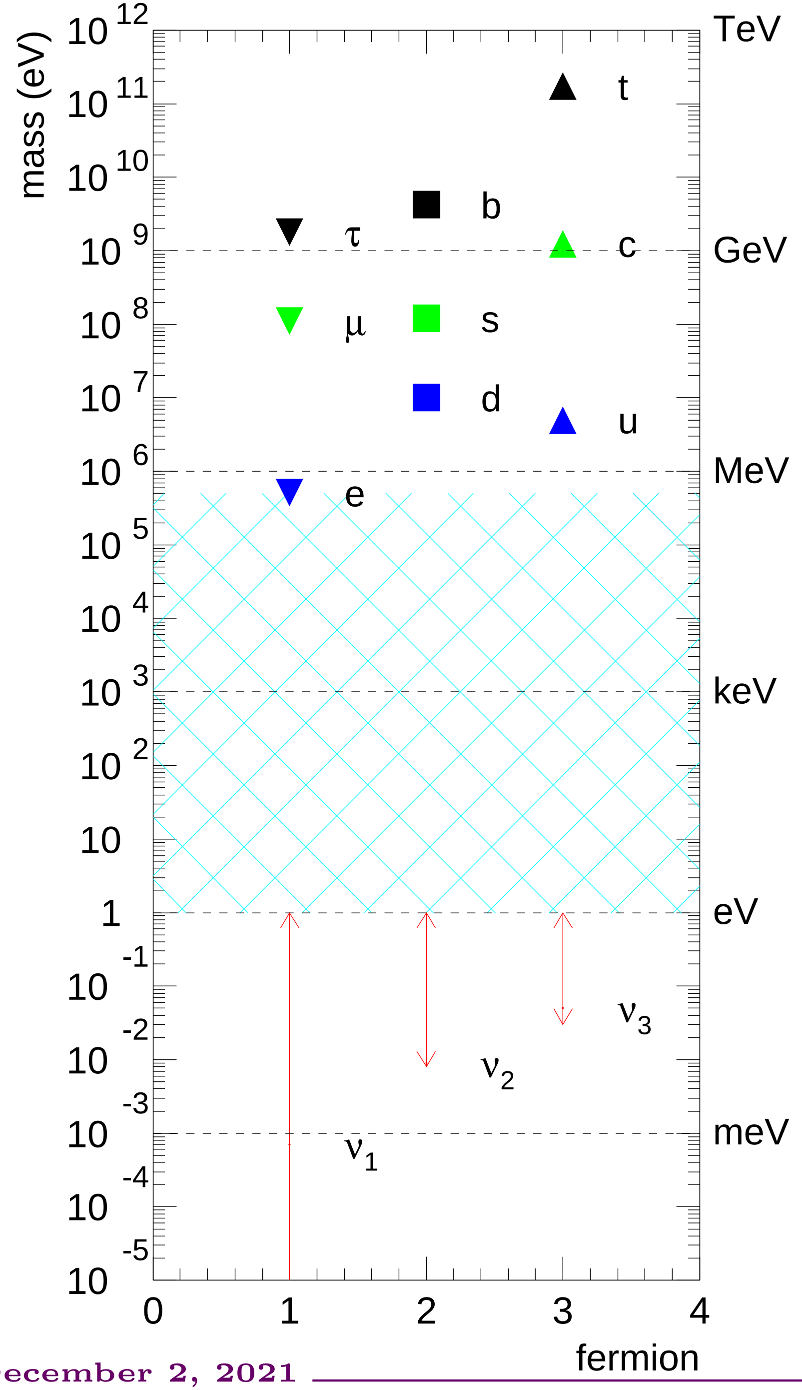


NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

$\boxed{\text{So What?}}$

$\Downarrow$

$\boxed{\text{NEW PHYSICS}}$

Nonzero neutrino masses imply the existence of new fundamental fields ⇒ New Particles

We know nothing about these new particles. They can be bosons or fermions, very light or very heavy, they can be charged or neutral, experimentally accessible or hopelessly out of reach…

There is only a handful of questions the standard model for particle physics cannot explain (these are personal. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there so much ordinary matter in the Universe? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM).

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Fork on the Road: Are Neutrinos Majorana or Dirac Fermions?

Best (Only?) Bet: Neutrinoless Double-Beta Decay.

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 95%
limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- \, {}^{32}\text{S} \to e^+ \, {}^{32}\text{Si}^*)$ / $\sigma(\mu^- \, {}^{32}\text{S} \to \nu_\mu \, {}^{32}\text{P}^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \, {}^{127}\text{I} \to e^+ \, {}^{127}\text{Sb}^*)$ / $\sigma(\mu^- \, {}^{127}\text{I} \to \text{anything})$		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \text{Ti} \to e^+ \text{Ca})$ / $\sigma(\mu^- \text{Ti} \to \text{capture})$ $\Leftarrow \mu^- \to e^+$-conversion		$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-\pi^-)/\Gamma_{\text{total}}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-\pi^-)/\Gamma_{\text{total}}$		$<3.9 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-K^-)/\Gamma_{\text{total}}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+K^-K^-)/\Gamma_{\text{total}}$		$<3.3 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-K^-)/\Gamma_{\text{total}}$		$<4.8 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+K^-K^-)/\Gamma_{\text{total}}$		$<4.7 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to p\mu^-\mu^-)/\Gamma_{\text{total}}$		$<4.4 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\mu^+\mu^-)/\Gamma_{\text{total}}$		$<3.3 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{\text{total}}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{\text{total}}$		$<3.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{\text{total}}$		$<8.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{\text{total}}$		$<2.7 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{\text{total}}$		$<7.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{\text{total}}$		$<1.4 \times 10^{-7}$, CL = 90%
$t_{1/2}({}^{76}\text{Ge} \to {}^{76}\text{Se} + 2\,e^-)$ $\Leftarrow 0\nu\beta\beta$		$>1.9 \times 10^{25}$ yr, CL = 90%
$\Gamma(\pi^+ \to \mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$	[q]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^-\mu^+e^+)/\Gamma_{\text{total}}$		$<5.0 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^-e^+e^+)/\Gamma_{\text{total}}$		$<6.4 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^-\mu^+\mu^+)/\Gamma_{\text{total}}$	[q]	$<1.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$	[q]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0e^+\overline{\nu}_e)/\Gamma_{\text{total}}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^-2e^+)/\Gamma_{\text{total}}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \pi^-2\mu^+)/\Gamma_{\text{total}}$		$<2.2 \times 10^{-8}$, CL = 90%
$\Gamma(D^+ \to \pi^-e^+\mu^+)/\Gamma_{\text{total}}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \rho^-2\mu^+)/\Gamma_{\text{total}}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^-2e^+)/\Gamma_{\text{total}}$		$<9 \times 10^{-7}$, CL = 90%
$\Gamma(D^+ \to K^-2\mu^+)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to K^-e^+\mu^+)/\Gamma_{\text{total}}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to K^*(892)^-2\mu^+)/\Gamma_{\text{total}}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^-2e^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<1.12 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^-2\mu^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<2.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-2e^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<2.06 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-2\mu^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<3.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-2e^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<1.52 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-2\mu^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<9.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^-\pi^-e^+\mu^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<7.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-e^+\mu^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<2.18 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-e^+\mu^+ + \text{c.c.})/\Gamma_{\text{total}}$		$<5.7 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to pe^-)/\Gamma_{\text{total}}$	[r]	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{p}e^+)/\Gamma_{\text{total}}$	[s]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-2e^+)/\Gamma_{\text{total}}$		$<4.1 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-2\mu^+)/\Gamma_{\text{total}}$		$<1.2 \times 10^{-7}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-e^+\mu^+)/\Gamma_{\text{total}}$		$<8.4 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^-2e^+)/\Gamma_{\text{total}}$		$<5.2 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^-2\mu^+)/\Gamma_{\text{total}}$		$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to K^-e^+\mu^+)/\Gamma_{\text{total}}$		$<6.1 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^*(892)^-2\mu^+)/\Gamma_{\text{total}}$		$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^-e^+e^+)/\Gamma_{\text{total}}$		$<2.3 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \pi^-\mu^+\mu^+)/\Gamma_{\text{total}}$		$<4.0 \times 10^{-9}$, CL = 95%
$\Gamma(B^+ \to \pi^-e^+\mu^+)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^-e^+e^+)/\Gamma_{\text{total}}$		$<1.7 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^-\mu^+\mu^+)/\Gamma_{\text{total}}$		$<4.2 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^-e^+\mu^+)/\Gamma_{\text{total}}$		$<4.7 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^-e^+e^+)/\Gamma_{\text{total}}$		$<3.0 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to K^-\mu^+\mu^+)/\Gamma_{\text{total}}$		$<4.1 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to K^-e^+\mu^+)/\Gamma_{\text{total}}$		$<1.6 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^-e^+e^+)/\Gamma_{\text{total}}$		$<4.0 \times 10^{-7}$, CL = 90%
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$\Gamma(B^+ \to K^*(892)^-e^+\mu^+)/\Gamma_{\text{total}}$		$<3.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to D^-e^+e^+)/\Gamma_{\text{total}}$		$<2.6 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-e^+\mu^+)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-\mu^+\mu^+)/\Gamma_{\text{total}}$		$<6.9 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to D^{*-}\mu^+\mu^+)/\Gamma_{\text{total}}$		$<2.4 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to D_s^-\mu^+\mu^+)/\Gamma_{\text{total}}$		$<5.8 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to \overline{D}^0\pi^-\mu^+\mu^+)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to \Lambda^0\mu^+)/\Gamma_{\text{total}}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0e^+)/\Gamma_{\text{total}}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0\mu^+)/\Gamma_{\text{total}}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0e^+)/\Gamma_{\text{total}}$		$<8 \times 10^{-8}$, CL = 90%

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$\Gamma(\tau^- \to \mu^+K^-K^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to p\mu^-\mu^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}\mu^+\mu^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{total}$		
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$t_{1/2}({}^{76}Ge \to {}^{76}Se + 2e^-)$		
$\Gamma(\pi^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$		
$\Gamma(K^+ \to \pi^-\mu^+e^+)/\Gamma_{total}$		
$\Gamma(K^+ \to \pi^-e^+e^+)/\Gamma_{total}$		
$\Gamma(K^+ \to \pi^-\mu^+\mu^+)/\Gamma_{total}$	[q]	$<1.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$	[q]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0e^+\overline{\nu}_e)/\Gamma_{total}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^-2e^+)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \pi^-2\mu^+)/\Gamma_{total}$		$<2.2 \times 10^{-8}$, CL = 90%
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$\Gamma(D^+ \to K^-2e^+)/\Gamma_{total}$		$<9 \times 10^{-7}$, CL = 90%
$\Gamma(D^+ \to K^-2\mu^+)/\Gamma_{total}$		$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to K^-e^+\mu^+)/\Gamma_{total}$		$<1.9 \times 10^{-6}$, CL = 90%

$\Gamma(B^0 \to \Lambda_c^+\mu^-)/\Gamma_{total}$	$<1.4 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to \Lambda_c^+e^-)/\Gamma_{total}$	$<4 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to \pi^+e^-)/\Gamma_{total}$	$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^+\mu^-)/\Gamma_{total}$	$<6 \times 10^{-7}$, CL = 90%
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$\Gamma(\Lambda \to K^+e^-)/\Gamma_{total}$	$<2 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^+\mu^-)/\Gamma_{total}$	$<3 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^-e^+)/\Gamma_{total}$	$<2 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^-\mu^+)/\Gamma_{total}$	$<3 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K_S^0\nu)/\Gamma_{total}$	$<2 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^- \to p\mu^-\mu^-)/\Gamma_{total}$	$<4 \times 10^{-8}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}2e^+)/\Gamma_{total}$	$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}2\mu^+)/\Gamma_{total}$	$<9.4 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}e^+\mu^+)/\Gamma_{total}$	$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \Sigma^-\mu^+\mu^+)/\Gamma_{total}$	$<7.0 \times 10^{-4}$, CL = 90%

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$\Gamma(D^0 \to 2\pi^-2e^+ +$ c.c.$)/\Gamma_{total}$		$<1.12 \times 10^{-4}$, CL = 90%
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$\Gamma(D^0 \to K^-\pi^-2e^+ +$ c.c.$)/\Gamma_{total}$		$<2.06 \times 10^{-4}$, CL = 90%
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$\Gamma(D^0 \to K^-\pi^-e^+\mu^+ +$ c.c.$)/\Gamma_{total}$		$<2.18 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-e^+\mu^+ +$ c.c.$)/\Gamma_{total}$		$<5.7 \times 10^{-5}$, CL = 90%
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$\Gamma(D^0 \to \overline{p}e^+)/\Gamma_{total}$	[s]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-2e^+)/\Gamma_{total}$		$<4.1 \times 10^{-6}$, CL = 90%
		$<1.2 \times 10^{-7}$, CL = 90%
		$<8.4 \times 10^{-6}$, CL = 90%
		$<5.2 \times 10^{-6}$, CL = 90%
		$<1.3 \times 10^{-5}$, CL = 90%
		$<6.1 \times 10^{-6}$, CL = 90%
		$<1.4 \times 10^{-3}$, CL = 90%
		$<2.3 \times 10^{-8}$, CL = 90%
		$<4.0 \times 10^{-9}$, CL = 95%
		$<1.5 \times 10^{-7}$, CL = 90%
		$<1.7 \times 10^{-7}$, CL = 90%
		$<4.2 \times 10^{-7}$, CL = 90%
		$<4.7 \times 10^{-7}$, CL = 90%
		$<3.0 \times 10^{-8}$, CL = 90%
		$<4.1 \times 10^{-8}$, CL = 90%
		$<1.6 \times 10^{-7}$, CL = 90%
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$\Gamma(B^+ \to K^*(892)^-e^+\mu^+)/\Gamma_{total}$		$<3.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to D^-e^+e^+)/\Gamma_{total}$		$<2.6 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-e^+\mu^+)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-\mu^+\mu^+)/\Gamma_{total}$		$<6.9 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to D^{*-}\mu^+\mu^+)/\Gamma_{total}$		$<2.4 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to D_s^-\mu^+\mu^+)/\Gamma_{total}$		$<5.8 \times 10^{-7}$, CL = 95%
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νSM – One Path

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\mathrm{SM}} \supset -y_{ij}\frac{L^i H L^j H}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $\Lambda \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB } \mathcal{L}_{\nu\mathrm{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = y_{ij}\frac{v^2}{\Lambda}.$$

- Neutrino masses are small: $\Lambda \gg v \to m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above at most Λ.
- What is Λ? First naive guess is that Λ is the Planck scale – does not work. Data require $\Lambda \sim 10^{14}$ GeV (related to GUT scale?) [note $y^{\max} \equiv 1$]

What else is this "good for"? Depends on the ultraviolet completion!

The Seesaw Lagrangian

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N^i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions.

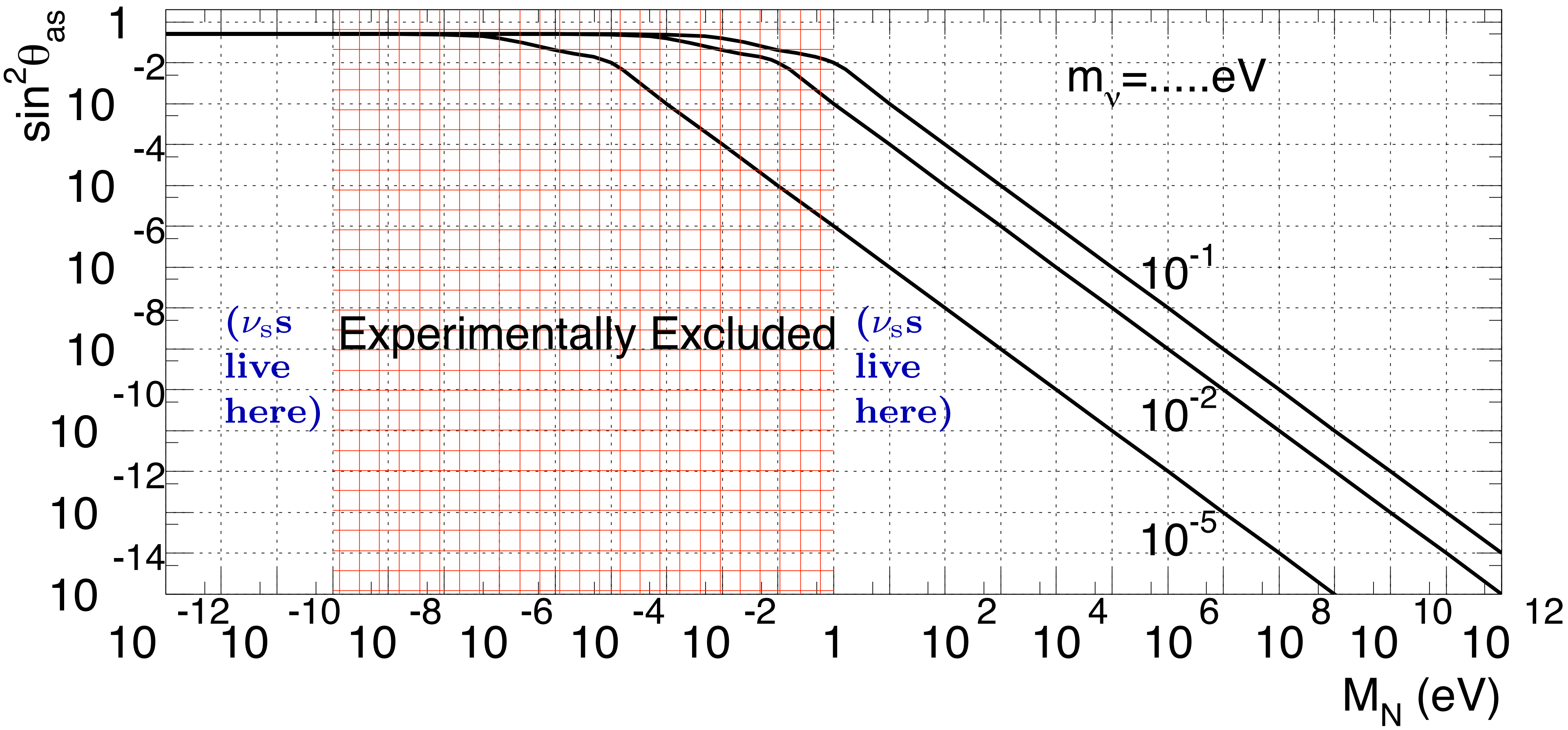
$\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

Constraining the Seesaw Lagrangian

[AdG, Huang, Jenkins, arXiv:0906.1611]



Theoretical upper bound: $M_N < 7.6 \times 10^{24}\ \text{eV} \times \left(\frac{0.1\ \text{eV}}{m_\nu}\right) \Rightarrow\Rightarrow\Rightarrow$

Higher Order Neutrino Masses from $\Delta L = 2$ Physics – Other Paths

Imagine that there is new physics that breaks lepton number by 2 units at some energy scale Λ, but that it does not, in general, lead to neutrino masses at the tree level.

