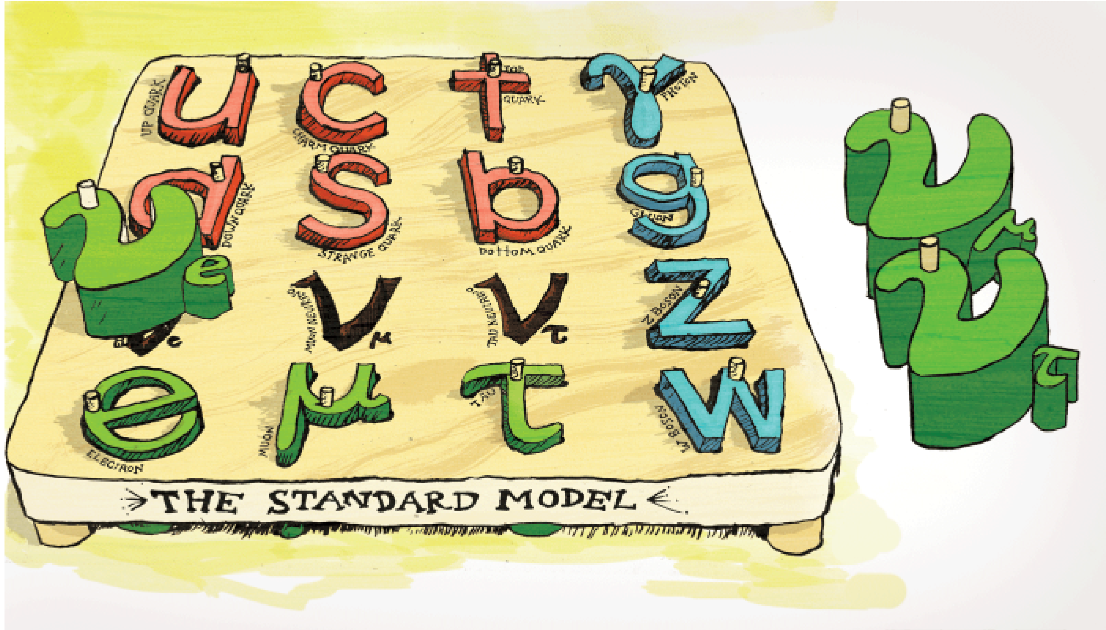
Neutrino Physics – Some Recent Developments



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NCTS Annual Theory Meeting 2020: Particles, Cosmology and Strings

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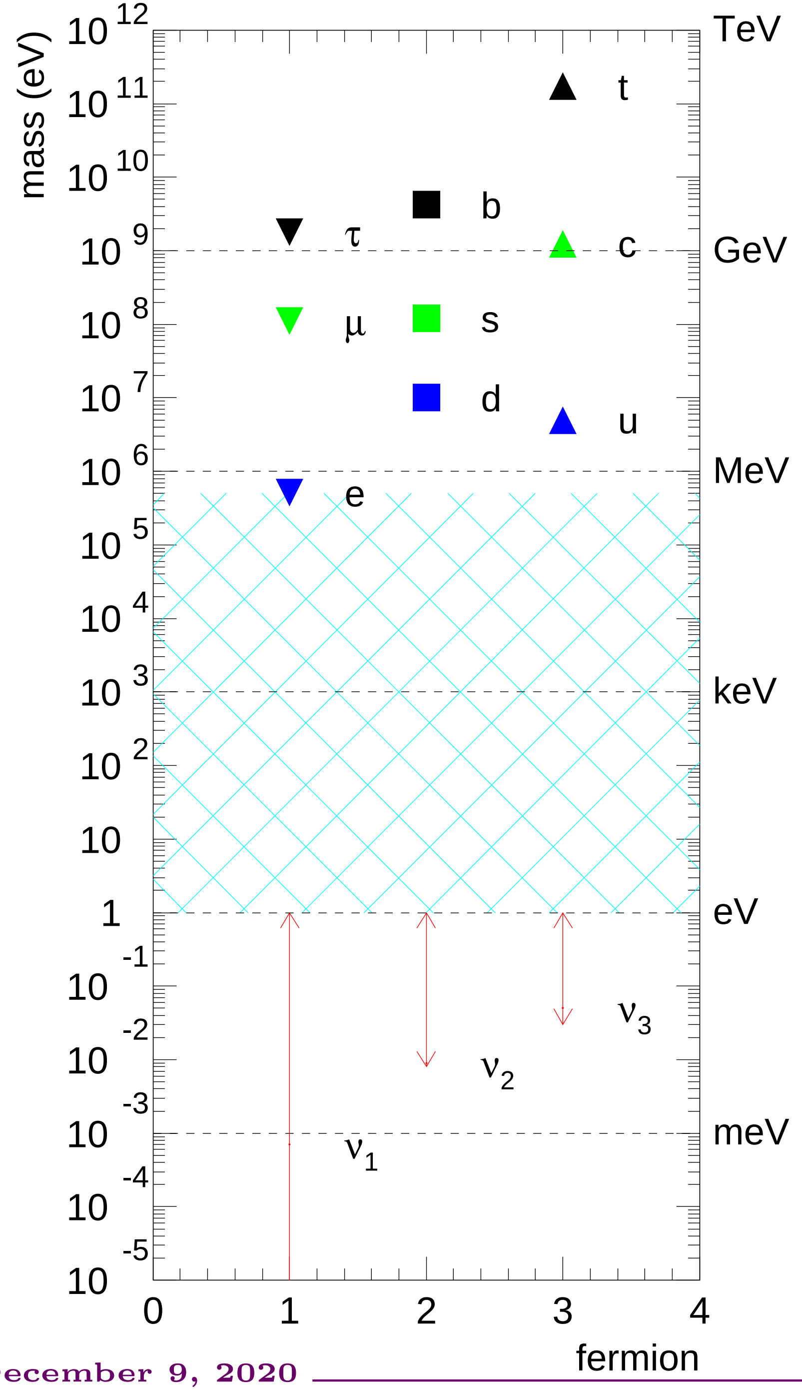
Something Funny Happened on the Way to the 21st Century

ν Flavor Oscillations

Neutrino oscillation experiments have revealed that neutrinos change flavor after propagating a finite distance. The rate of change depends on the neutrino energy E_ν and the baseline L. The evidence is overwhelming.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric and accelerator experiments;
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor experiments;
- $\nu_\mu \to \nu_{\rm other}$ and $\bar{\nu}_\mu \to \bar{\nu}_{\rm other}$— atmospheric and accelerator expts;
- $\nu_\mu \to \nu_e$ — accelerator experiments.

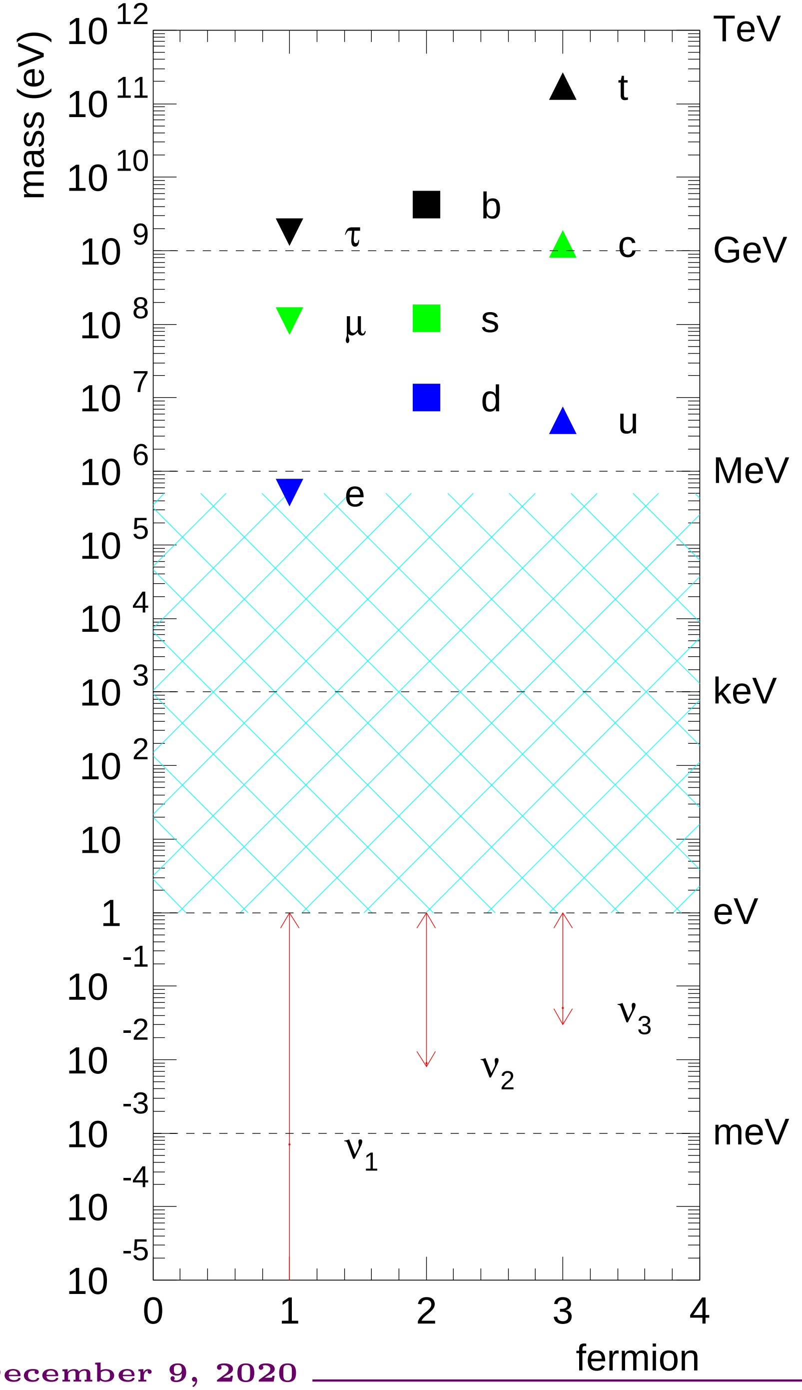
The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and mix.



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

⇓

NEW PHYSICS

Given the known “ingredients” of the SM – Q, u^c, d^c, L, e^c $(\times 3) + H$ – and the known rules – $SU(3) \times SU(2) \times U(1)$ gauge symmetry – we can predict that the neutrino masses are exactly zero.

Neutrino masses require new ingredients. We are still trying to figure out what these new ingredients are.

On the plus side, we probably know what they could be...

In Summary: Neutrino Masses are the Only* "Palpable" Evidence of Physics Beyond the Standard Model

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* There is only a handful of questions our model for fundamental physics cannot explain (my personal list. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there more matter than antimatter 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 [inflation]? (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.

νSM – One Possibility

SM as an effective field theory – non-renormalizable operators

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

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

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

- 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!

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").

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

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.

One Approach Aimed at Phenomenology

- Only consider $\Delta L = 2$ operators;
- Operators made up of only standard model fermions and the Higgs doublet (no gauge bosons);
- Electroweak symmetry breaking characterized as prescribed in SM;
- Effective operator couplings assumed to be "flavor indifferent", unless otherwise noted;
- Operators "turned on" one at a time, assumed to be leading order (tree-level) contribution of new lepton number violating physics.
- We can use the effective operator to estimate the coefficient of all other lepton-number violating lower-dimensional effective operators (loop effects, computed with a hard cutoff).

Results presented are order of magnitude *estimates*, not precise quantitative results. Q: Does this really make sense? A: Sometimes...

$\mathcal{O}$	Operator	Λ [TeV]
$\mathcal{O}_1$	$(LH)(LH)$	$6 \times 10^{10-11}$
$\mathcal{O}_2$	$(LL)(LH)e^c$	$4 \times 10^{6-7}$
$\mathcal{O}_{3_a}$	$(LL)(QH)d^c$	$2 \times 10^{4-5}$
$\mathcal{O}_{3_b}$	$(LQ)(LH)d^c$	$1 \times 10^{7-8}$
$\mathcal{O}_{4_a}$	$(L\overline{Q})(LH)\overline{u^c}$	$4 \times 10^{8-9}$
$\mathcal{O}_{4_b}$	$(LL)(\overline{Q}H)\overline{u^c}$	$2-7$
$\mathcal{O}_8$	$(LH)\overline{e^c}\overline{u^c}d^c$	$6 \times 10^{2-3}$

