# Neutrino mass generation: connections with other aspects of particle physics

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# 1. Introduction

The discovery of neutrino masses is the discovery of New Physics (NP).

But exactly what that physics is remains unknown.

Pure type-I seesaw model: NP at an inaccessibly high scale.

Great feature: connection with baryogenesis via leptogenesis.
That doesn't improve the discovery prospects, unfortunately.
I know there are other games one can play, e.g. seesaw = PQ!

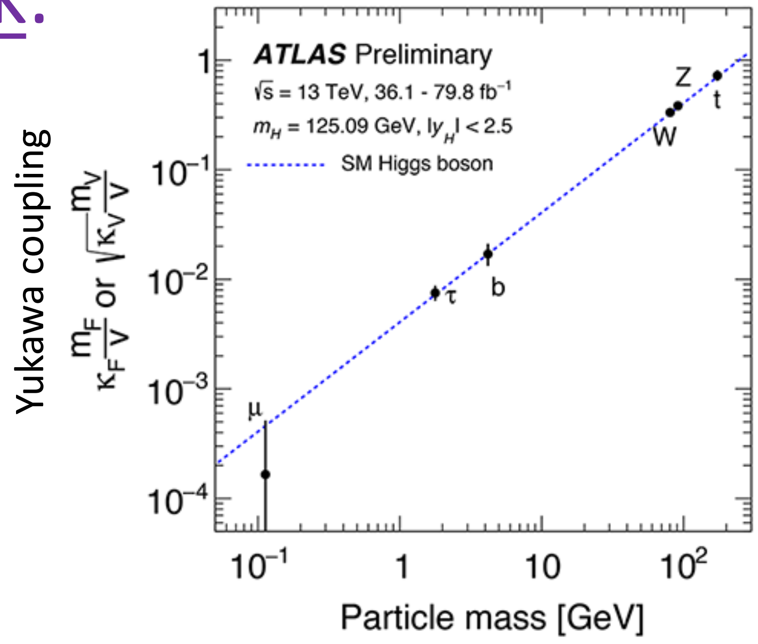
For some scenarios, connections with discoverable NP could signpost us to the origin of neutrino masses.

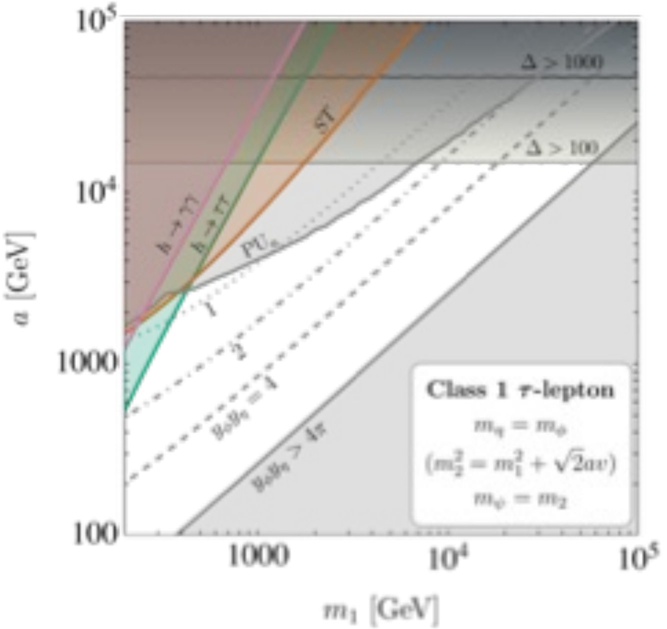
A driver of neutrino mass model building: the tiny $m_\nu$.

Two common approaches: (i) high seesaw scale
(ii) loop-level, radiative models

# 2. Radiative models: connections with flavour and collider physics

Side remark:




Despite the leftmost plot, not yet proven that even the b and τ masses must have SM origin.

Radiative origin also works!

Baker, Cox, RV 2021a, 2021b

# Systematic model-building and classification procedure (Majorana case)

$\Delta L = 2$ effective operator → open it up aka UV complete → neutrino self-energy and mass

They occur at mass dimension 5, 7, 9, 11, …

Babu, Leung 2001; de Gouvêa, Jenkins 2008; Melbourne group (many papers);
Valencia group: Hirsch, Cepedello+ (many papers)

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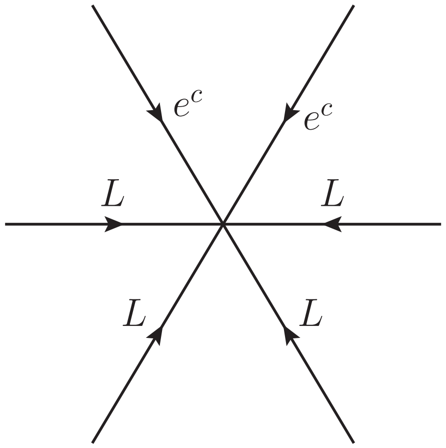
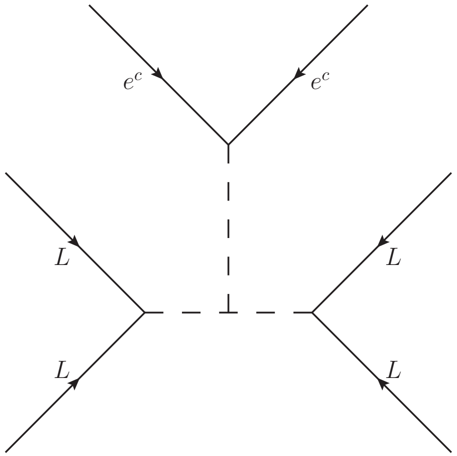
# Historic example: Zee-Babu model




$$O_9 = LLLe^cLe^c$$

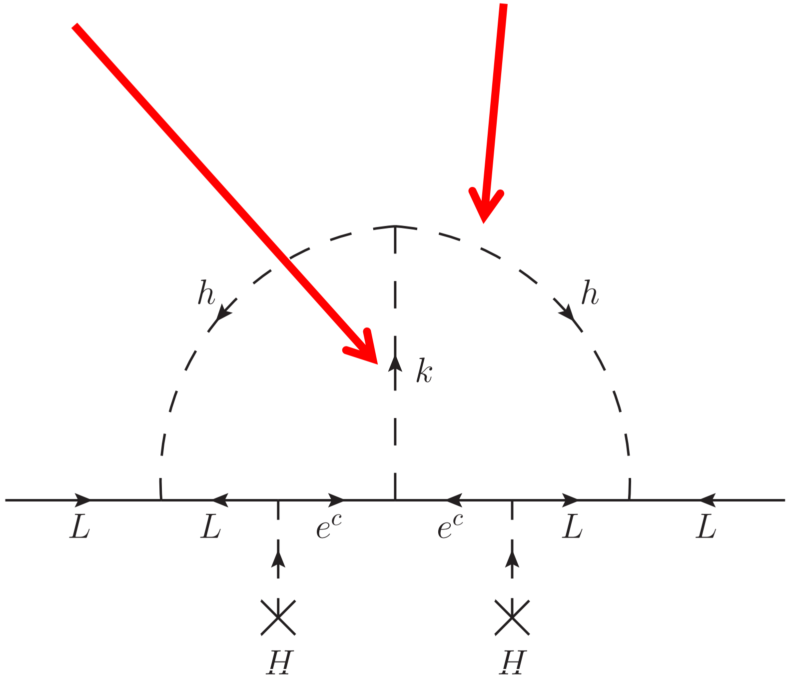
Effective op




Opening it up

Doubly-charged scalar k

Singly-charged scalar h




2-loop ν mass diagram

The exotics k and h can be searched for at the LHC.