We know that neutrinos will get a mass at some order in perturbation theory – which order is model dependent!

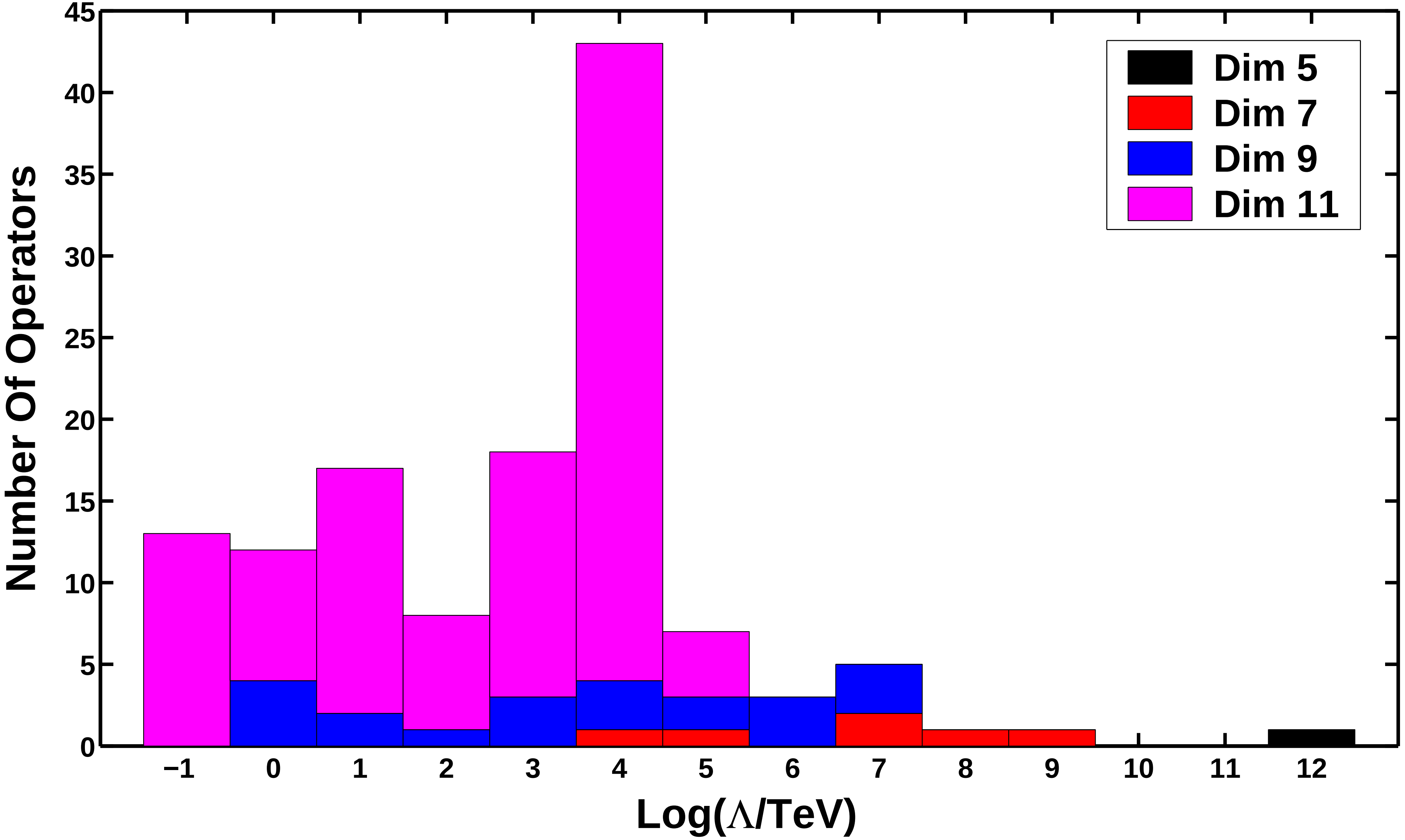
For example:

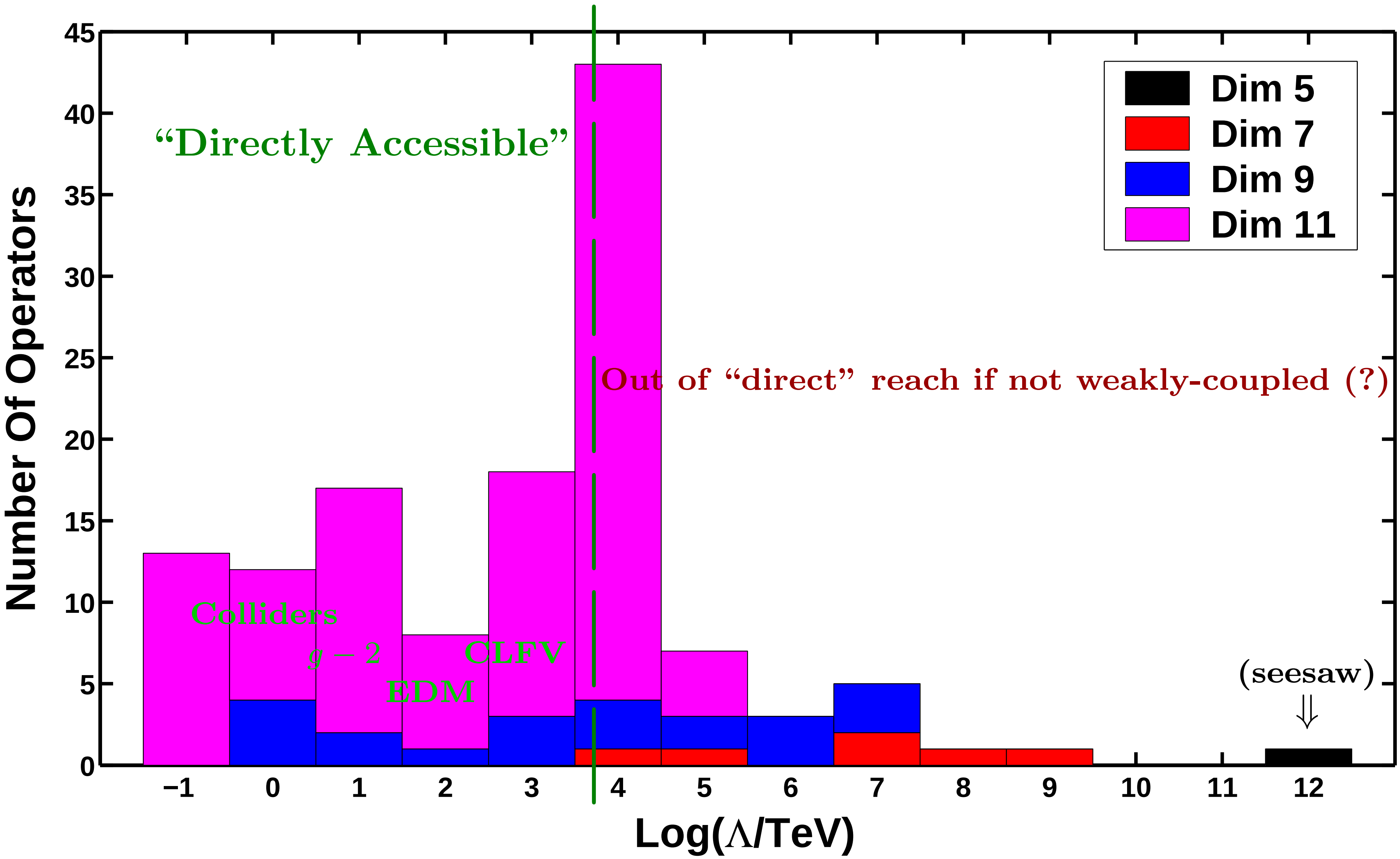
- SUSY with trilinear R-parity violation – neutrino masses at one-loop;
- Zee models – neutrino masses at one-loop;
- Babu and Ma – neutrino masses at two loops;
- Chen et al, 0706.1964 – neutrino masses at two loops;
- Angel et al, 1308.0463 – neutrino masses at two loops;
- etc.

$\mathcal{O}$	Operator	Λ [TeV]
$\mathcal{O}_1$	$(LH)(LH)$	$6\times10^{10-11}$
$\mathcal{O}_2$	$(LL)(LH)e^c$	$4\times10^{6-7}$
$\mathcal{O}_{3_a}$	$(LL)(QH)d^c$	$2\times10^{4-5}$
$\mathcal{O}_{3_b}$	$(LQ)(LH)d^c$	$1\times10^{7-8}$
$\mathcal{O}_{4_a}$	$(L\overline{Q})(LH)\overline{u^c}$	$4\times10^{8-9}$
$\mathcal{O}_{4_b}$	$(LL)(\overline{Q}H)\overline{u^c}$	$2-7$
$\mathcal{O}_8$	$(LH)\overline{e^c}\overline{u^c}d^c$	$6\times10^{2-3}$
$\mathcal{O}_5$	$(L\overline{H})(LH)(QH)d^c$	$6\times10^{4-5}$
$\mathcal{O}_6$	$(LH)(L\overline{H})(\overline{Q}H)\overline{u^c}$	$2\times10^{6-7}$
$\mathcal{O}_7$	$(LH)(QH)(\overline{Q}H)\overline{e^c}$	$4\times10^{1-2}$
$\mathcal{O}_9$	$(LL)(LL)e^ce^c$	$3\times10^{2-3}$
$\mathcal{O}_{10}$	$(LL)(LQ)e^cd^c$	$6\times10^{2-3}$
$\mathcal{O}_{11_a}$	$(LL)(QQ)d^cd^c$	$3-30$
$\mathcal{O}_{11_b}$	$(LQ)(LQ)d^cd^c$	$2\times10^{3-4}$
$\mathcal{O}_{12_a}$	$(L\overline{Q})(L\overline{Q})\overline{u^c}\overline{u^c}$	$2\times10^{6-7}$
$\mathcal{O}_{12_b}$	$(LL)(\overline{Q}\overline{Q})\overline{u^c}\overline{u^c}$	$0.3-0.6$
$\mathcal{O}_{13}$	$(L\overline{Q})(LL)\overline{u^c}e^c$	$2\times10^{4-5}$
$\mathcal{O}_{14_a}$	$(LL)(Q\overline{Q})\overline{u^c}d^c$	10^{2-3}
$\mathcal{O}_{14_b}$	$(L\overline{Q})(LQ)\overline{u^c}d^c$	$6\times10^{4-5}$
$\mathcal{O}_{15}$	$(LL)(L\overline{L})d^c\overline{u^c}$	10^{2-3}
$\mathcal{O}_{16}$	$(LL)e^cd^c\overline{e^c}\overline{u^c}$	$0.2-2$
$\mathcal{O}_{17}$	$(LL)d^cd^c\overline{d^c}\overline{u^c}$	$0.2-2$
$\mathcal{O}_{18}$	$(LL)d^cu^c\overline{u^c}\overline{u^c}$	$0.2-2$
$\mathcal{O}_{19}$	$(LQ)d^cd^c\overline{e^c}\overline{u^c}$	$0.1-1$
$\mathcal{O}_{20}$	$(L\overline{Q})d^c\overline{u^c}\overline{e^c}\overline{u^c}$	$4-40$
$\mathcal{O}_s$	$e^ce^cu^cu^c\overline{d^c}\overline{d^c}$	10^{-3}

- Ignore Lorentz, $SU(3)_C$ structure
- $SU(2)_L$ contractions denoted with parentheses
- Λ indicates range in which $m_\nu \in [0.05\text{ eV}, 0.5\text{ eV}]$

hep-ph/0106054; K.S. Babu & C.N. Leung
arXiv:0708.1344; A. de Gouvêa & J. Jenkins
arXiv:1212.6111; P.W. Angel, et al.
arXiv:1404.4057; A. de Gouvêa, at al.


Number Of Operators
Log(Λ/TeV)
Dim 5
Dim 7
Dim 9
Dim 11
0 5 10 15 20 25 30 35 40 45
−1 0 1 2 3 4 5 6 7 8 9 10 11 12


Dim 5
Dim 7
Dim 9
Dim 11
"Directly Accessible"
Out of "direct" reach if not weakly-coupled (?)
Colliders
$g-2$
EDM
CLFV
(seesaw)
Number Of Operators
Log(Λ/TeV)
45
40
35
30
25
20
15
10
5
0
−1
0
1
2
3
4
5
6
7
8
9
10
11
12

Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

Back to

$$\mathcal{L}_{\nu} = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^{\alpha} H N^{i} - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions.

Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

If all $M_i \equiv 0$, the neutrinos are Dirac fermions.

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. In this case, the νSM global symmetry structure is enhanced. For example, $U(1)_{B-L}$ is an exactly conserved, global symmetry. This is new!

Downside: The neutrino Yukawa couplings λ are tiny, less than 10^{-12}. What is wrong with that? We don't like tiny numbers, but Nature seems to not care very much about what we like…

There are lots of ideas that lead to very small Dirac neutrino masses.

Maybe right-handed neutrinos exist, but neutrino Yukawa couplings are forbidden – hence neutrino masses are tiny.

One possibility is that the N fields are charged under some new symmetry (gauged or global) that is spontaneously broken.

$$\lambda_{\alpha i} L^{\alpha} H N^{i} \to \frac{\kappa_{\alpha i}}{\Lambda}(L^{\alpha}H)(N^{i}\Phi),$$

where Φ (spontaneously) breaks the new symmetry at some energy scale v_{Φ}. Hence, $\lambda = \kappa v_{\Phi}/\Lambda$. How do we test this?

E.g., AdG and D. Hernández, arXiv:1507.00916

Gauged chiral new symmetry for the right-handed neutrinos, no Majorana masses allowed, plus a heavy messenger sector. Predictions: new stable massive states (mass around v_{Φ}) which look like (i) dark matter, (ii) (Dirac) sterile neutrinos are required. Furthermore, there is a new heavy Z'-like gauge boson.

$\Rightarrow$ Natural Conections to Dark Matter, Sterile Neutrinos, Dark Photons!

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts . . .

- understanding the fate of lepton-number. Neutrinoless double-beta decay. What else?
- A comprehensive long baseline neutrino program. (On-going T2K, NOνA, etc. DUNE and HyperK next steps towards the ultimate “superbeam” experiment.)
- Different baselines and detector technologies a must for both over-constraining the system and looking for new phenomena.
- Probes of neutrino properties, including neutrino scattering experiments. And what are the neutrino masses anyway? Kinematical probes.
- Precision measurements of charged-lepton properties ($g-2$, edm) and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Neutrino properties affect, in a significant way, the history of the universe (Cosmology). Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?

HOWEVER. . .

We have only ever objectively "seen" neutrino masses in long-baseline oscillation experiments. It is the clearest way forward!

Does this mean we will reveal the origin of neutrino masses with oscillation experiments? We don't know, and we won't know until we try!

Three Flavor Mixing Hypothesis Fits All* Data Really Well.