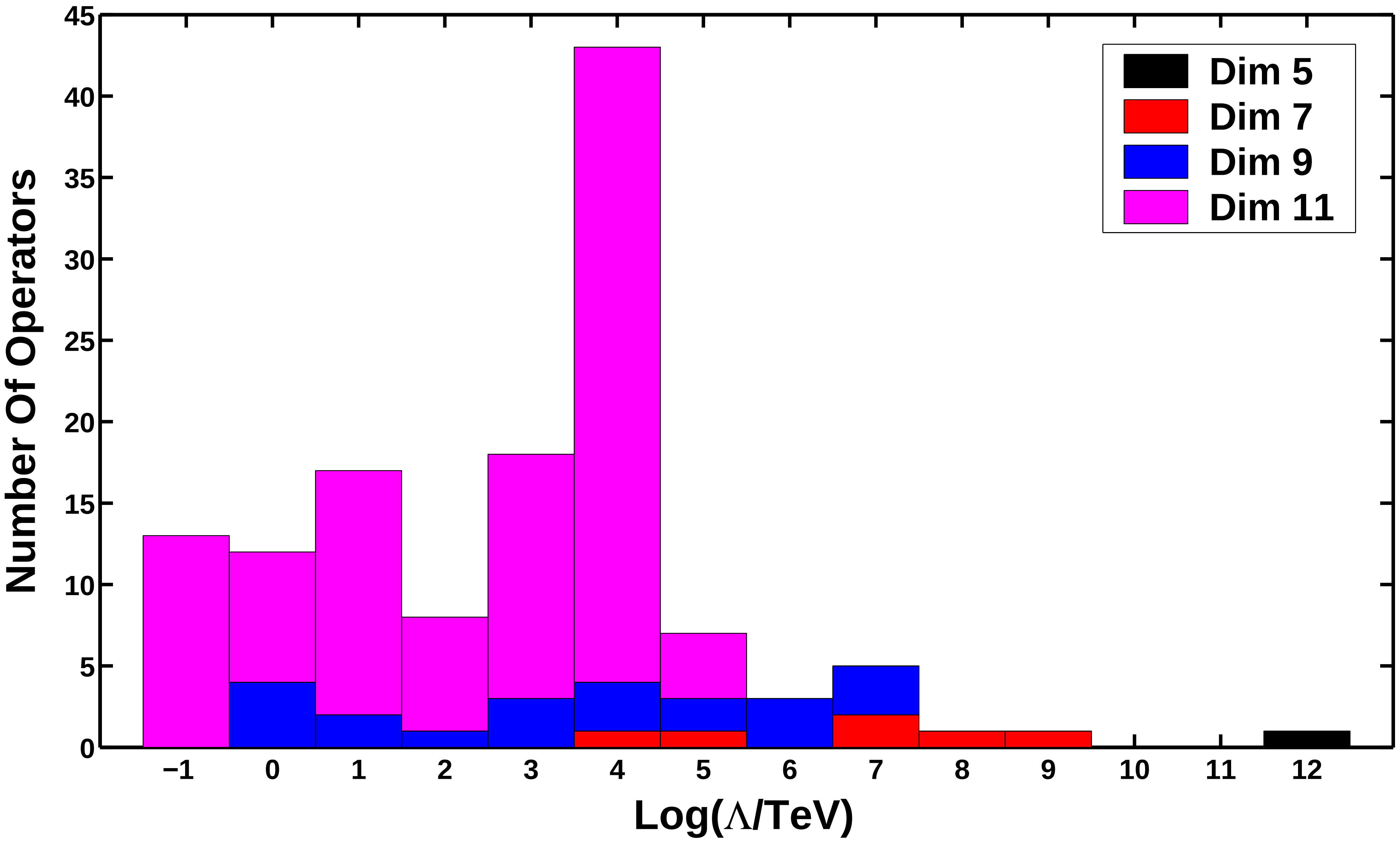
$\mathcal{O}$	Operator	Λ [TeV]
$\mathcal{O}_5$	$(L\overline{H})(LH)(QH)d^c$	$6 \times 10^{4-5}$
$\mathcal{O}_6$	$(LH)(L\overline{H})(\overline{Q}H)\overline{u^c}$	$2 \times 10^{6-7}$
$\mathcal{O}_7$	$(LH)(QH)(\overline{Q}H)\overline{e^c}$	$4 \times 10^{1-2}$
$\mathcal{O}_9$	$(LL)(LL)e^c e^c$	$3 \times 10^{2-3}$
$\mathcal{O}_{10}$	$(LL)(LQ)e^c d^c$	$6 \times 10^{2-3}$
$\mathcal{O}_{11_a}$	$(LL)(QQ)d^c d^c$	$3-30$
$\mathcal{O}_{11_b}$	$(LQ)(LQ)d^c d^c$	$2 \times 10^{3-4}$

$\mathcal{O}_{12_a}$	$(L\overline{Q})(L\overline{Q})\overline{u^c u^c}$	$2 \times 10^{6-7}$
$\mathcal{O}_{12_b}$	$(LL)(\overline{QQ})\overline{u^c u^c}$	$0.3-0.6$
$\mathcal{O}_{13}$	$(L\overline{Q})(LL)\overline{u^c}e^c$	$2 \times 10^{4-5}$
$\mathcal{O}_{14_a}$	$(LL)(Q\overline{Q})\overline{u^c}d^c$	10^{2-3}
$\mathcal{O}_{14_b}$	$(L\overline{Q})(LQ)\overline{u^c}d^c$	$6 \times 10^{4-5}$
$\mathcal{O}_{15}$	$(LL)(L\overline{L})d^c\overline{u^c}$	10^{2-3}
$\mathcal{O}_{16}$	$(LL)e^c d^c\overline{e^c u^c}$	$0.2-2$
$\mathcal{O}_{17}$	$(LL)d^c d^c\overline{d^c u^c}$	$0.2-2$

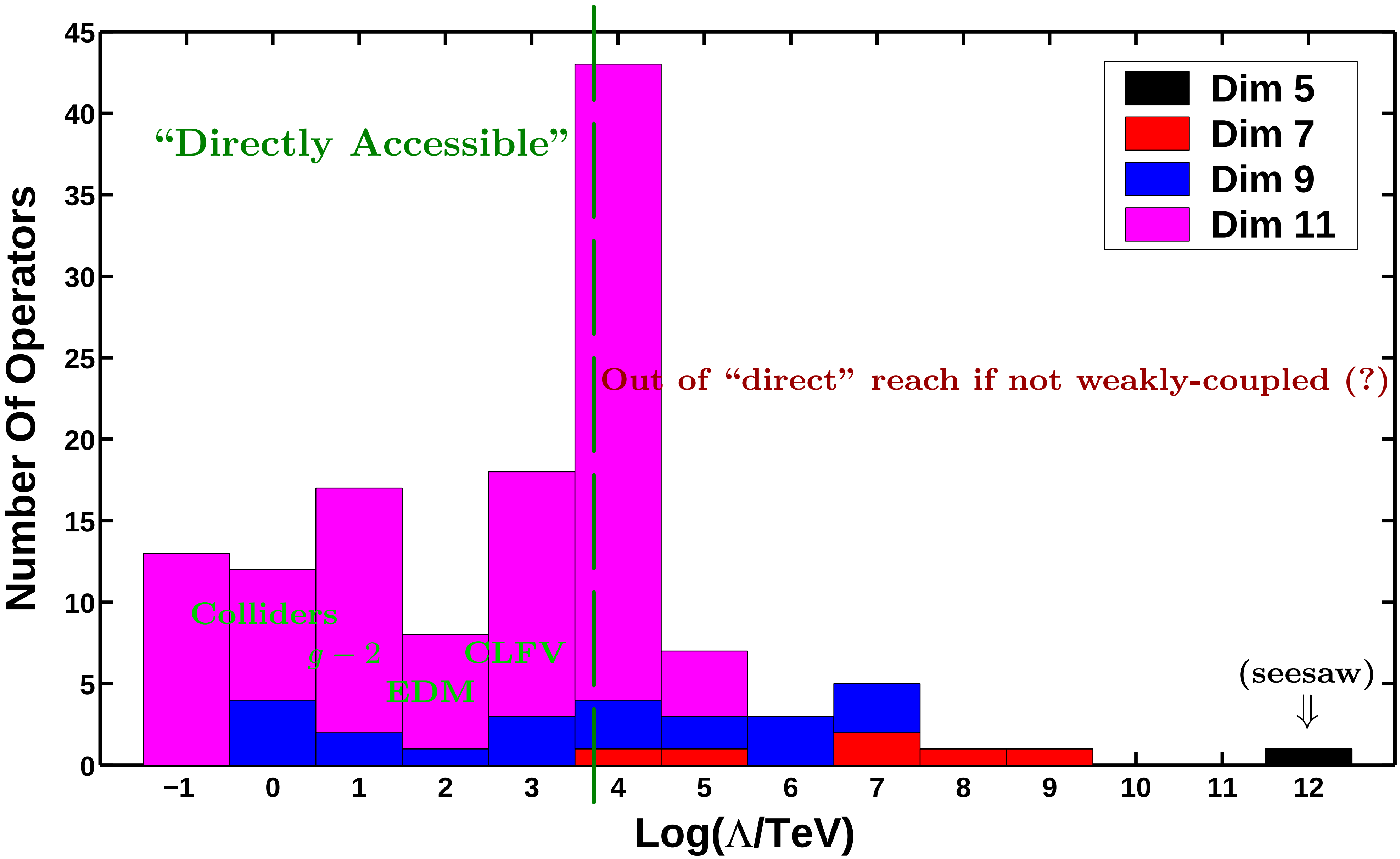
$\mathcal{O}_{18}$	$(LL)d^c u^c\overline{u^c u^c}$	$0.2-2$
$\mathcal{O}_{19}$	$(LQ)d^c d^c\overline{e^c u^c}$	$0.1-1$
$\mathcal{O}_{20}$	$(L\overline{Q})d^c\overline{u^c e^c u^c}$	$4-40$
$\mathcal{O}_s$	$e^c e^c u^c u^c\overline{d^c d^c}$	10^{-3}

- 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.



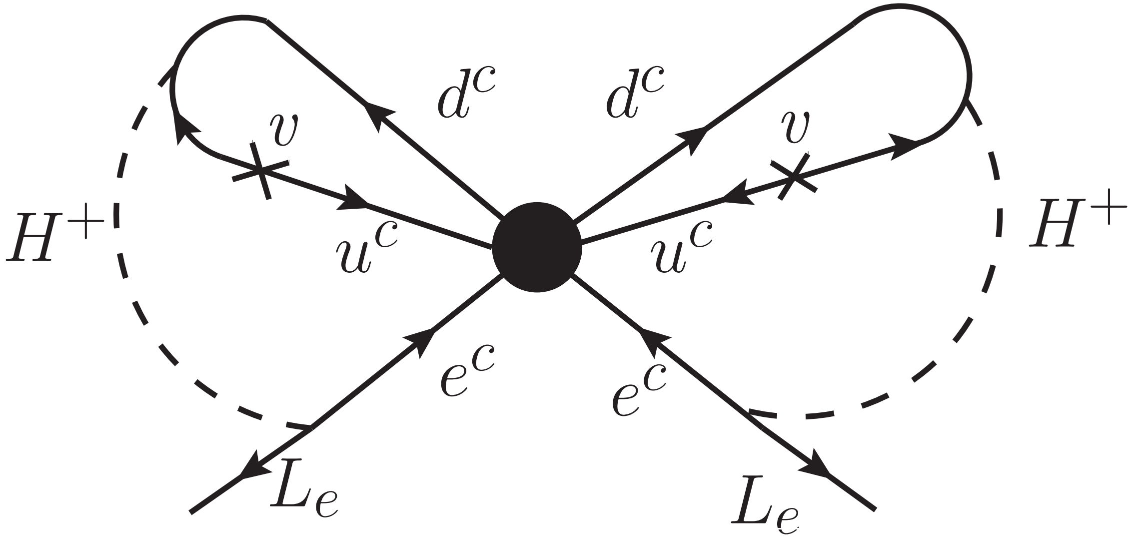
Number Of Operators
Log(Λ/TeV)
Dim 5
Dim 7
Dim 9
Dim 11
0
5
10
15
20
25
30
35
40
45
−1
0
1
2
3
4
5
6
7
8
9
10
11
12



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

[AdG et al, arXiv:1907.02541]

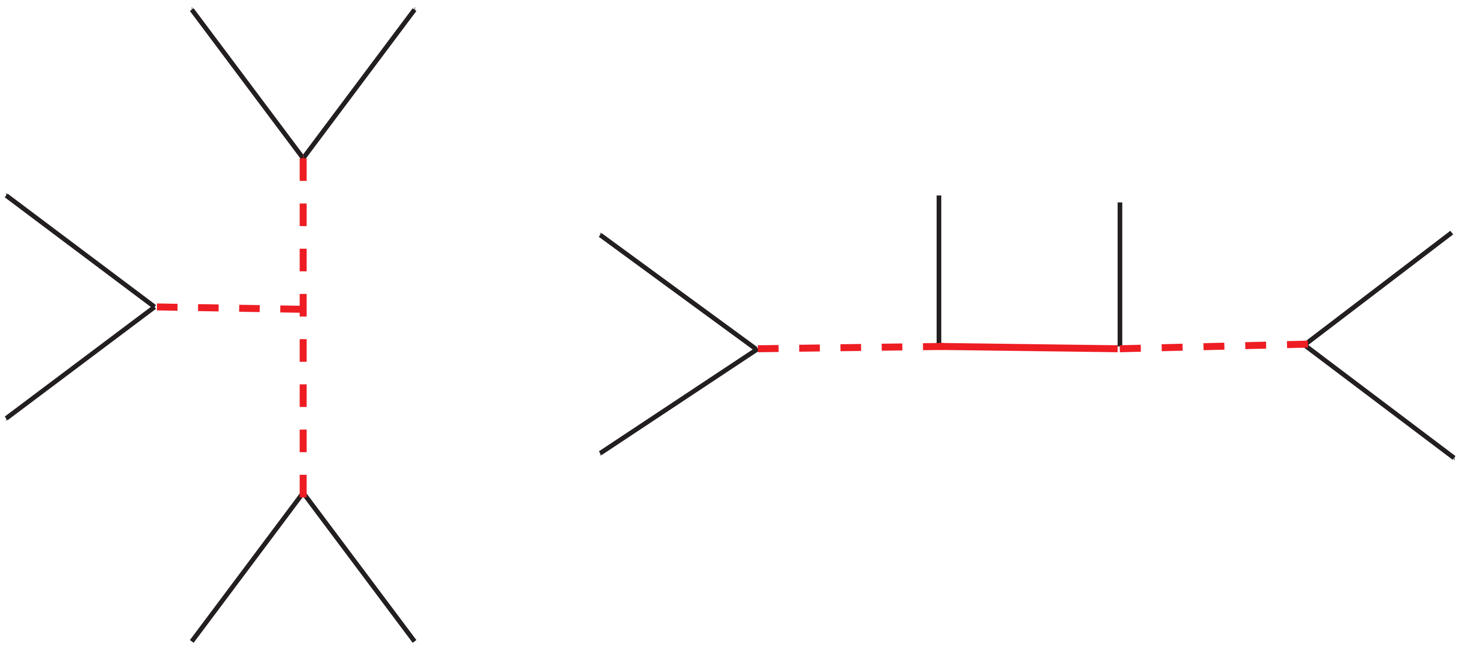
$$\mathcal{O}_s^{\alpha\beta} = \ell^c_\alpha \ell^c_\beta u^c u^c \overline{d^c}\,\overline{d^c}$$



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

[AdG et al, arXiv:1907.02541]

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



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	$\Big(\mathrm{SU(3)_C},\, \mathrm{SU(2)_L}\Big)_{\mathrm{U(1)_Y}}$	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

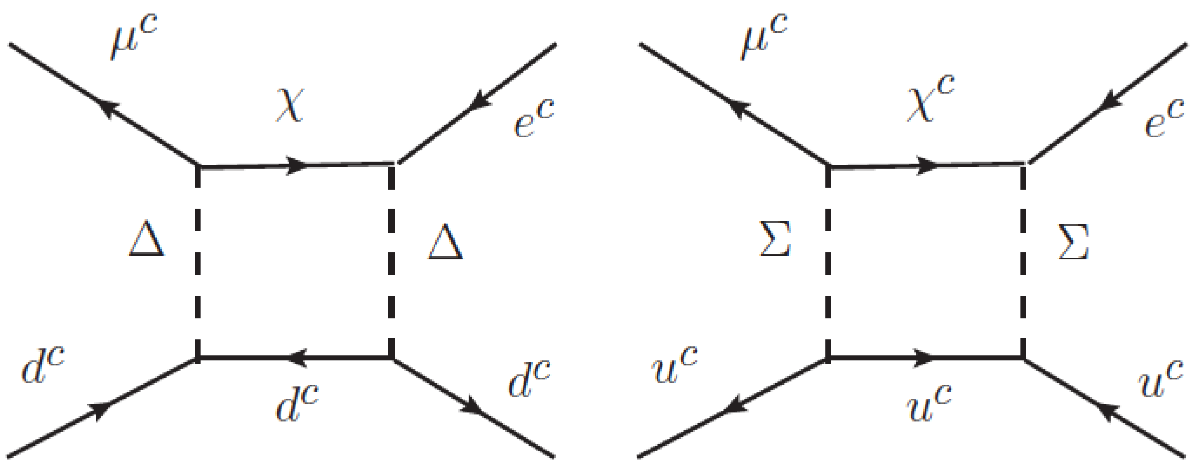


FIG. 8: Feynman diagrams (box-diagrams) contributing to the CLFV process $\mu^- \to e^-$-conversion, in Model $\chi\Delta\Sigma$.

