ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

Neutrino theory: open questions and future opportunities

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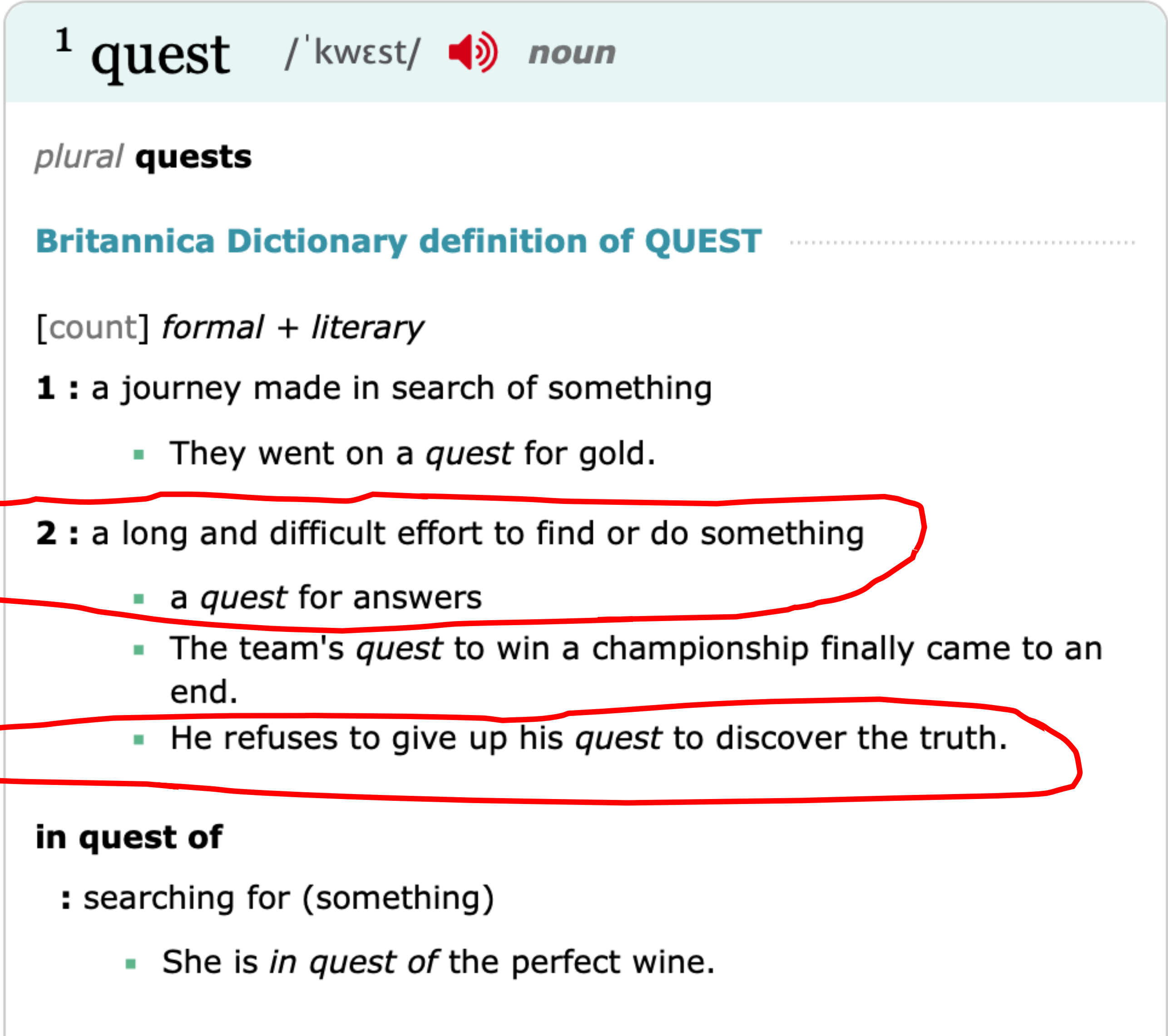
Important topics I will not cover include:

- Flavour symmetry models
- Oscillation parameter fitting
- Neutrino interactions
- CEvNS – coherent neutrino scattering
- Sterile neutrinos
- Cosmological bounds

See the many excellent talks slides on these and other topics from the parallel sessions here, and from Neutrino 2024.