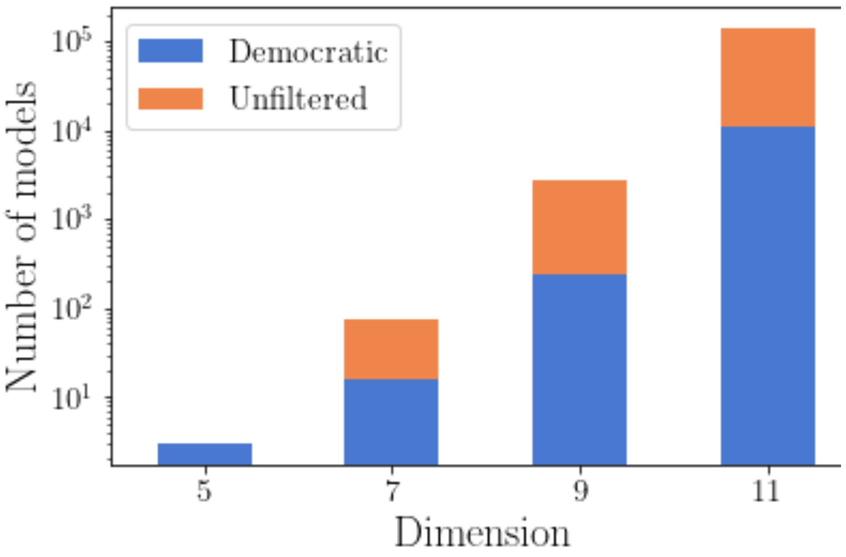
The following discussion is based on J. Gargalionis and RV, JHEP 01, 074 (2021)
"Exploding operators for Majorana neutrino masses and beyond"

J. Gargalionis (2020), "neutrinomass" at https://github.com/johngarg/neutrinomass
Full database at https://doi.org/10.5281/zenodo.4054618

Assumptions: exotics are scalars, vector-like or Majorana fermions only, up to dim=11.

How many models?

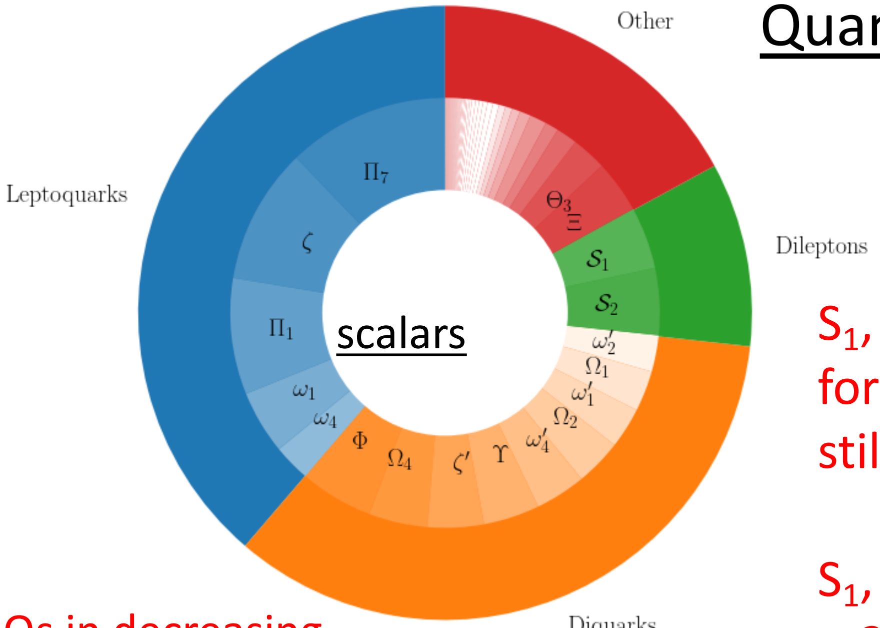
11,216 genuine models!





Most models have 5 exotics

# Quantum numbers of the exotic species




| Name | $N$ | $E$ | $\Delta_1$ | $\Delta_3$ | $\Sigma$ | $\Sigma_1$ | |
|---|---|---|---|---|---|---|---|
| Irrep | $(\mathbf{1},\mathbf{1},0)$ | $(\mathbf{1},\mathbf{1},1)$ | $(\mathbf{1},\mathbf{2},\frac{1}{2})$ | $(\mathbf{1},\mathbf{2},\frac{3}{2})$ | $(\mathbf{1},\mathbf{3},0)$ | $(\mathbf{1},\mathbf{3},1)$ | |
| Name | $U$ | $D$ | $Q_1$ | $Q_5$ | $Q_7$ | $T_1$ | $T_2$ |
| Irrep | $(\mathbf{3},\mathbf{1},\frac{2}{3})$, | $(\bar{\mathbf{3}},\mathbf{1},\frac{1}{3})$ | $(\mathbf{3},\mathbf{2},\frac{1}{6})$ | $(\mathbf{3},\mathbf{2},-\frac{5}{6})$ | $(\mathbf{3},\mathbf{2},\frac{7}{6})$ | $(\bar{\mathbf{3}},\mathbf{3},\frac{1}{3})$ | $(\mathbf{3},\mathbf{3},\frac{2}{3})$ |

$S_1$, $S_3$, $R_2$ (were?) of great interest for B-meson anomalies. $R_{D(*)}$ anomaly still alive …

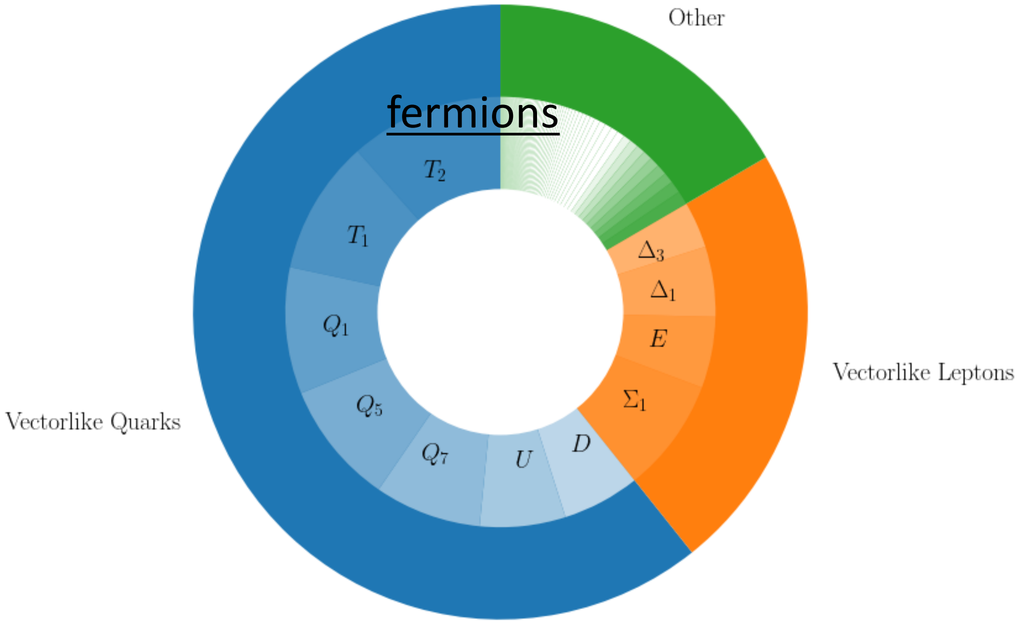
$S_1$, $R_2$ of great interest for g-2 of muon and electron.

