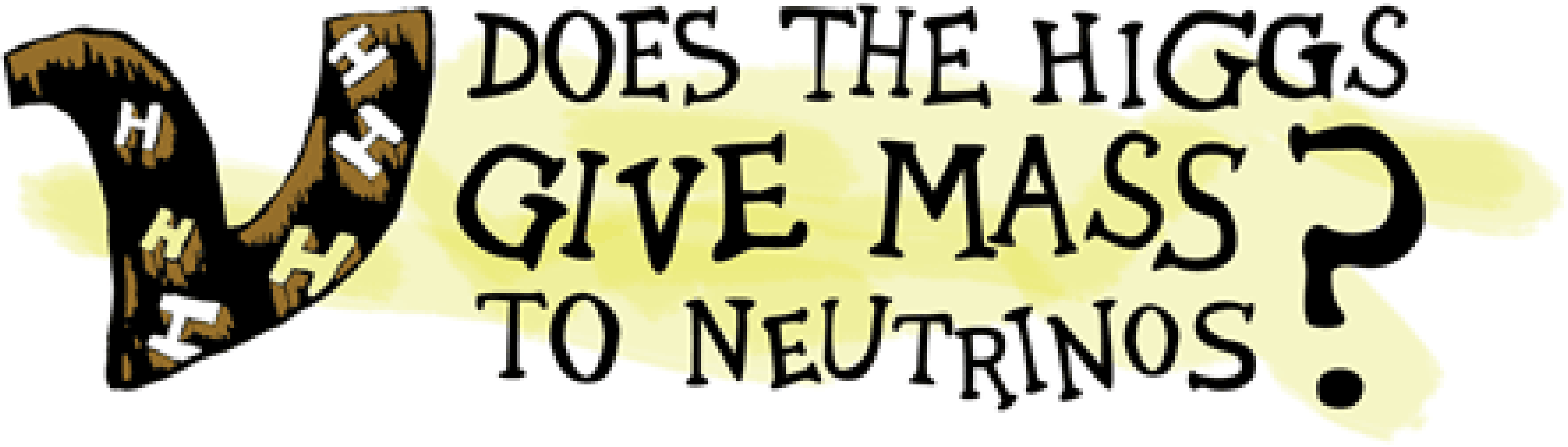
Higgs Decays to Neutrinos, Broadly Speaking



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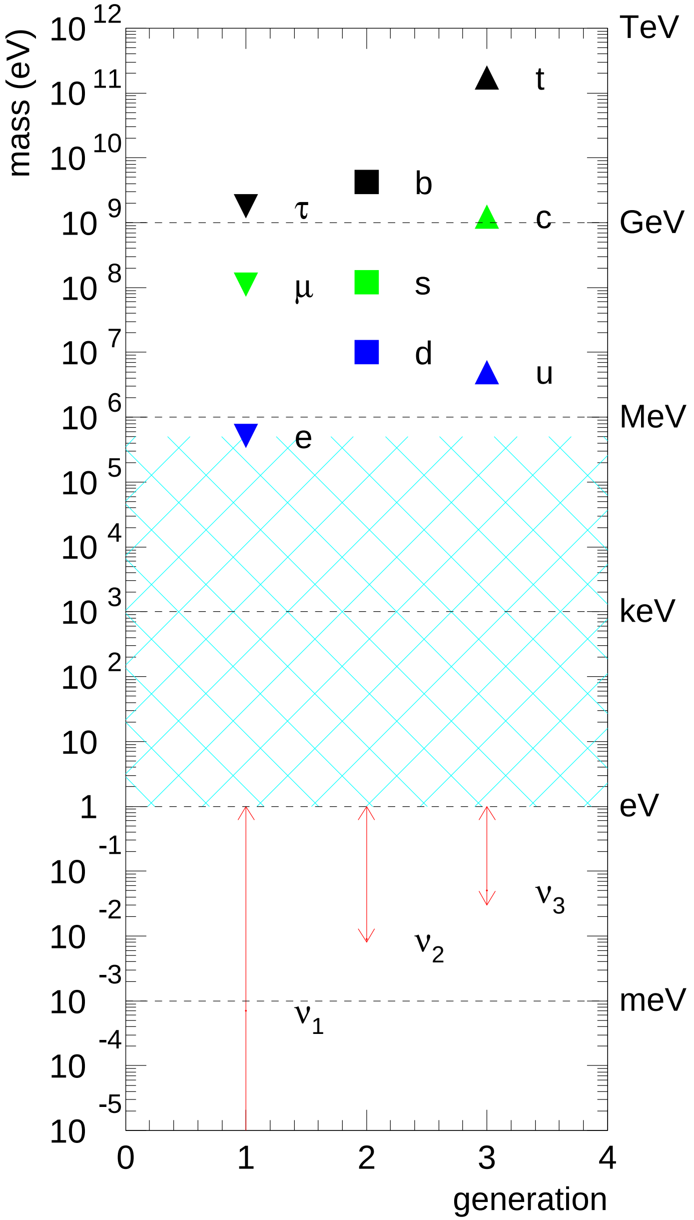
Fermilab, May 21–22, 2015