Subtitle:

The quest for understanding the origin of neutrino masses



1 quest /ˈkwɛst/ ***noun***

plural **quests**

Britannica Dictionary definition of QUEST

[count] *formal + literary*

1 : a journey made in search of something

- They went on a *quest* for gold.

2 : a long and difficult effort to find or do something

- a *quest* for answers
- The team's *quest* to win a championship finally came to an end.
- He refuses to give up his *quest* to discover the truth.

in quest of

: searching for (something)

- She is *in quest of* the perfect wine.

credit: Britannica.com

Image credits: Wikipedia & Ancient Origins

Sir Galahad, the quest for the Holy Grail
by Arthur Hughes (1870)

The mad quest to revive chivalry

Don Quixote by Pablo Picasso (1955)

$$\mathcal{L}_{SM} = -\frac{1}{4}\left(B^{\mu\nu}B_{\mu\nu} + \sum_{a=1}^{3} W_a^{\mu\nu}W^a_{\mu\nu} + \sum_{b=1}^{8} G_b^{\mu\nu}G^b_{\mu\nu}\right) + i\bar{L}^i_L \not{D} L^i_L + i\bar{e}^i_R \not{D} e^i_R + i\bar{Q}^i_L \not{D} Q^i_L + i\bar{d}^i_R \not{D} d^i_R +$$

$$i\bar{u}^i_R \not{D} u^i_R + \left(D_\mu\phi\right)^\dagger\left(D^\mu\phi\right) + \mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2 + \left(\lambda_1^{ij}\bar{L}^i_L\phi e^j_R + \lambda_2^{ij}\bar{Q}^i_L\phi d^j_R + \lambda_3^{ij}\bar{Q}^i_L\phi^c u^j_R + h.c.\right)$$

+ . . . ← This is our quest!

Are we hopeful like Sir Galahad? What angels will guide us?

Or, are we mad like Don Quixote?

$$\mathcal{L}_{SM} = -\frac{1}{4}\left(B^{\mu\nu}B_{\mu\nu} + \sum_{a=1}^{3} W_a^{\mu\nu}W^a_{\mu\nu} + \sum_{b=1}^{8} G_b^{\mu\nu}G^b_{\mu\nu}\right) + i\bar{L}^i_L \not{D} L^i_L + i\bar{e}^i_R \not{D} e^i_R + i\bar{Q}^i_L \not{D} Q^i_L + i\bar{d}^i_R \not{D} d^i_R +$$

$$i\bar{u}^i_R \not{D} u^i_R + \left(D_\mu\phi\right)^\dagger\left(D^\mu\phi\right) + \underbrace{\mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2}_{\text{Higgs self-coupling to be confirmed}} + \underbrace{\left(\lambda_1^{ij}\bar{L}^i_L\phi e^j_R + \lambda_2^{ij}\bar{Q}^i_L\phi d^j_R + \lambda_3^{ij}\bar{Q}^i_L\phi^c u^j_R + h.c.\right)}_{\text{Almost all of this has not been established yet.}}$$

+ . . .

1. ν mass = new physics
2. ν mass = new mass scale?
3. Tree-level high-scale seesaw models
4. Tree-level low-scale seesaw models
5. Radiative or loop-level models
6. Closing remarks

1. ν mass = new physics

Minimal standard model:

no RH neutrinos, no Y=1 scalar triplet ⇒ massless neutrinos, perturbative $L_{e,\mu,\tau}$ conservation