LQs in decreasing order of frequency

$$\Pi_7 = R_2 \sim (3,2,\tfrac{7}{6})$$
$$\zeta = S_3 \sim (\bar{3},3,\tfrac{1}{3})$$
$$\Pi_1 = \tilde{R}_2 \sim (3,2,\tfrac{1}{6})$$
$$\omega_1 = S_1 \sim (\bar{3},1,\tfrac{1}{3})$$
$$\omega_4 = \tilde{S}_1 \sim (\bar{3},1,\tfrac{4}{3})$$

| Symbol | $(SU(3)_c, SU(2)_L, U(1)_Y)$ | Interactions | $F = 3B + L$ |
|---|---|---|---|
| $S_3$ | $(\bar{\mathbf{3}},\mathbf{3},1/3)$ | $\overline{Q}^C L$ | $-2$ |
| $R_2$ | $(\mathbf{3},\mathbf{2},7/6)$ | $\overline{u}_R L$, $\overline{Q} e_R$ | $0$ |
| $\widetilde{R}_2$ | $(\mathbf{3},\mathbf{2},1/6)$ | $\overline{d}_R L$ | $0$ |
| $\widetilde{S}_1$ | $(\bar{\mathbf{3}},\mathbf{1},4/3)$ | $\overline{d}_R^C e_R$ | $-2$ |
| $S_1$ | $(\bar{\mathbf{3}},\mathbf{1},1/3)$ | $\overline{Q}^C L$, $\overline{u}_R^C e_R$ | $-2$ |

Table from Doršner+ 2020



## Economical and testable models: less than 4 exotic multiplets and $\Lambda$ < 100 TeV

| Field content | Operators | $\Lambda$ [TeV] | Dominant? |
|---|---|---|---|
| $(3,2,\frac{1}{6})_S, (3,2,\frac{7}{6})_F$ | $8, D15$ | 15 | Y |
| $(1,2,\frac{1}{2})_F, (1,1,1)_S, (1,2,\frac{3}{2})_S$ | $62b$ | 16 | N |
| $(\bar{3},2,\frac{5}{6})_S, (3,2,\frac{1}{6})_F, (3,2,\frac{1}{6})_S$ | $8'$ | 1 | N |
| $(\bar{3},1,\frac{1}{3})_S, (\bar{6},2,\frac{1}{6})_S, (3,2,\frac{1}{6})_F$ | $24f$ | 89 | N |
| $(\bar{3},3,\frac{1}{3})_F, (\bar{6},2,\frac{1}{6})_S, (3,2,\frac{1}{6})_S$ | $24d$ | 89 | N |
| $(\bar{3},2,\frac{5}{6})_S, (1,2,\frac{3}{2})_F, (3,2,\frac{1}{6})_S$ | $8'$ | 1 | N |
| $(\bar{3},3,\frac{1}{3})_F, (\bar{6},4,\frac{1}{6})_S, (3,2,\frac{1}{6})_S$ | $24f$ | 89 | N |
| $(\bar{3},1,\frac{1}{3})_F, (\bar{6},2,\frac{1}{6})_S, (3,2,\frac{1}{6})_S$ | $24d$ | 89 | N |
| $(\bar{6},2,\frac{7}{6})_F, (8,2,\frac{1}{2})_S, (3,2,\frac{1}{6})_S$ | 20 | 0.8 | Y |
| $(6,1,\frac{4}{3})_S, (6,1,\frac{1}{3})_F, (3,2,\frac{1}{6})_S$ | 20 | 0.8 | Y |
| $(6,2,\frac{5}{6})_S, (3,2,\frac{1}{6})_F, (3,2,\frac{1}{6})_S$ | $50a, b$ | 10 | Y |
| $(\bar{6},2,\frac{1}{6})_S, (\bar{3},2,\frac{5}{6})_F, (3,2,\frac{1}{6})_S$ | $50a, b$ | 10 | Y |

The only previously known model.

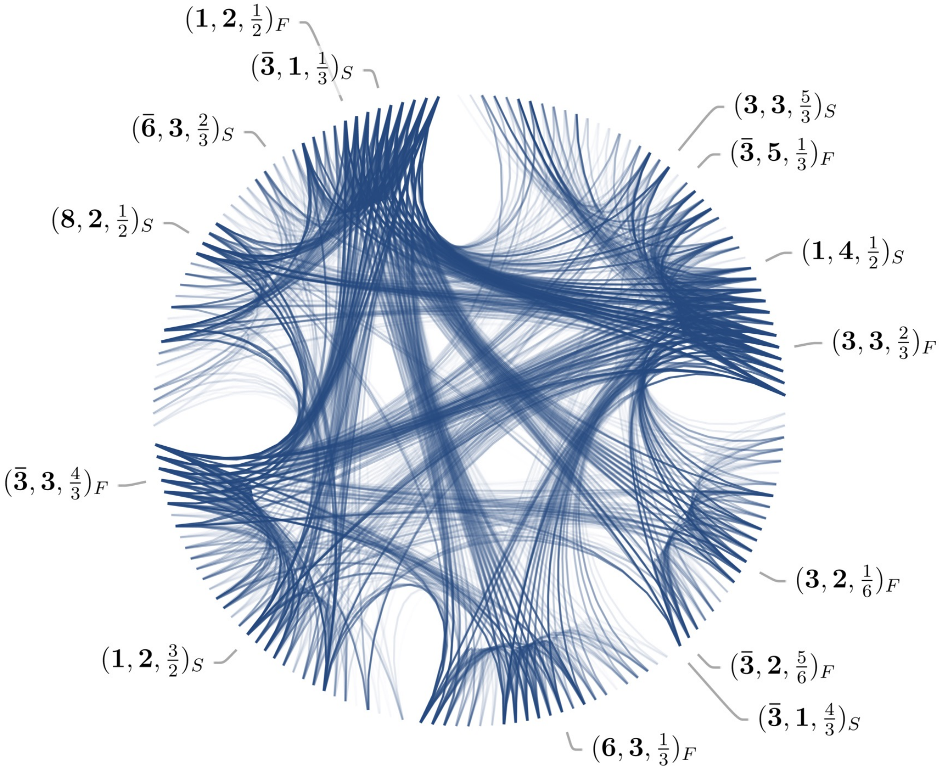
Y. Cai+ 2015
Klein, Lindner, Ohmer 2019

Dominant contribution is from loop-level exotic-only completion of Weinberg operator.

The Y models have upper bounds on New Physics scale in the range 0.8-15 TeV.

Note: Sextets can be replaced by anti-triplets.

# Which exotics often occur together?




Each point on circumference is an exotic field.
Lines between points indicate those fields occur together.
The darker the colour, the more often a pairing occurs.

| Rank | Edge |
|---|---|
| 1 | $(3, 3, \frac{2}{3})_F, (3, 4, \frac{1}{6})_S$ |
| 2 | $(3, 2, \frac{1}{6})_S, (3, 2, \frac{1}{6})_F$ |
| 3 | $(3, 3, \frac{2}{3})_S, (3, 2, \frac{7}{6})_S$ |
| 4 | $(3, 2, \frac{7}{6})_F, (3, 2, \frac{1}{6})_S$ |
| 5 | $(3, 3, \frac{2}{3})_F, (3, 4, \frac{7}{6})_F$ |
| 6 | $(\bar{3}, 3, \frac{1}{3})_S, (3, 4, \frac{1}{6})_S$ |
| 7 | $(3, 2, \frac{1}{6})_F, (3, 3, \frac{2}{3})_S$ |
| 8 | $(\bar{3}, 3, \frac{4}{3})_F, (\bar{3}, 2, \frac{5}{6})_F$ |
| 9 | $(3, 2, \frac{1}{6})_S, (3, 3, \frac{2}{3})_S$ |
| 10 | $(3, 2, \frac{7}{6})_S, (\bar{3}, 2, \frac{5}{6})_F$ |

The ten most common pairings.

# 3. Seesaw scale = Peccei-Quinn scale

Solution of strong-CP problem by PQ mechanism => axion DM for PQ scale of $10^{10} – 10^{11}$ GeV.

Seesaw formula $M = \lambda^2 \frac{v^2}{m_\nu} \sim \lambda^2\ 10^{14}\ \text{GeV}$ gives M ~ $10^{10\text{-}11}$ GeV for $\lambda \sim 10^{-2,\,-1.5}$

(like $m_b/v$ and $m_\tau/v$).