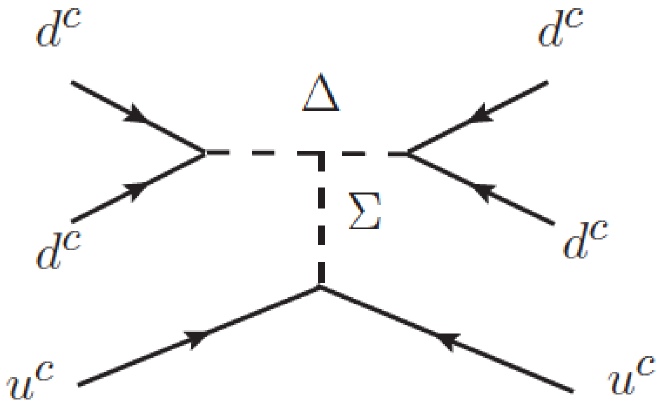
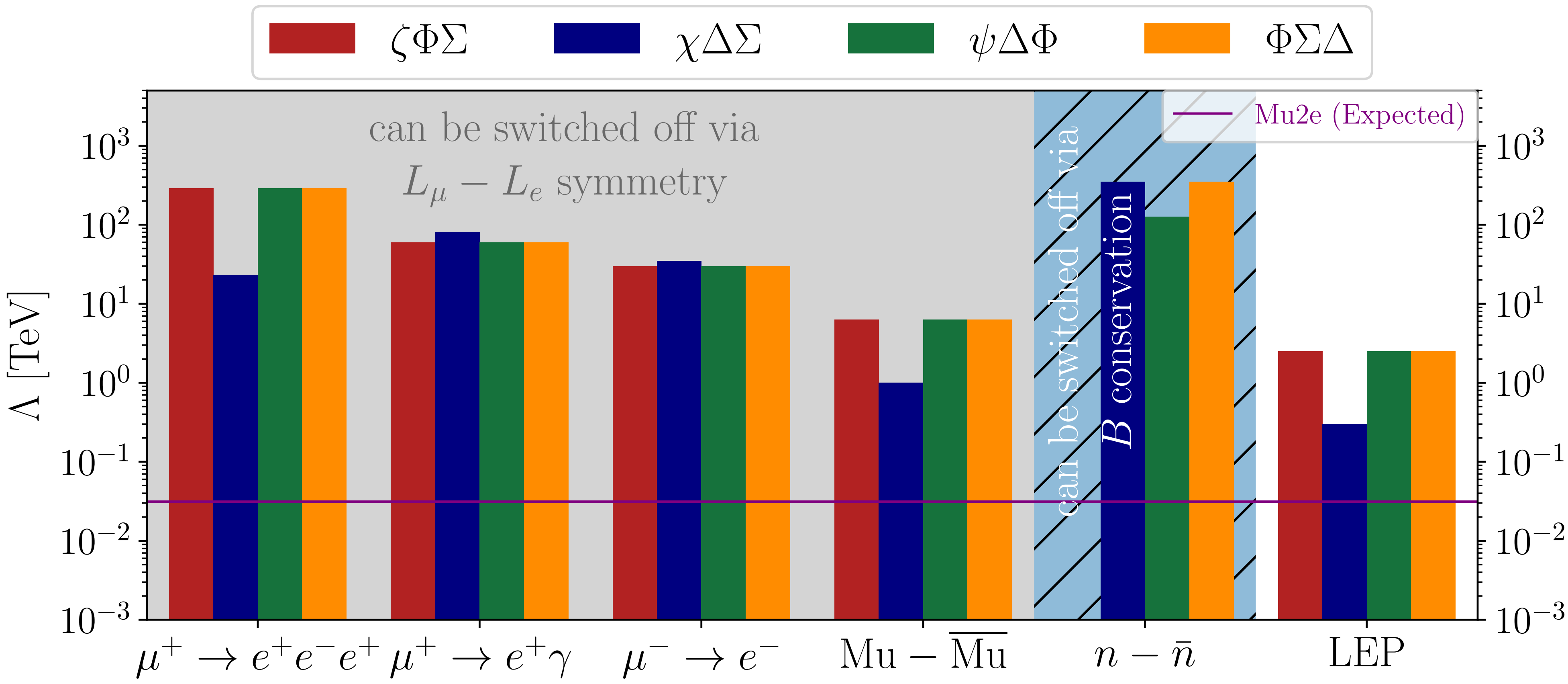


FIG. 9: Tree-level Feynman diagram that mediates $n - \overline{n}$ oscillations in Model $\chi\Delta\Sigma$.

[AdG et al, arXiv:1907.02541]



(models with new vector bosons not included)

[AdG et al, arXiv:1907.02541]

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!

A Realistic, Reasonable, and Simple Paradigm:

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

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ — $\Delta m^2_{13} < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ — $\Delta m^2_{13} > 0$ – Normal Mass Hierarchy

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

[For a detailed discussion see e.g. AdG, Jenkins, PRD78, 053003 (2008)]

Three Flavor Mixing Hypothesis Fits All* Data Really Well.

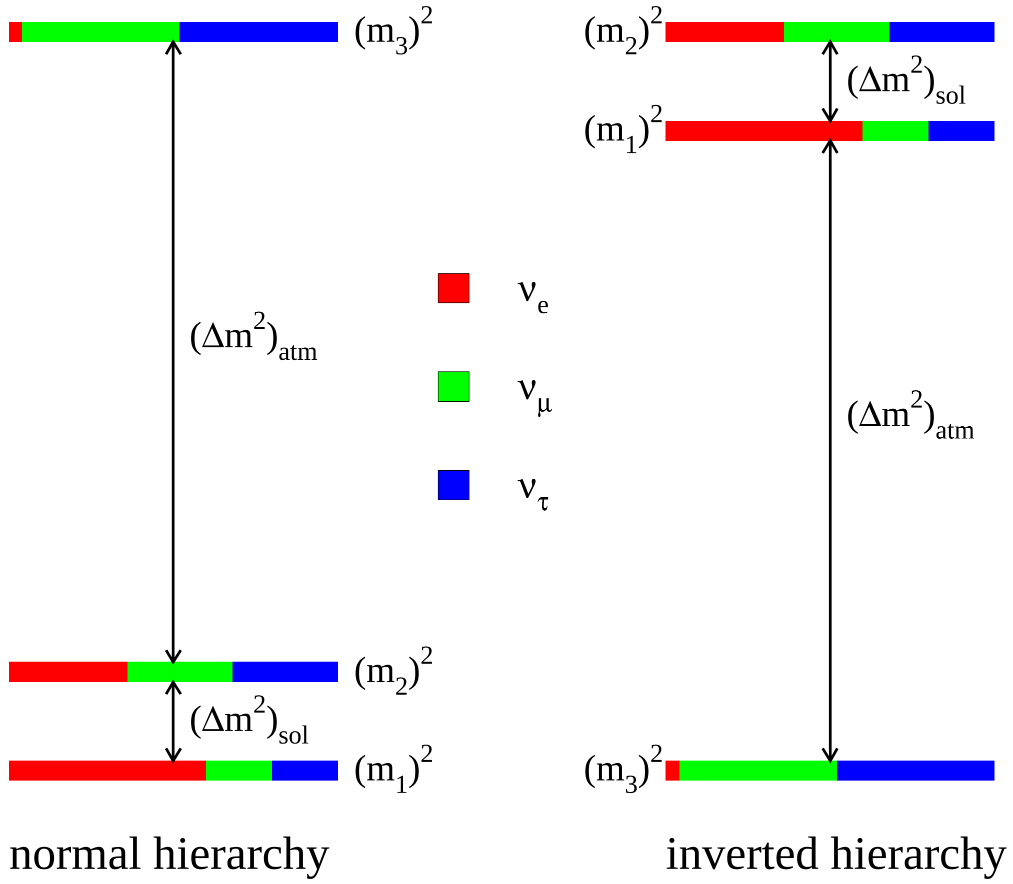
* Modulo short-baseline anomalies.

NuFIT 5.0 (2020)

without SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

[Esteban *et al*, arXiv:2007.14792, http://www.nu-fit.org]

Understanding Neutrino Oscillations: Are We There Yet? [NO!]

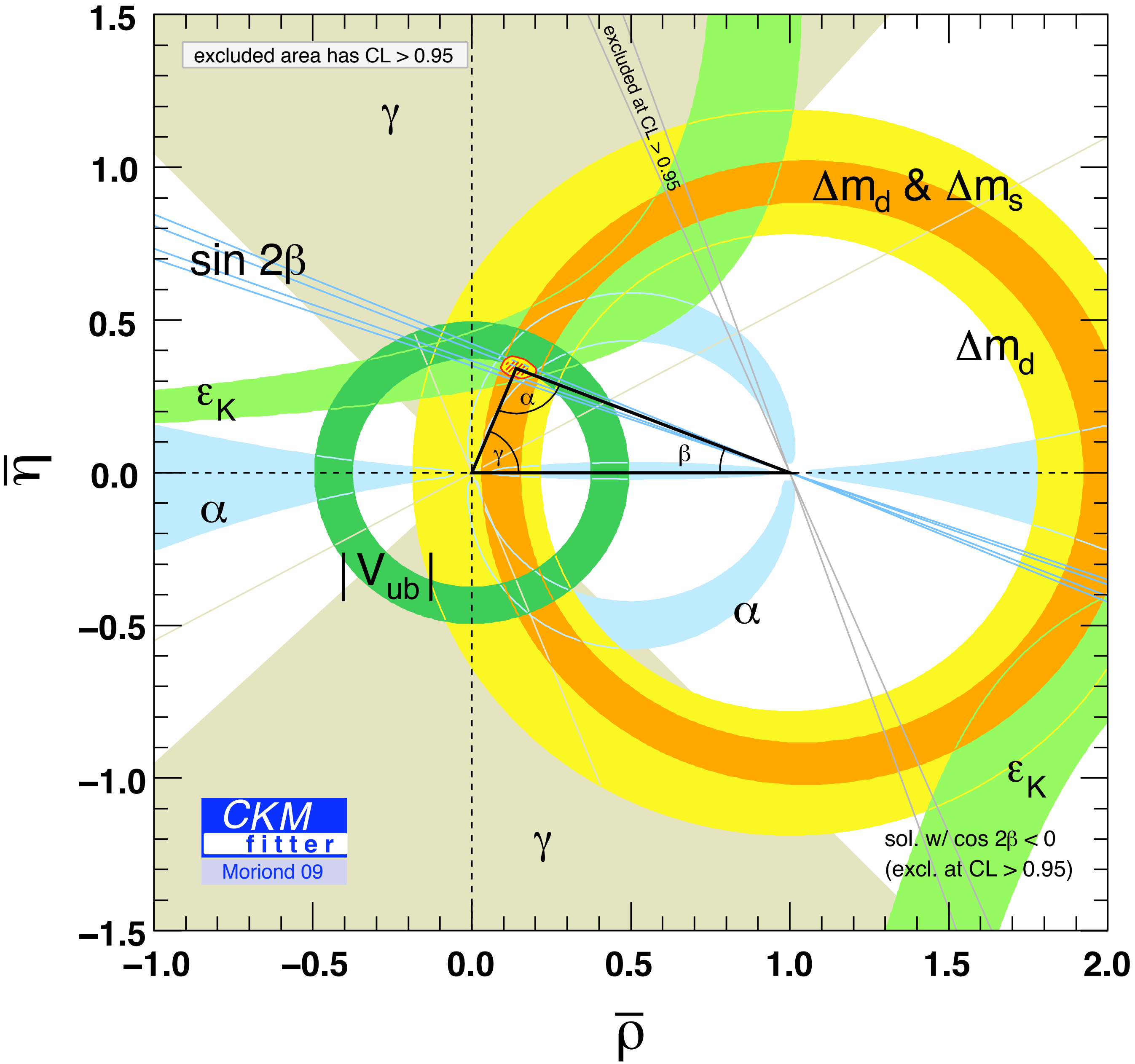


- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?) ['yes' hint]
- Is ν_3 mostly ν_μ or ν_τ? [$\theta_{23} \neq \pi/4$ hint]
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?) [NH weak hint]

$\Rightarrow$ 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 $\rightarrow$ evidence) – MINOS, T2K.

We still have a ways to go!

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.

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.