$Q = I_3 + Y$

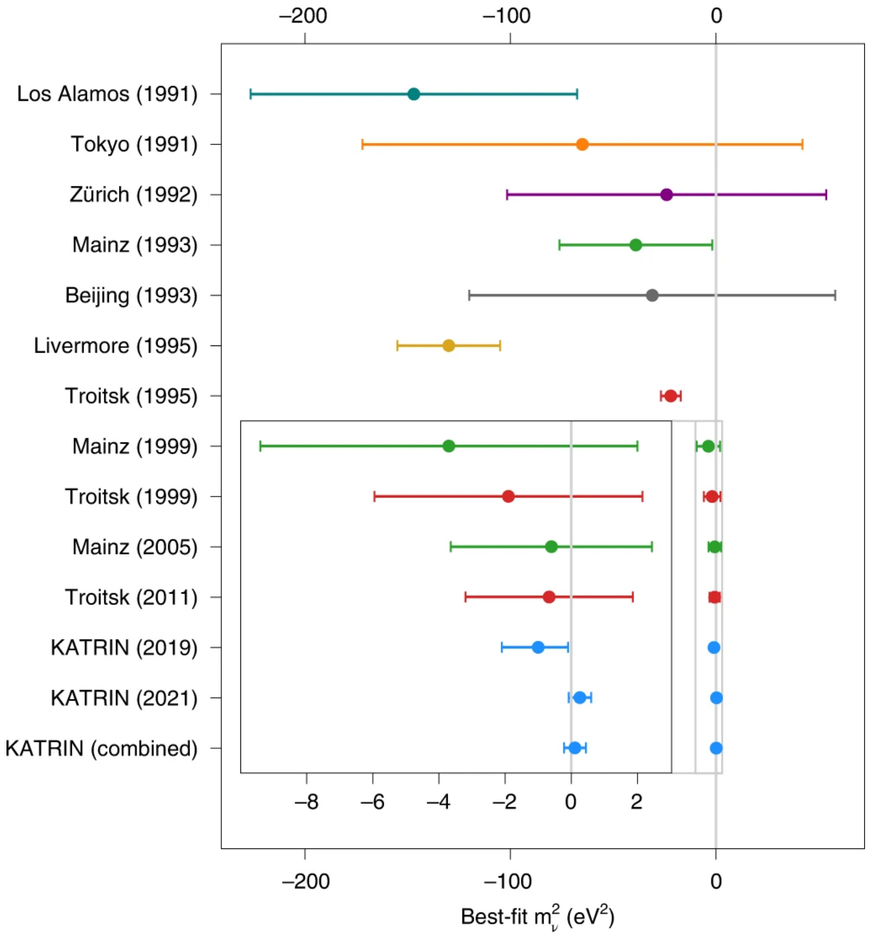
Massive neutrinos may be Dirac or Majorana.

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*.)

2. ν mass = new mass scale?

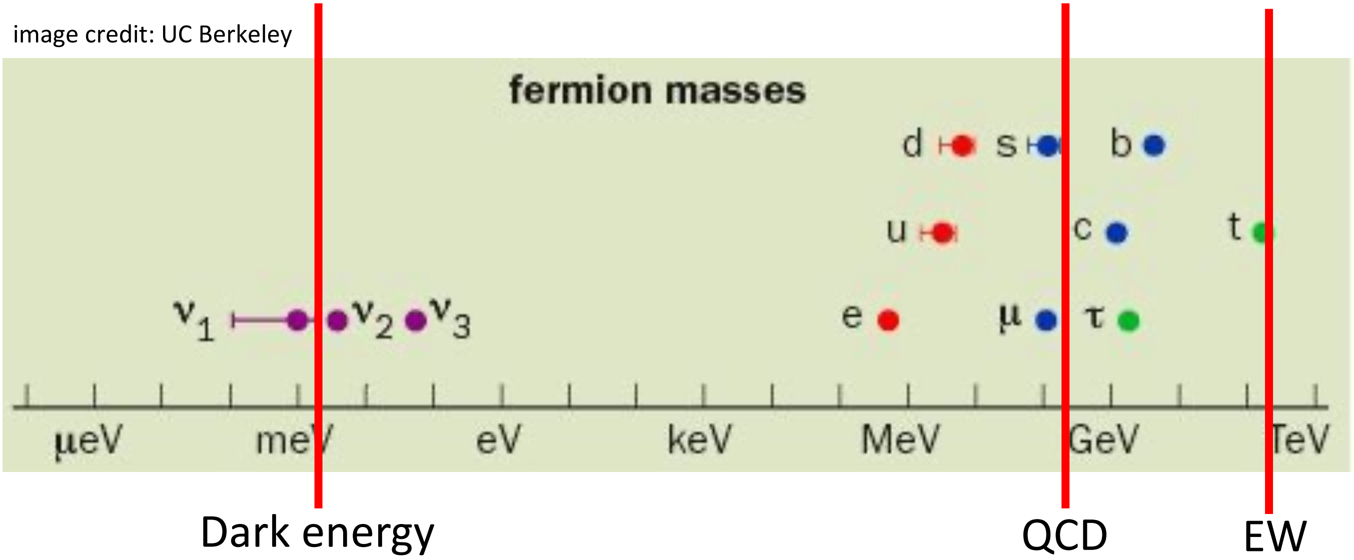
image credit: Nature Physics, KATRIN



KATRIN β-decay endpoint: $m_\nu \lesssim 0.45 \text{ eV}$ Weisinger talk

Cosmology: $m_\nu \lesssim 0.1 \text{ eV}$

image credit: UC Berkeley



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

Dirac ν with Yukawa coupling ~ 10^{-12} ?