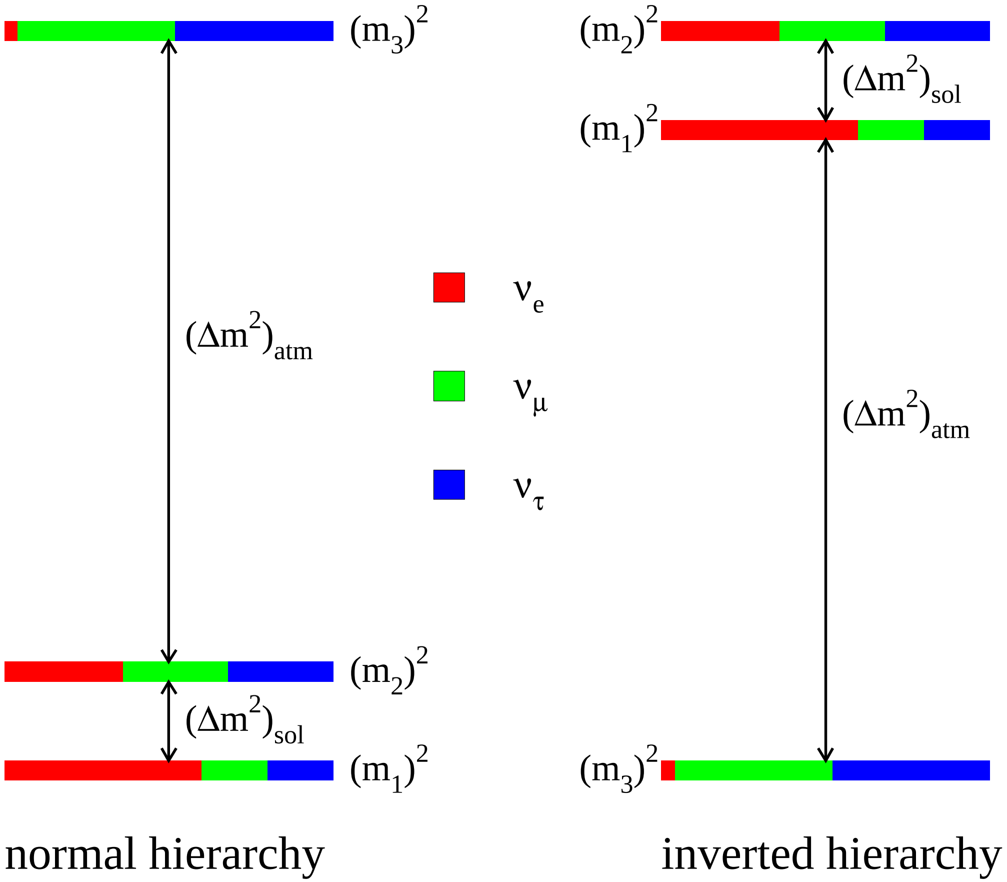
NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{\rm CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

[Esteban *et al*, JHEP 01 (2017) 087, http://www.nu-fit.org]

*Modulo a handful of 2σ to 3σ anomalies.

New Neutrino Oscillation Experiments: Missing Oscillation Parameters

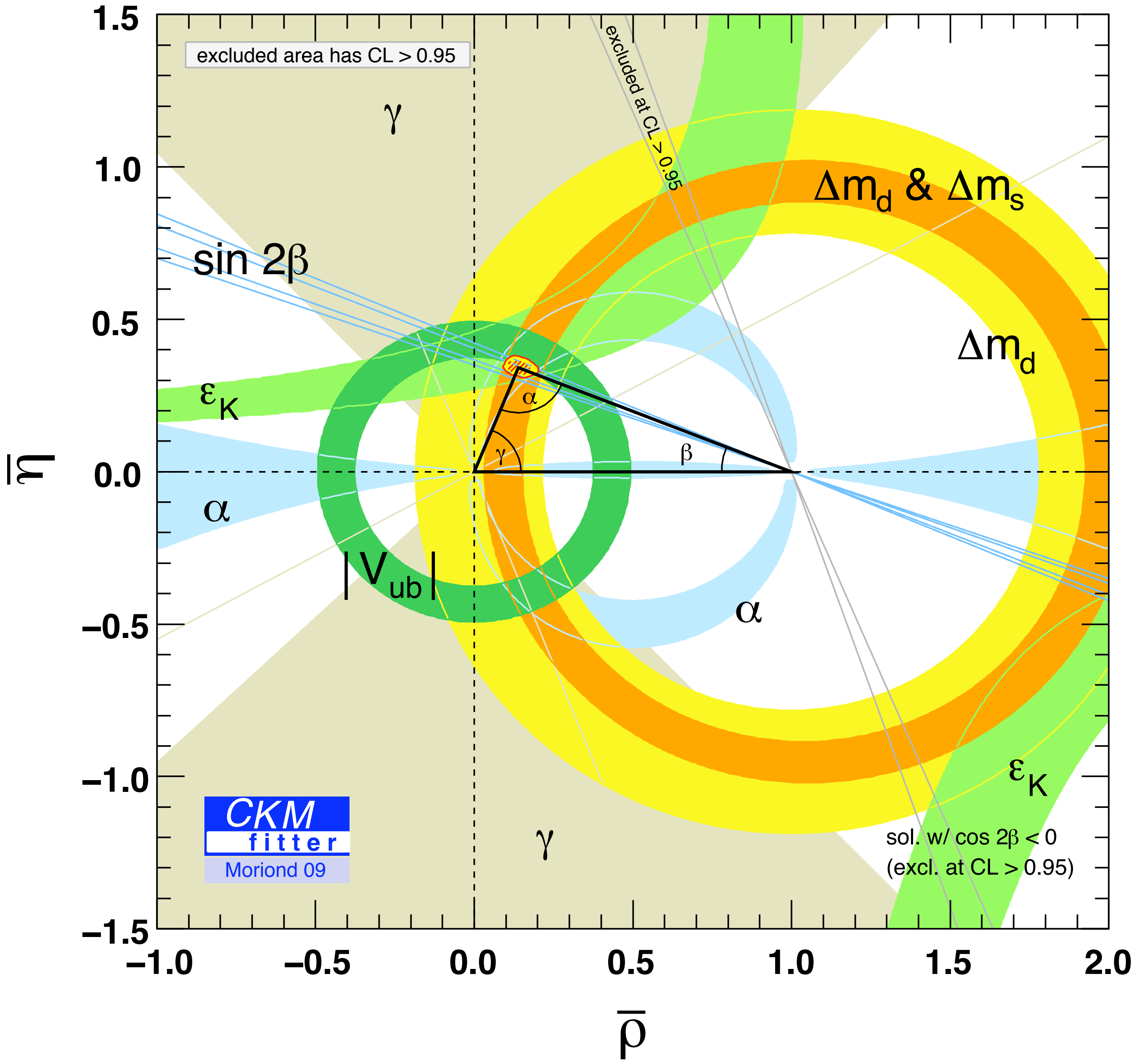


- ~~What is the ν_e component of ν_3?~~ $(\theta_{13} \neq 0!)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13}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

$\Rightarrow$ 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!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu2}|^2 + |U_{\tau2}|^2$ – solar data;
- $|U_{e2}|^2|U_{e1}|^2$ – KamLAND;
- $|U_{\mu3}|^2(1 - |U_{\mu3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2(1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2|U_{\mu3}|^2$ (upper bound $\rightarrow$ evidence) – MINOS, T2K.

We still have a ways to go!

Golden Opportunity to Understand Matter versus Antimatter?

The SM with massive Majorana neutrinos accommodates **five** irreducible CP-invariance violating phases.

- One is the phase in the CKM phase. We have measured it, it is large, and we don't understand its value. At all.
- One is θ_{QCD} term ($\theta G\tilde{G}$). We don't know its value but it is only constrained to be very small. We don't know why (there are some good ideas, however).
- Three are in the neutrino sector. One can be measured via neutrino oscillations. 50% increase on the amount of information.

We don't know much about CP-invariance violation. Is it really fair to presume that CP-invariance is generically violated in the neutrino sector solely based on the fact that it is violated in the quark sector? Why? Cautionary tale: "Mixing angles are small."

What Could We Run Into?

since $m_\nu \neq 0$ and leptons mix ...

What Could We Run Into?

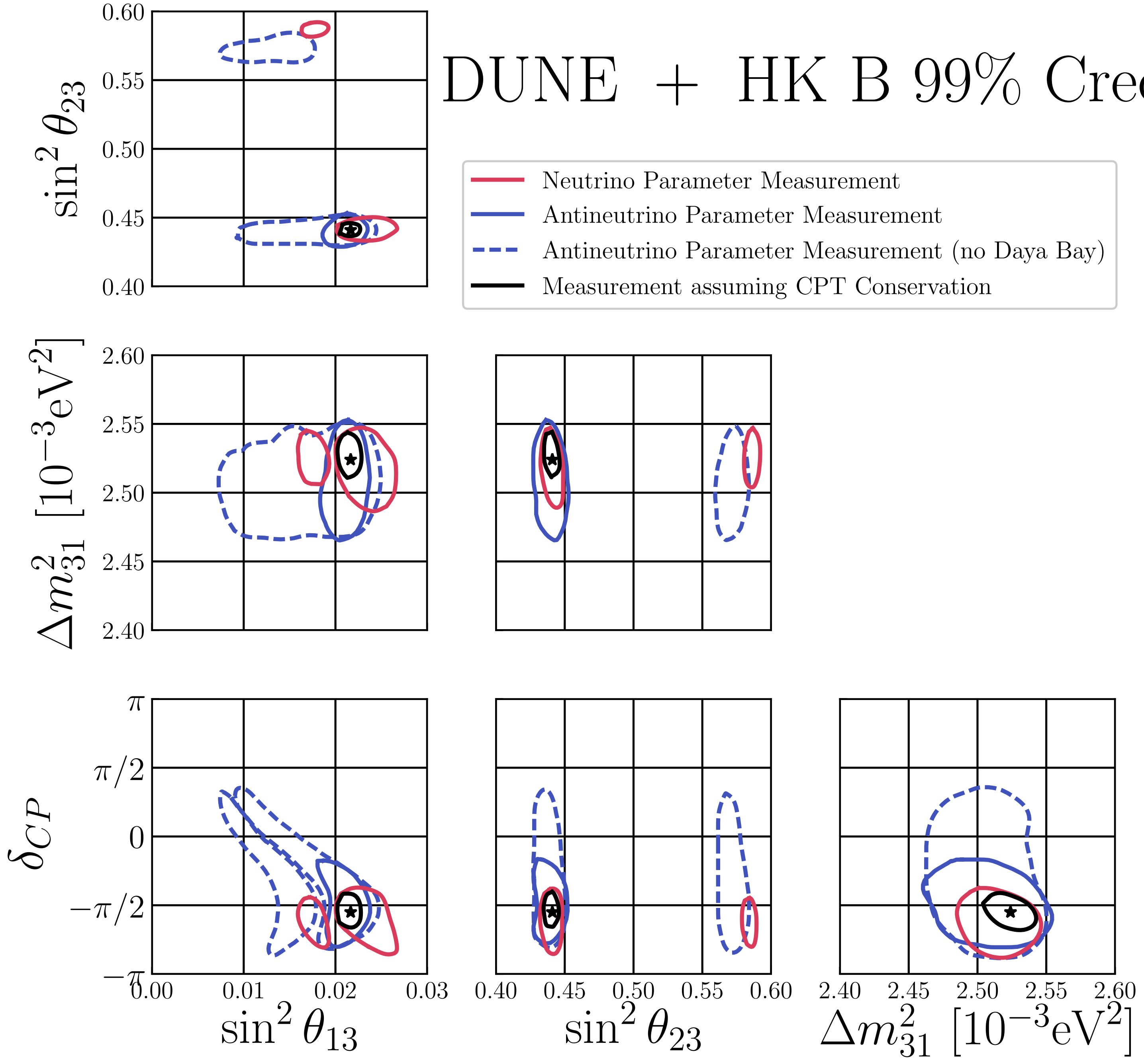
- New neutrino states. In this case, the 3×3 mixing matrix would not be unitary.
- New short-range neutrino interactions. These lead to, for example, new matter effects. If we don't take these into account, there is no reason for the three flavor paradigm to "close."
- New, unexpected neutrino properties. 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.

Different Oscillation Parameters for Neutrinos and Antineutrinos?

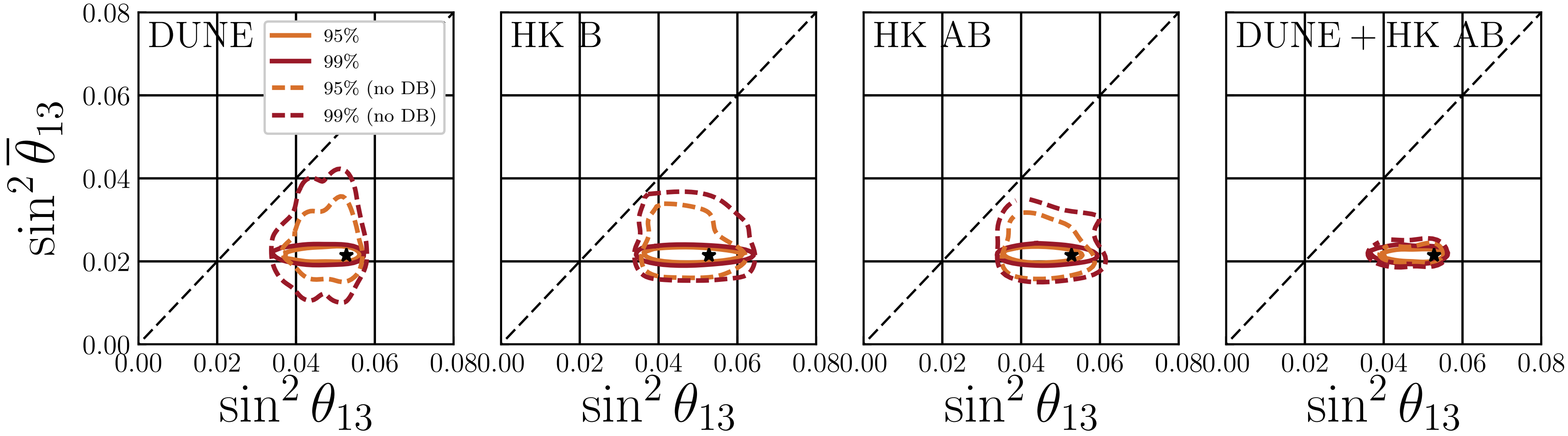
[AdG, Kelly, arXiv:1709.06090]

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

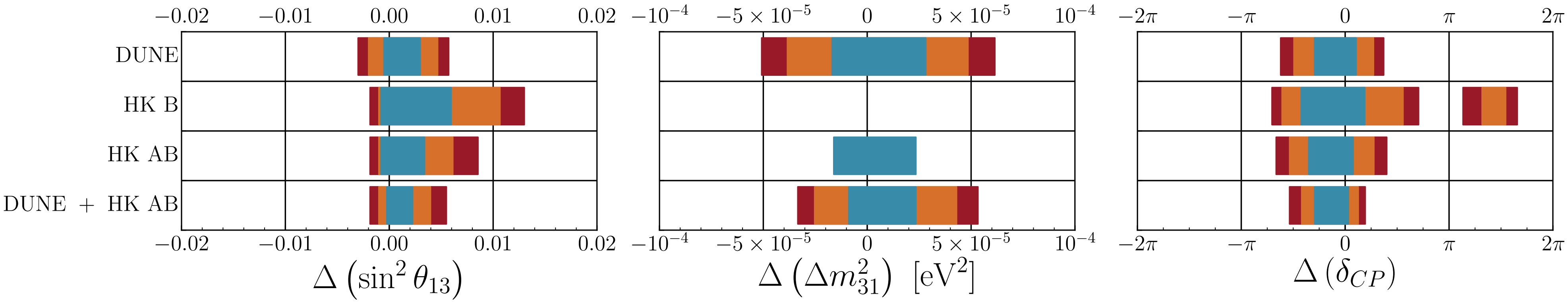
DUNE + HK B 99% Cred.