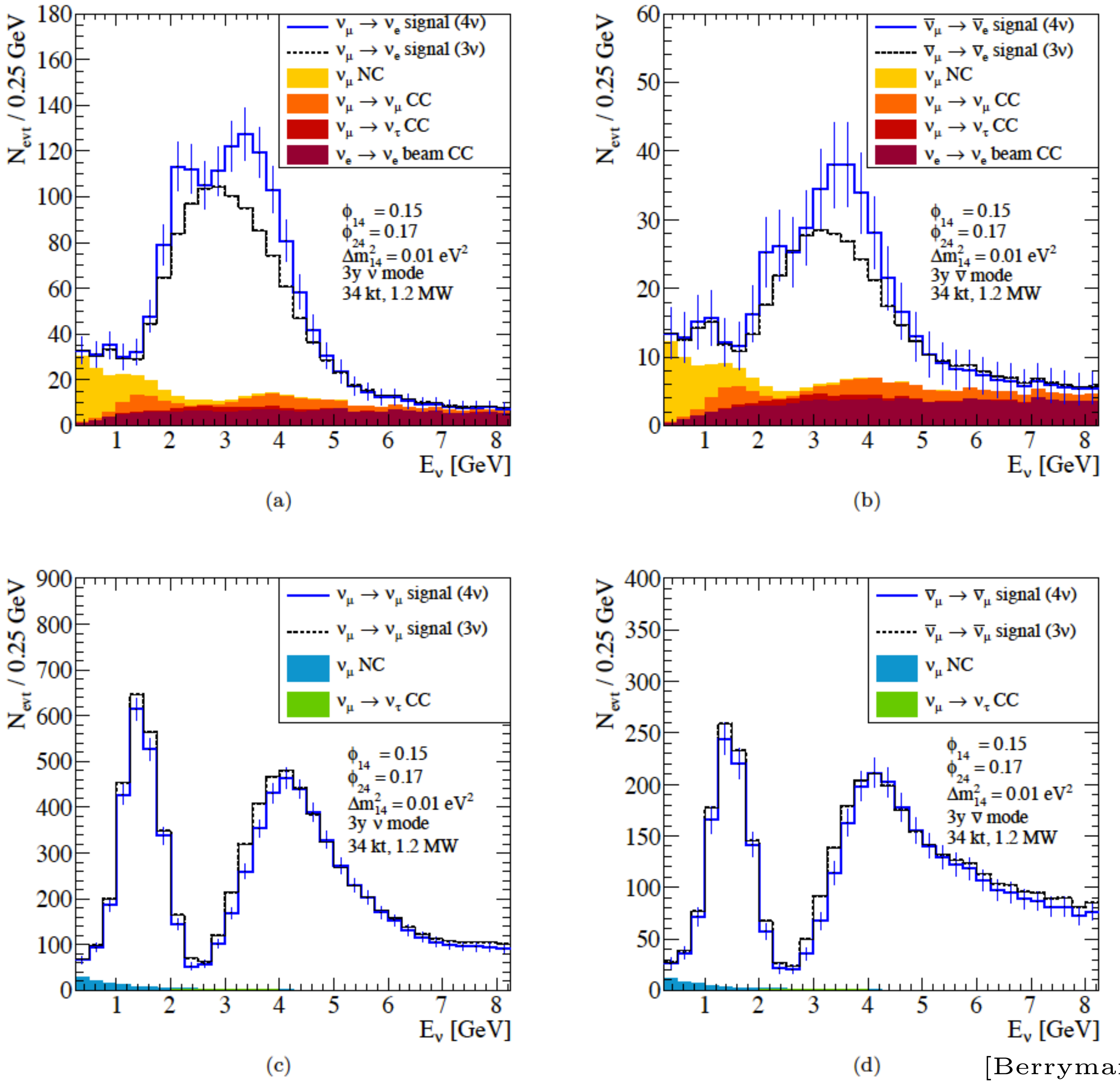
$$
\begin{aligned}
U_{e2} &= s_{12}c_{13}c_{14}, \\
U_{e3} &= e^{-i\eta_1}s_{13}c_{14}, \\
U_{e4} &= e^{-i\eta_2}s_{14}, \\
U_{\mu 2} &= c_{24}\left(c_{12}c_{23} - e^{i\eta_1}s_{12}s_{13}s_{23}\right) - e^{i(\eta_2-\eta_3)}s_{12}s_{14}s_{24}c_{13}, \\
U_{\mu 3} &= s_{23}c_{13}c_{24} - e^{i(\eta_2-\eta_3-\eta_1)}s_{13}s_{14}s_{24},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

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

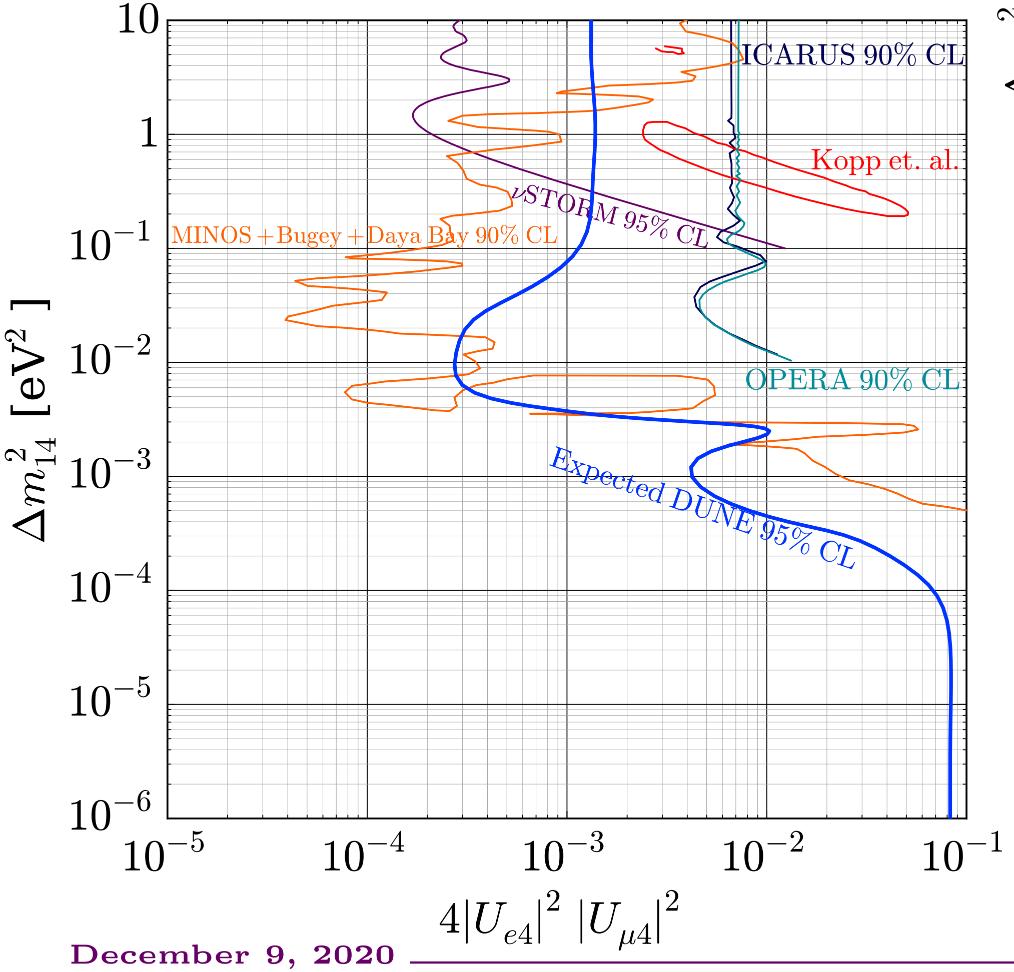
$$\eta_s \equiv \eta_2 - \eta_3,$$

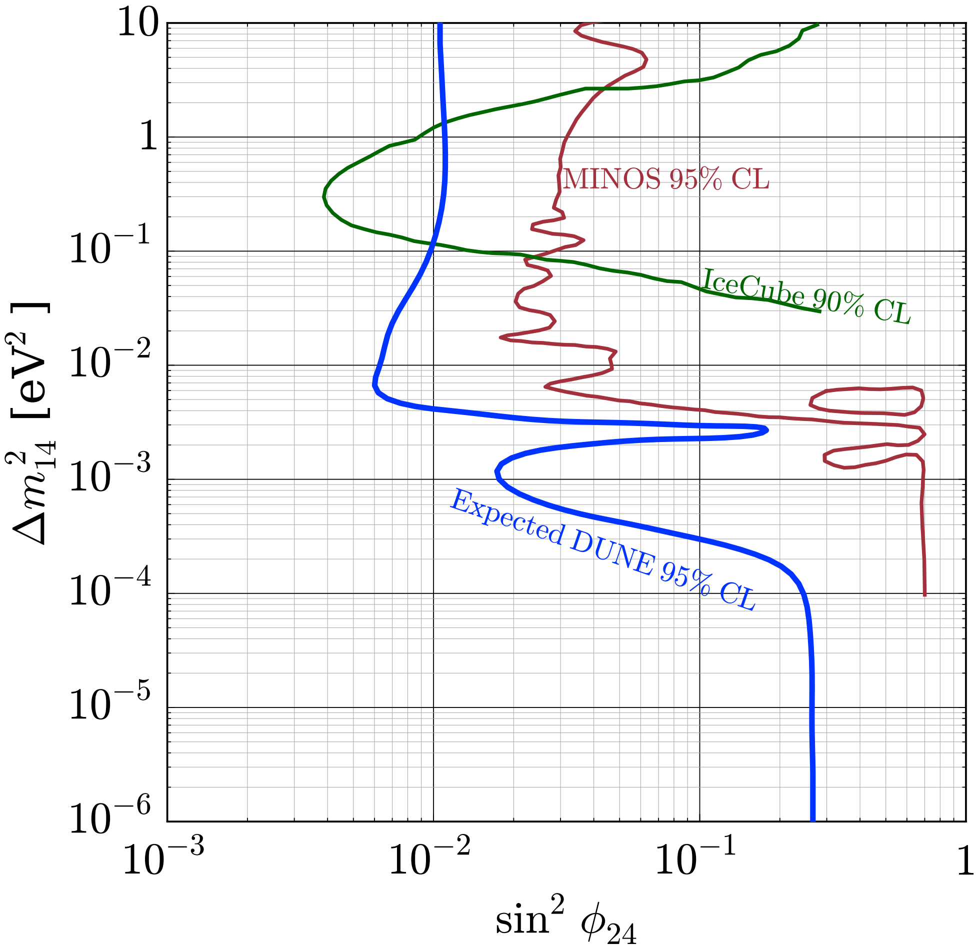
is the only new CP-odd parameter to which oscillations among ν_e and ν_μ are sensitive.



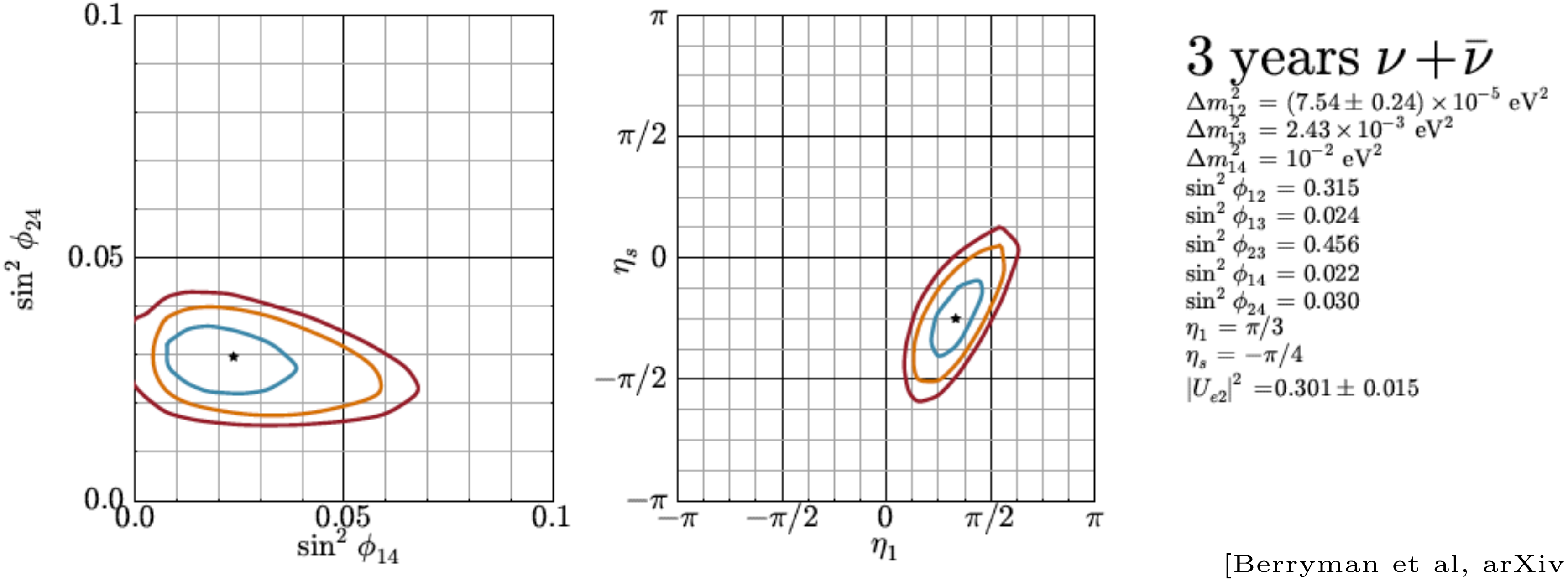
[Berryman et al, arXiv:1507.03986]

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 $\sin^2\theta_{12} = 0.308$, $\sin^2\theta_{13} = 0.0235$, $\sin^2\theta_{23} = 0.437$, $\Delta m^2_{12} = 7.54\times10^{-5}$ eV^2, $\Delta m^2_{13} = 2.43\times10^{-3}$ 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 $\overline{\nu}$), 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}	$\pi/3$