What We Are Trying To Understand:



⇐ **NEUTRINOS HAVE TINY MASSES**

⇓ **LEPTON MIXING IS “WEIRD”** ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Neutrino Masses, EWSB, and a New Mass Scale of Nature

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, *et al* may provide more information.

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.**

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[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

What We Know About M:

- $M = 0$: the six neutrinos “fuse” into three Dirac states. Neutrino mass matrix given by $\mu_{\alpha i} \equiv \lambda_{\alpha i} v$.

  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are 'tHooft natural.

- $M \gg \mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$ $[m \propto 1/\Lambda \;\Rightarrow\; \Lambda = M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

- $M \sim \mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

- $M \ll \mu$: neutrinos are quasi-Dirac fermions. Active–sterile mixing is maximal, but new oscillation lengths are very long (*cf.* 1 A.U.).

Why are Neutrino Masses Small in the $M \neq 0$ Case?

If $\mu \ll M$, 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,

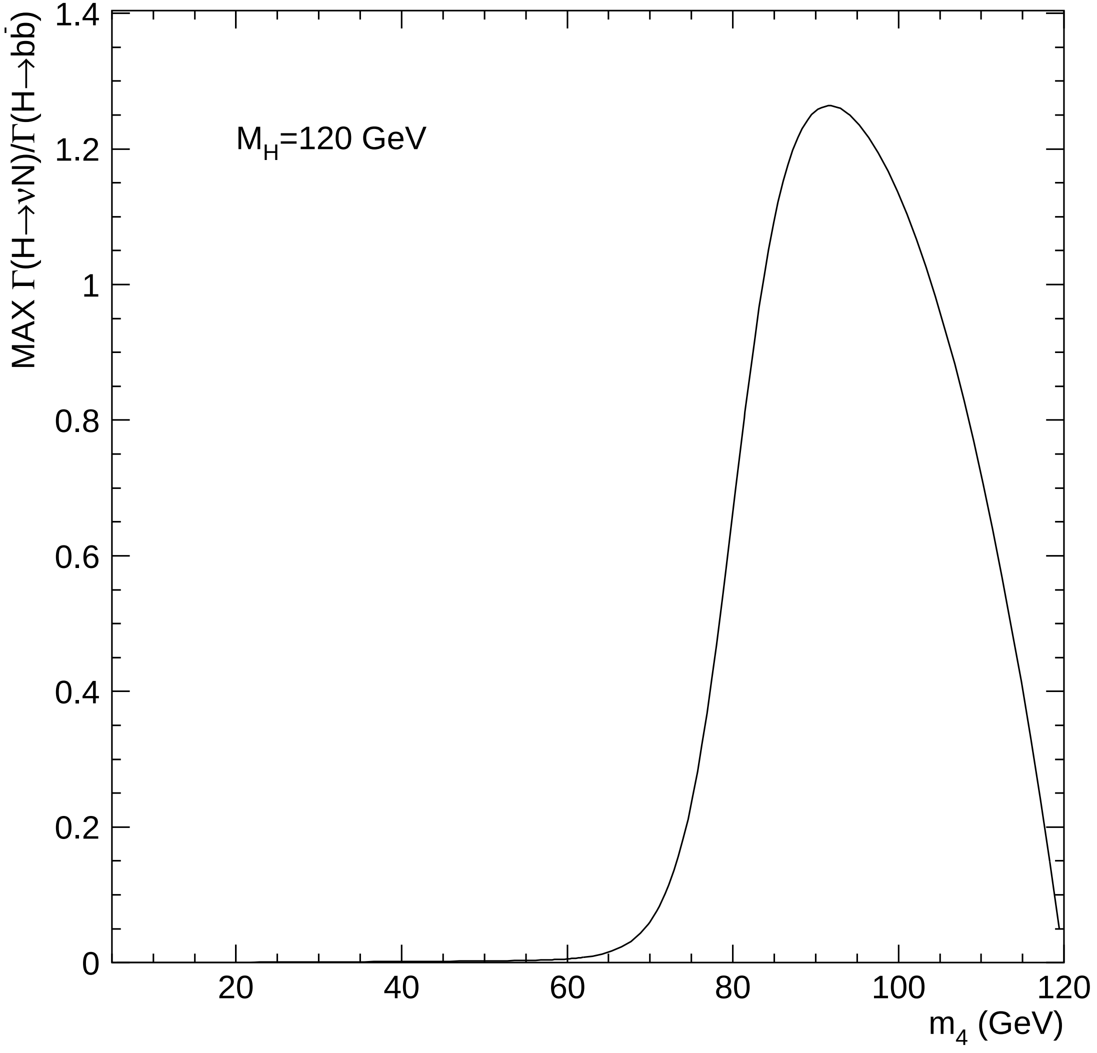
$$\Lambda \sim \frac{M}{\lambda^2},$$

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”).