Modify type-1 seesaw model through $\mathcal{L} \supset h\, \overline{(\nu_R)^c}\, \nu_R\, S_{\text{PQ}} + h.c.$ with M ~ h <$S_{PQ}$>.

And leptogenesis, of course.

Langacker, Peccei, Yanagida (1986)
Shin (1987)
Fukugita, Yanagida (1986)

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And old idea, but a bit neglected. Recent developments: SMASH model (KSVZ extension)

Salvio (2015, 2019)
Ballesteros, Redondo, Ringwald, Tamarit (2017a, 2017b, 2019)

Explain: strong-CP, neutrino masses, baryogenesis, dark matter.
VISHν and SMASH added inflationary cosmology via non-minimal coupling to gravity.

VISHν model (DFSZ extension/variant)

Sopov, RV (2022)
Sopov, Tamarit, RV (work in progress)
building on RV, Davies, Joshi (1988) & Clarke, RV (2016)

What would be evidence for VISHν model?

- Axion dark matter.
- Two Higgs doublets.
- Flavour-changing Higgs processes (to solve domain wall problem).
- Continued excellent agreement with inflationary observables.
- Lack of evidence for alternative $m_\nu$ and baryogenesis mechanisms!

# 4. To take home

- We know neutrinos have tiny masses, but not what Lagrangian[1] to write in the textbooks.
- Whatever it is, it is New Physics.
- Radiative models have much new physics; connections with B-meson and g-2 anomalies.
- Type-1 seesaw scale could also be Peccei-Quinn scale; multiple connections.

[1] I really really want to know this.
I really really want to know what dark matter is too.

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# Back up slides

# High-scale seesaw models

Interesting, well-known fact: lowest non-renormalisable SM effective operator is the Weinberg operator

L = LH lepton doublet
H = Higgs doublet
λ = dimensionless coupling
M = new ΔL=2 physics scale

$$\frac{\lambda}{M} LLHH$$

⇒ Majorana neutrinos

$$m_\nu \sim \lambda \frac{v^2}{M}$$

seesaw formula

$$m_\nu \ll v \quad \text{when} \quad M \gg v$$

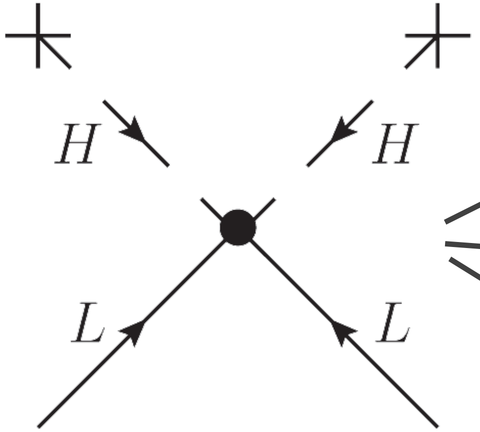
i.e. seesaw effect when L-violation scale very high

$$m_\nu \sim 0.1\ \text{eV}, \quad v \sim 10^2\ \text{GeV} \implies M \sim 10^{14}\ \text{GeV}$$

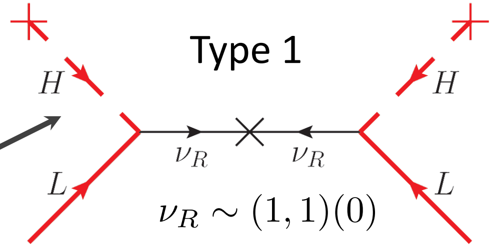
In its pure form, the seesaw scale is very high.
Testability is very low.

# Type-1,2,3 seesaw models:

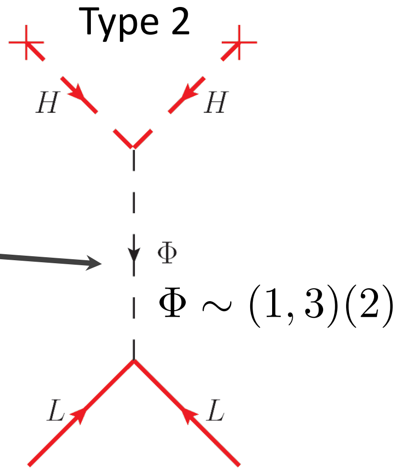
"Open up" LLHH in all minimal, tree-level ways.



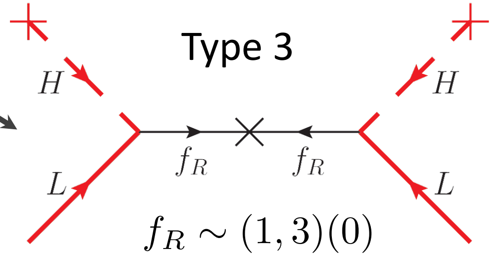

Advantage of effective operator approach to constructing models is that you don't miss any.




Minkowski 1977
Yanagida 1979
Gell-Mann, Ramond, Slansky 1979
Mohapatra, Senjanovic 1980




Magg, Wetterich 1980
Schechter, Valle 1980
Cheng, Li 1980
Lazarides, Shafi, Wetterich 1981
Wetterich 1981
Mohapatra, Senjanovic 1981




Foot, Lew, He, Joshi 1989

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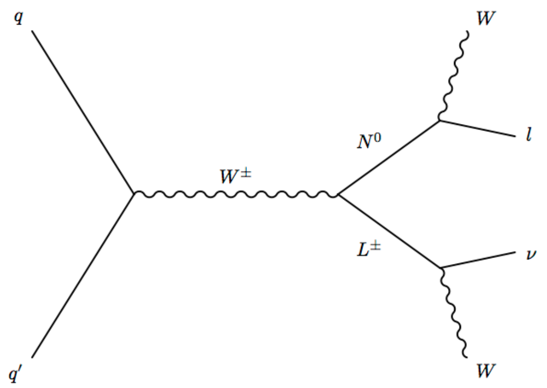
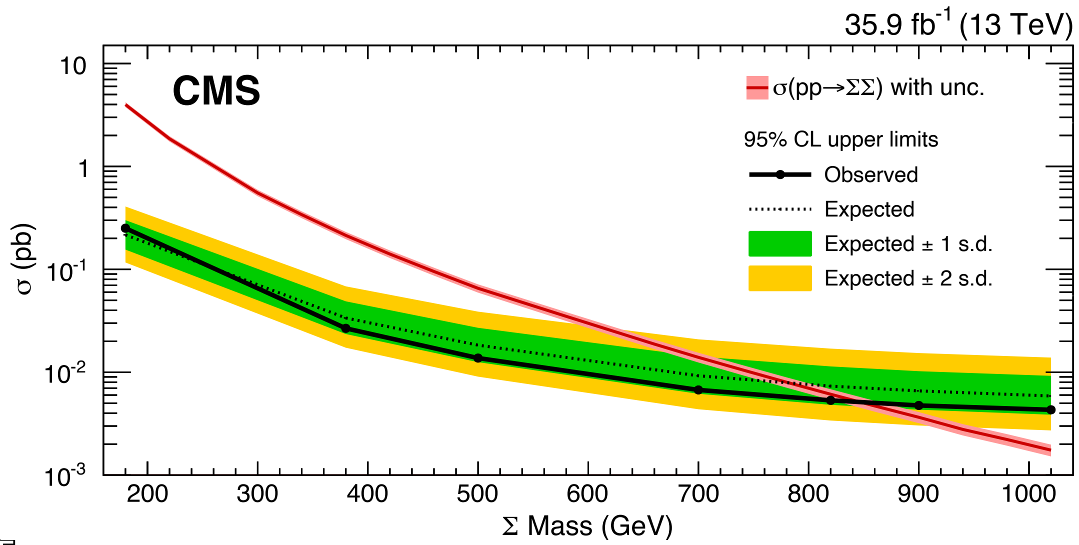
# Example of search and bound: type 3 seesaw.