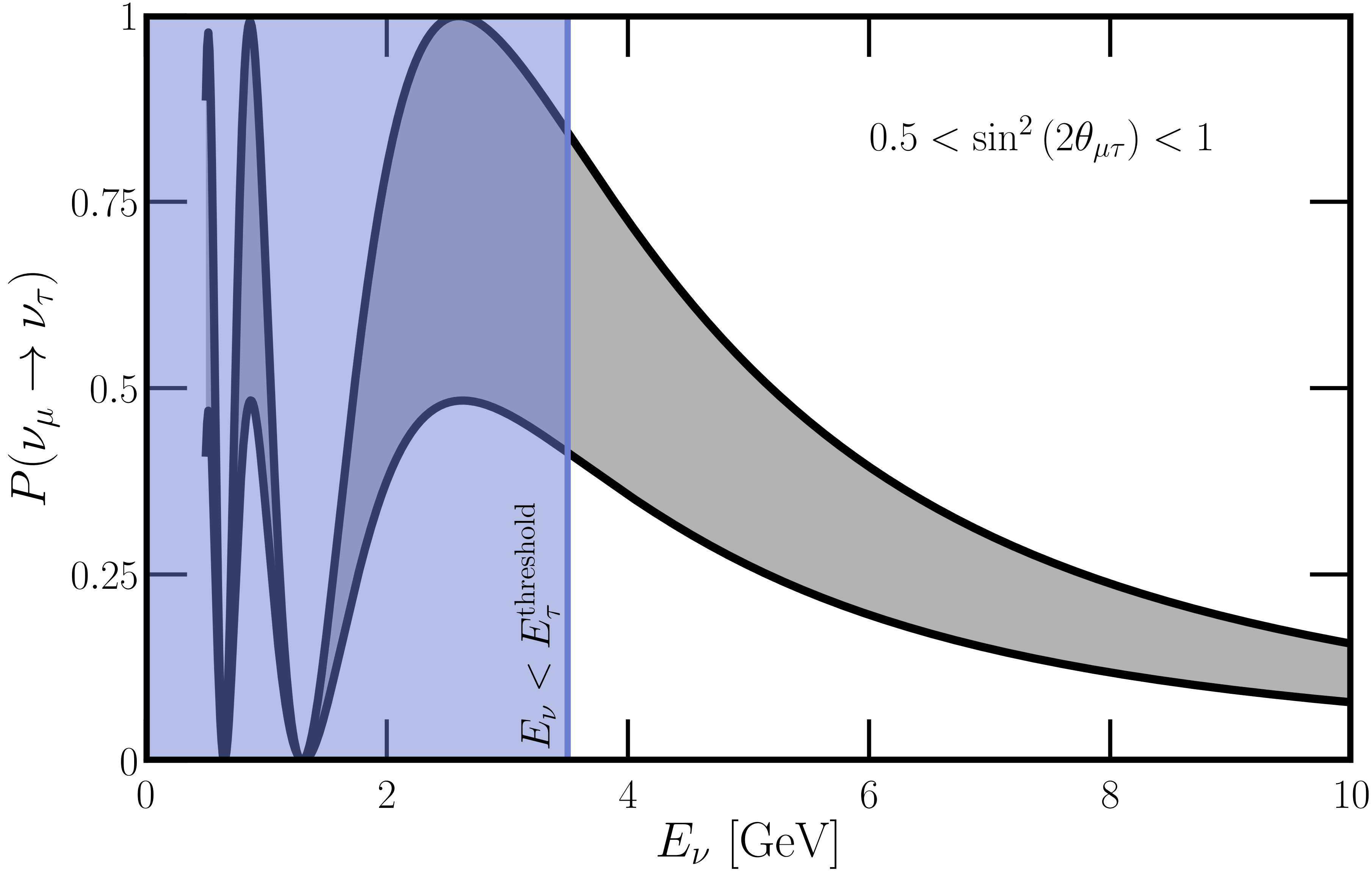
TABLE I: Input values of the parameters for the three scenarios considered for the four-neutrino hypothesis. Values of ϕ_{12}, ϕ_{13}, and ϕ_{23} are chosen to be consistent with the best-fit values of $|U_{e2}|^2$, $|U_{e3}|^2$, and $|U_{\mu3}|^2$, given choices of ϕ_{14} and ϕ_{24}. Here, $\eta_s \equiv \eta_2 - \eta_3$. Note that Δm^2_{14} is explicitly assumed to be positive, i.e., $m^2_4 > m^2_1$.

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

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

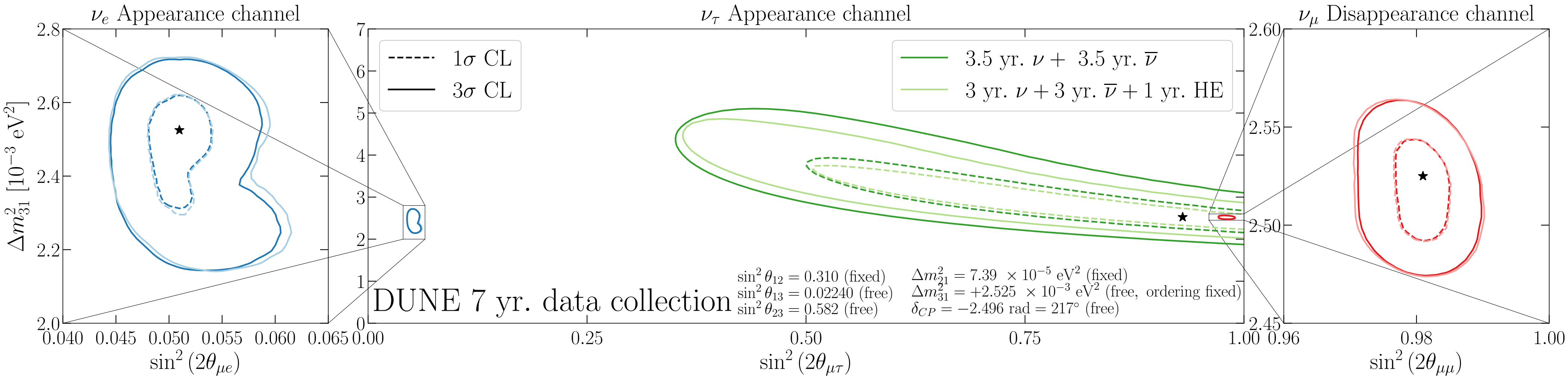
ν_τ sample: why?

- 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]



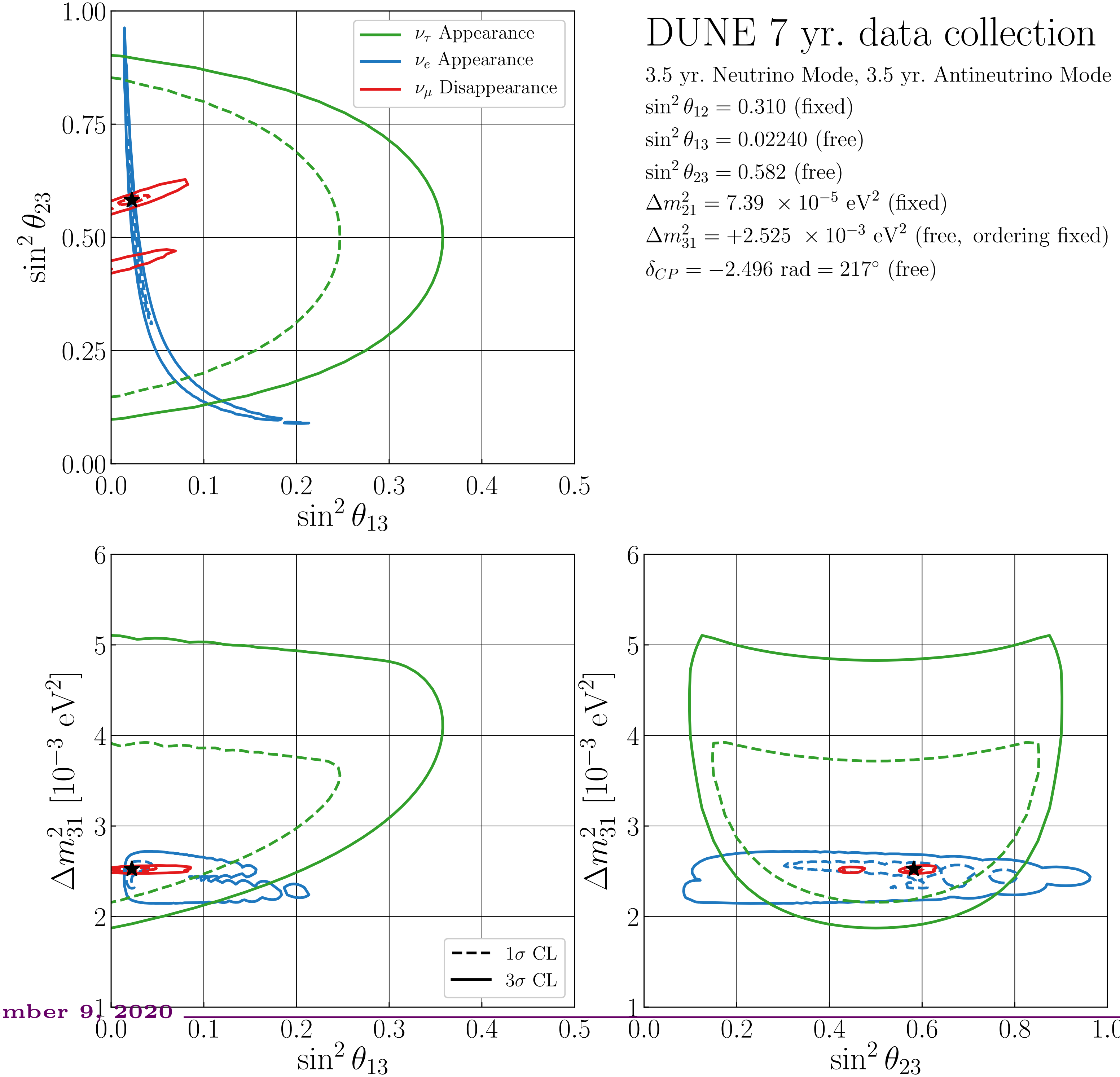
$0.5 < \sin^2(2\theta_{\mu\tau}) < 1$
$E_\nu < E_\tau^{\rm threshold}$
$P(\nu_\mu \to \nu_\tau)$
E_ν [GeV]
1
0.75
0.5
0.25
0
0
2
4
6
8
10

Testing the Three-Massive-Neutrinos Paradigm

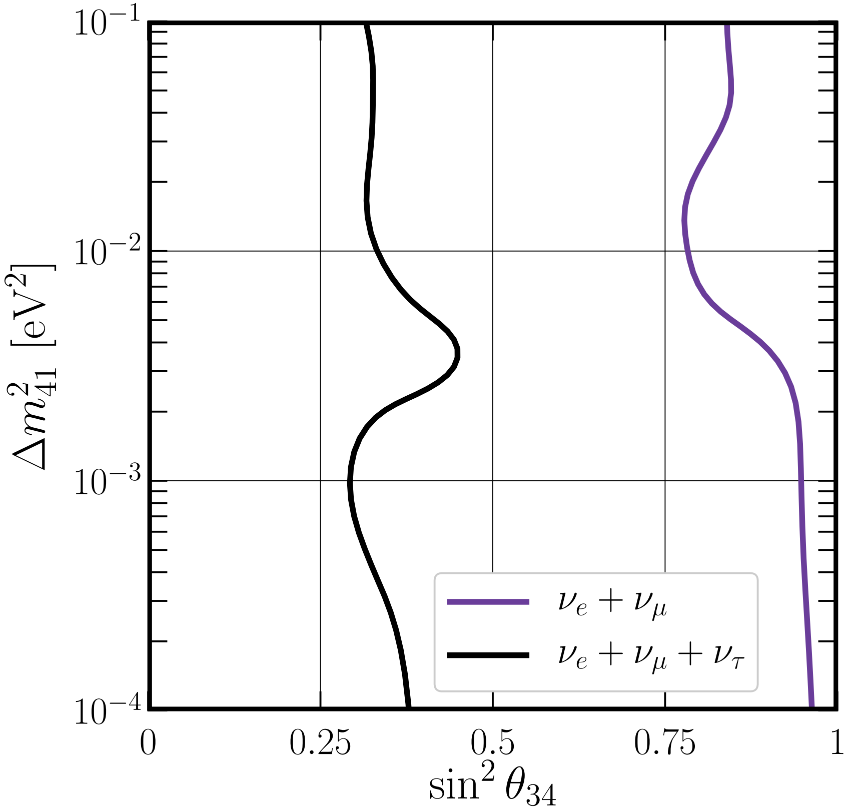


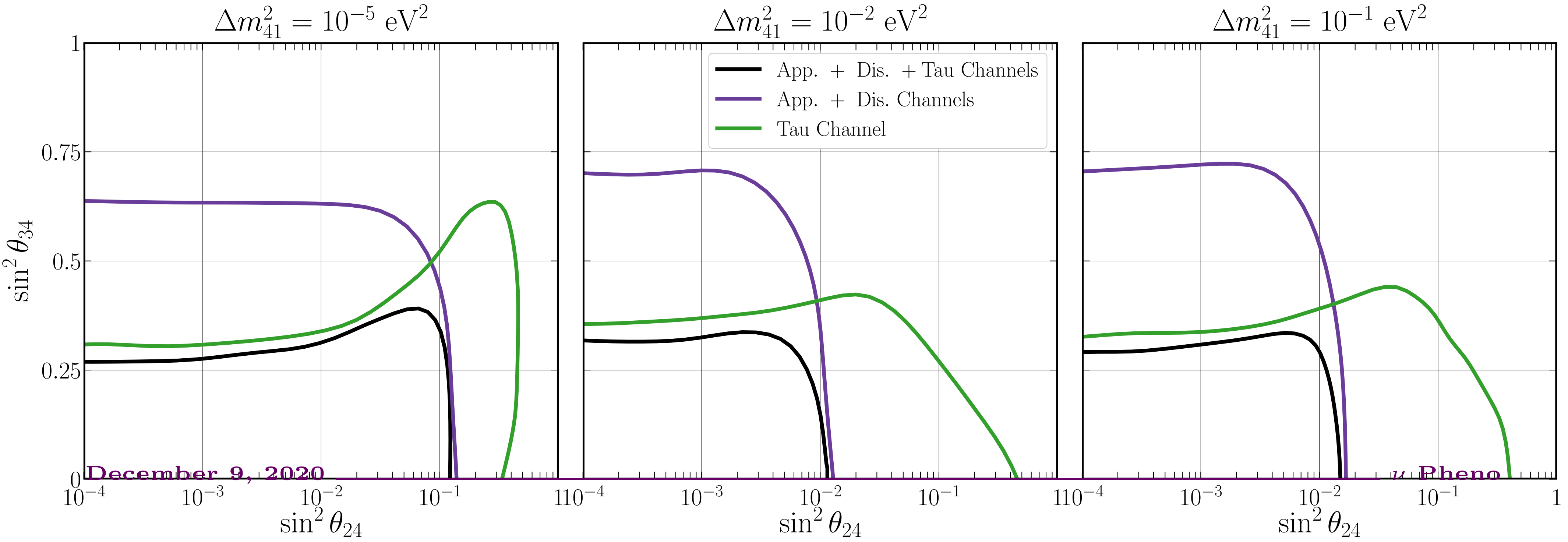
$$\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 3}|^2|U_{e3}|^2, \quad \sin^2 2\theta_{\mu\tau} \equiv 4|U_{\mu 3}|^2|U_{\tau 3}|^2, \quad \sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1-|U_{\mu 3}^2|)$$