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…

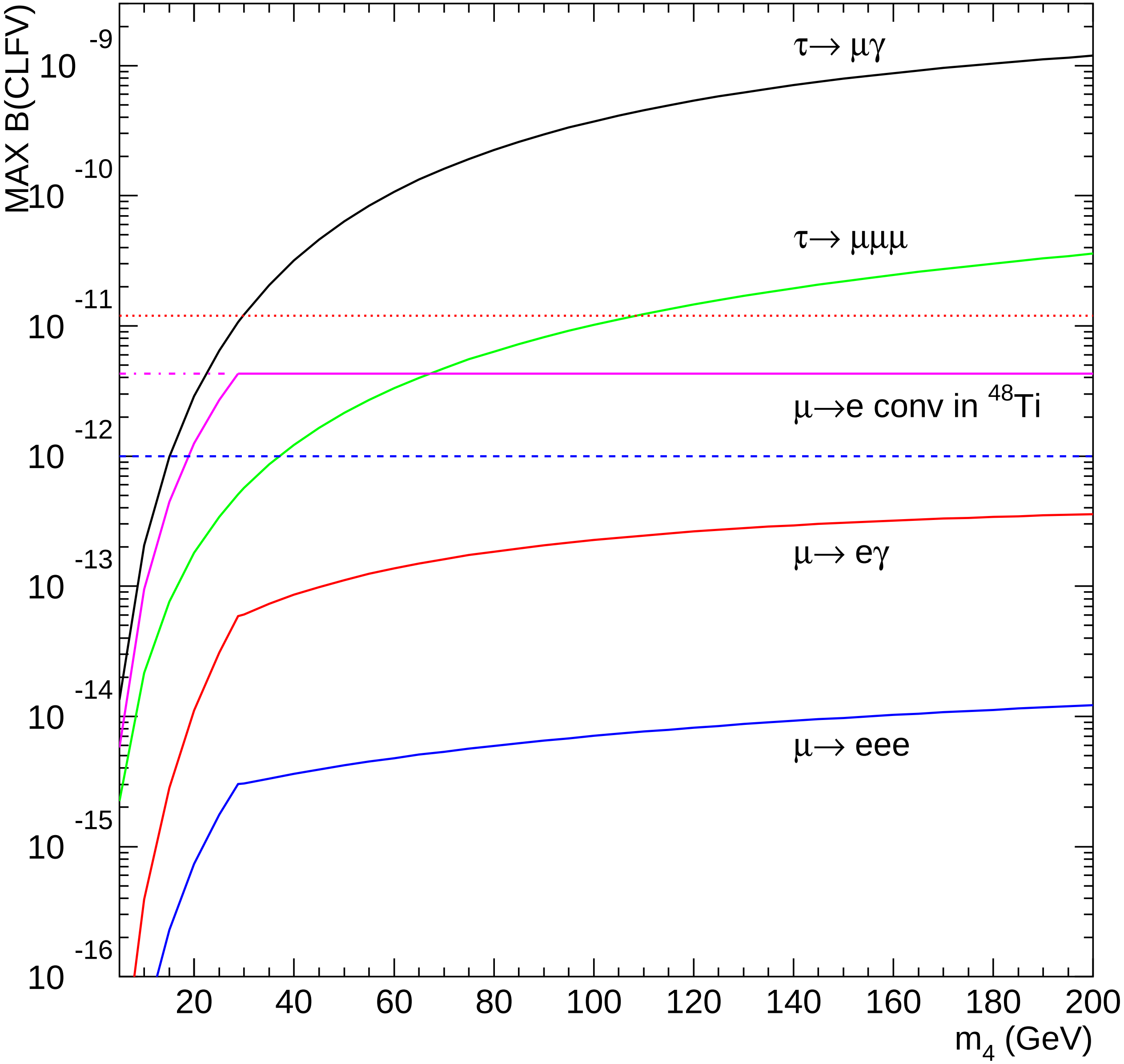
- $M_N \sim 1 - 100$ GeV,
- Yukawa couplings larger than naive expectations.

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

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

"Weird" Higgs decay signature! $\Big)$

e.g.: SeeSaw Mechanism [minus "Theoretical Prejudice"]



arXiv:0706.1732 [hep-ph]

