Seeking the origin of neutrino masses: a brief review

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1. ν mass = new physics
2. ν mass = new mass scale?
3. High-scale seesaw models
4. Low-scale models
5. Radiative models
6. Closing remarks

1. ν mass = new physics

Minimal standard model:

no RH neutrinos, no Y=2 scalar triplet ⇒ massless neutrinos, perturbative $L_{e,\mu,\tau}$ conservation

old-fashioned normalisation, sorry: $Q = I_3 + Y/2$

Massive neutrinos may be Dirac or Majorana.

If Majorana: first such states discovered ⇒ *new physics*. Plethora of mechanisms, always *new dofs*.

If Dirac: RH neutrinos needed ⇒ *new dofs*. (For singlet ν_R, no Majorana masses ⇒ impose L, *new principle*.)

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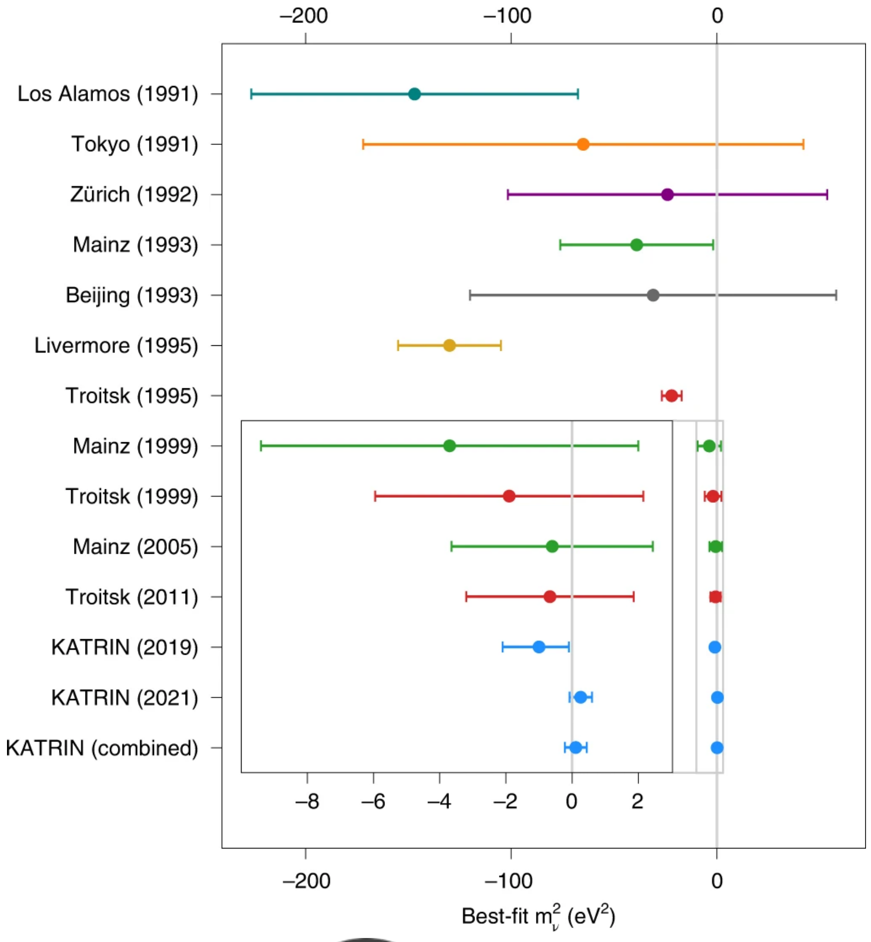
2. ν mass = new mass scale?