[AdG and Kelly, arXiv:1709.06090]



[AdG and Kelly, arXiv:1709.06090]

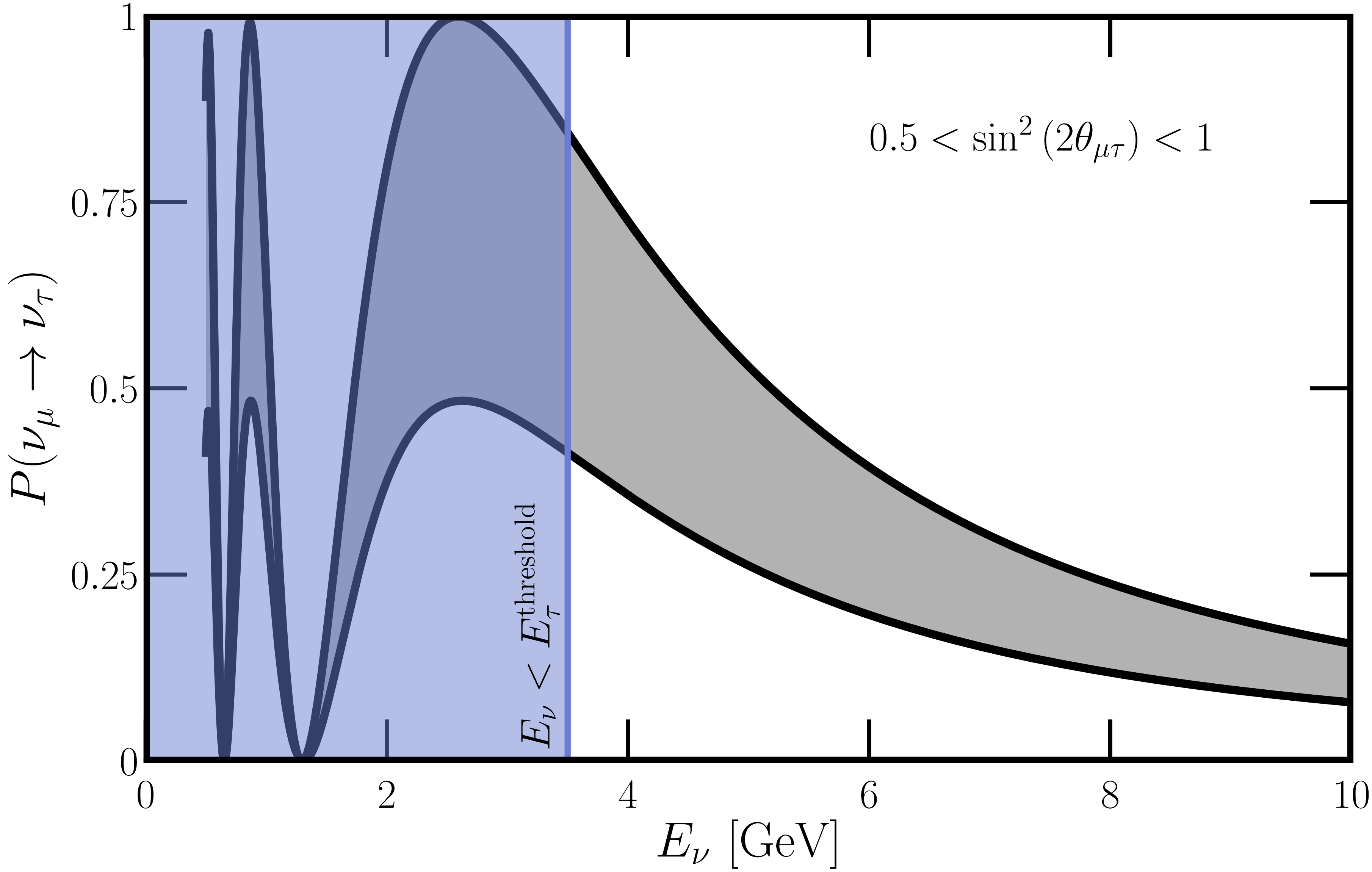


Physics with Beam ν_τ's at the DUNE Far Detector Site

[AdG, Kelly, Pasquini, Stenico, arXiv:1904.07265]

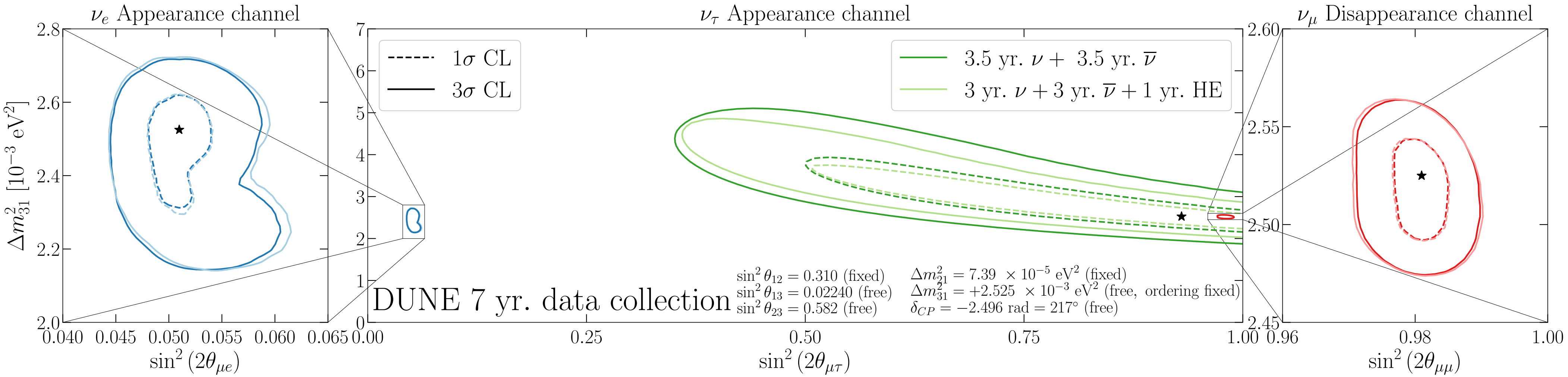
ν_τ sample: why?

- 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]



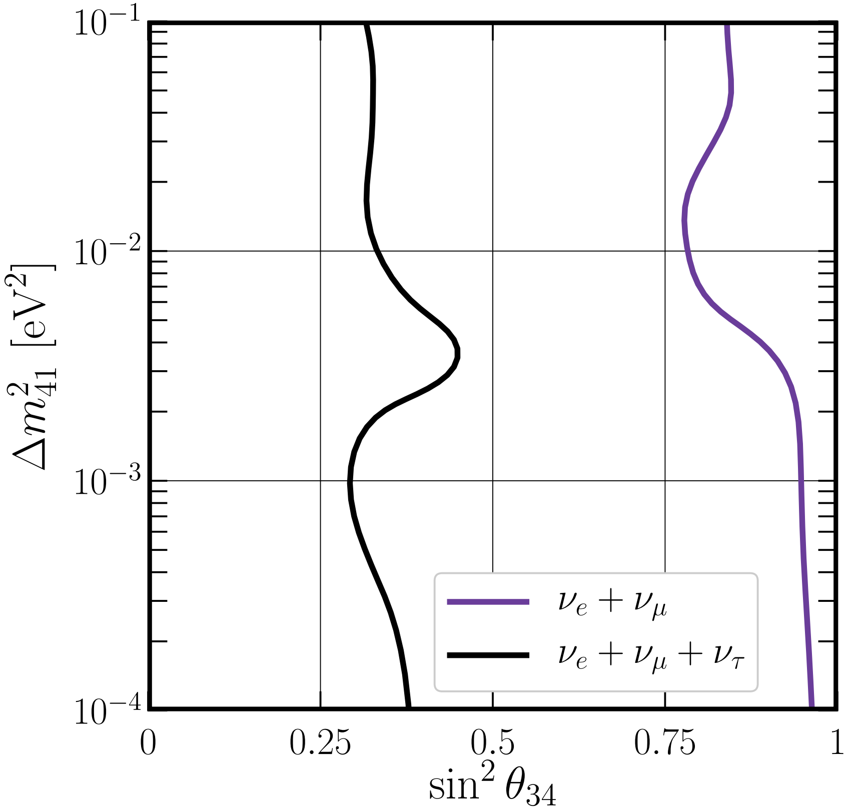
$0.5 < \sin^2(2\theta_{\mu\tau}) < 1$
$E_\nu < E_\tau^{\text{threshold}}$
$P(\nu_\mu \to \nu_\tau)$
1
0.75
0.5
0.25
0
0
2
4
6
8
10
E_ν [GeV]

Testing the Three-Massive-Neutrinos Paradigm

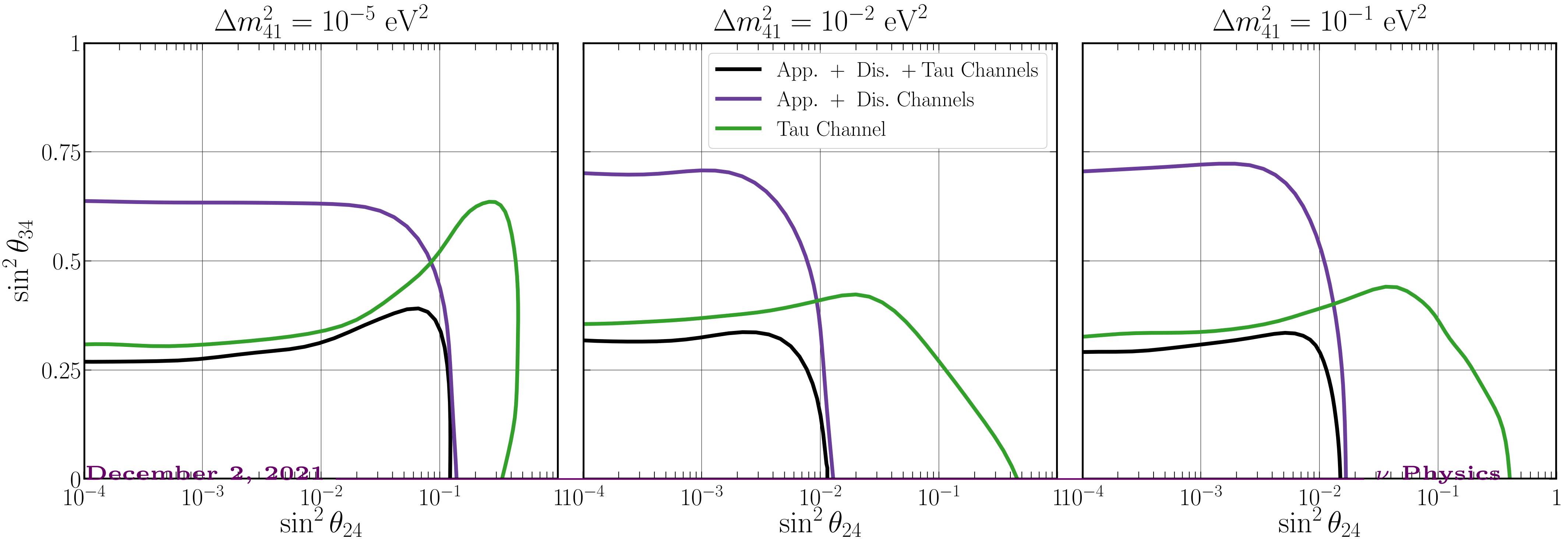


$$\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 3}|^2|U_{e3}|^2, \qquad \sin^2 2\theta_{\mu\tau} \equiv 4|U_{\mu 3}|^2|U_{\tau 3}|^2, \qquad \sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1-|U^2_{\mu 3}|)$$

Unitarity Test: $|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1^{+0.05}_{-0.06}$ [one sigma] $\quad (1^{+0.13}_{-0.17}$ [three sigma])



Fourth Neutrino Hypothesis



Summary

At the end of the 20th Century, the venerable Standard Model sprung a leak: **neutrinos are not massless!**

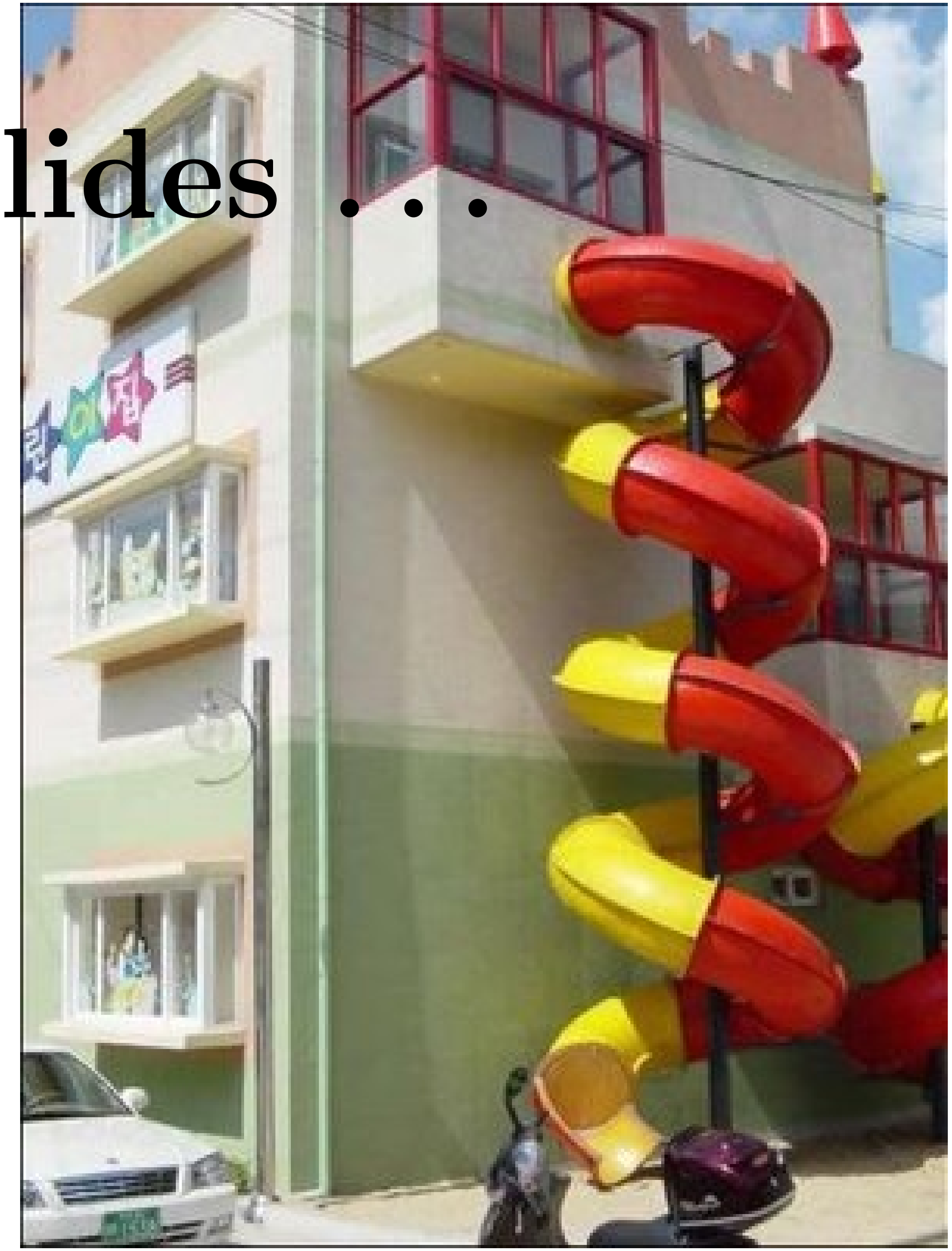
1. We still **know very little** about the new physics uncovered by neutrino oscillations. In particular, the new physics (broadly defined) can live almost anywhere between sub-eV scales and the GUT scale.

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 data** – from everywhere – and the data are on their way. Stay tuned!

Backup Slides . . .



High-Energy Seesaw: Brief Comments

- This is everyone's favorite scenario.
- Upper bound for M (e.g. Maltoni, Niczyporuk, Willenbrock, hep-ph/0006358):

$$M < 7.6 \times 10^{15}\ \text{GeV} \times \left(\frac{0.1\ \text{eV}}{m_\nu}\right).$$

- Hierarchy problem hint (e.g., Casas et al, hep-ph/0410298; Farina et al, ; 1303.7244; AdG et al, 1402.2658):

$$M < 10^7\ \text{GeV}.$$

- Leptogenesis! "Vanilla" Leptogenesis requires, very roughly, smallest

$$M > 10^9\ \text{GeV}.$$

- Stability of the Higgs potential (e.g., Elias-Miró et al, 1112.3022):

$$M < 10^{13}\ \text{GeV}.$$

- Physics "too" heavy! No observable consequence other than leptogenesis. Will we ever convince ourselves that this is correct? (Buckley et al, hep-ph/0606088)

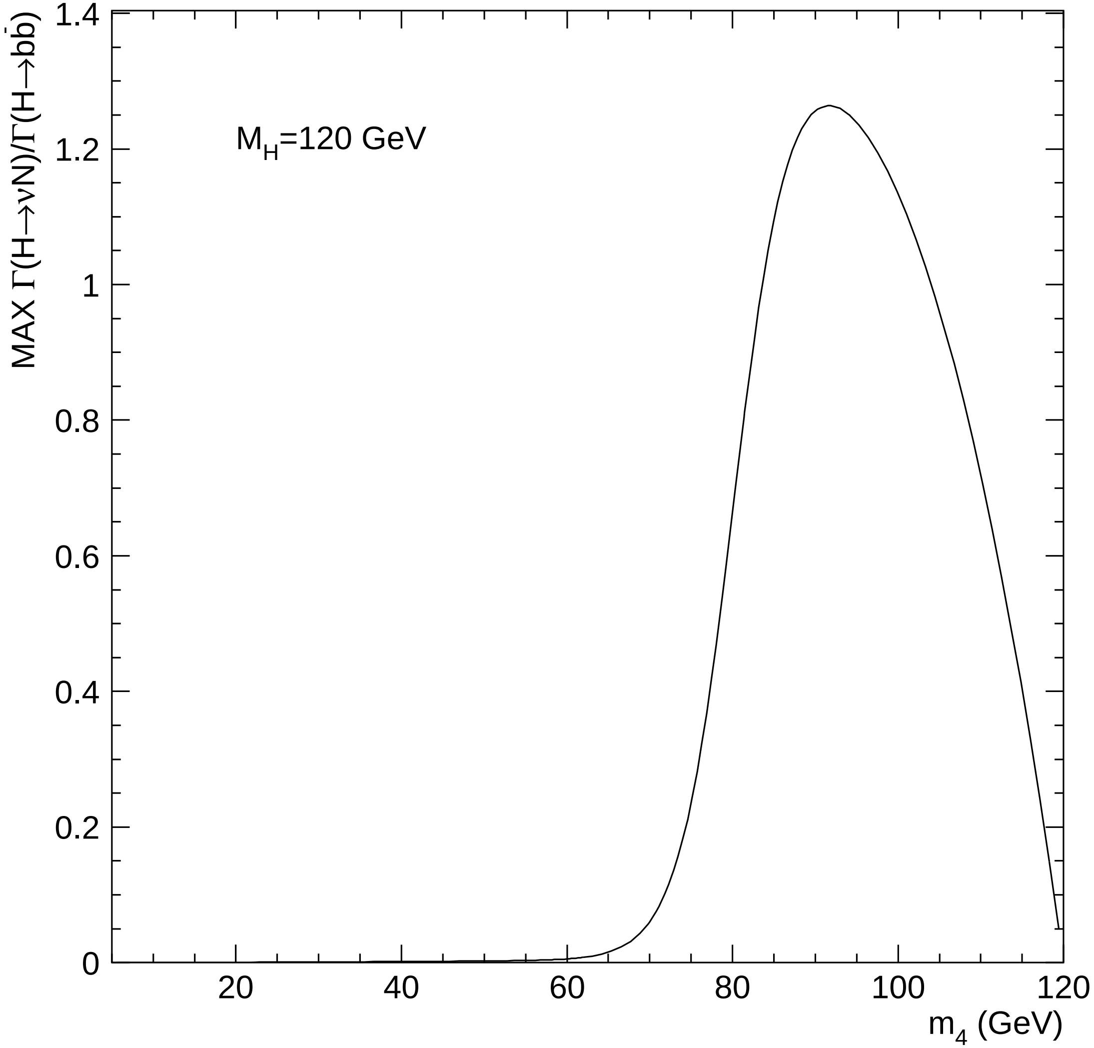
Low-Energy Seesaw: Brief Comments [AdG PRD72,033005)]

The other end of the M spectrum ($M < 100$ GeV). What do we get?