Unitarity Test: $|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1^{+0.05}_{-0.06}$ [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]

Fourth Neutrino Hypothesis





Summary

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

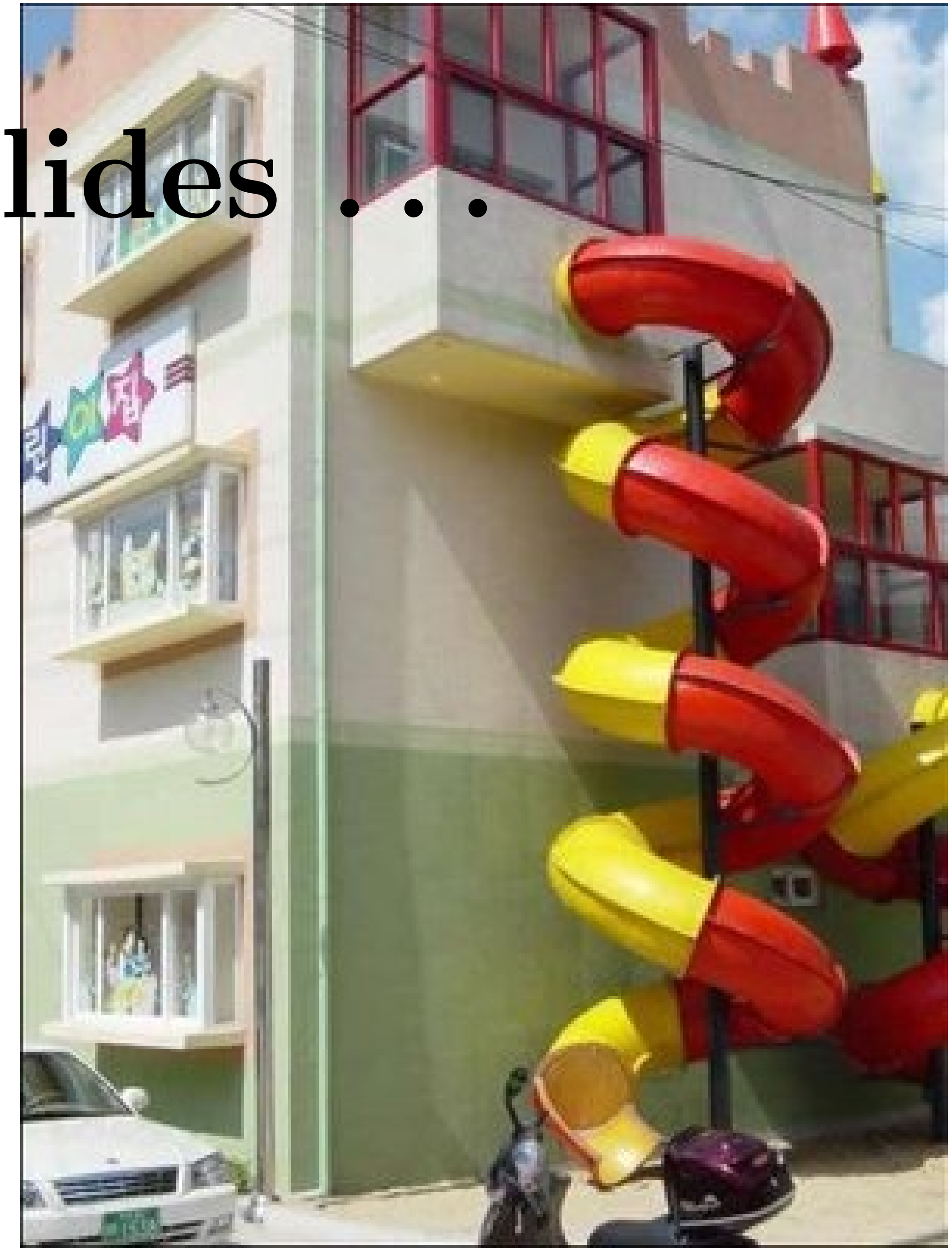
1. We still **know very little** about the new physics uncovered by neutrino oscillations. In particular, the new physics (broadly defined) can live almost anywhere between sub-eV scales and the GUT scale.

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)

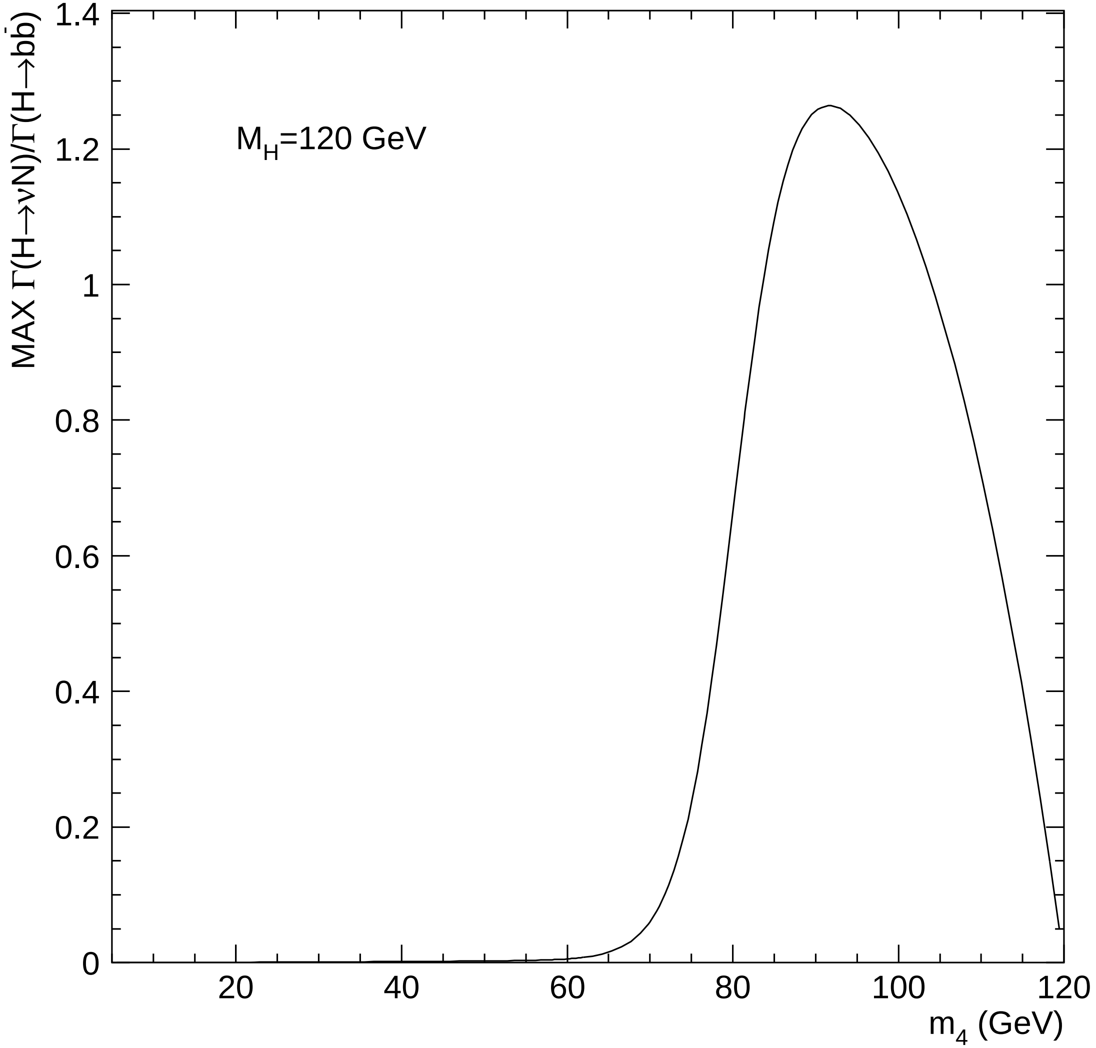
Low-Energy Seesaw: Brief Comments [AdG PRD72,033005)]

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]]



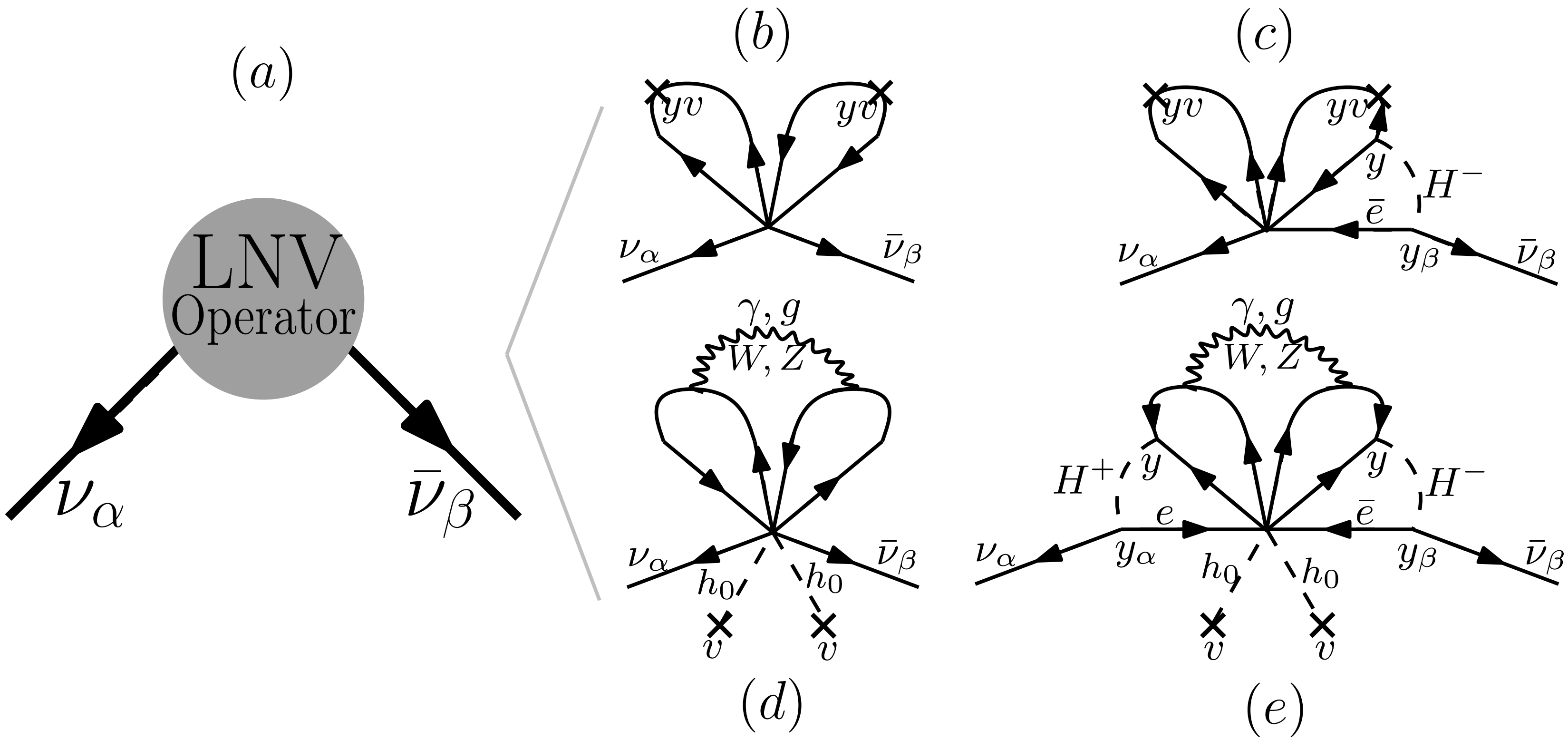
What does the seesaw Lagrangian predict for the LHC?