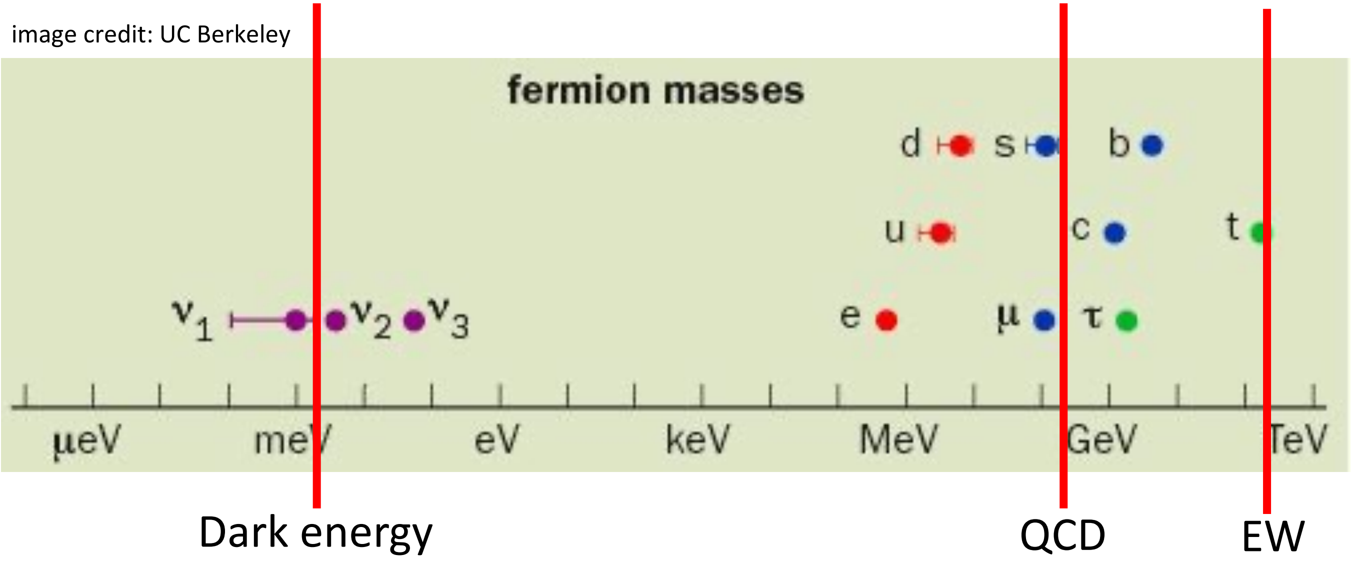
image credit: Nature Physics, KATRIN



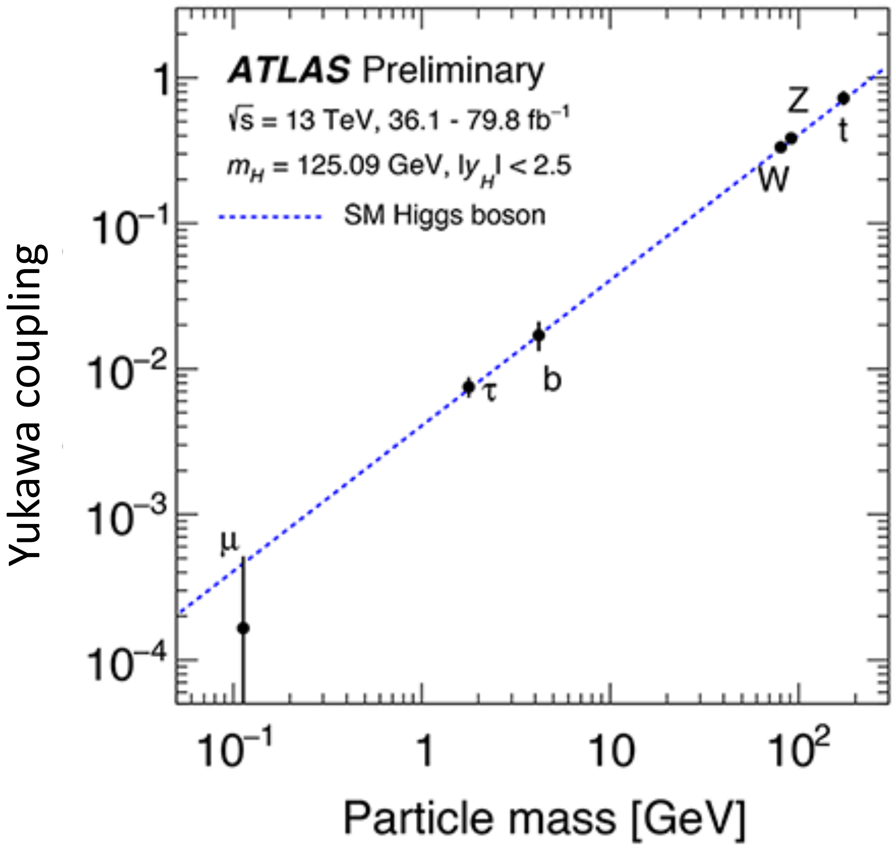
KATRIN β-decay endpoint: $m_\nu \lesssim 0.8\ \mathrm{eV}$

Cosmology: $m_\nu \lesssim 0.12 - 0.26\ \mathrm{eV}$

image credit: UC Berkeley



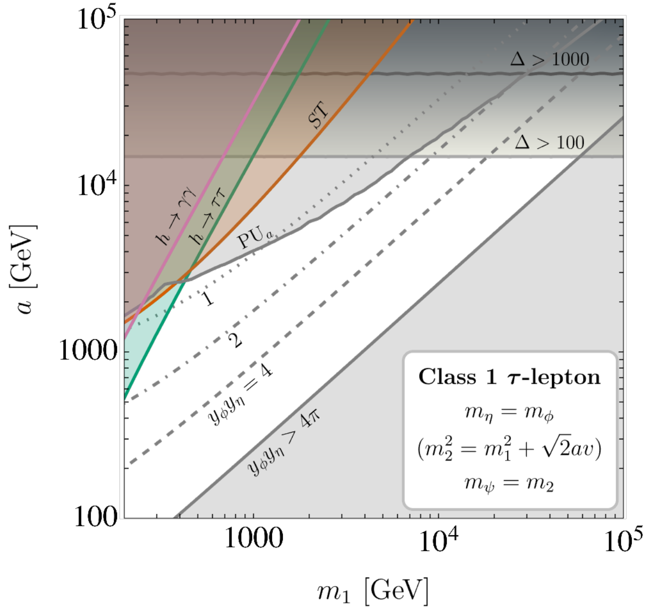
Maybe *not* new scale, *despite* m_ν << any other known nonzero particle mass?



Dirac ν, Yukawa coupling ~ 10^{-12} ?

SM says electron Yukawa ~ 10^{-6}.

Is 10^{-6} OK? If so, is another factor of 10^{-6} also OK?



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

Radiative origin also works.

Baker, Cox, RV 2021a, 2021b

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For rest of talk, hypothesise that:

- m_ν ***is*** a new scale
- ν is Majorana

Model building dominated by

- explaining small m_ν
- origin of L violation

3. 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

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

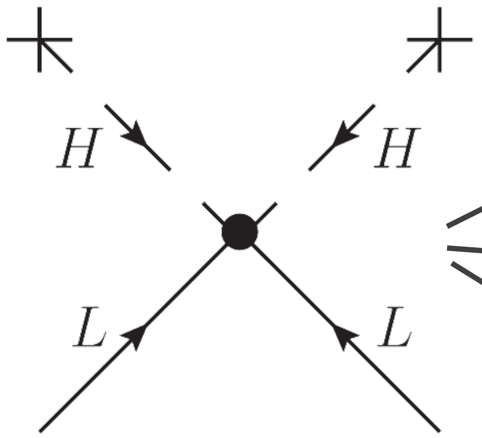
i.e. seesaw effect when L-violation scale very high

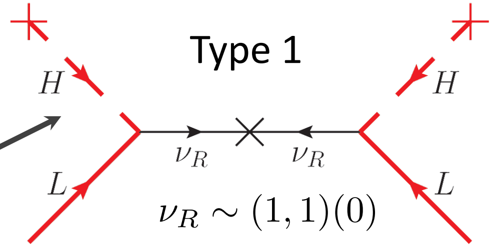
$$m_\nu \sim 0.1 \text{ eV}, \quad v \sim 10^2 \text{ GeV} \implies M \sim 10^{14} \text{ GeV}$$

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

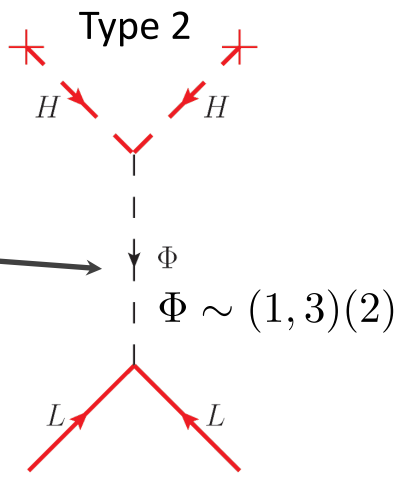
Type-1,2,3 seesaw models:

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

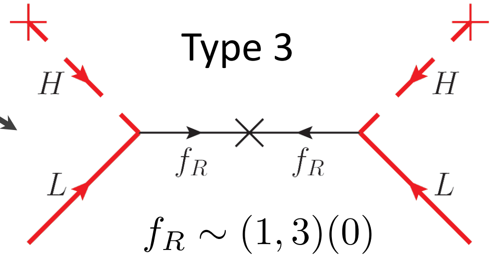




Minkowski 1977
Yanagida 1979
Gell-Mann, Ramond, Slansky 1979
Mohapatra, Senjanovic 1980



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



Foot, Lew, He, Joshi 1989

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

Type I: Mediator is massive Majorana ν_R gauge singlet.

If M very large, then untestable. ☹

But has leptogenesis. ☺ Fukugita, Yanagida: 1986

(Same Lagrangian with small ν_R Majorana masses also interesting: the νMSM.)

Asaka, Shaposhnikov 2005
Asaka, Blanchet, Shaposhnikov 2005

Type 2 and 3: Mediators have EW quantum numbers.

Better (but not great) prospects at colliders.