$f_R \sim (1,3)(0) = (L^+, N^0, L^-)$

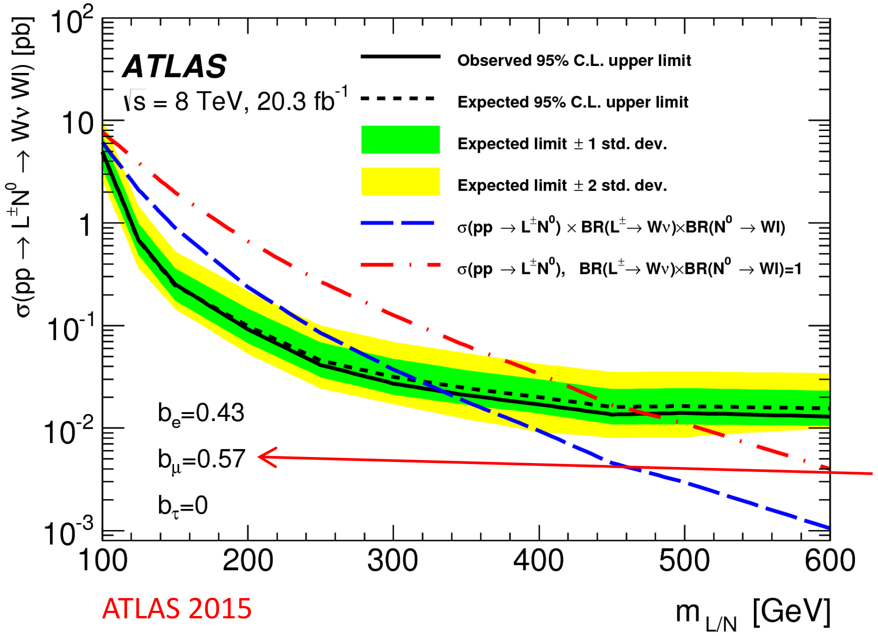
Heavy lepton EW pair production.




CMS 2017

Flavour democratic BR choice




Benchmark BR

ATLAS 2015

## There are many operators up to mass dimension 11 …


Babu, Leung 2001
de Gouvêa, Jenkins 2008
Angel, Rodd, RV 2013
Angel, Cai, Rodd, Schmidt, RV 2013
Cai, Clarke, Schmidt, RV 2015
Bigaran, Gargalionis, RV 2019
Gargalionis, Popa-Mateiu, RV 2020
Gargalionis, RV 2021


| Labels | Operator | Models | Filtered | Loops | Λ [TeV] |
|---|---|---|---|---|---|
| 1 | $L^iL^jH^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 3 | 3 | 0 | $6 \cdot 10^{11}$ |
| 2 | $L^iL^jL^k\bar{e}H^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 8 | 2 | 1 | $4 \cdot 10^7$ |
| 3a | $L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 9 | 2 | 2 | $2 \cdot 10^5$ |
| 3b | $L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 14 | 5 | 1 | $9 \cdot 10^7$ |
| 4a | $L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 5 | 0 | 1 | $4 \cdot 10^9$ |
| 4b | $L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 4 | 2 | 2 | $10 \cdot 10^6$ |
| 5a | $L^iL^jQ^k\bar{d}H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$ | 790 | 36 | 2 | $6 \cdot 10^5$ |
| 5b | $\mathcal{O}_1 \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$ | 492 | 14 | 1,2 | $6 \cdot 10^5$ |
| 5c | $\mathcal{O}_{3a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 509 | 0 | 2,3 | $1 \cdot 10^3$ |
| 5d | $\mathcal{O}_{3b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 799 | 16 | 1,2 | $6 \cdot 10^5$ |
| 6a | $L^iL^j\tilde{Q}^k\bar{u}^\dagger H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$ | 289 | 14 | 2 | $2 \cdot 10^7$ |
| 6b | $\mathcal{O}_1 \cdot \tilde{Q}^i\bar{u}^\dagger\tilde{H}^j \cdot \epsilon_{ij}$ | 177 | 0 | 1,2 | $2 \cdot 10^7$ |
| 6c | $\mathcal{O}_{4a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 262 | 0 | 1,2 | $2 \cdot 10^7$ |
| 6d | $\mathcal{O}_{4b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 208 | 0 | 2,3 | $6 \cdot 10^4$ |
| 7 | $L^i\bar{e}^\dagger Q^j\tilde{Q}^kH^lH^mH^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$ | 240 | 15 | 2 | $2 \cdot 10^5$ |
| 8 | $L^i\bar{e}^\dagger\bar{u}^\dagger\bar{d}H^j \cdot \epsilon_{ij}$ | 5 | 1 | 2,3 | $2 \cdot 10^1$ |
| 9 | $L^iL^jL^kL^l\bar{e}\bar{e} \cdot \epsilon_{ik}\epsilon_{jl}$ | 14 | 1 | 2 | $3 \cdot 10^3$ |
| 10 | $L^iL^jL^k\bar{e}Q^l\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$ | 50 | 1 | 2 | $6 \cdot 10^3$ |
| 11a | $L^iL^jQ^kQ^l\bar{d}\bar{d} \cdot \epsilon_{ij}\epsilon_{kl}$ | 48 | 0 | 3 | $4 \cdot 10^1$ |
| 11b | $L^iL^jQ^kQ^l\bar{d}\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$ | 72 | 16 | 2 | $1 \cdot 10^4$ |
| 12a | $L^iL^j\tilde{Q}^k\tilde{Q}^l\bar{u}^\dagger\bar{u}^\dagger \cdot \epsilon_{ik}\epsilon_{jl}$ | 19 | 0 | 2 | $2 \cdot 10^7$ |
| 12b | $L^iL^j\tilde{Q}^k\tilde{Q}^l\bar{u}^\dagger\bar{u}^\dagger \cdot \epsilon_{ij}\epsilon_{kl}$ | 17 | 4 | 3 | $6 \cdot 10^4$ |
| 13 | $L^iL^jL^k\bar{e}\tilde{Q}^l\bar{u}^\dagger \cdot \epsilon_{ik}\epsilon_{jl}$ | 12 | 0 | 2 | $2 \cdot 10^5$ |
| 14a | $L^iL^jQ^k\tilde{Q}^l\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}\epsilon_{kl}$ | 29 | 1 | 3 | $1 \cdot 10^3$ |