- Neutrino masses are small because the Yukawa couplings are very small $\lambda \in [10^{-6}, 10^{-11}]$;
- No standard thermal leptogenesis – right-handed neutrinos way too light? [For a possible alternative see Canetti, Shaposhnikov, arXiv: 1006.0133 and reference therein.]
- No obvious connection with other energy scales (EWSB, GUTs, etc);
- Right-handed neutrinos are propagating degrees of freedom. They look like sterile neutrinos $\Rightarrow$ sterile neutrinos associated with the fact that the active neutrinos have mass;
- sterile–active mixing can be predicted – hypothesis is falsifiable!
- Small values of M are natural (in the 'tHooft sense). In fact, theoretically, no value of M should be discriminated against!

Weak Scale Seesaw, and Accidentally Light Neutrino Masses

[AdG arXiv:0706.1732 [hep-ph]]



What does the seesaw Lagrangian predict for the LHC?

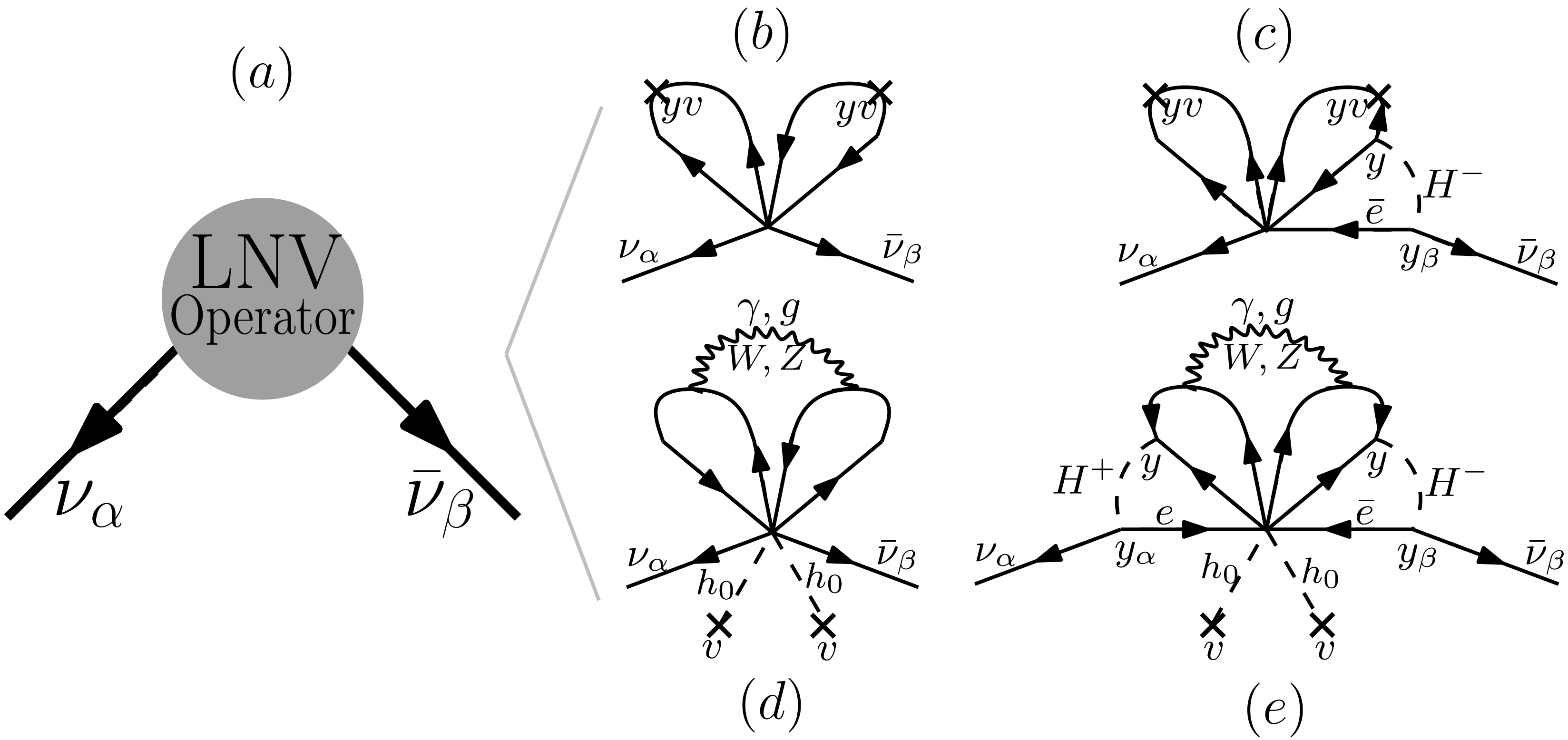
Nothing much, unless...

- $M_N \sim 1 - 100$ GeV,
- Yukawa couplings larger than naive expectations.

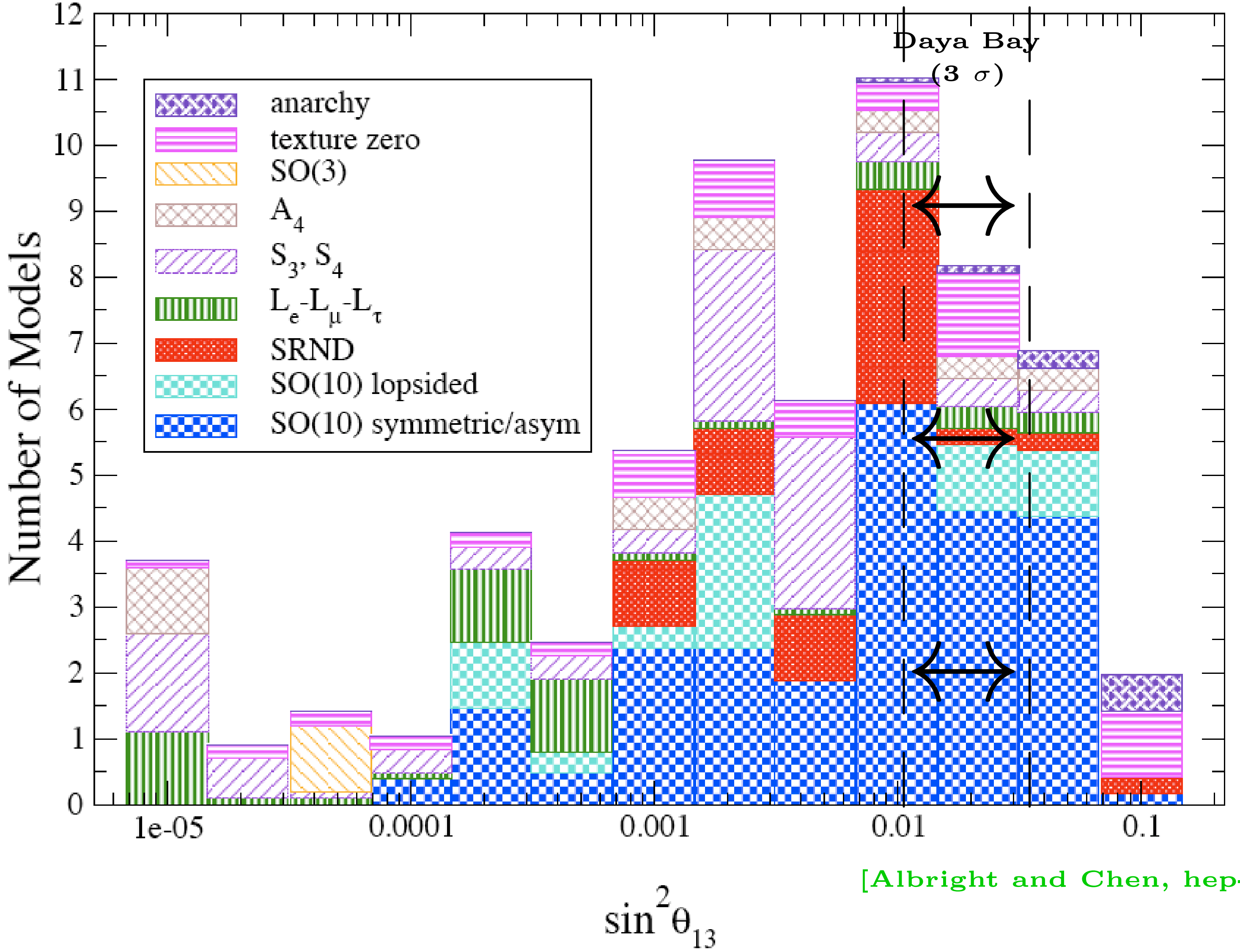
$\Leftarrow$ $H \to \nu N$ as likely as $H \to b\bar{b}$!

(NOTE: $N \to \ell q'\bar{q}$ or $\ell\ell'\nu$ (prompt)

"Weird" Higgs decay signature!)



(a)
LNV
Operator
ν_α
$\bar{\nu}_\beta$
(b)
yv
yv
ν_α
$\bar{\nu}_\beta$
(c)
yv
yv
y
H^-
$\bar{e}$
y_β
ν_α
$\bar{\nu}_\beta$
γ, g
W, Z
ν_α
$\bar{\nu}_\beta$
h_0
h_0
v
v
(d)
γ, g
W, Z
H^+
y
y
H^-
e
$\bar{e}$
ν_α
y_α
h_0
h_0
y_β
$\bar{\nu}_\beta$
v
v
(e)

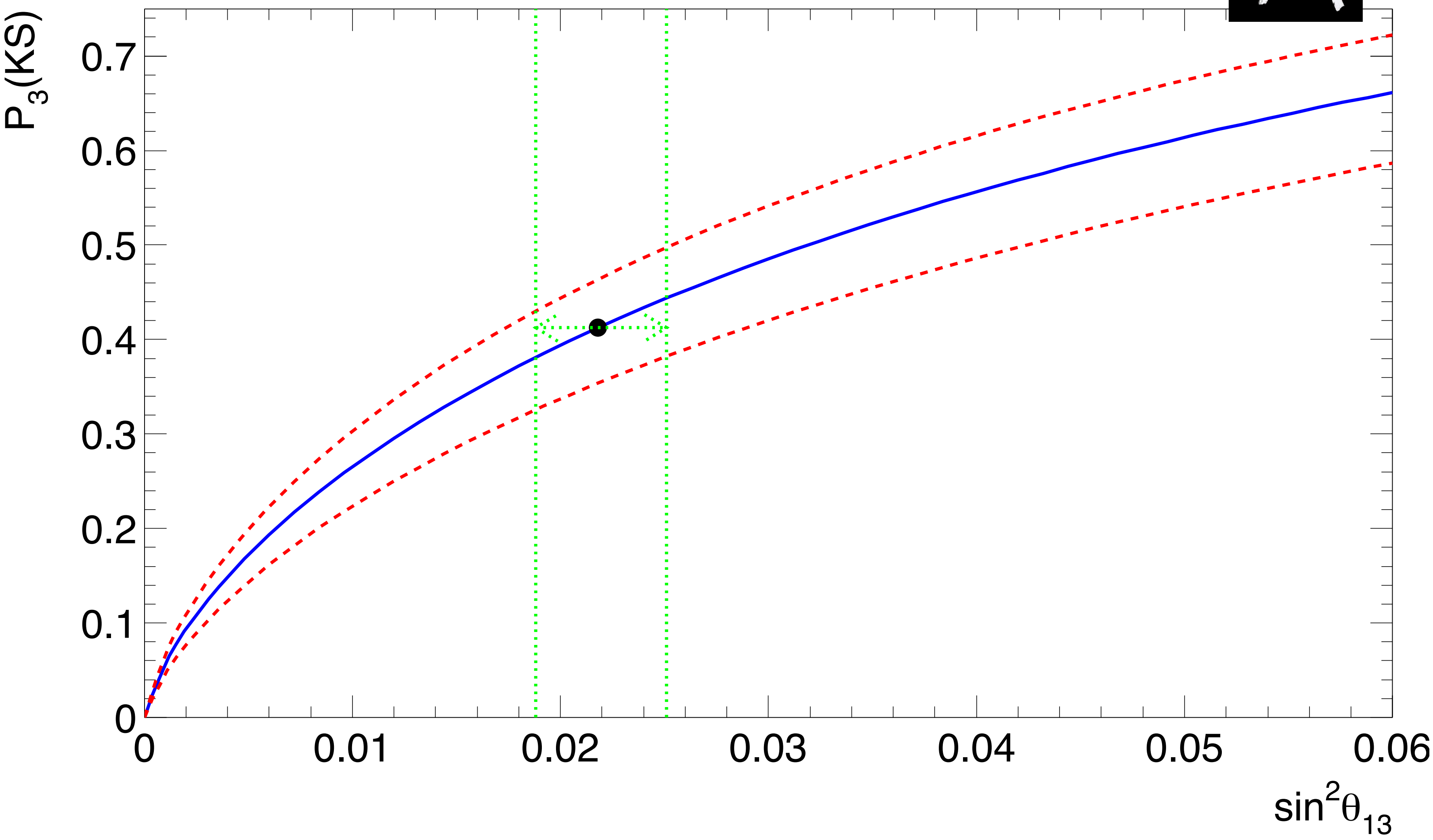


[Albright and Chen, hep-ph/0608137]

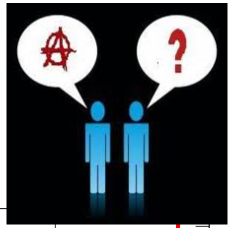
"Left-Over" Predictions: δ, mass-hierarchy, $\cos 2\theta_{23}$

Neutrino Mixing Anarchy: Alive and Kicking!

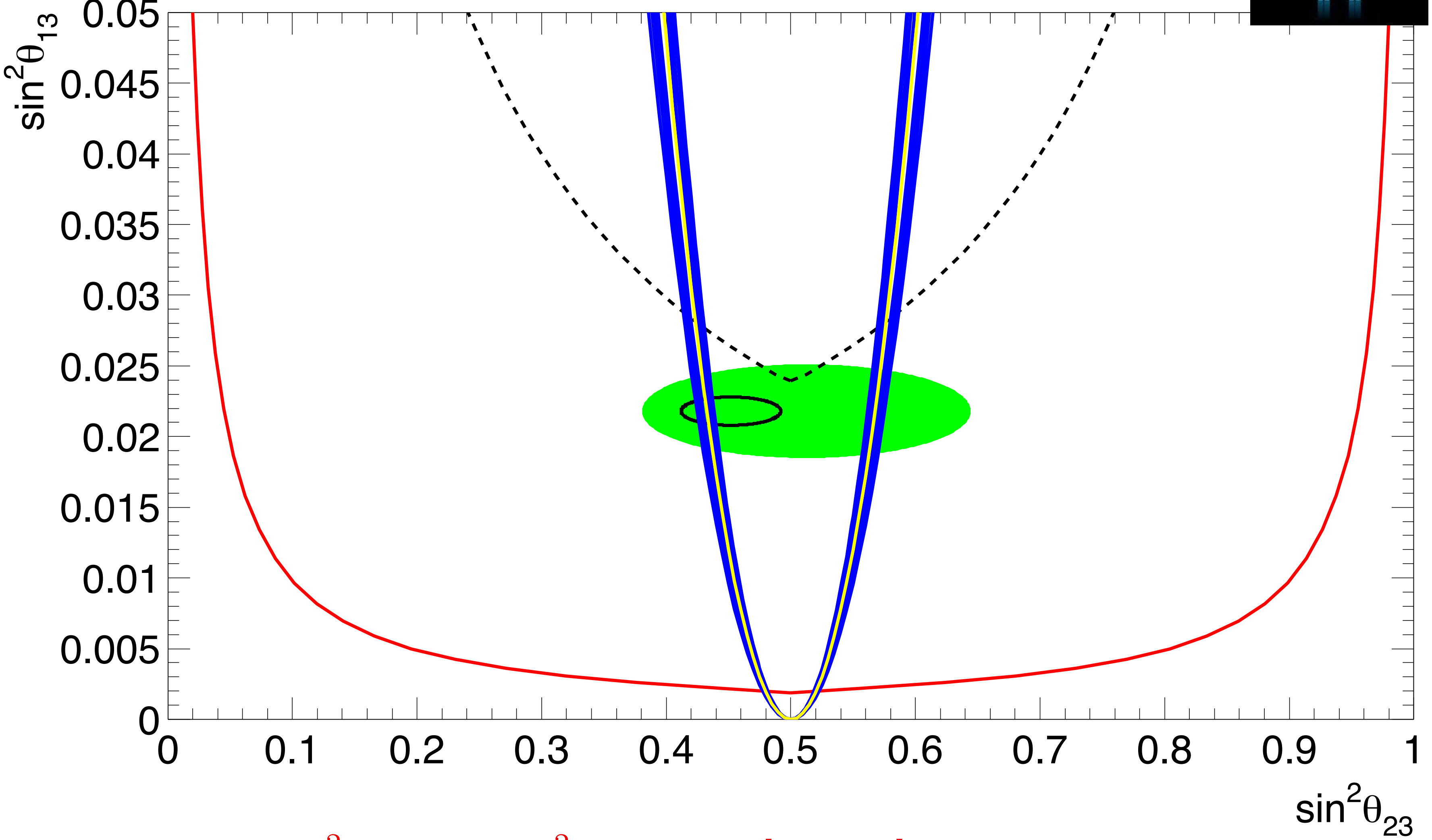
[Hall, Murayama, Weiner hep-ph/9911341]



[AdG, Murayama, 1204.1249]



Anarchy vs. Order — more precision required!