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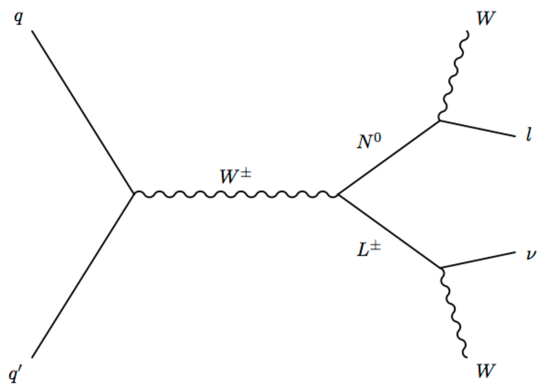
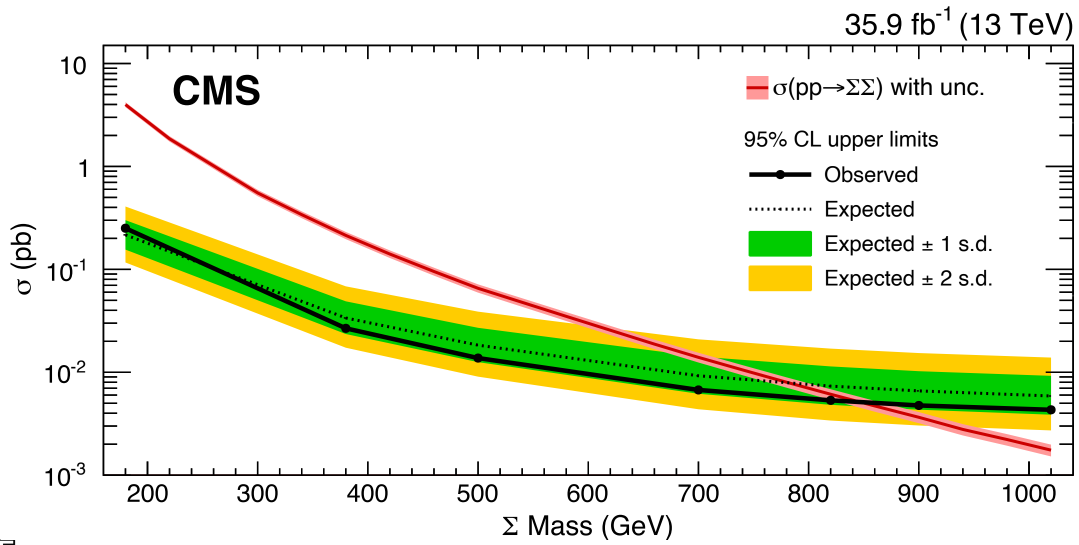
Example of search and bound: type 3 seesaw.

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

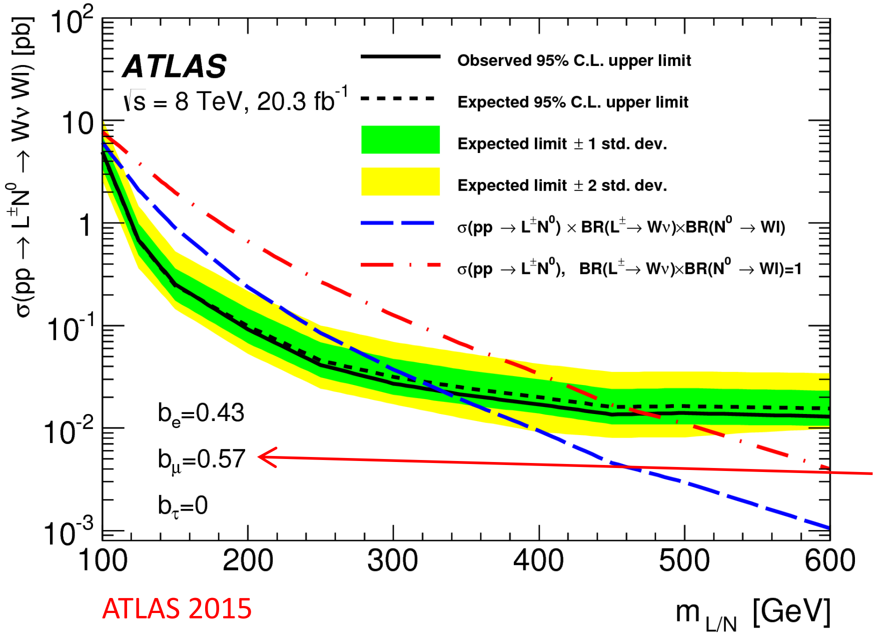
Heavy lepton EW pair production.





CMS 2017

Flavour democratic BR choice



Benchmark BR

ATLAS 2015

Comments on Type I seesaw

At SM gauge group level, very compelling:

- Simply add gauge-singlet RH neutrinos
- Use most general renormalisable Lagrangian (standard Yukawa, ν_R Maj. masses)
- Get leptogenesis as wonderful byproduct
- Can identify seesaw and Peccei-Quinn scales (SMASH, VISHν)

Langacker, Peccei, Yanagida 1986
Shin 1987
Salvio 2015, 2019
Ballesteros+ 2017a, 2017b, 2019
Sopov, RV 2022

But more complicated when ν_R embedded in non-trivial gauge multiplet:

- LR symmetric model: ν_R masses from Yuk with RH triplet scalar
- Pati-Salam: need (10*,1,3) scalar
- SO(10): need 126 scalar

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Some may like connection with GUT breaking, but if you like smaller multiplets then …

4. Low-scale models

aka inverse and linear seesaws

In LRSM = $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, add a gauge singlet fermion S_R:

$$\left(\overline{\nu}_L, \overline{(\nu_R)^c (S_R)^c}\right) \begin{bmatrix} \cancel{(3,1)(2)} & (2,2)(0) & (2,1)(-1) \\ (2,2)(0) & \cancel{(1,3)(2)} & (1,2)(-1) \\ (2,1)(-1) & (1,2)(-1) & (1,1)(0) \end{bmatrix} \begin{pmatrix} (\nu_L)^c \\ \nu_R \\ S_R \end{pmatrix}$$

The triplet scalars are not needed. Doublets suffice.

SO(10) level:

$$\begin{bmatrix} \cancel{126} & 10 + \cancel{120} & 16 \\ 10 + \cancel{120} & \cancel{126} & 16 \\ 16 & 16 & 1 \end{bmatrix}$$

126 can be replaced by 16.

Putting in mass scales:

$$\begin{bmatrix} 0 & m & m_L \\ m & 0 & m_R \\ m_L & m_R & \mu \end{bmatrix}$$

<u>Inverse seesaw</u>: $m_L = 0$ and $\mu << m << m_R$

Wyler, Wolfenstein 1983
Mohapatra 1986
Mohapatra, Valle 1986
Ma 1987

Light neutrino mass:

$$m_\nu \sim \mu \left(\frac{m}{m_R} \right)^2$$

Double suppression: small μ and m/m_R.

Sterile admixture ~ m/m_R, so relatively large if m_R ~ few TeV.

Small μ explicitly violates L. Technically natural.

Putting m_R ~ 10 TeV gives m_ν ~ 0.1 eV $\quad \frac{\mu}{\text{MeV}} \sim \frac{10}{(m/\text{GeV})^2}$ so not ridiculously small.