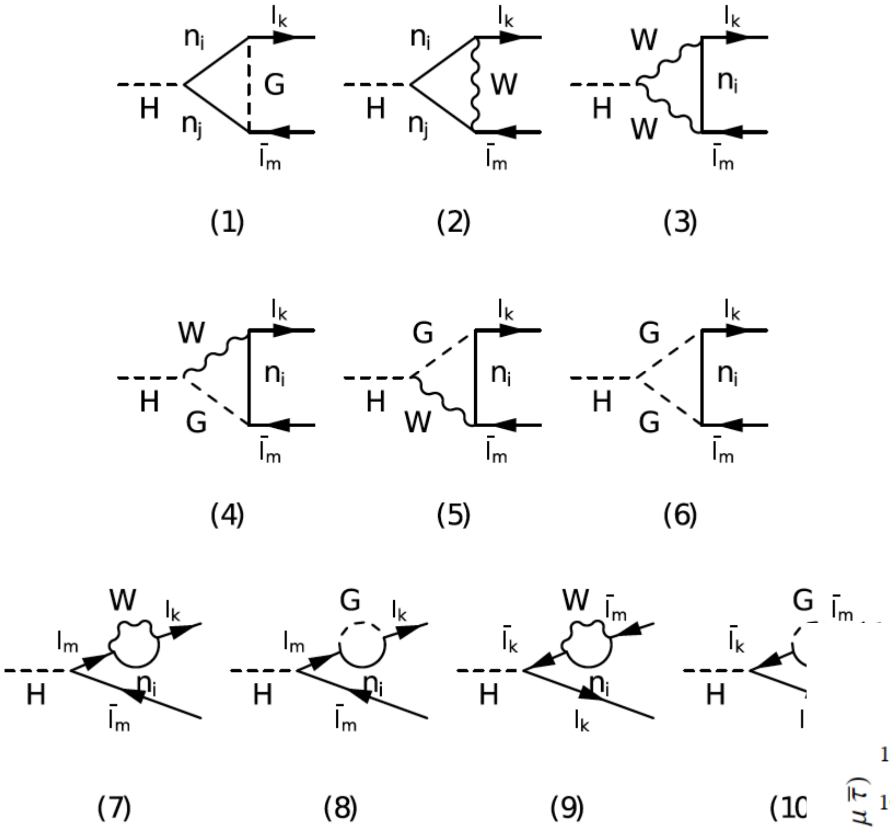


Figure 1: One-loop contributing diagrams to the LFV Higgs decays $H \to l_k \bar{l}_m$ in the massive neutrinos n_i $(i = 1, .., 9)$.

arXiv:1405.4300 [hep-ph]