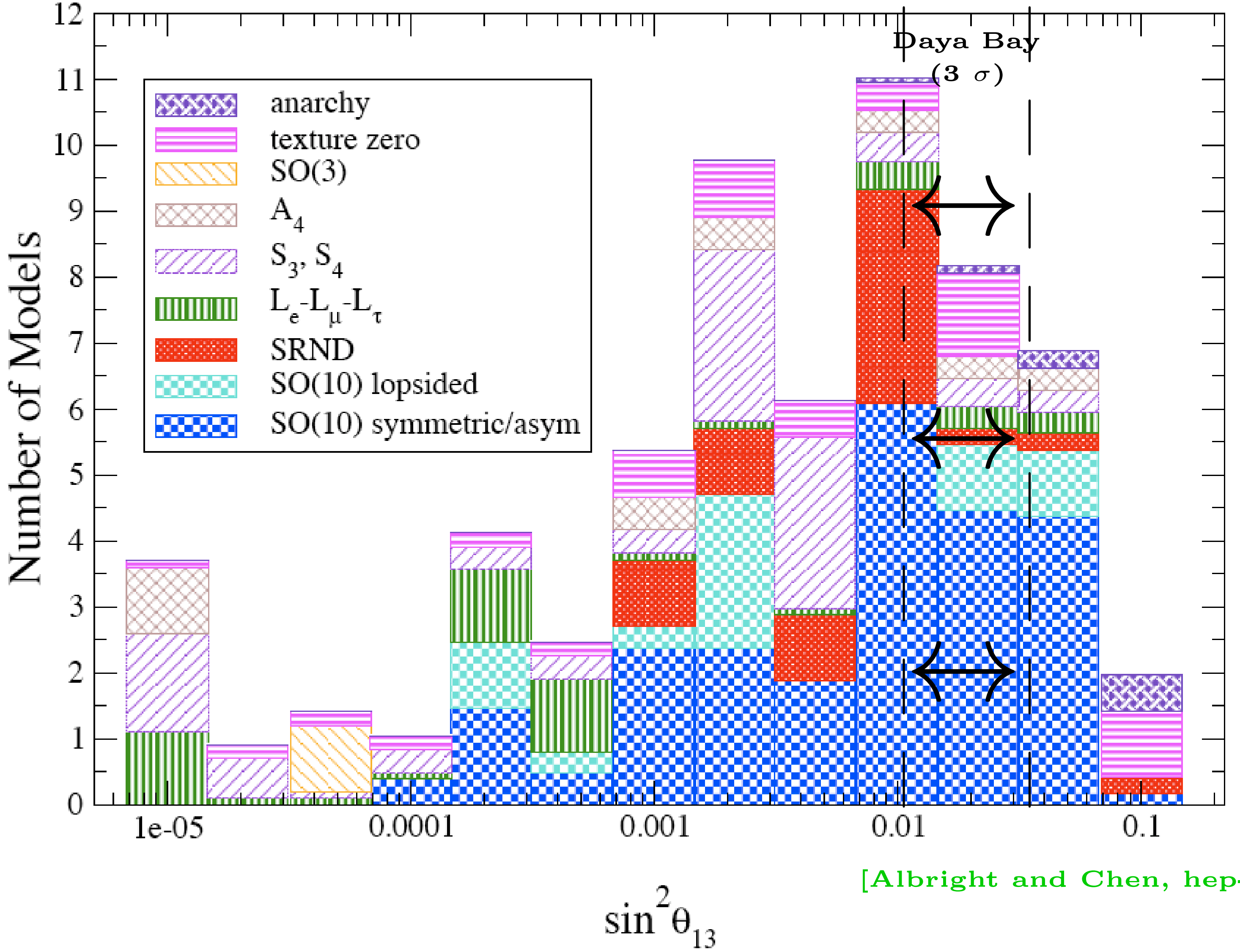
Nothing much, unless. . .

- $M_N \sim 1 - 100$ 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^-
$\bar{e}$
ν_α
y_β
$\bar{\nu}_\beta$
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
y_β
$\bar{\nu}_\beta$
h_0
h_0
v
v
(e)

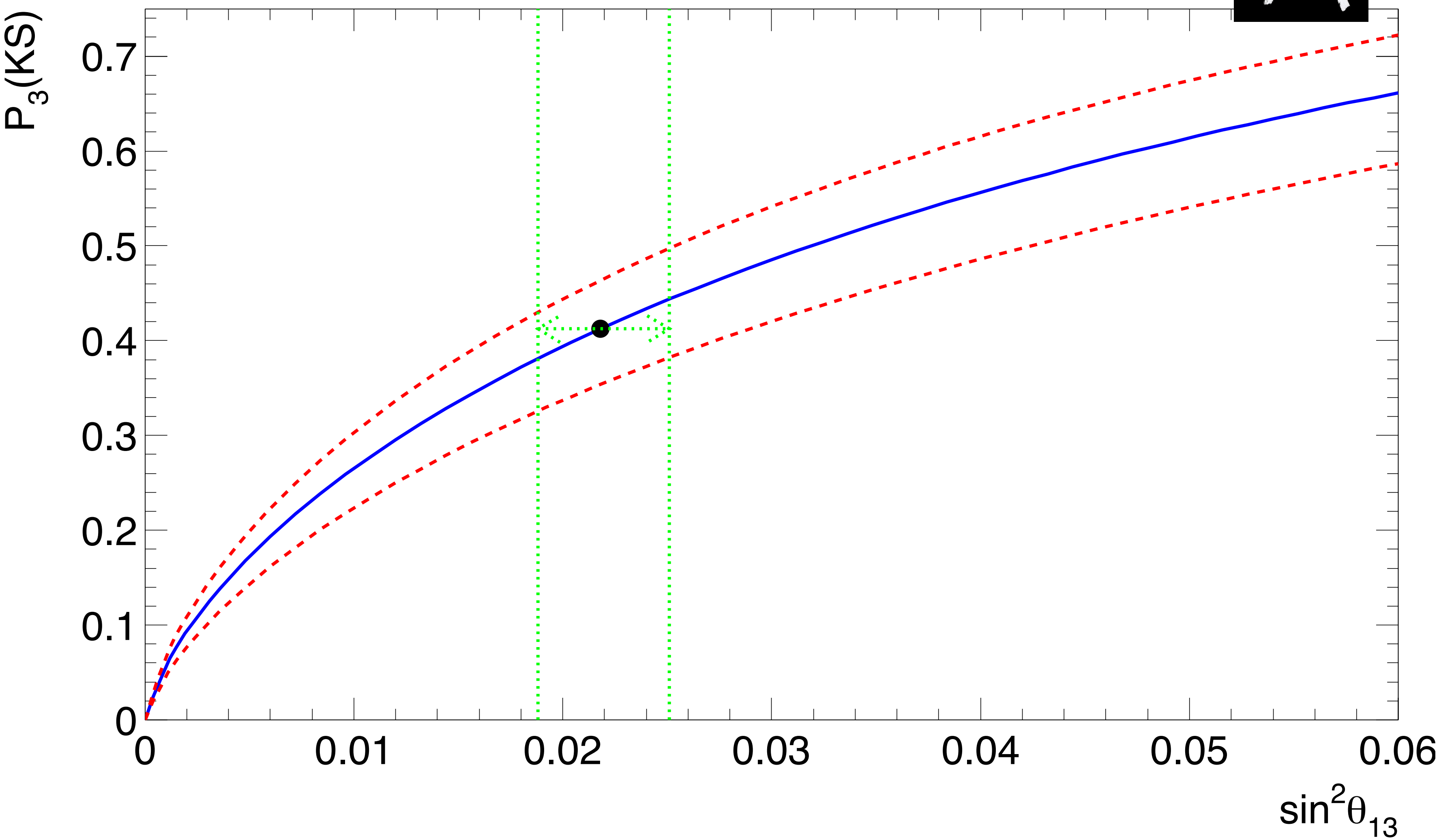


[Albright and Chen, hep-ph/0608137]

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

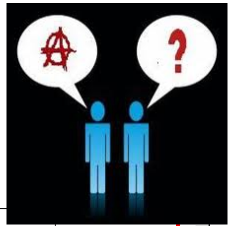
Neutrino Mixing Anarchy: Alive and Kicking!

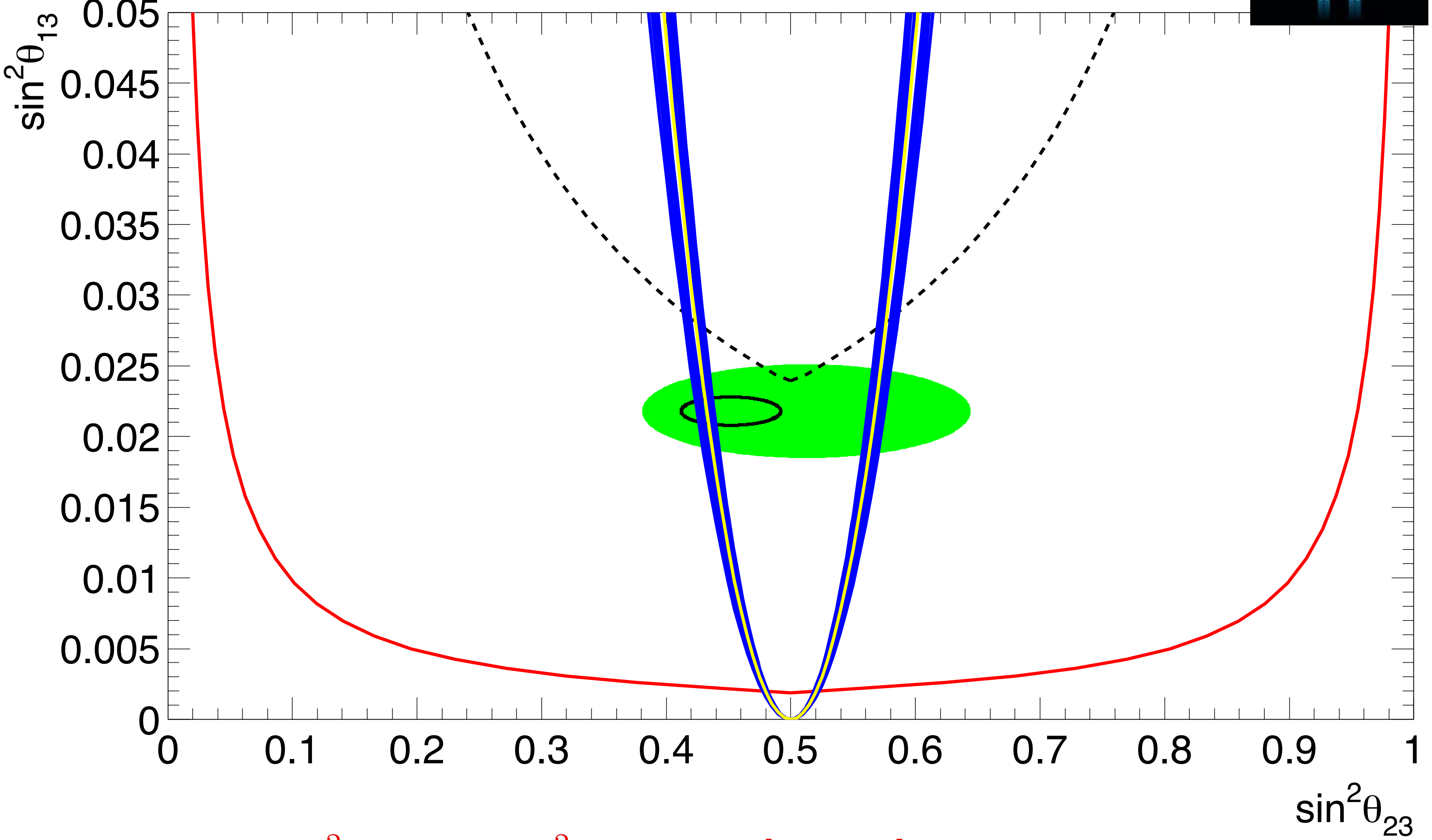
[Hall, Murayama, Weiner hep-ph/9911341]



[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.

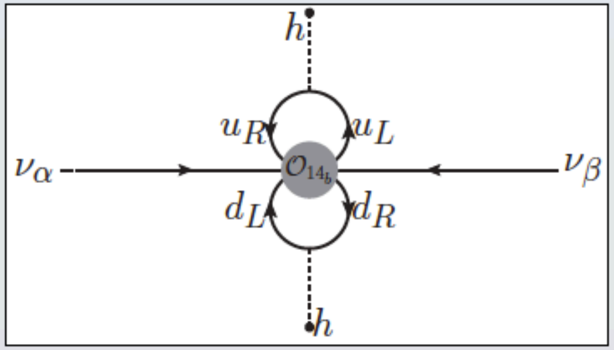
Approach: try out some UV completions. Concentrate on $\mathcal{O}_s$.

[AdG et al, arXiv:1907.02541]

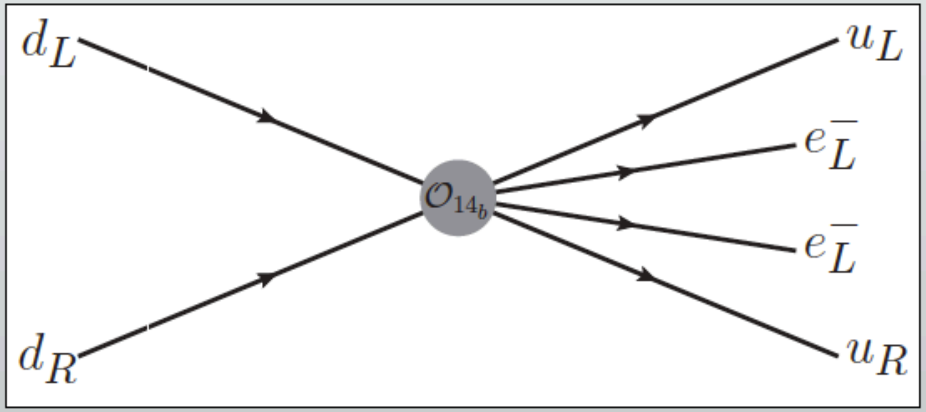
LNV from Effective Operators

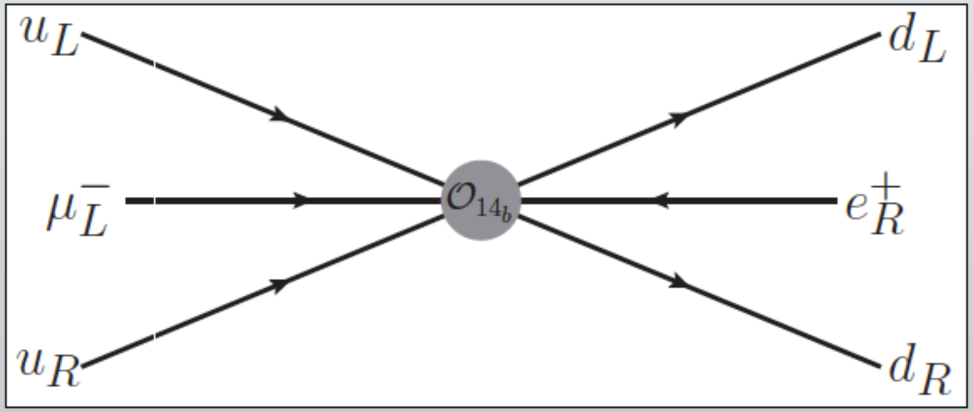
What do these operators do? Consider $\mathcal{O}_{14b}=(LQ)(LQ)u^c d^c$.