Linear seesaw: $\mu=0$, $m_L \leq m << m_R$

Akhmedov+ 1996
Malinksý, Ramão, Valle 2005

Light neutrino mass: $$m_\nu \sim \frac{m m_L}{m_R}$$

$m_L=0$ restores L conservation, so $m_L << m$ technically natural.

Thus double suppression possible: small m_L and m/m_R.

Scale of new physics can again be relatively low e.g. $m_R \sim 10$ TeV get $\frac{m_L}{\mathrm{MeV}} \sim \frac{10^{-3}}{m/\mathrm{GeV}}$

ISS & LSS produce small m_ν

- without tiny ν Dirac masses, and
- with low scale of new physics,

but at the expense of introducing (technically natural) small L-violation scales μ and m_L.

Q: Are they improvements over regular Dirac neutrinos?

5. Radiative models

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

Systematic model-building and classification procedure.

Two complementary approaches:

(Generalised) Weinberg operators $\frac{\lambda}{M^{1+2n}} LLHH(H^\dagger H)^n$ Valencia group: Hirsch, Cepedello et al (many papers)

non-Weinberg operators → ν self-energy graphs with both SM particles and exotics Babu, Leung 2001
de Gouvêa, Jenkins 2008
Melbourne group
(many papers)

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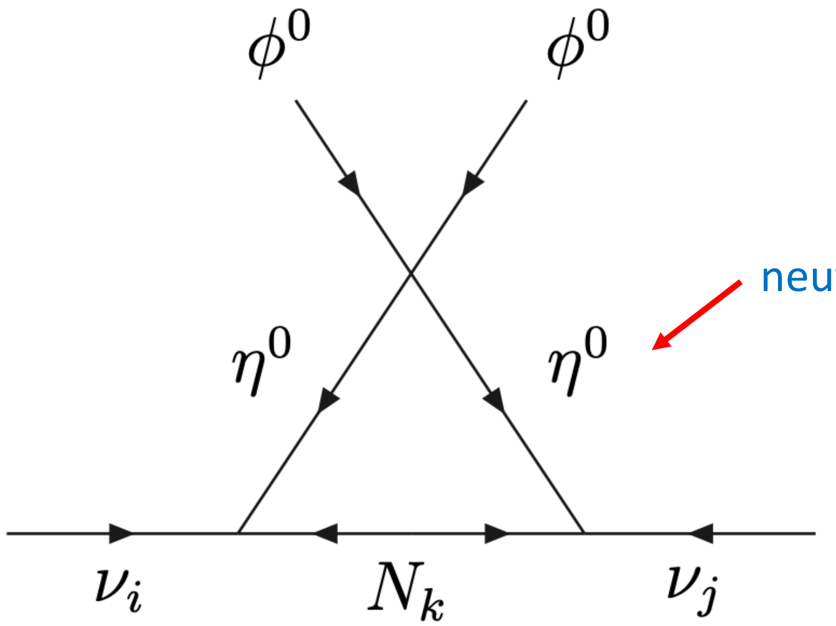
Possible connection with the Dark Side: scotogenesis!

Ma 2006



neutral component of inert scalar doublet

Both are Z_2 odd DM candidates

heavy neutral Majorana fermions

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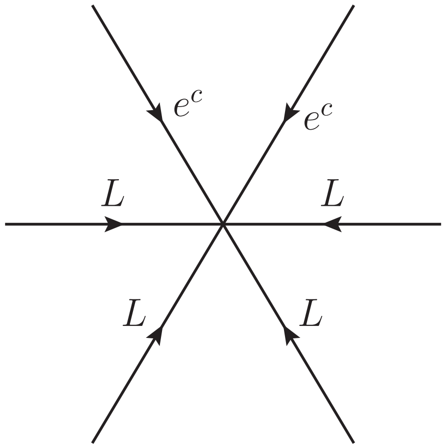
Historic example: Zee-Babu model