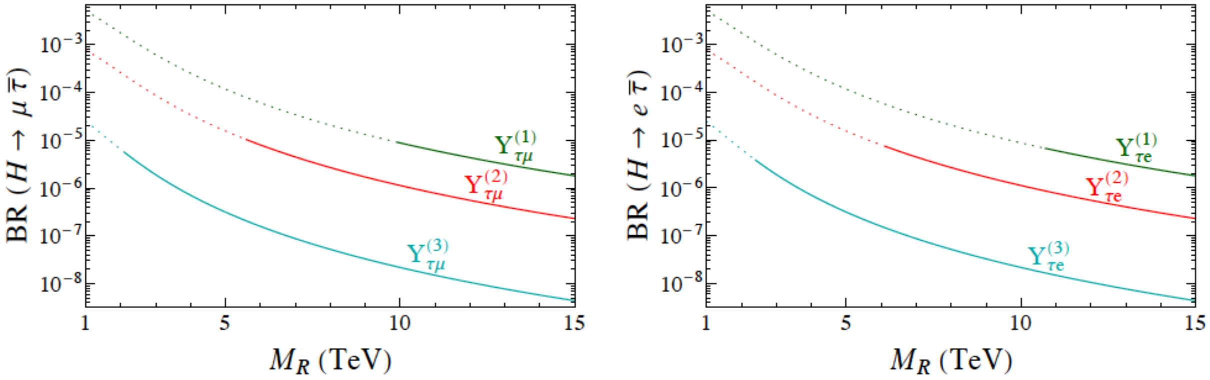
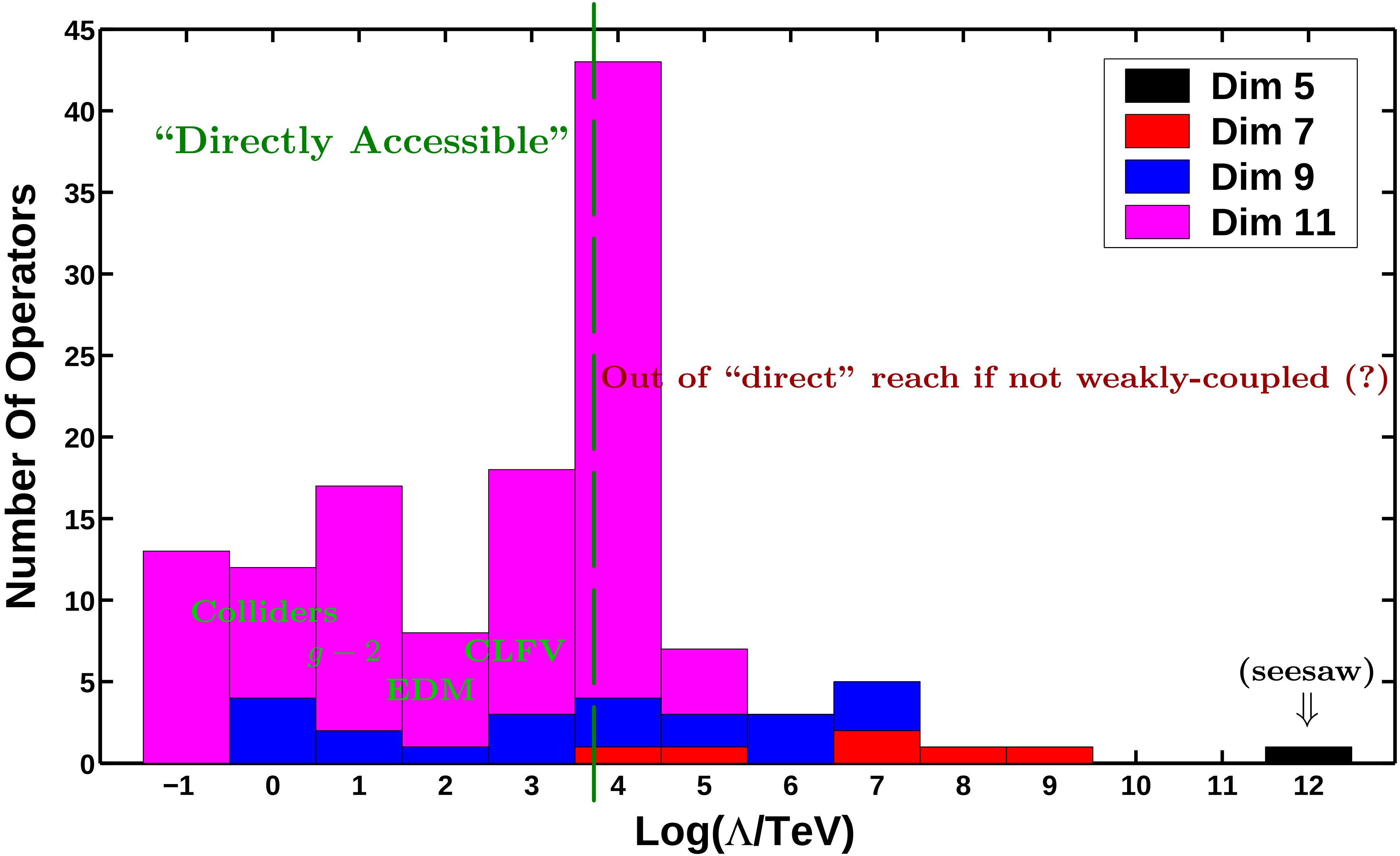