| Labels | Operator | Models | Filtered | Loops | Λ [TeV] |
|---|---|---|---|---|---|
| 14b | $L^iL^jQ^k\tilde{Q}^l\bar{u}^\dagger\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$ | 43 | 1 | 2 | $6 \cdot 10^5$ |
| 15 | $L^iL^jL^k\tilde{L}^l\bar{u}^\dagger\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$ | 12 | 1 | 3 | $1 \cdot 10^3$ |
| 16 | $L^iL^j\bar{e}\bar{e}^\dagger\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}$ | 13 | 1 | 3 | $1 \cdot 10^3$ |
| 17 | $L^iL^j\bar{u}^\dagger\bar{d}\bar{d}\bar{d}^\dagger \cdot \epsilon_{ij}$ | 18 | 12 | 3 | $1 \cdot 10^3$ |
| 18 | $L^iL^j\bar{u}\bar{u}^\dagger\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}$ | 22 | 8 | 3 | $1 \cdot 10^3$ |
| 19 | $L^i\bar{e}^\dagger Q^j\bar{u}^\dagger\bar{d}\bar{d} \cdot \epsilon_{ij}$ | 27 | 0 | 3,4 | $2 \cdot 10^{-1}$ |
| 20 | $L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}$ | 27 | 3 | 3,4 | $8 \cdot 10^{-1}$ |
| 21a | $L^iL^jL^k\bar{e}Q^l\bar{u}H^mH^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$ | 3943 | 1 | 2,3 | $2 \cdot 10^3$ |
| 21b | $L^iL^jL^k\bar{e}Q^l\bar{u}H^mH^n \cdot \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}$ | 4080 | 4 | 3 | $2 \cdot 10^3$ |
| 22a | $L^iL^jL^k\tilde{L}^l\bar{e}\bar{e}^\dagger H^mH^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$ | 726 | 0 | 2 | $2 \cdot 10^7$ |
| 22b | $\mathcal{O}_2 \cdot \tilde{L}^i\bar{e}^\dagger H^j\epsilon_{ij}$ | 931 | 0 | 2 | $2 \cdot 10^7$ |
| 23a | $L^iL^jL^k\bar{e}\tilde{Q}^l\bar{d}^\dagger H^mH^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$ | 780 | 0 | 2,3 | $4 \cdot 10^1$ |
| 23b | $\mathcal{O}_2 \cdot \tilde{Q}^i\bar{d}^\dagger H^j \cdot \epsilon_{ij}$ | 969 | 0 | 2,3 | $4 \cdot 10^1$ |
| 24a | $L^iL^jQ^kQ^l\bar{d}\bar{d}H^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$ | 9613 | 193 | 3 | $9 \cdot 10^1$ |
| 24b | $L^iL^jQ^kQ^l\bar{d}\bar{d}H^m\tilde{H}^n \cdot \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$ | 6058 | 110 | 3 | $9 \cdot 10^1$ |
| 24c | $\mathcal{O}_{3a} \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$ | 6022 | 34 | 3,4 | 1 |
| 24d | $\mathcal{O}_{3b} \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$ | 9616 | 211 | 2,3 | $9 \cdot 10^1$ |
| 24e | $\mathcal{O}_{11a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 3834 | 18 | 3,4 | 1 |
| 24f | $\mathcal{O}_{11b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 5915 | 131 | 2,3 | $9 \cdot 10^1$ |
| 25a | $L^iL^jQ^kQ^l\bar{u}\bar{d}H^mH^n \cdot \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$ | 5960 | 151 | 2,3 | $4 \cdot 10^3$ |
| 25b | $\mathcal{O}_{3a} \cdot Q^i\bar{u}H^j \cdot \epsilon_{ij}$ | 5913 | 9 | 3,4 | 10 |
| 25c | $\mathcal{O}_{3b} \cdot Q^i\bar{u}H^j \cdot \epsilon_{ij}$ | 14036 | 470 | 2,3 | $4 \cdot 10^3$ |
| 26a | $L^iL^j\tilde{L}^k\bar{e}^\dagger Q^l\bar{d}H^mH^n \cdot \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}$ | 1600 | 0 | 3 | $4 \cdot 10^1$ |
| 26b | $L^iL^j\tilde{L}^k\bar{e}^\dagger Q^l\bar{d}H^mH^n \cdot \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$ | 1040 | 0 | 2,3 | $4 \cdot 10^1$ |
| 26c | $\mathcal{O}_{3a} \cdot \tilde{L}^i\bar{e}^\dagger H^j \cdot \epsilon_{ij}$ | 1149 | 0 | 3 | $4 \cdot 10^1$ |
| 26d | $\mathcal{O}_{3b} \cdot \tilde{L}^i\bar{e}^\dagger H^j \cdot \epsilon_{ij}$ | 1797 | 0 | 2,3 | $4 \cdot 10^1$ |
| 27a | $L^iL^jQ^k\tilde{Q}^l\bar{d}\bar{d}^\dagger H^mH^n \cdot \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}$ | 3851 | 164 | 2 | $2 \cdot 10^7$ |
| 27b | $L^iL^jQ^k\tilde{Q}^l\bar{d}\bar{d}^\dagger H^mH^n \cdot \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$ | 2226 | 74 | 2 | $2 \cdot 10^7$ |
| 27c | $\mathcal{O}_{3a} \cdot \tilde{Q}^i\bar{d}^\dagger H^j \cdot \epsilon_{ij}$ | 2469 | 33 | 3 | $6 \cdot 10^4$ |
| 27d | $\mathcal{O}_{3b} \cdot \tilde{Q}^i\bar{d}^\dagger H^j \cdot \epsilon_{ij}$ | 3443 | 165 | 2 | $2 \cdot 10^7$ |
| 28a | $L^iL^jQ^k\tilde{Q}^l\bar{u}^\dagger\bar{d}H^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$ | 4038 | 64 | 3 | $4 \cdot 10^3$ |
| 28b | $L^iL^jQ^k\tilde{Q}^l\bar{u}^\dagger\bar{d}H^m\tilde{H}^n \cdot \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$ | 4103 | 0 | 3,4 | 10 |
| 28c | $L^iL^jQ^k\tilde{Q}^l\bar{u}^\dagger\bar{d}H^m\tilde{H}^n \cdot \epsilon_{ik}\epsilon_{jn}\epsilon_{lm}$ | 4305 | 123 | 3 | $4 \cdot 10^3$ |
| 28d | $\mathcal{O}_{3a} \cdot \tilde{Q}^i\bar{u}^\dagger\tilde{H}^j \cdot \epsilon_{ij}$ | 2749 | 7 | 3,4 | 10 |
| 28e | $\mathcal{O}_{3b} \cdot \tilde{Q}^i\bar{u}^\dagger\tilde{H}^j \cdot \epsilon_{ij}$ | 4304 | 90 | 2,3 | $4 \cdot 10^3$ |
| 28f | $\mathcal{O}_{4a} \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$ | 4039 | 74 | 2,3 | $4 \cdot 10^3$ |
| 28g | $\mathcal{O}_{4b} \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$ | 2748 | 14 | 3,4 | 10 |