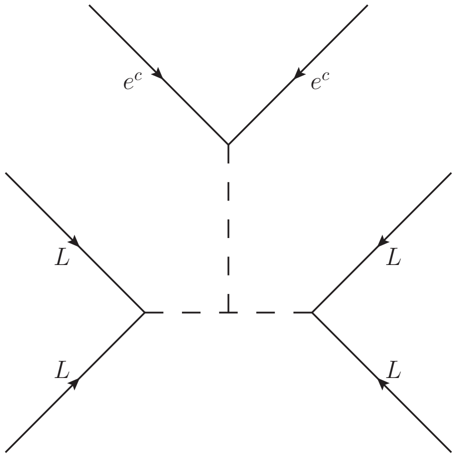
Doubly-charged scalar k

Singly-charged scalar h

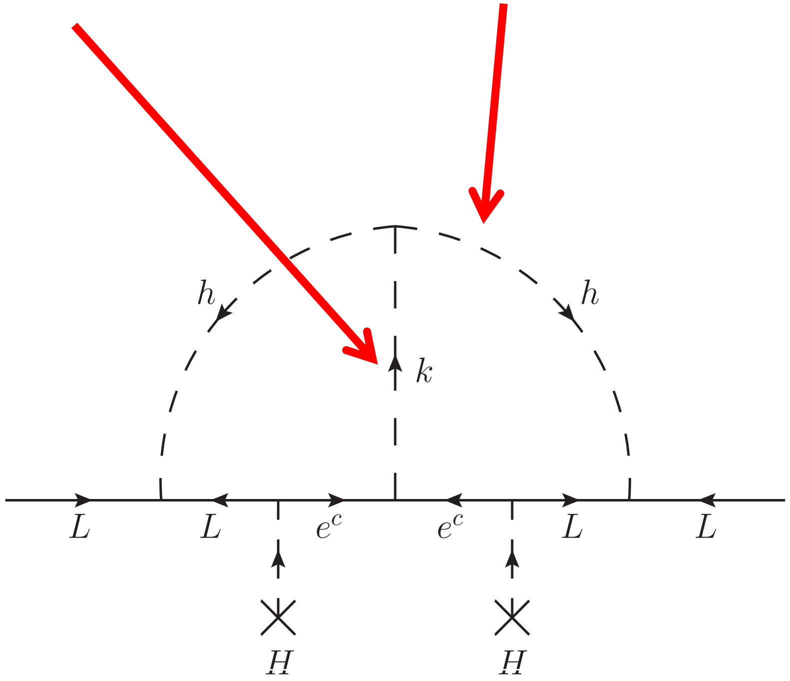


$$O_9 = LLLe^cLe^c$$

Effective op



Opening it up



2-loop ν mass diagram

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

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	$6\cdot10^{11}$
2	$L^iL^jL^k\bar{e}H^l \cdot \epsilon_{ik}\epsilon_{jl}$	8	2	1	$4\cdot10^7$
3a	$L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ij}\epsilon_{kl}$	9	2	2	$2\cdot10^5$
3b	$L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ik}\epsilon_{jl}$	14	5	1	$9\cdot10^7$
4a	$L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ik}\epsilon_{jl}$	5	0	1	$4\cdot10^9$
4b	$L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ij}\epsilon_{kl}$	4	2	2	$10\cdot10^6$
5a	$L^iL^jQ^k\bar{d}H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	790	36	2	$6\cdot10^5$
5b	$\mathcal{O}_1 \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$	492	14	1,2	$6\cdot10^5$
5c	$\mathcal{O}_{3a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	509	0	2,3	$1\cdot10^3$
5d	$\mathcal{O}_{3b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	799	16	1,2	$6\cdot10^5$
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	$2\cdot10^7$
6b	$\mathcal{O}_1 \cdot \tilde{Q}^i\bar{u}^\dagger\tilde{H}^j \cdot \epsilon_{ij}$	177	0	1,2	$2\cdot10^7$
6c	$\mathcal{O}_{4a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	262	0	1,2	$2\cdot10^7$
6d	$\mathcal{O}_{4b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	208	0	2,3	$6\cdot10^4$
7	$L^i\bar{e}^\dagger Q^j\tilde{Q}^kH^lH^mH^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	240	15	2	$2\cdot10^5$
8	$L^i\bar{e}^\dagger\bar{u}^\dagger\bar{d}H^j \cdot \epsilon_{ij}$	5	1	2,3	$2\cdot10^1$
9	$L^iL^jL^kL^l\bar{e}\bar{e} \cdot \epsilon_{ik}\epsilon_{jl}$	14	1	2	$3\cdot10^3$
10	$L^iL^jL^k\bar{e}Q^l\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$	50	1	2	$6\cdot10^3$
11a	$L^iL^jQ^kQ^l\bar{d}\bar{d} \cdot \epsilon_{ij}\epsilon_{kl}$	48	0	3	$4\cdot10^1$
11b	$L^iL^jQ^kQ^l\bar{d}\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$	72	16	2	$1\cdot10^4$
12a	$L^iL^j\tilde{Q}^k\tilde{Q}^l\bar{u}^\dagger\bar{u}^\dagger \cdot \epsilon_{ik}\epsilon_{jl}$	19	0	2	$2\cdot10^7$
12b	$L^iL^j\tilde{Q}^k\tilde{Q}^l\bar{u}^\dagger\bar{u}^\dagger \cdot \epsilon_{ij}\epsilon_{kl}$	17	4	3	$6\cdot10^4$
13	$L^iL^jL^k\bar{e}\tilde{Q}^l\bar{u}^\dagger \cdot \epsilon_{ik}\epsilon_{jl}$	12	0	2	$2\cdot10^5$
14a	$L^iL^jQ^k\tilde{Q}^l\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}\epsilon_{kl}$	29	1	3	$1\cdot10^3$

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	$6\cdot10^5$
15	$L^iL^jL^k\tilde{L}^l\bar{u}^\dagger\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$	12	1	3	$1\cdot10^3$
16	$L^iL^j\bar{e}\bar{e}^\dagger\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}$	13	1	3	$1\cdot10^3$
17	$L^iL^j\bar{u}^\dagger\bar{d}\bar{d}\bar{d}^\dagger \cdot \epsilon_{ij}$	18	12	3	$1\cdot10^3$
18	$L^iL^j\bar{u}\bar{u}^\dagger\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}$	22	8	3	$1\cdot10^3$
19	$L^i\bar{e}^\dagger Q^j\bar{u}^\dagger\bar{d}\bar{d} \cdot \epsilon_{ij}$	27	0	3,4	$2\cdot10^{-1}$
20	$L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger\bar{u}^\dagger\bar{d} \cdot \epsilon_{ij}$	27	3	3,4	$8\cdot10^{-1}$
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	$2\cdot10^3$
21b	$L^iL^jL^k\bar{e}Q^l\bar{u}H^mH^n \cdot \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}$	4080	4	3	$2\cdot10^3$
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	$2\cdot10^7$
22b	$\mathcal{O}_2 \cdot \tilde{L}^i\bar{e}^\dagger H^j\epsilon_{ij}$	931	0	2	$2\cdot10^7$
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	$4\cdot10^1$
23b	$\mathcal{O}_2 \cdot \tilde{Q}^i\bar{d}^\dagger H^j \cdot \epsilon_{ij}$	969	0	2,3	$4\cdot10^1$
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	$9\cdot10^1$
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	$9\cdot10^1$
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	$9\cdot10^1$
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	$9\cdot10^1$
25a	$L^iL^jQ^kQ^l\bar{u}\bar{d}H^mH^n \cdot \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$	5960	151	2,3	$4\cdot10^3$
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	$4\cdot10^3$
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	$4\cdot10^1$
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	$4\cdot10^1$
26c	$\mathcal{O}_{3a} \cdot \tilde{L}^i\bar{e}^\dagger H^j \cdot \epsilon_{ij}$	1149	0	3	$4\cdot10^1$
26d	$\mathcal{O}_{3b} \cdot \tilde{L}^i\bar{e}^\dagger H^j \cdot \epsilon_{ij}$	1797	0	2,3	$4\cdot10^1$
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	$2\cdot10^7$
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	$2\cdot10^7$
27c	$\mathcal{O}_{3a} \cdot \tilde{Q}^i\bar{d}^\dagger H^j \cdot \epsilon_{ij}$	2469	33	3	$6\cdot10^4$
27d	$\mathcal{O}_{3b} \cdot \tilde{Q}^i\bar{d}^\dagger H^j \cdot \epsilon_{ij}$	3443	165	2	$2\cdot10^7$
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	$4\cdot10^3$
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	$4\cdot10^3$
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	$4\cdot10^3$
28f	$\mathcal{O}_{4a} \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$	4039	74	2,3	$4\cdot10^3$
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	$10\cdot10^6$
D8d	$L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{im}\epsilon_{jk}\epsilon_{ln}$	53	11	1	$4\cdot10^9$
D8e	$L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{im}\epsilon_{jl}\epsilon_{kn}$	44	6	1	$4\cdot10^9$
D8f	$L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$	30	5	1	$4\cdot10^9$
D8g	$L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	35	7	2	$10\cdot10^6$
D8h	$L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{ij}\epsilon_{kn}\epsilon_{lm}$	35	7	2	$10\cdot10^6$
D8i	$L^iL^jQ^k\tilde{Q}^l(DH)^mH^n \cdot \epsilon_{ij}\epsilon_{kl}\epsilon_{mn}$	16	3	2	$10\cdot10^6$
D9a	$L^iL^j\bar{d}\bar{d}^\dagger(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	30	5	1	$4\cdot10^9$
D9b	$L^iL^j\bar{d}\bar{d}^\dagger(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$	16	4	2	$10\cdot10^6$
D10a	$(DL)^iL^j\bar{u}^\dagger\bar{d}H^k\tilde{H}^l \cdot \epsilon_{il}\epsilon_{jk}$	56	13	2,3	$1\cdot10^3$
D10b	$(DL)^iL^j\bar{u}^\dagger\bar{d}H^k\tilde{H}^l \cdot \epsilon_{ij}\epsilon_{kl}$	36	7	2,3	$1\cdot10^3$
D10c	$(DL)^iL^j\bar{u}^\dagger\bar{d}H^k\tilde{H}^l \cdot \epsilon_{ik}\epsilon_{jl}$	56	13	2,3	$1\cdot10^3$
D11	$(DL)^iL^j(D\bar{u}^\dagger)(D\bar{d}) \cdot \epsilon_{ij}$	—	—	2,3	$1\cdot10^3$
D12a	$L^iL^j\bar{u}\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	30	5	1	$4\cdot10^9$
D12b	$L^iL^j\bar{u}\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$	16	4	2	$10\cdot10^6$
D13a	$(DL)^iL^j\tilde{Q}^k(D\bar{u}^\dagger)H^l \cdot \epsilon_{ij}\epsilon_{kl}$	4	2	2	$10\cdot10^6$
D13b	$(DL)^iL^j\tilde{Q}^k(D\bar{u}^\dagger)H^l \cdot \epsilon_{ik}\epsilon_{jl}$	5	0	1	$4\cdot10^9$
D14a	$L^i\bar{e}^\dagger Q^j\bar{d}(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	53	0	2	$6\cdot10^3$
D14b	$L^i\bar{e}^\dagger Q^j\bar{d}(DH)^kH^l \cdot \epsilon_{il}\epsilon_{jk}$	53	0	2	$6\cdot10^3$
D14c	$L^i\bar{e}^\dagger Q^j\bar{d}(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$	27	0	2	$6\cdot10^3$
D15	$(DL)^i\bar{e}^\dagger(D\bar{u}^\dagger)\bar{d}H^j \cdot \epsilon_{ij}$	5	1	2,3	$2\cdot10^1$
D16a	$L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	58	8	2	$2\cdot10^5$
D16b	$L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{il}\epsilon_{jk}$	58	8	2	$2\cdot10^5$
D16c	$L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$	27	4	2	$2\cdot10^5$
D17	$\bar{e}^\dagger\bar{e}^\dagger\bar{u}^\dagger\bar{d}(DH)^iH^j \cdot \epsilon_{ij}$	16	7	3,4	$2\cdot10^{-1}$
D18a	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}$	53	1	0,1	$4\cdot10^9$
D18b	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ik}\epsilon_{jl}\epsilon_{mn}$	53	1	0,1	$4\cdot10^9$
D18c	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{im}\epsilon_{jl}\epsilon_{kn}$	53	1	0,1	$4\cdot10^9$
D18d	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	24	1	1,2	$10\cdot10^6$
D18e	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{in}\epsilon_{jl}\epsilon_{km}$	34	0	1	$4\cdot10^9$
D18f	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	34	0	1	$4\cdot10^9$
D19a	$(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$	1	0	1	$2\cdot10^9$
D19b	$(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{il}\epsilon_{jk}$	3	3	0	$6\cdot10^{11}$
D19c	$(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	3	3	0	$6\cdot10^{11}$
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	$2\cdot10^5$
D21	$(DL)^i(D\bar{e}^\dagger)H^jH^k(DH)^l \cdot \epsilon_{ik}\epsilon_{jl}$	2	0	1	$4\cdot10^7$
D22	$\bar{e}^\dagger\bar{e}^\dagger(DH)^i(DH)^jH^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	9	0	2	$3\cdot10^3$