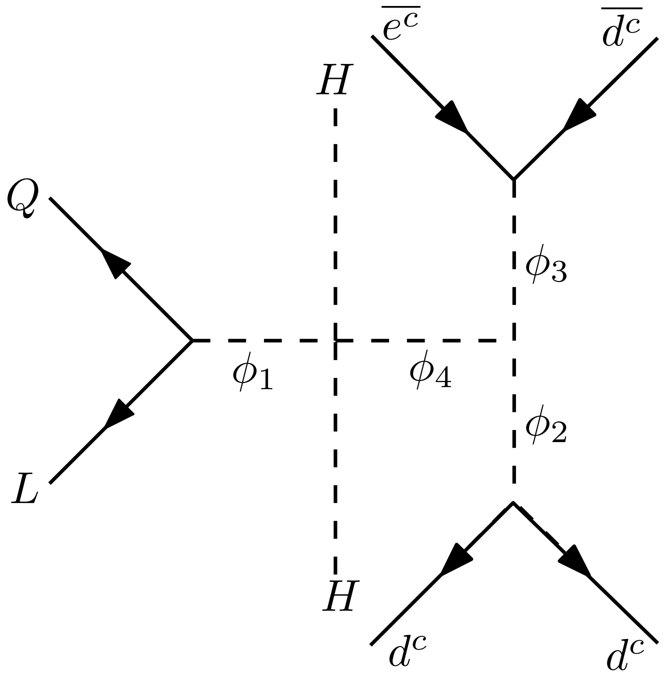