⋮ 4 pages omitted

| Labels | Operator | Models | Filtered | Loops | Λ [TeV] |
|---|---|---|---|---|---|
| D8c | $L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{ik}\epsilon_{jl}\epsilon_{mn}$ | 25 | 0 | 2 | $10 \cdot 10^6$ |
| D8d | $L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{im}\epsilon_{jk}\epsilon_{ln}$ | 53 | 11 | 1 | $4 \cdot 10^9$ |
| D8e | $L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{im}\epsilon_{jl}\epsilon_{kn}$ | 44 | 6 | 1 | $4 \cdot 10^9$ |
| D8f | $L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$ | 30 | 5 | 1 | $4 \cdot 10^9$ |
| D8g | $L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{ij}\epsilon_{km}\epsilon_{ln}$ | 35 | 7 | 2 | $10 \cdot 10^6$ |
| D8h | $L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{ij}\epsilon_{kn}\epsilon_{lm}$ | 35 | 7 | 2 | $10 \cdot 10^6$ |
| D8i | $L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{ij}\epsilon_{kl}\epsilon_{mn}$ | 16 | 3 | 2 | $10 \cdot 10^6$ |
| D9a | $L^iL^j\bar{d}\bar{d}^\dagger(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 30 | 5 | 1 | $4 \cdot 10^9$ |
| D9b | $L^iL^j\bar{d}\bar{d}^\dagger(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 16 | 4 | 2 | $10 \cdot 10^6$ |
| D10a | $(DL)^iL^j\bar{u}^\dagger\bar{d}H^k\tilde{H}^l \cdot \epsilon_{il}\epsilon_{jk}$ | 56 | 13 | 2,3 | $1 \cdot 10^3$ |
| D10b | $(DL)^iL^j\bar{u}^\dagger\bar{d}H^k\tilde{H}^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 36 | 7 | 2,3 | $1 \cdot 10^3$ |
| D10c | $(DL)^iL^j\bar{u}^\dagger\bar{d}H^k\tilde{H}^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 56 | 13 | 2,3 | $1 \cdot 10^3$ |
| D11 | $(DL)^iL^j(D\bar{u}^\dagger)(D\bar{d}) \cdot \epsilon_{ij}$ | — | — | 2,3 | $1 \cdot 10^3$ |
| D12a | $L^iL^j\bar{u}\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 30 | 5 | 1 | $4 \cdot 10^9$ |
| D12b | $L^iL^j\bar{u}\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 16 | 4 | 2 | $10 \cdot 10^6$ |
| D13a | $(DL)^iL^j\tilde{Q}^k(D\bar{u}^\dagger)H^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 4 | 2 | 2 | $10 \cdot 10^6$ |
| D13b | $(DL)^iL^j\tilde{Q}^k(D\bar{u}^\dagger)H^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 5 | 0 | 1 | $4 \cdot 10^9$ |
| D14a | $L^i\bar{e}^\dagger Q^j\bar{d}(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 53 | 0 | 2 | $6 \cdot 10^3$ |
| D14b | $L^i\bar{e}^\dagger Q^j\bar{d}(DH)^kH^l \cdot \epsilon_{il}\epsilon_{jk}$ | 53 | 0 | 2 | $6 \cdot 10^3$ |
| D14c | $L^i\bar{e}^\dagger Q^j\bar{d}(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 27 | 0 | 2 | $6 \cdot 10^3$ |
| D15 | $(DL)^i\bar{e}^\dagger(D\bar{u}^\dagger)\bar{d}H^j \cdot \epsilon_{ij}$ | 5 | 1 | 2,3 | $2 \cdot 10^1$ |
| D16a | $L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 58 | 8 | 2 | $2 \cdot 10^5$ |
| D16b | $L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{il}\epsilon_{jk}$ | 58 | 8 | 2 | $2 \cdot 10^5$ |
| D16c | $L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 27 | 4 | 2 | $2 \cdot 10^5$ |
| D17 | $\bar{e}^\dagger\bar{e}^\dagger\bar{u}^\dagger\bar{d}(DH)^iH^j \cdot \epsilon_{ij}$ | 16 | 7 | 3,4 | $2 \cdot 10^{-1}$ |
| D18a | $(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}$ | 53 | 1 | 0,1 | $4 \cdot 10^9$ |
| D18b | $(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ik}\epsilon_{jl}\epsilon_{mn}$ | 53 | 1 | 0,1 | $4 \cdot 10^9$ |
| D18c | $(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{im}\epsilon_{jl}\epsilon_{kn}$ | 53 | 1 | 0,1 | $4 \cdot 10^9$ |
| D18d | $(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ij}\epsilon_{km}\epsilon_{ln}$ | 24 | 1 | 1,2 | $10 \cdot 10^6$ |
| D18e | $(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{in}\epsilon_{jl}\epsilon_{km}$ | 34 | 0 | 1 | $4 \cdot 10^9$ |
| D18f | $(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$ | 34 | 0 | 1 | $4 \cdot 10^9$ |
| D19a | $(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 1 | 0 | 1 | $2 \cdot 10^9$ |
| D19b | $(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{il}\epsilon_{jk}$ | 3 | 3 | 0 | $6 \cdot 10^{11}$ |
| D19c | $(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 3 | 3 | 0 | $6 \cdot 10^{11}$ |
| D20 | $L^i\bar{e}^\dagger H^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$ | 129 | 0 | 1,2 | $2 \cdot 10^5$ |
| D21 | $(DL)^i(D\bar{e}^\dagger)H^jH^k(DH)^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 2 | 0 | 1 | $4 \cdot 10^7$ |
| D22 | $\bar{e}^\dagger\bar{e}^\dagger(DH)^i(DH)^jH^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 9 | 0 | 2 | $3 \cdot 10^3$ |

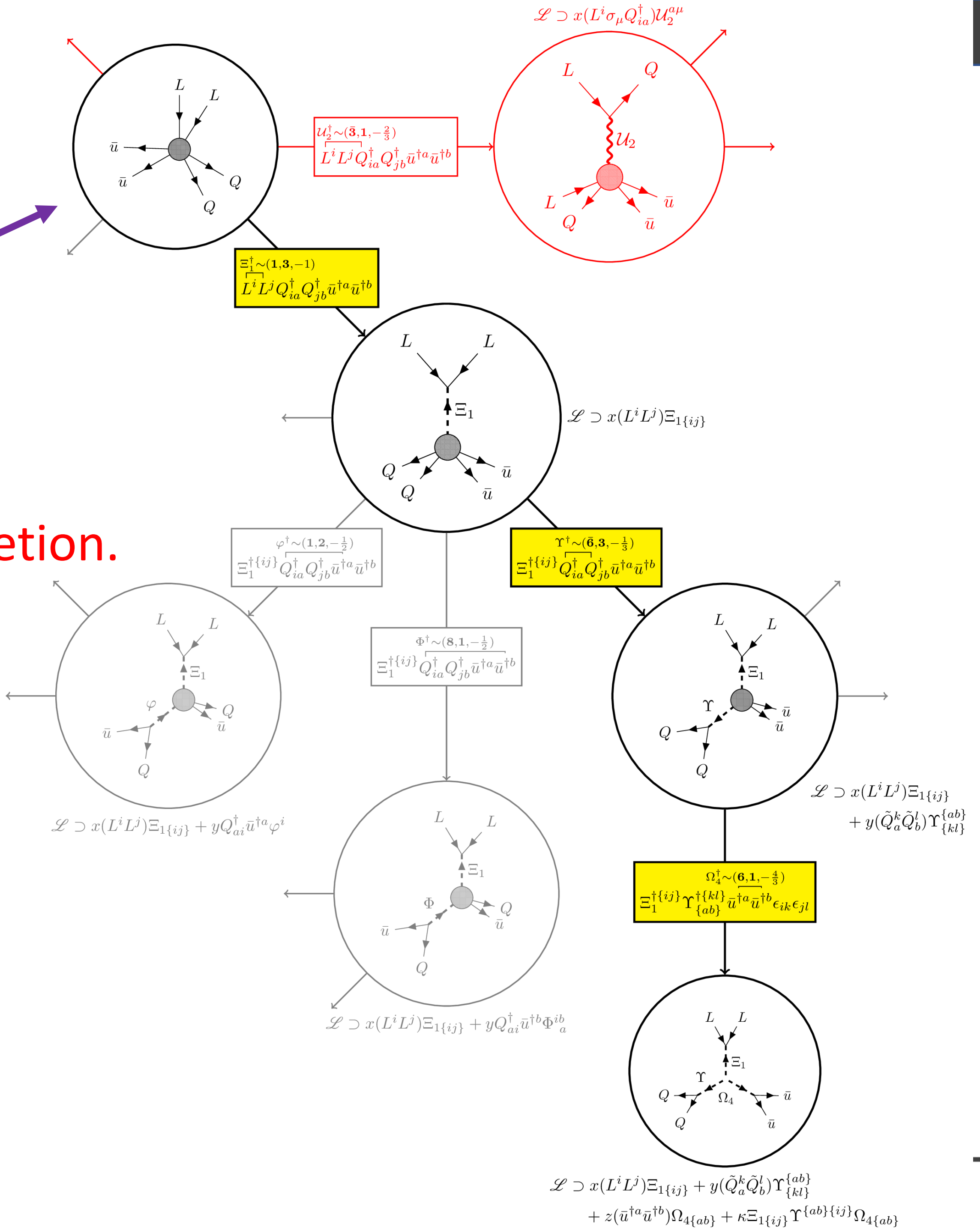
**Example**: opening of $\mathcal{O}_{12a} = L^i L^j \tilde{Q}^k \tilde{Q}^\ell \bar{u}^\dagger \bar{u}^\dagger \epsilon_{ik}\epsilon_{jl}$

2-component notation: $\tilde{Q}^i \equiv \epsilon^{ij} Q^\dagger_j \quad \tilde{Q}\bar{u}^\dagger = \text{colour singlet}$

Effective operator

The yellow boxes track one pathway to opening $O_{12a}$ at tree level, producing a scalar-only completion.