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

- All gauge-invariant $\Delta L=2$ operators containing SM fields are listed, including EW index contractions and derivatives, completing the Babu+Leung list.
- An algorithm for tree-level openings of those operators is developed, validated e.g. against dim=6 SMEFT.
- The subsequent theories are filtered to produce genuine neutrino mass models.
- Statistics for the properties of the theories are derived.
- New illustrative models are constructed.
- The code and a searchable database of these models made available online for community use.
- The code can be used for all sets of effective operators, not limited to Majorana neutrino application.

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

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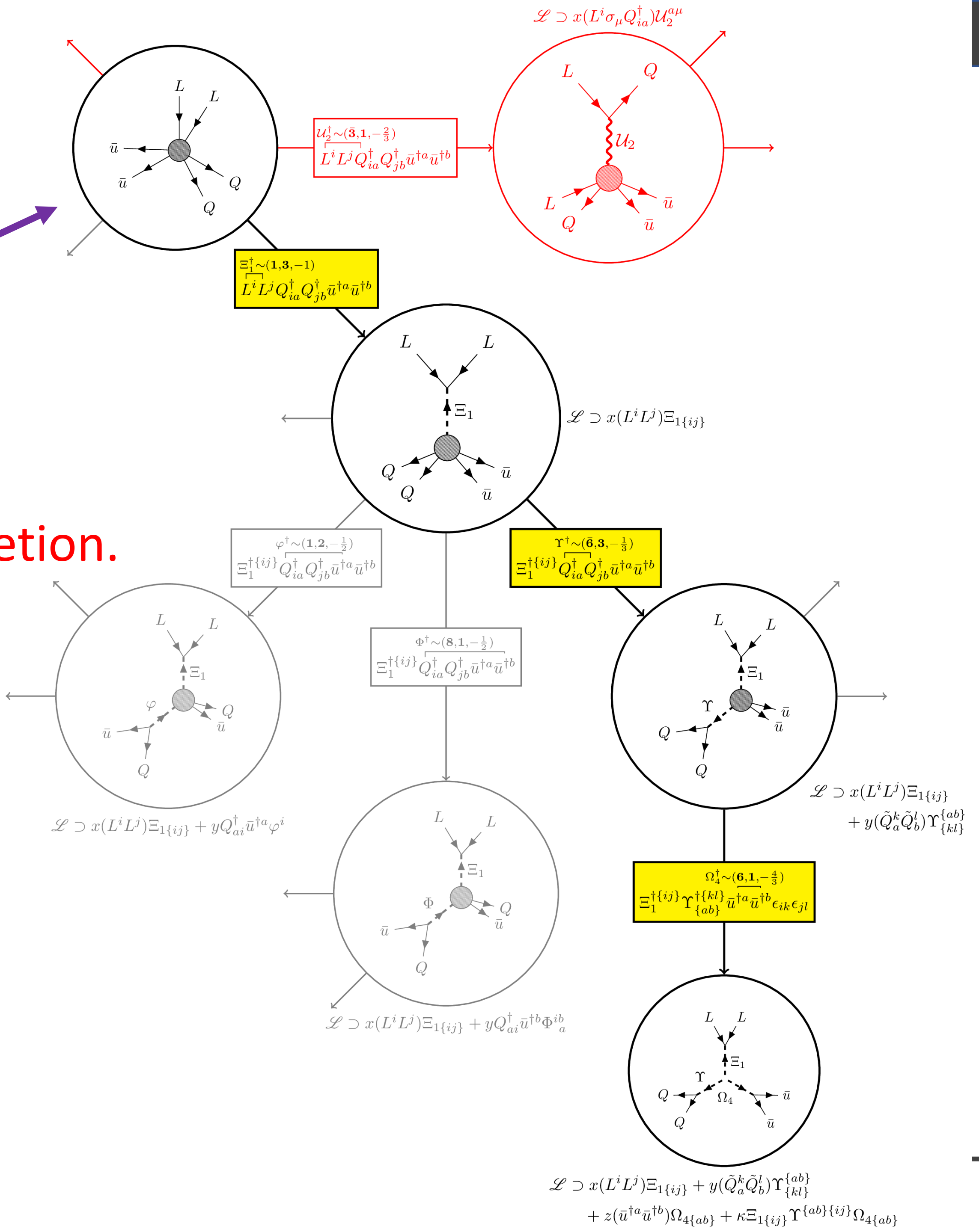
<u>Example</u>: opening of $\mathcal{O}_{12a} = L^i L^j \tilde{Q}^k \tilde{Q}^\ell \bar{u}^\dagger \bar{u}^\dagger \epsilon_{ik}\epsilon_{jl}$