Figure 13: Examples in the ISS with large LFVHD rates obtained using the full one-loop formulas. Left panel: BR$(H \to \mu\bar{\tau})$ versus M_R for $Y^{(1)}_{\tau\mu}$ (upper green line), $Y^{(2)}_{\tau\mu}$ (middle red line) and $Y^{(3)}_{\tau\mu}$ (lower blue line) given in eq. (52). Dotted lines indicate disallowed input values leading to BR$(\tau \to \mu\gamma)$ above the present experimental bound in eq.(25). Right panel: BR$(H \to e\bar{\tau})$ versus M_R for $Y^{(1)}_{\tau e}$ (upper green line), $Y^{(2)}_{\tau e}$ (middle red line), and $Y^{(3)}_{\tau e}$ (lower blue line) given in eq. (53). Dotted lines indicate disallowed input values leading to BR$(\tau \to e\gamma)$ above the present experimental bound in eq. (24). Solid lines indicate predictions allowed by all the constraints.



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

[arXiv:0708.1344 [hep-ph]]



Order-One Coupled, Weak Scale Physics Can Also Explain Naturally Small Majorana Neutrino Masses:

Multi-loop neutrino masses from lepton number violating new physics.

$$-\mathcal{L}_{\nu\text{SM}} \supset \sum_{i=1}^{4} M_i\phi_i\bar{\phi}_i + iy_1QL\phi_1 + y_2d^cd^c\phi_2 + y_3e^cd^c\phi_3 + \lambda_{14}\bar{\phi}_1\phi_4HH + \lambda_{234}M\phi_2\bar{\phi}_3\phi_4 + h.c.$$

$m_\nu \propto (y_1y_2y_3\lambda_{234})\lambda_{14}/(16\pi)^4$ → neutrino masses at 4 loops, requires $M_i \sim 100$ GeV!

WARNING: For illustrative purposes only. Details still to be worked out. Scenario most likely ruled out by charged-lepton flavor-violation, LEP, Tevatron, and HERA.

Type-II Seesaw: SM plus $SU(2)$ Triplet Higgs, $Y_T = 1$

$$\mathcal{L} \in \frac{\lambda_{\alpha\beta}}{2} L^\alpha L^\beta T.$$

Neutrino Majorana masses if T develops a vev ...

$$m_{\alpha\beta} = \lambda_{\alpha\beta} v_T$$

There are three new Higgs bosons, with charges +2, +1 and 0. All decay violate lepton number. The neutral component can mix with the SM Higgs boson, and will mediate the decay

$$h \to \nu\nu$$

Of course, the other decays are subject of more intense searches at colliders – $h^+ + \to \ell^+\ell^+$, $h^+ \to \ell^+\nu$.

Key issue: are neutrino masses small because λ are small or because v_T is small (or both)? EWPD already push v_T below ~ 1 GeV...