The starts of other pathways are indicated in light grey.

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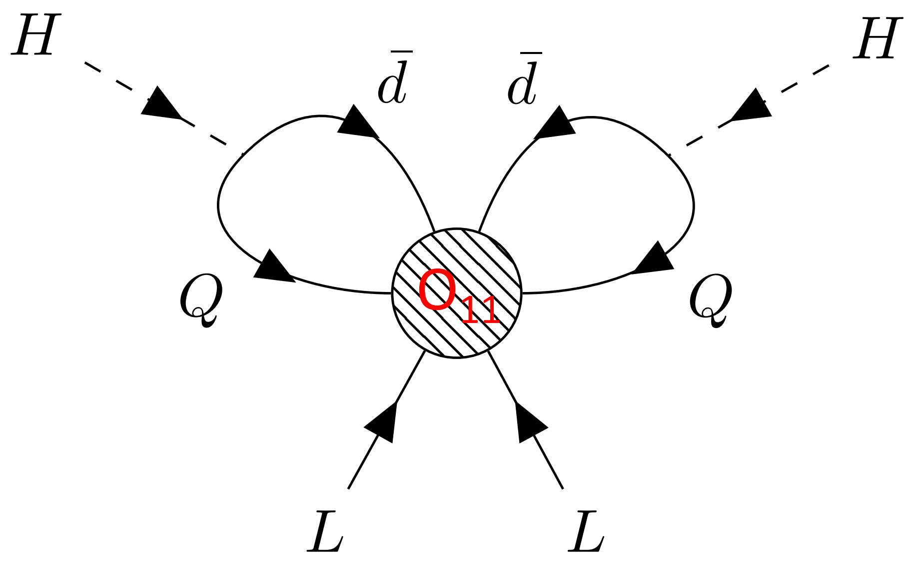
Example: closing $\mathcal{O}_{11} = LLQQ\bar{d}\bar{d}$ into a Majorana neutrino mass diagram.




$O_{11}$ ➞ LLHH at 2-loop order

Opening up $O_{11}$ at tree level produces a 2-loop contribution to neutrino mass. The virtual states consist of both exotics and SM fields.

This enables the systematic construction of radiative neutrino mass models.

Tiny ν mass due to (i) large exotic masses, (ii) $1/16\pi^2$ loop factors, and (iii) products of mag.<1 coupling constants.

Review of radiative models: Cai, Herrero-García, Schmidt, Vicente, RV Frontiers in Physics 5, 63 (2017)

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## Filtering

Opening up an operator produces sets of exotic field content, defining unfiltered models.

These fields then implicitly define the most general renormalisable Lagrangian.

If necessary, baryon-number conservation is imposed. Fields with the same SM quantum numbers but different B are considered different.

It often happens that the resulting interactions generate the largest* contribution to neutrino masses from an effective operator that is different from that used to derive the field content.

The resulting models are then re-tagged against the dominant operator, giving filtered models.

* We assume that there are no special parameter hierarchies when deriving the neutrino mass. This is called democratic filtering in the paper.

Our analysis looked at tree-level openings only. Some of our filtered models may produce exotic-only, loop-level contributions to the Weinberg operator that are larger than the closure of the dominant operator: use Valencia group's results to do more filtering.

# Models with exotic scalars and fermions only.

Scale of new physics assuming O(1) exotic couplings

unfiltered

The tree-level seesaw models

Some operators produce no filtered models

Subtlety to do with the higher-dim Weinberg ops

Zee-Babu model

| Labels | Operator | Models | Filtered | Loops | $\Lambda$ [TeV] |
|---|---|---|---|---|---|
| 1 | $L^iL^jH^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 3 | 3 | 0 | $6 \cdot 10^{11}$ |
| 2 | $L^iL^jL^k\bar{e}H^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 8 | 2 | 1 | $4 \cdot 10^{7}$ |
| 3*a* | $L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 9 | 2 | 2 | $2 \cdot 10^{5}$ |
| 3*b* | $L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 14 | 5 | 1 | $9 \cdot 10^{7}$ |
| 4*a* | $L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ik}\epsilon_{jl}$ | 5 | 0 | 1 | $4 \cdot 10^{9}$ |
| 4*b* | $L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ij}\epsilon_{kl}$ | 4 | 2 | 2 | $10 \cdot 10^{6}$ |
| 5*a* | $L^iL^jQ^k\bar{d}H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$ | 790 | 36 | 2 | $6 \cdot 10^{5}$ |
| 5*b* | $\mathcal{O}_1 \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$ | 492 | 14 | 1,2 | $6 \cdot 10^{5}$ |
| 5*c* | $\mathcal{O}_{3a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 509 | 0 | 2,3 | $1 \cdot 10^{3}$ |
| 5*d* | $\mathcal{O}_{3b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 799 | 16 | 1,2 | $6 \cdot 10^{5}$ |
| 6*a* | $L^iL^j\tilde{Q}^k\bar{u}^\dagger H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$ | 289 | 14 | 2 | $2 \cdot 10^{7}$ |
| 6*b* | $\mathcal{O}_1 \cdot \tilde{Q}^i\bar{u}^\dagger\tilde{H}^j \cdot \epsilon_{ij}$ | 177 | 0 | 1,2 | $2 \cdot 10^{7}$ |
| 6*c* | $\mathcal{O}_{4a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 262 | 0 | 1,2 | $2 \cdot 10^{7}$ |
| 6*d* | $\mathcal{O}_{4b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$ | 208 | 0 | 2,3 | $6 \cdot 10^{4}$ |
| 7 | $L^i\bar{e}^\dagger Q^j\tilde{Q}^kH^lH^mH^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$ | 240 | 15 | 2 | $2 \cdot 10^{5}$ |
| 8 | $L^i\bar{e}^\dagger\bar{u}^\dagger\bar{d}H^j \cdot \epsilon_{ij}$ | 5 | 1 | 2,3 | $2 \cdot 10^{1}$ |
| 9 | $L^iL^jL^kL^l\bar{e}\bar{e} \cdot \epsilon_{ik}\epsilon_{jl}$ | 14 | 1 | 2 | $3 \cdot 10^{3}$ |
| 10 | $L^iL^jL^k\bar{e}Q^l\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$ | 50 | 1 | 2 | $6 \cdot 10^{3}$ |
| 11*a* | $L^iL^jQ^kQ^l\bar{d}\bar{d} \cdot \epsilon_{ij}\epsilon_{kl}$ | 48 | 0 | 3 | $4 \cdot 10^{1}$ |
| 11*b* | $L^iL^jQ^kQ^l\bar{d}\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$ | 72 | 16 | 2 | $1 \cdot 10^{4}$ |
| 12*a* | $L^iL^j\tilde{Q}^k\tilde{Q}^l\bar{u}^\dagger\bar{u}^\dagger \cdot \epsilon_{ik}\epsilon_{jl}$ | 19 | 0 | 2 | $2 \cdot 10^{7}$ |
| 12*b* | $L^iL^j\tilde{Q}^k\tilde{Q}^l\bar{u}^\dagger\bar{u}^\dagger \cdot \epsilon_{ij}\epsilon_{kl}$ | 17 | 4 | 3 | $6 \cdot 10^{4}$ |
| 13 | $L^iL^jL^k\bar{e}\tilde{Q}^l\bar{u}^\dagger \cdot \epsilon_{ik}\epsilon_{jl}$ | 12 | 0 | 2 | $2 \cdot 10^{5}$ |
| 14*a* | $L^iL^jQ^k\tilde{Q}^l\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}\epsilon_{kl}$ | 29 | 1 | 3 | $1 \cdot 10^{3}$ |

⋮