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

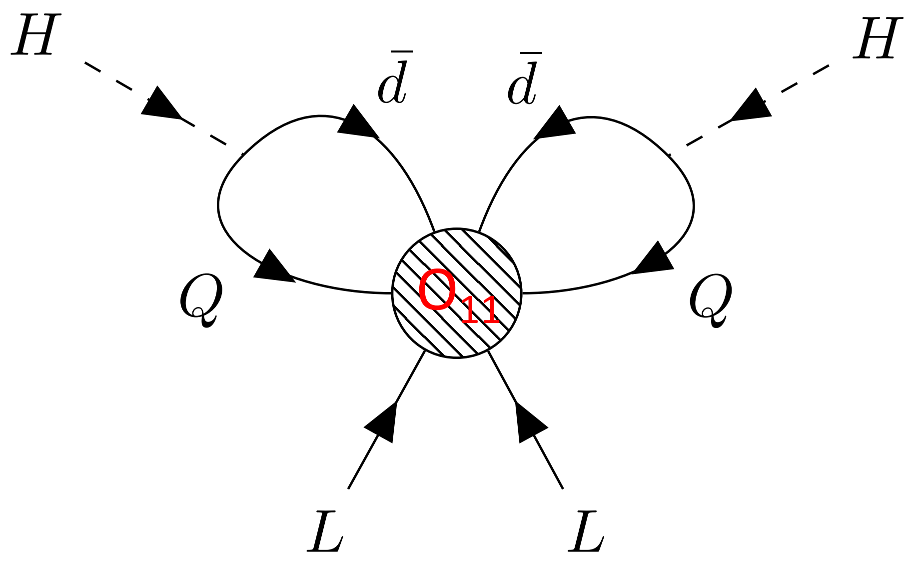
Effective operator

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

The starts of other pathways are indicated in light grey.



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.

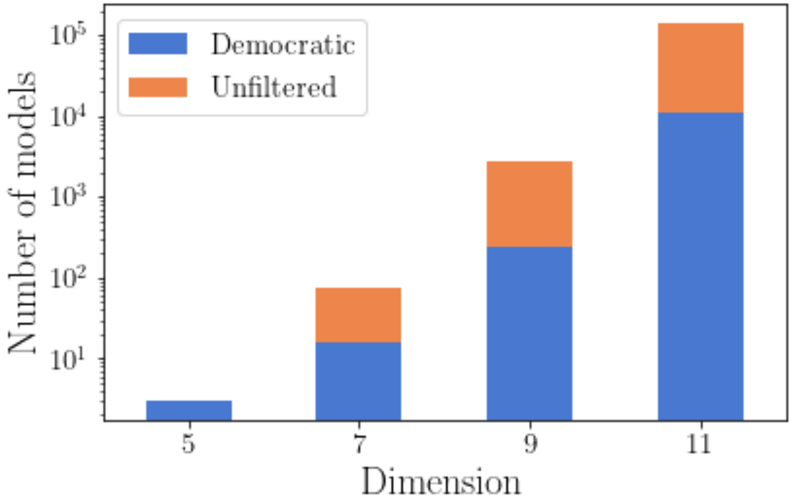
This enables the systematic construction of radiative neutrino mass models.

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)

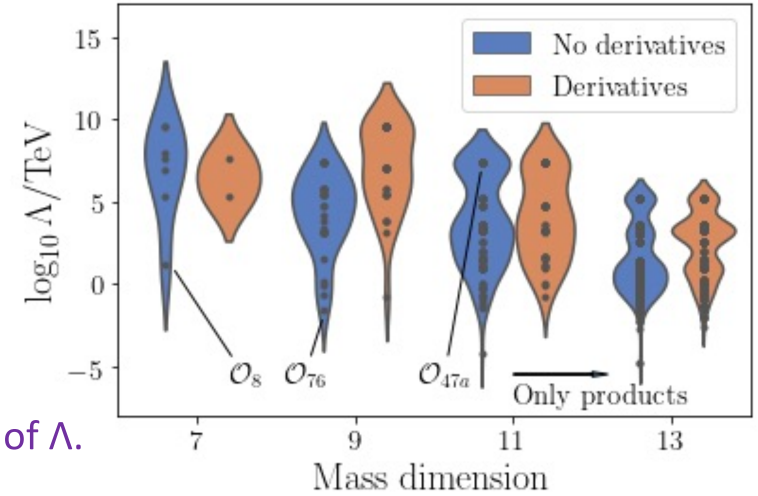
How many models?

141,989 unfiltered models
11,216 filtered models



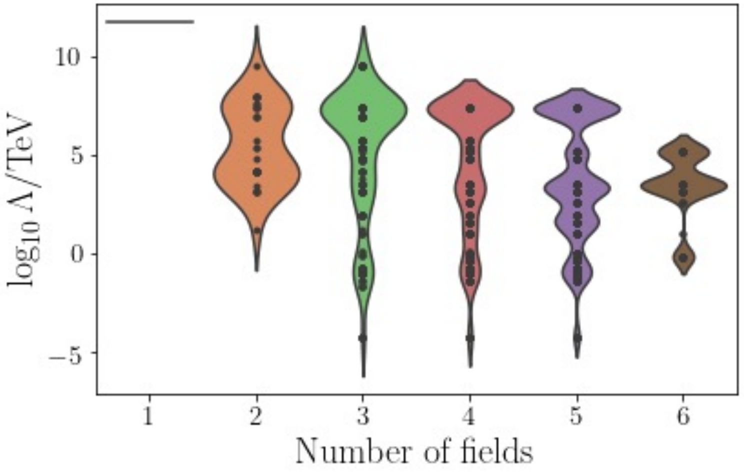
← # of models vs mass-dim

# of operators for given Λ vs mass dim for O(1) couplings →



Why stop at dim=11?
At dim=11, ave. # of Yukawas = 6,
so if each ~0.1, then 10^{-6} suppression of Λ.