Order: $\sin^2\theta_{13} = C\cos^2 2\theta_{23}$, $C \in [0.8, 1.2]$

[AdG, Murayama, 1204.1249]

How Do We Do More (or At Least Better)?

Questions:

- Are these results reliable? Which ones? How reliable?

  We assume, for example, that we can "turn on" one effective operator at a time. We also assume that the LNV physics, when integrated at tree-level, leads to effective operators of a certain mass dimension but not lower dimensional ones.

- How about constraints from lepton-number-conserving processes?

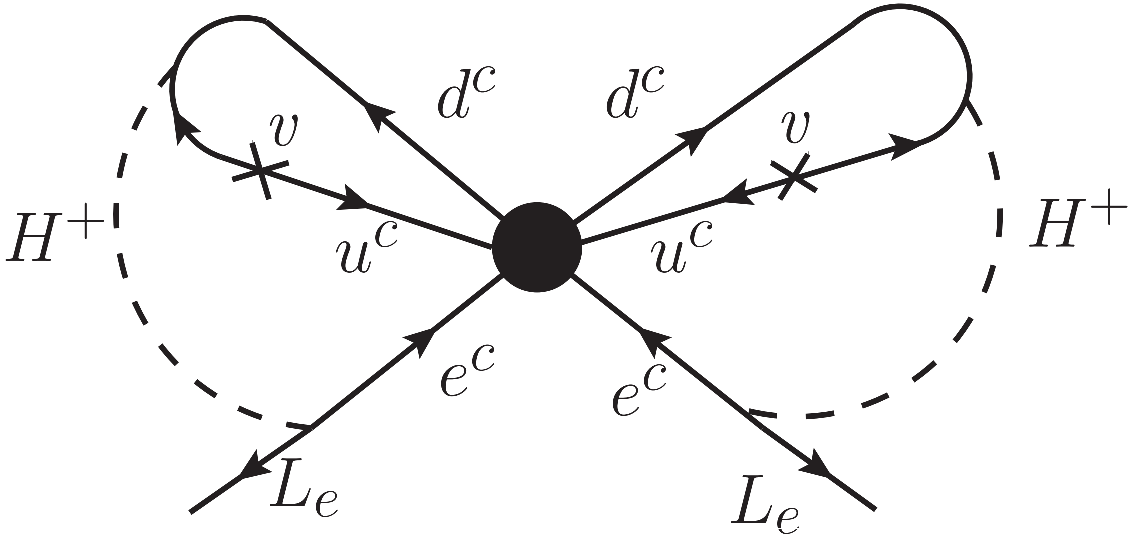
  The idea is that we can do a good job when it comes to low-energy, LNV observables (neutrino masses, $0\nu\beta\beta$). This EFT approach as "nothing to say" about lepton-number conserving phenomena.

Approach: try out some UV completions. Concentrate on $\mathcal{O}_s$.

[AdG et al, arXiv:1907.02541]

[AdG et al, arXiv:1907.02541]

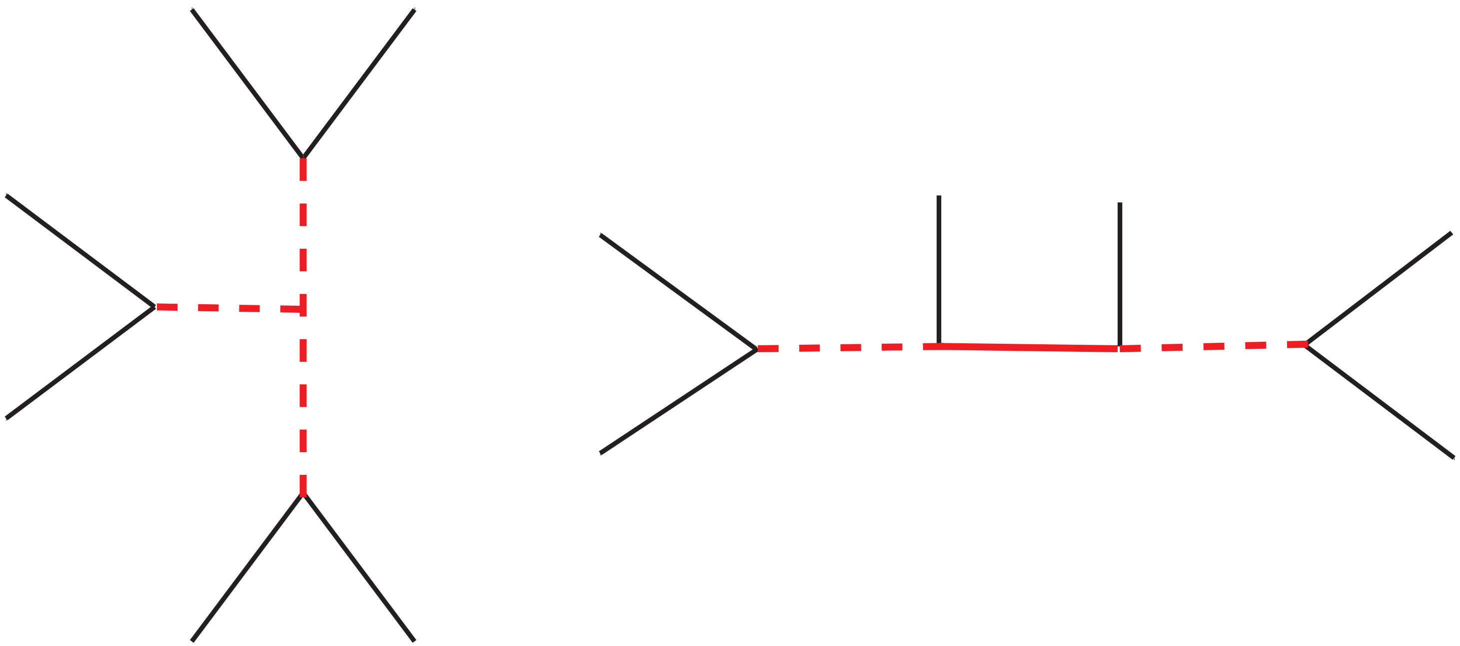
$$\mathcal{O}_s^{\alpha\beta} = \ell_\alpha^c \ell_\beta^c u^c u^c \overline{d^c}\,\overline{d^c}$$



$$m_{\alpha\beta} = \frac{g_{\alpha\beta}}{\Lambda}\frac{y_\alpha y_\beta (y_t y_b v)^2}{(16\pi^2)^4}$$

[AdG et al, arXiv:1907.02541]

$$\mathcal{O}_s^{\alpha\beta} = \ell^c_\alpha \ell^c_\beta u^c u^c \overline{d^c}\,\overline{d^c}$$



New particles in red. Easy to figure out their quantum numbers given what we know about e^c, d^c, u^c. Given what we know about L, Q, we can also figure out what quantum numbers we don't want in order to prevent other dimension-nine operators at the tree-level.

Table 1: All new particles required for all different tree-level realizations of the all-singlets dimension-nine operator $\mathcal{O}_s^{\alpha\beta}$.The fermions ψ, ζ, and χ come with a partner (ψ^c, ζ^c, and χ^c respectively), not listed. We don't consider fields that couple only to the antisymmetric combination of same-flavor quarks.

New particles	$\left(\mathrm{SU}(3)_\mathrm{C},\, \mathrm{SU}(2)_\mathrm{L}\right)_{\mathrm{U}(1)_\mathrm{Y}}$	Spin
$\Phi \equiv (\overline{l^c}\,\overline{l^c})$	$(1,1)_{-2}$	scalar
$\Sigma \equiv (\overline{u^c}\,\overline{u^c})$	$(6,1)_{4/3}$	scalar
$\Delta \equiv (\overline{d^c}\,\overline{d^c})$	$(6,1)_{-2/3}$	scalar
$C \equiv (\overline{u^c}\,d^c)$	$(1,1)_1,\ \ (8,1)_1$	vector
$\psi \equiv (u^c\,l^c\,l^c)$	$(\overline{3},1)_{4/3}$	fermion
$\zeta \equiv (d^c\,\overline{l^c}\,\overline{l^c})$	$(\overline{3},1)_{-5/3}$	fermion
$\chi \equiv (l^c\,u^c\,u^c)$	$(\overline{6},1)_{-1/3}$	fermion
$N \equiv (l^c\,\overline{d^c}\,u^c)$	$(1,1)_0,\ \ (8,1)_0$	fermion

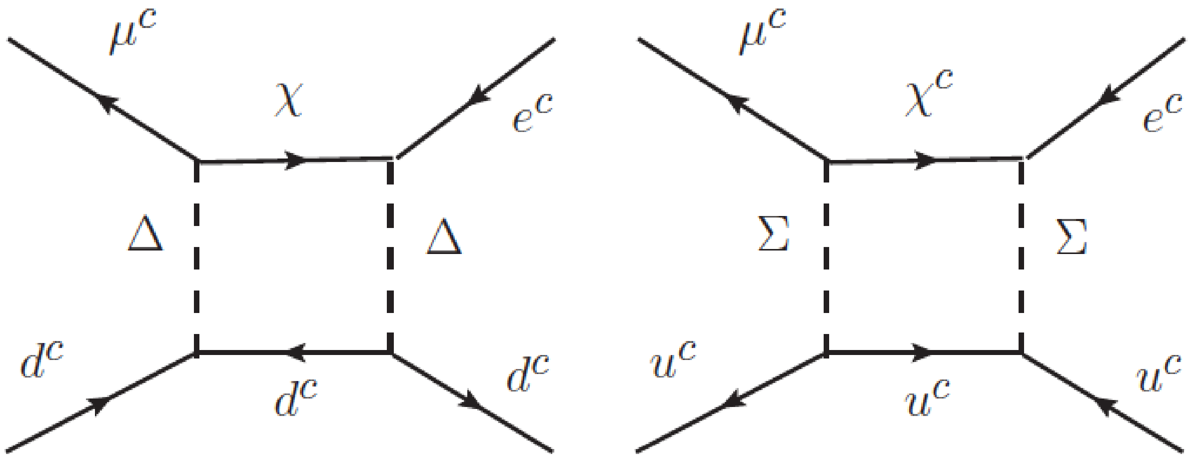


FIG. 8: Feynman diagrams (box-diagrams) contributing to the CLFV process $\mu^- \to e^-$-conversion, in Model $\chi\Delta\Sigma$.

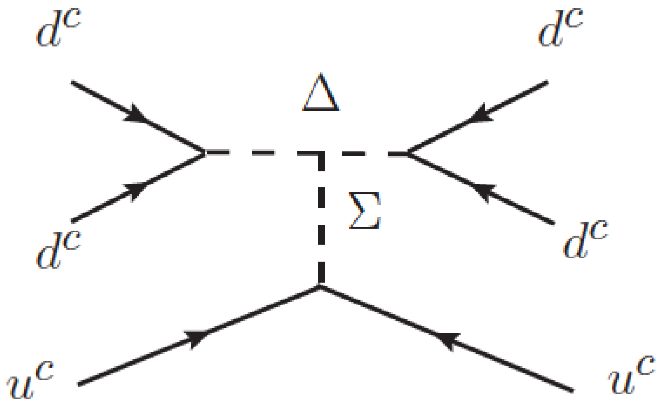
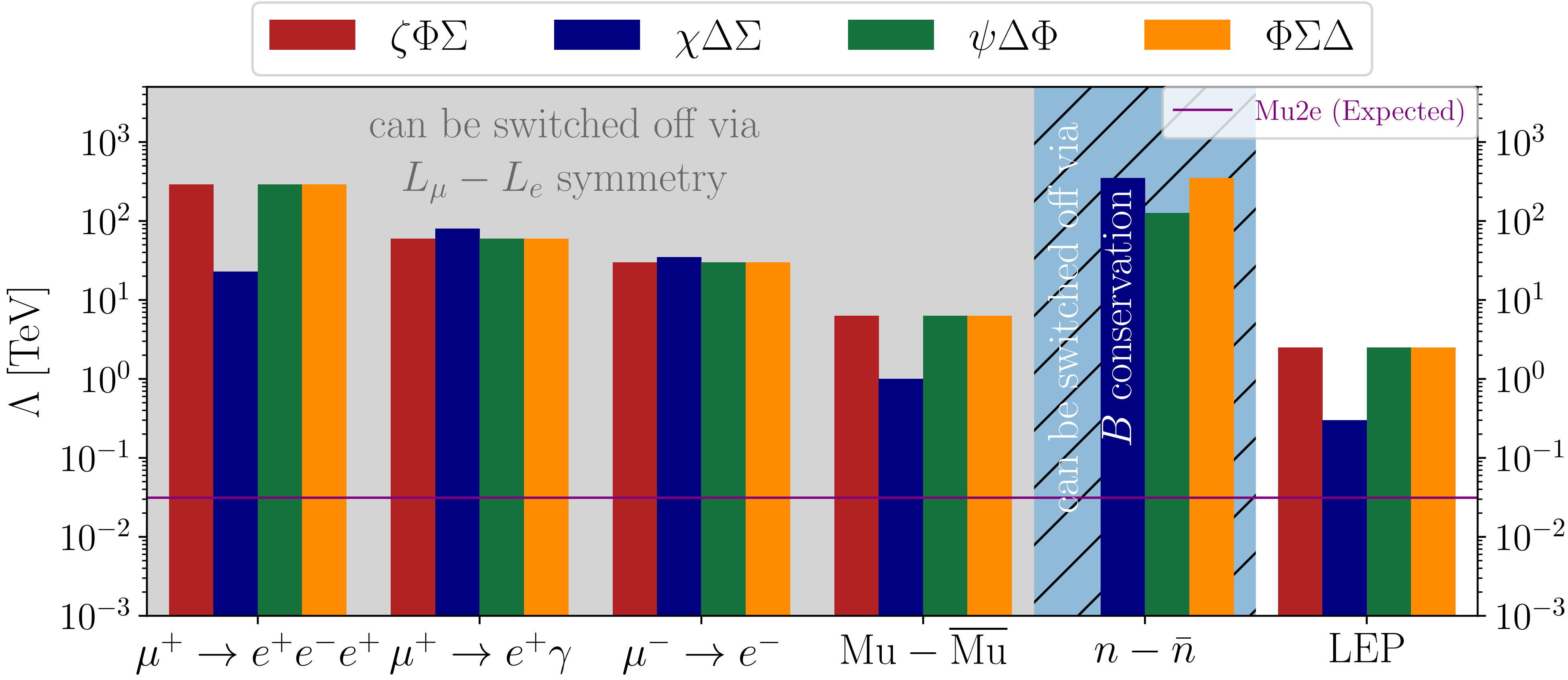


FIG. 9: Tree-level Feynman diagram that mediates $n - \overline{n}$ oscillations in Model $\chi\Delta\Sigma$.

[AdG et al, arXiv:1907.02541]



(models with new vector bosons not included)

[AdG et al, arXiv:1907.02541]

Tree-Level Realization of the Weinberg Operator

If $\mu = \lambda v \ll M$, below the mass scale M,

$$\mathcal{L}_5 = \frac{LHLH}{\Lambda}.$$

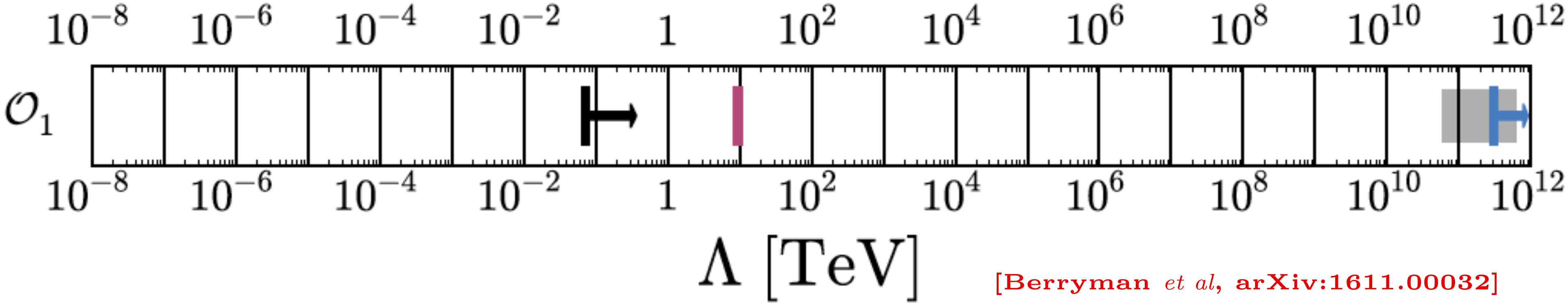
Neutrino masses are small if $\Lambda \gg \langle H \rangle$. Data require $\Lambda \sim 10^{14}$ GeV.