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$\mu \to e\gamma$, $\mu \to e$-conversion at the loop-level. However, $\mu \to eee$ at the tree level (note direct connection to neutrino mass-matrix flavor structure)…

$$\frac{1}{\Lambda^2} = \frac{m_{ee} m_{\mu e}}{v_T^2 M_T^2}$$

Key issue: are neutrino masses small because λ are small or because v_T is small (or both)? EWPD already push v_T below ~ 1 GeV…

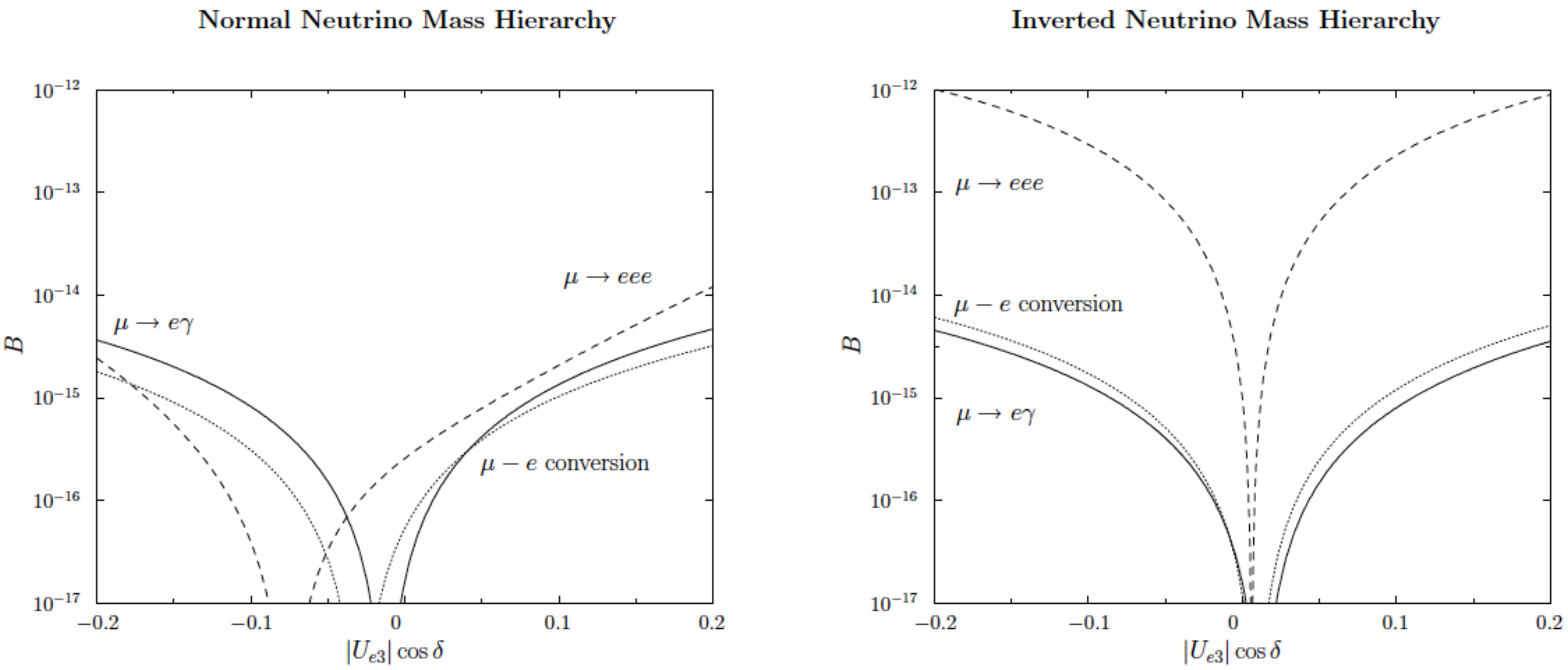

FIG. 1: The branching ratios B for $\mu \to e\gamma$ (solid line) and $\mu \to eee$ (dashed line), and the normalized capture rate B for $\mu \to e$-conversion in Ti (dotted line) as a function of $|U_{e3}| \cos\delta$ in a scenario where neutrino masses arise as a consequence of the presence of a triplet Higgs field with a small vacuum expectation value. The lightest neutrino mass is assumed to be negligible while the neutrino mass hierarchy is assumed to be normal (left-hand side) and inverted (right-hand side). See [1] for details.

Kakizaki, Ogura, Shima, PLB566, 210 (2003)