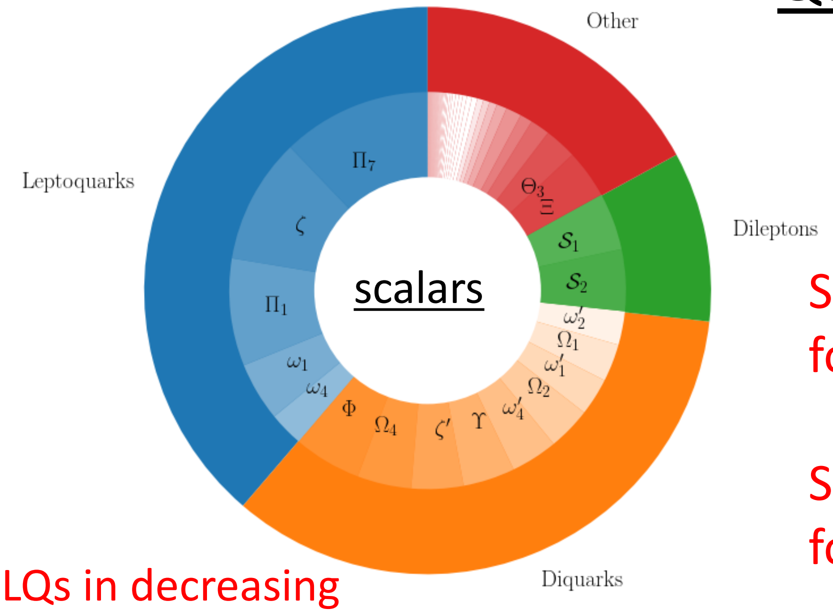
Most models have 5 exotics



New physics scale trends down (slowly) with both mass dim and # of exotics.

Many models at testable scales. Some already ruled out.

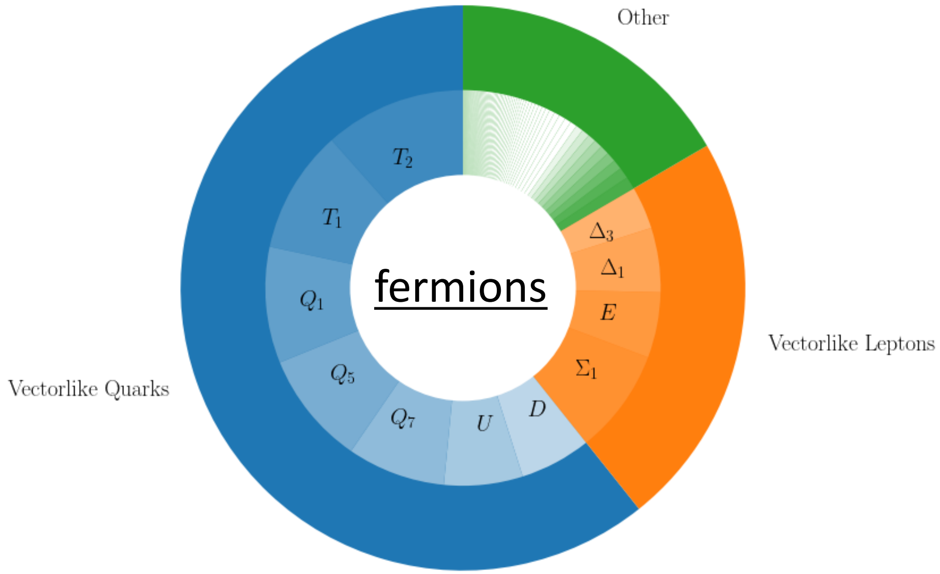
Quantum numbers of the exotics species



Name	N	E	Δ_1	Δ_3	Σ	Σ_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 of great interest for B-meson anomalies.

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
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\overline{d}_R L$	0
$\tilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	$\overline{d}_R^C e_R$	-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

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Economical and testable models: less than 4 exotic multiplets and Λ < 100 TeV

Field content	Operators	Λ [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.

6. Closing remarks

- We know neutrinos have tiny masses, but not what Lagrangian[1] to write in the textbooks.
- Whatever it is, it is New Physics.
- Neutrino mass scale probably a new mass scale in physics.
- High-scale seesaw models: well-motivated, leptogenesis benefit, but not very testable.
- Inverse and linear seesaws are interesting lower-energy alternatives.
- Radiative models have much new physics; connections with B-meson and g-2 anomalies.

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

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MIT

Stockholm University

INFN

The University Of Sheffield.

HZDR

University of Washington

Caltech

Back up slides

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

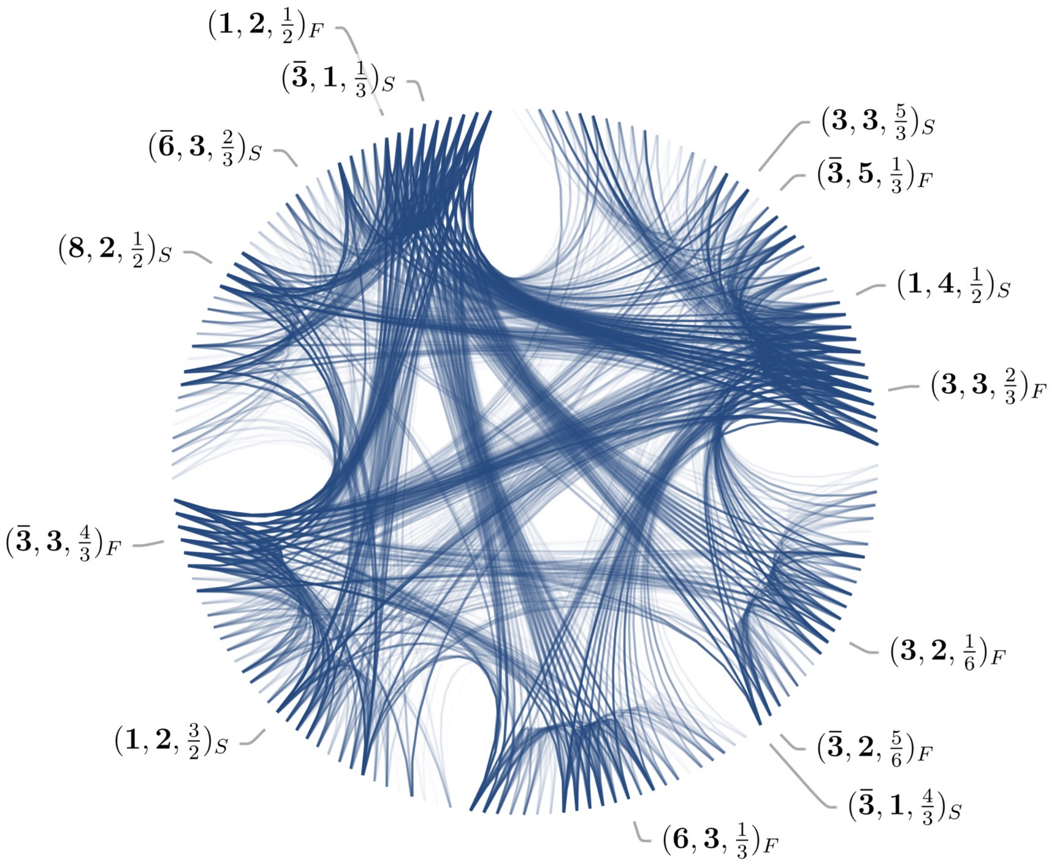
Subtlety to do with the higher-dim Weinberg ops

Zee-Babu model

Labels	Operator	Models	Filtered	Loops	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	$1 \cdot 10^{3}$

⋮

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.