In the case of the seesaw,

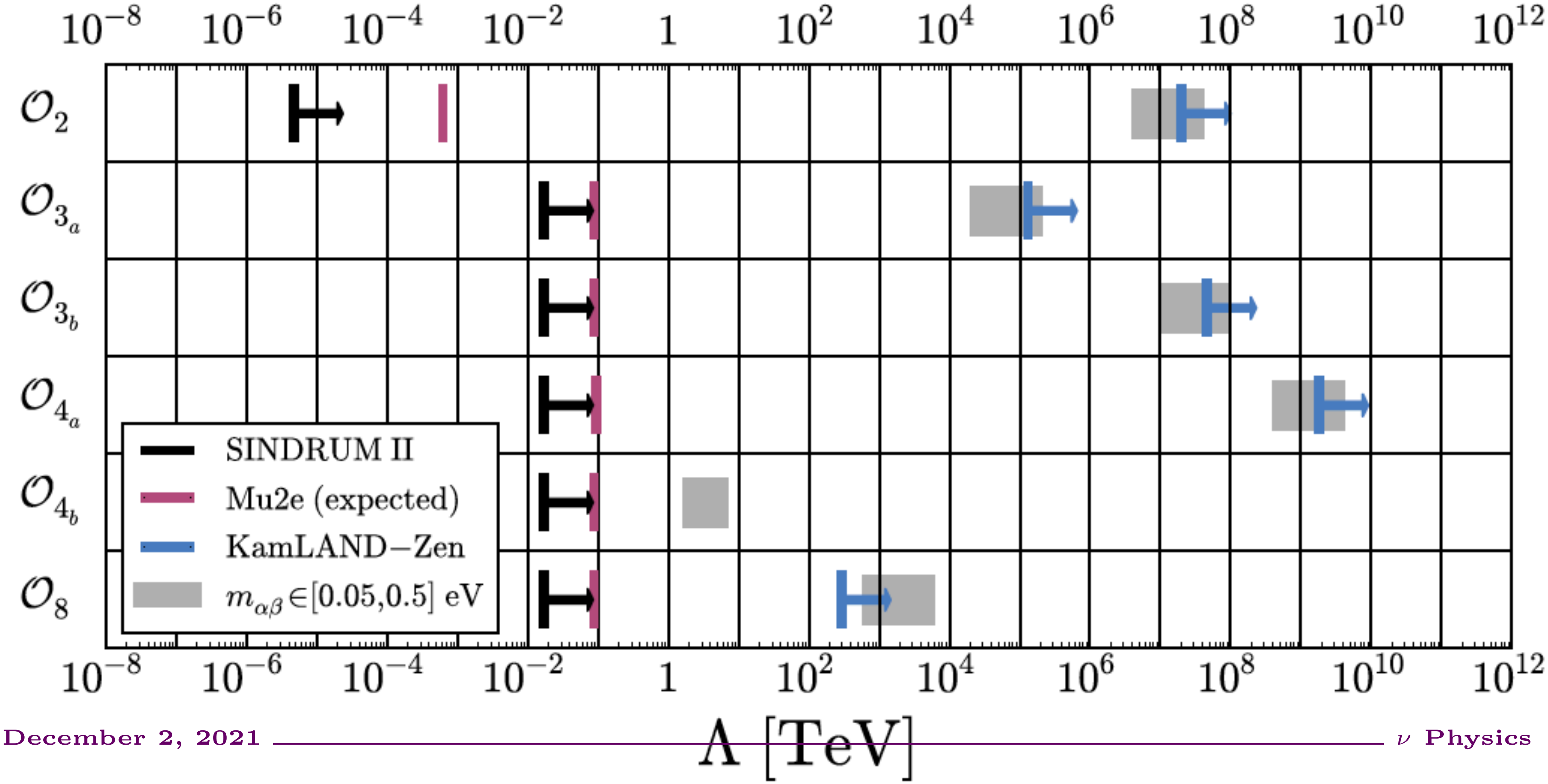
$$\Lambda \sim \frac{M}{\lambda^2},$$

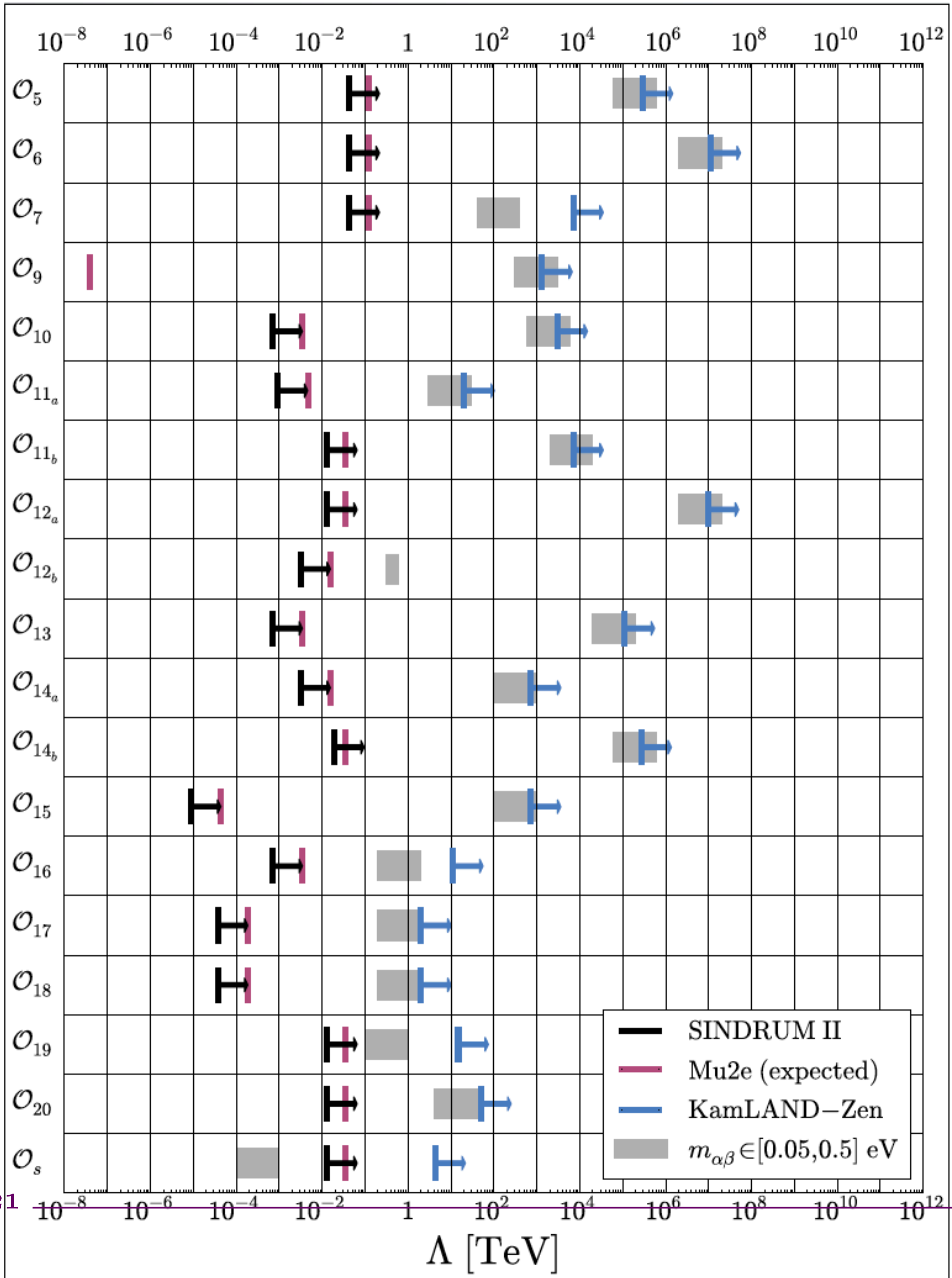
so neutrino masses are small if either

- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small ("fine-tuning").

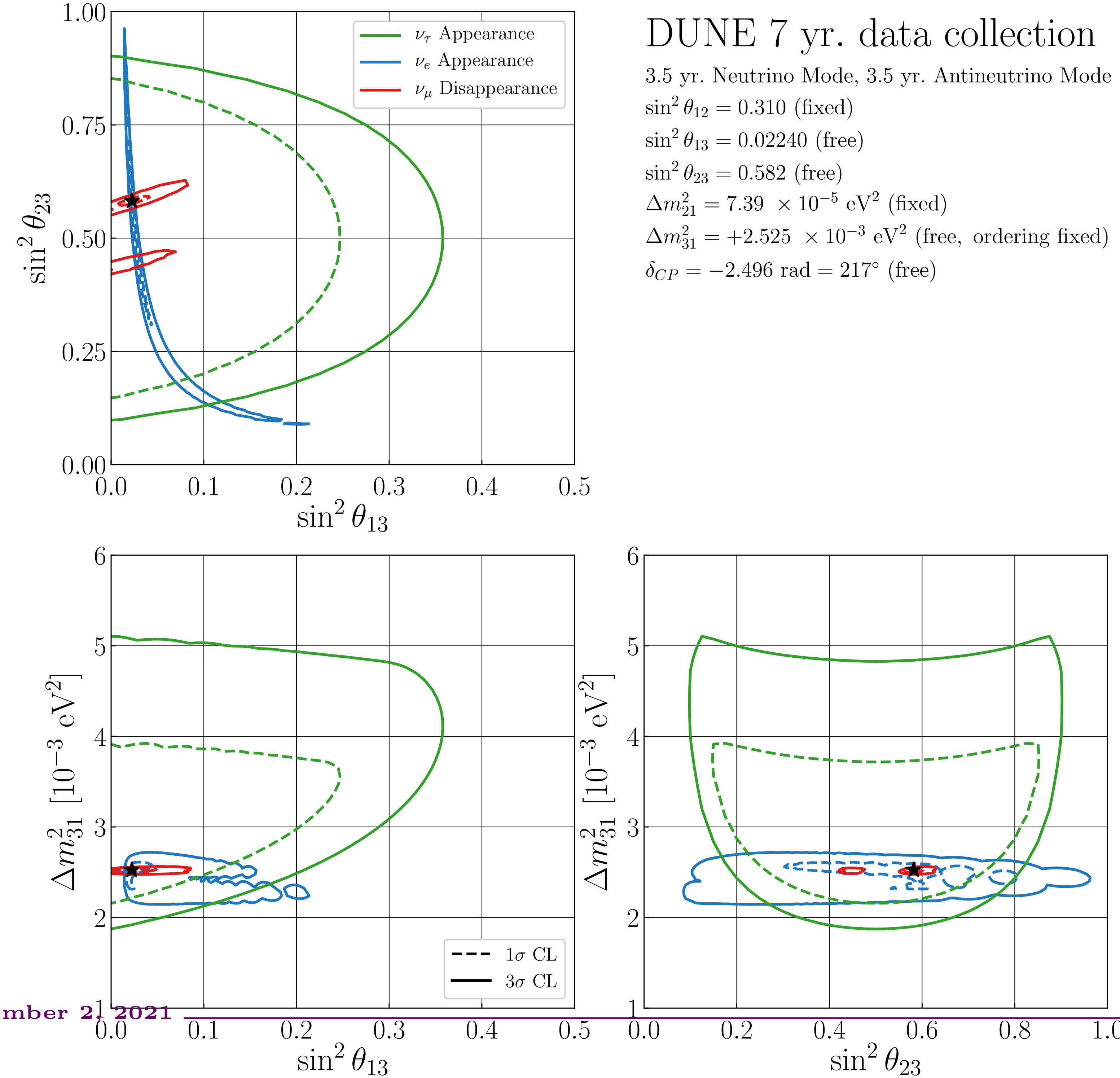


[Berryman *et al*, arXiv:1611.00032]





10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12}
$\mathcal{O}_5$
$\mathcal{O}_6$
$\mathcal{O}_7$
$\mathcal{O}_9$
$\mathcal{O}_{10}$
$\mathcal{O}_{11_a}$
$\mathcal{O}_{11_b}$
$\mathcal{O}_{12_a}$
$\mathcal{O}_{12_b}$
$\mathcal{O}_{13}$
$\mathcal{O}_{14_a}$
$\mathcal{O}_{14_b}$
$\mathcal{O}_{15}$
$\mathcal{O}_{16}$
$\mathcal{O}_{17}$
$\mathcal{O}_{18}$
$\mathcal{O}_{19}$
$\mathcal{O}_{20}$
$\mathcal{O}_s$
SINDRUM II
Mu2e (expected)
KamLAND−Zen
$m_{\alpha\beta}\in[0.05,0.5]$ eV
Λ [TeV]


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)
$\Delta m^2_{21} = 7.39 \times 10^{-5}\ \mathrm{eV}^2$ (fixed)
$\Delta m^2_{31} = +2.525 \times 10^{-3}\ \mathrm{eV}^2$ (free, ordering fixed)
$\delta_{CP} = -2.496$ rad $= 217°$ (free)
ν_τ Appearance
ν_e Appearance
ν_μ Disappearance
1σ CL
3σ CL
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
$\Delta m^2_{31}\ [10^{-3}\ \mathrm{eV}^2]$
0.00
0.25
0.50
0.75
1.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1.0
1
2
3
4
5
6

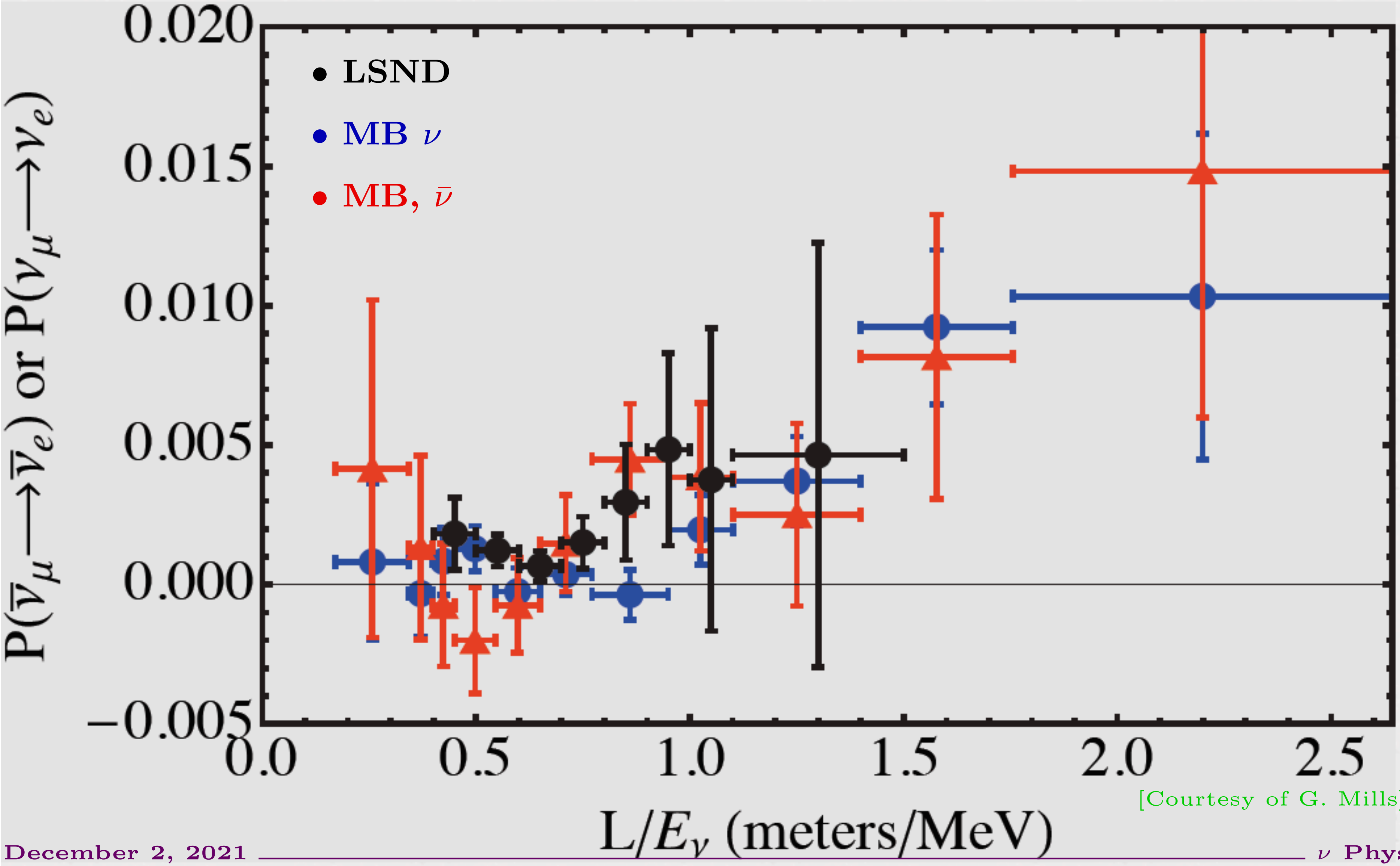
Not all is well(?): The Short Baseline Anomalies

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.