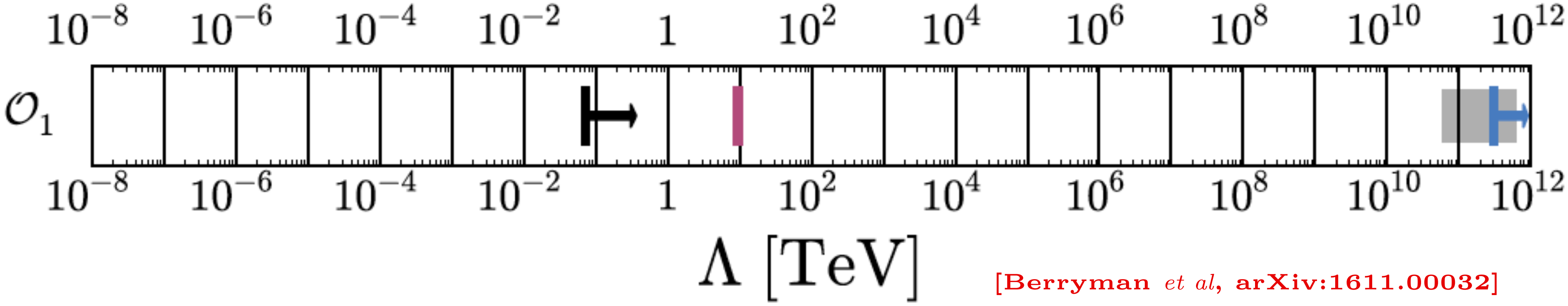
- They generate neutrino masses:



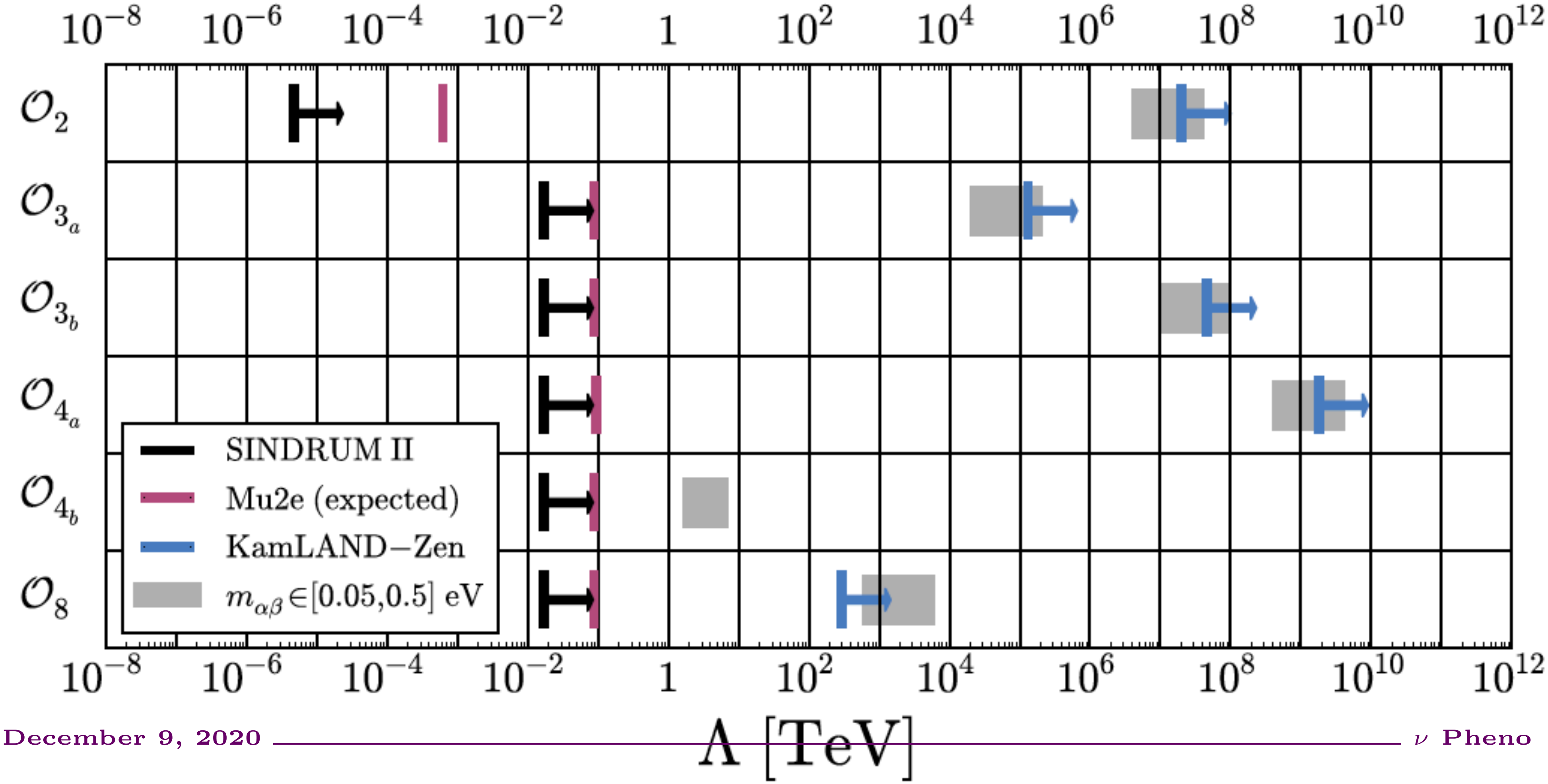
- They generate various LNV phenomena:

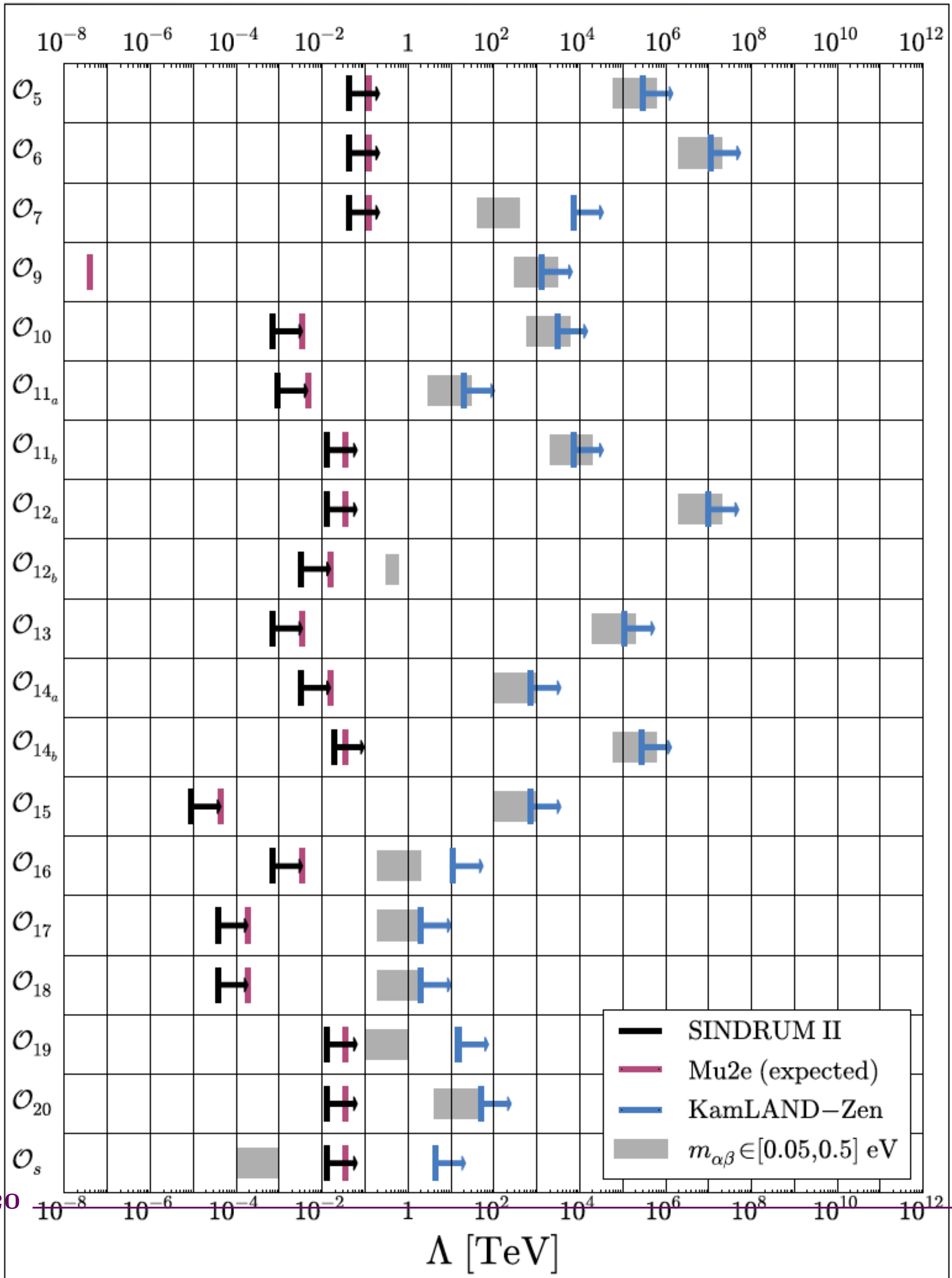






[Berryman *et al*, arXiv:1611.00032]




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

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).

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.

To be determined from data: λ and M.

The data can be summarized as follows: there is evidence for three neutrinos, mostly "active" (linear combinations of ν_e, ν_μ, and ν_τ). At least two of them are massive and, if there are other neutrinos, they have to be "sterile."

This provides very little information concerning the magnitude of M_i (assume $M_1 \sim M_2 \sim M_3$).

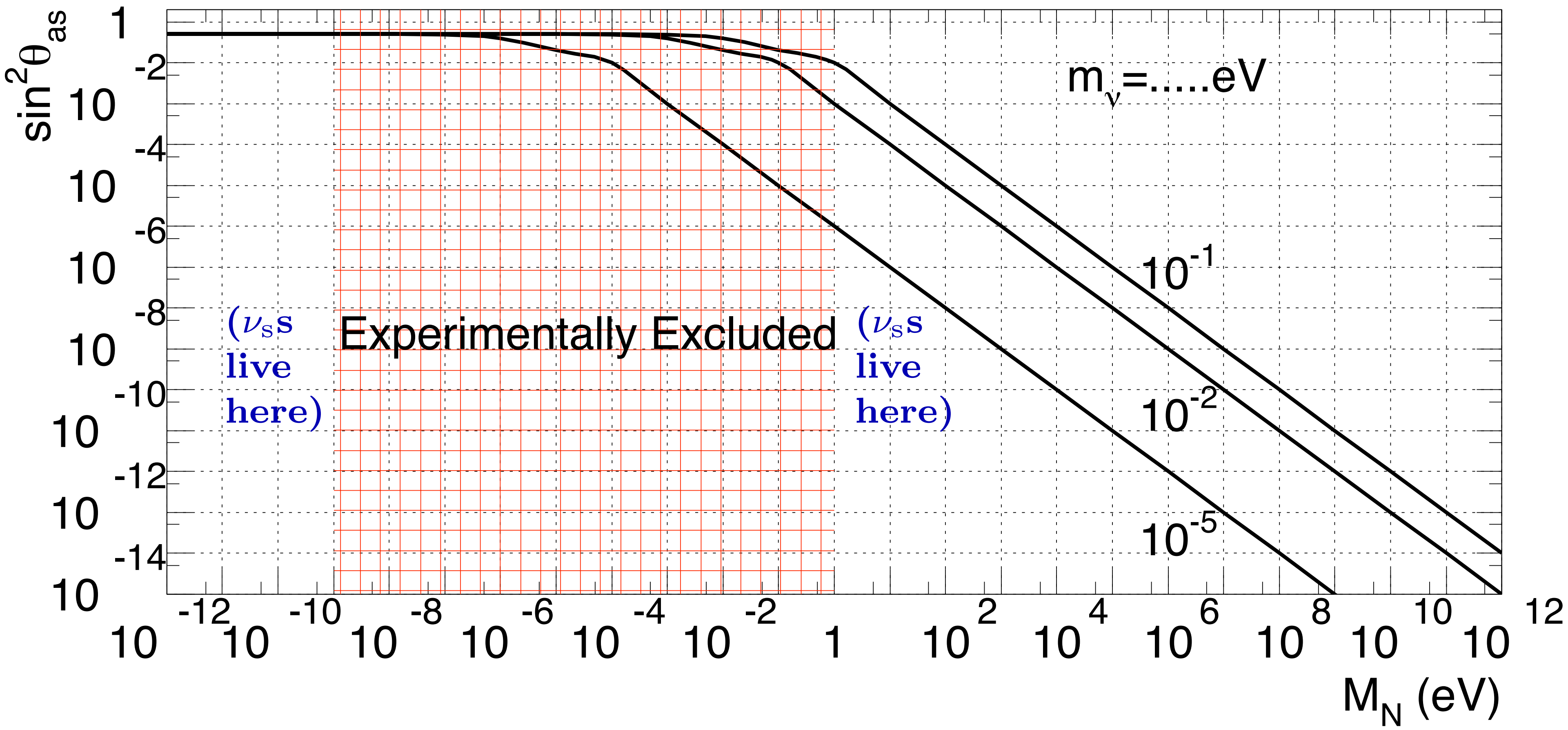
Theoretically, there is prejudice in favor of very large M: $M \gg v$. Popular examples include $M \sim M_{\rm GUT}$ (GUT scale), or $M \sim 1$ TeV (EWSB scale).

Furthermore, $\lambda \sim 1$ translates into $M \sim 10^{14}$ GeV, while thermal leptogenesis requires the lightest M_i to be around 10^{10} GeV.

we can impose very, very few experimental constraints on M

Constraining the Seesaw Lagrangian

[AdG, Huang, Jenkins, arXiv:0906.1611]



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