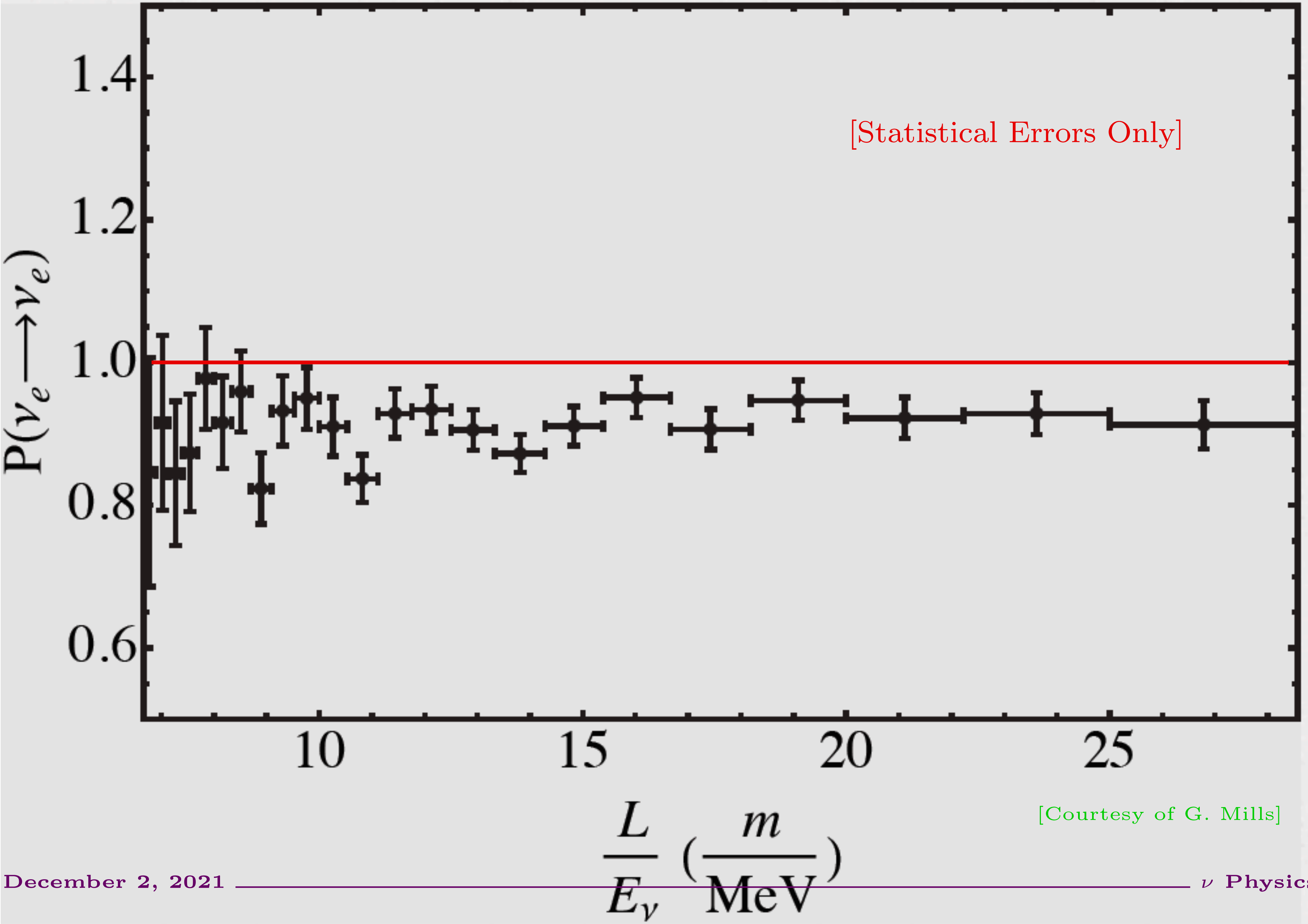
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND



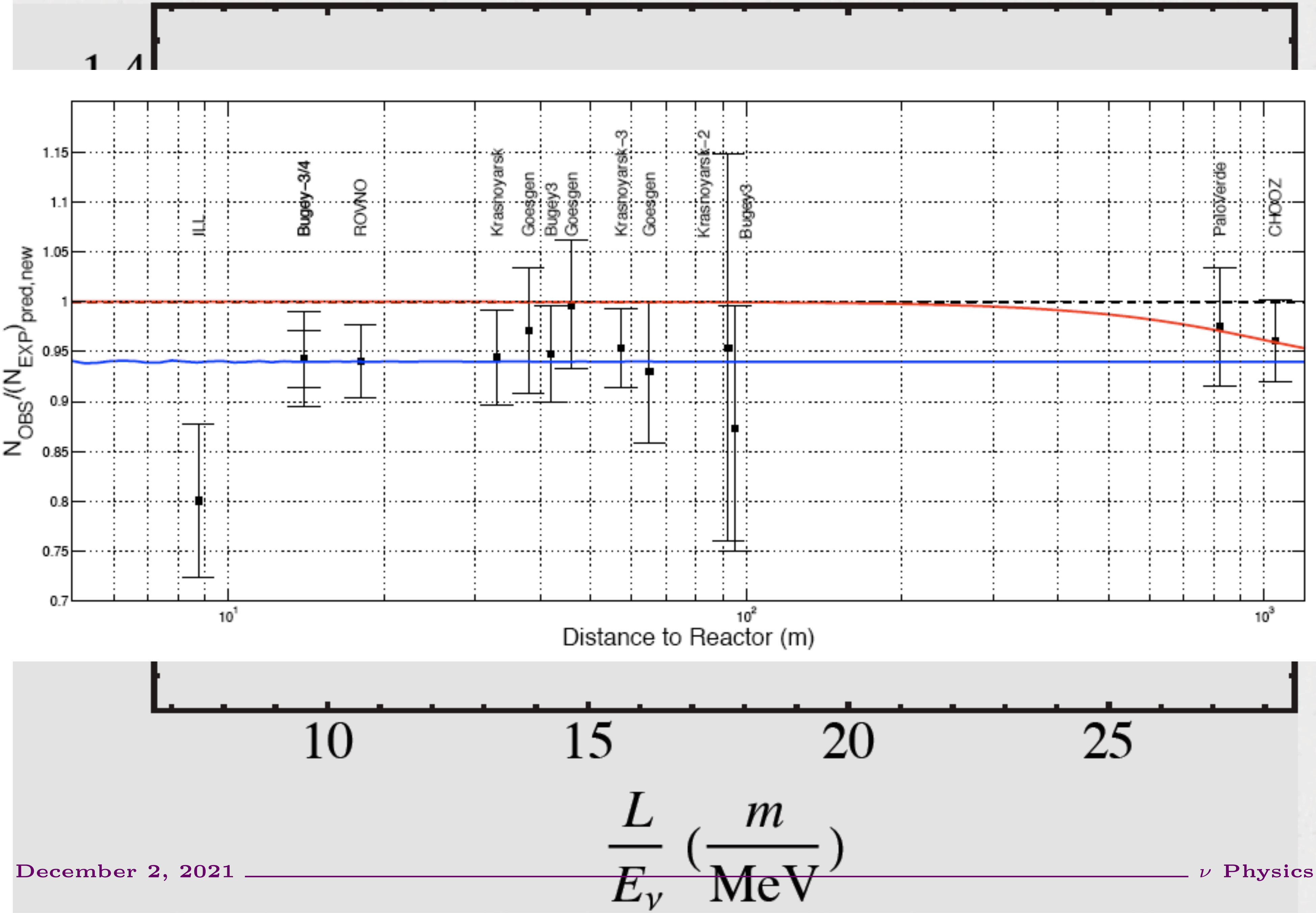
[Courtesy of G. Mills]

Bugey 40 m



[Courtesy of G. Mills]

Bugey 40 m



$N_{OBS}/(N_{EXP})_{pred,new}$
Distance to Reactor (m)
ILL
Bugey-3/4
ROVNO
Krasnoyarsk
Goesgen
Bugey3
Goesgen
Krasnoyarsk-3
Goesgen
Krasnoyarsk-2
Bugey3
PaloVerde
CHOOZ
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
10^1
10^2
10^3
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.

[MicroBooNE, arXiV:2110.14054 [hep-ex]]

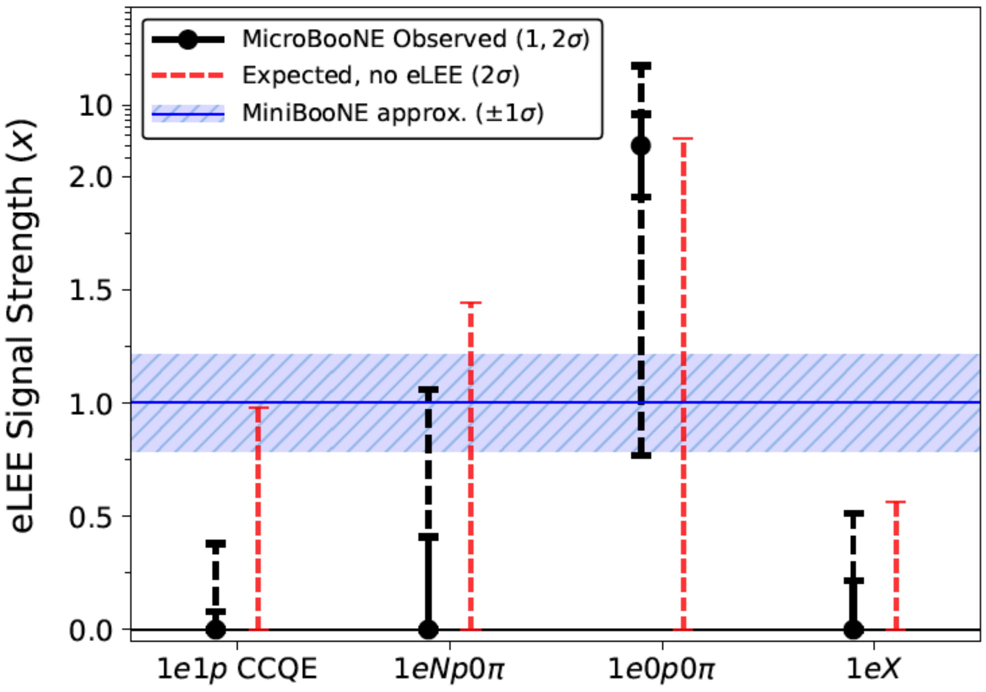


FIG. 5. Result of best-fit eLEE signal strength (x) in each analysis (black), along with the 1 and 2σ confidence intervals (solid and dashed lines, respectively). The expected 2σ upper bound for each analysis, assuming no eLEE signal, is also shown (red). Signal strength values approximated from the MiniBooNE statistical and systematic errors (at 1σ) are shown for comparison (blue). Note that the vertical scale is presented as linear from $x = 0$ to $x = 2$, while in logarithmic scale beyond that.

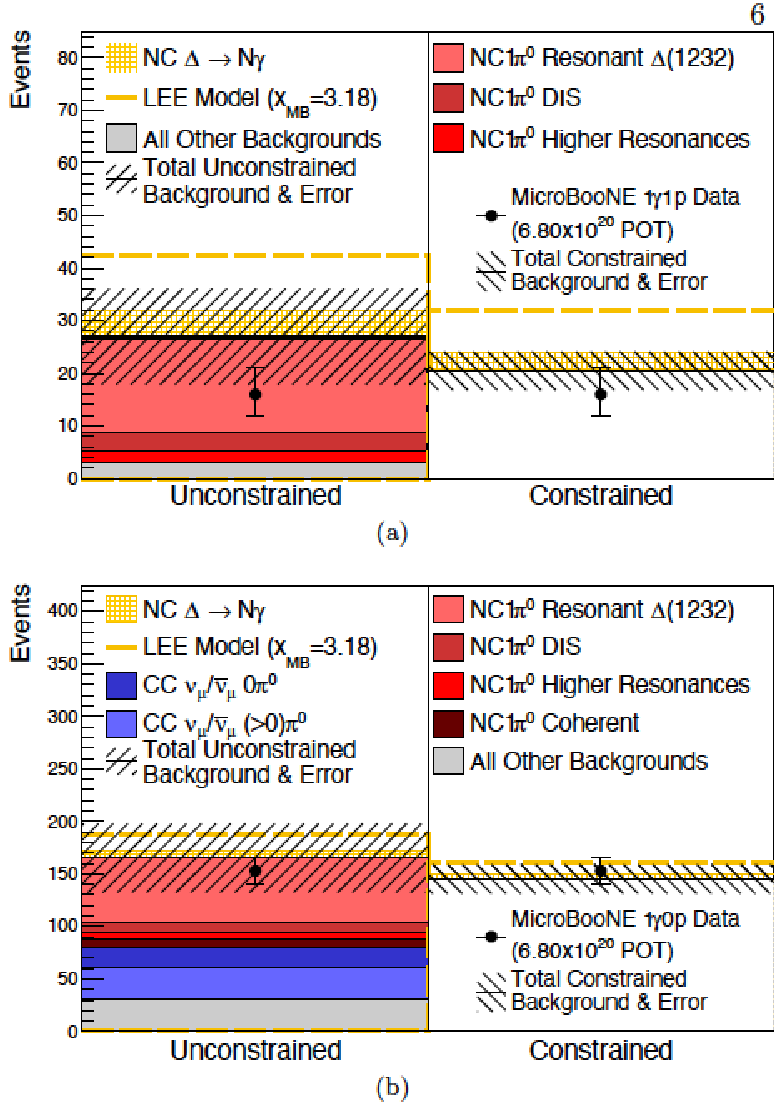


FIG. 3. The observed event rates for the (a) $1\gamma 1p$ and (b) $1\gamma 0p$ event samples, and comparisons to unconstrained (left) and constrained (right) background and LEE model predictions. The event rates are the sum of all events with reconstructed shower energy between 0-600 MeV and 100-700 MeV for (a) and (b), respectively. The one-bin background only conditionally constrained χ^2 is 0.63 and 0.18 for $1\gamma 1p$ and $1\gamma 0p$ respectively.

[MicroBooNE, arXiV:2110.00409 [hep-ex]]

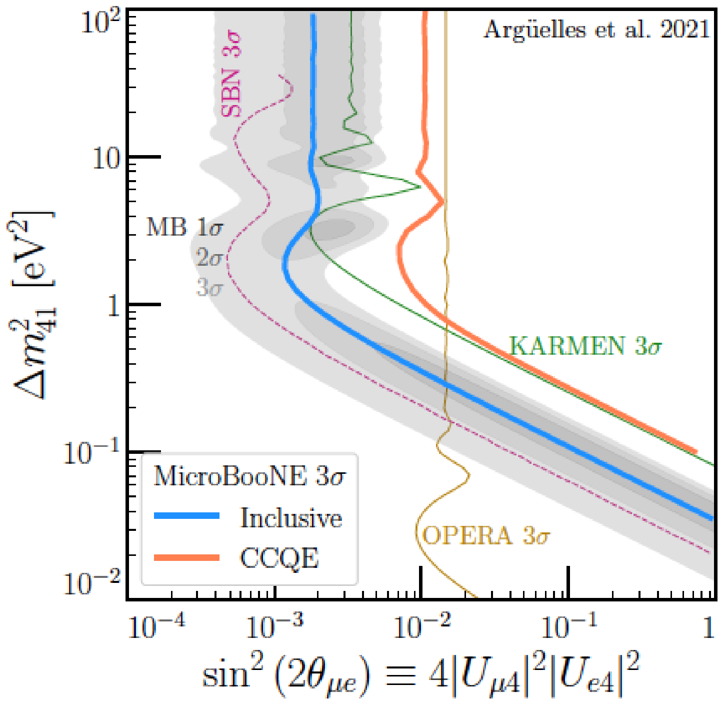


FIG. 3. MicroBooNE constraints on the sterile neutrino parameter space at 3σ C.L. (blue, inclusive and orange, CCQE). For reference, we show the MiniBooNE 1-, 2-, and 3-σ preferred regions in shades of grey [24], the future sensitivity of the three SBN detectors (pink [36]), and existing constraints from KARMEN (green [19]) and OPERA (gold [37]).

[Argüelles et al, arXiV:2111.10359 [hep-ph]]

simplified model is parametrized by a squared-mass difference Δm^2_{41} and an effective mixing angle $\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu 4}|^2$ with U the leptonic mixing matrix. Figure 3 presents the results of our analyses of MicroBooNE's inclusive and CCQE channels in blue and orange, respectively, at 3σ C.L.

While MicroBooNE data disfavors part of the region preferred by MiniBooNE, we find that there is still a large viable fraction of the parameter space, even within the 1σ preferred region of MiniBooNE. We find it unlikely that future MicroBooNE results will significantly improve on