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

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

Side remark: not yet proven that even the b and τ masses must have SM origin.

Radiative origin also works. Baker, Cox, RV 2021a, 2021b

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. Tree-level high-scale seesaw models

Talks: many!

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

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

⇒ Majorana neutrinos

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

seesaw formula

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

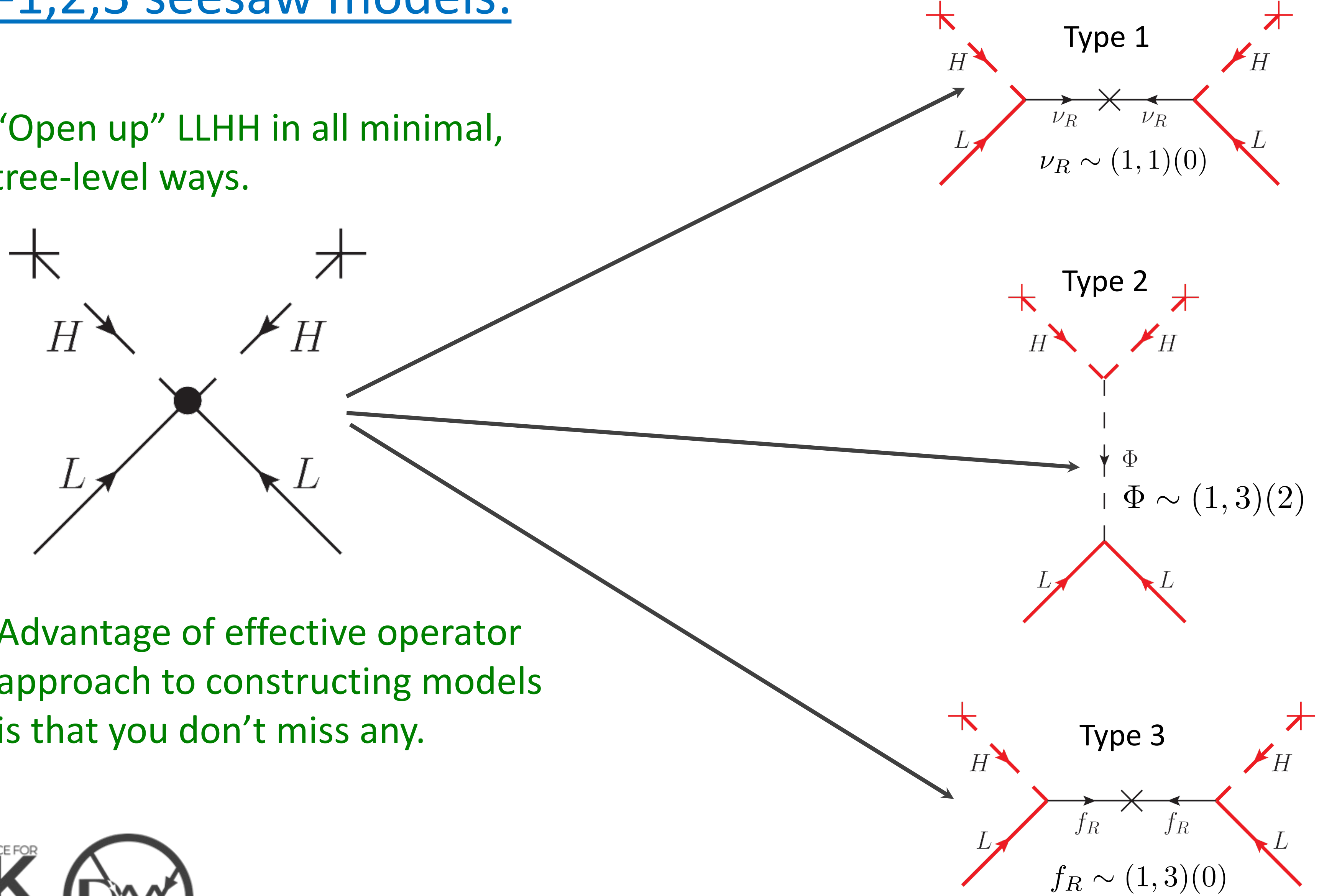
i.e. seesaw effect when L-violation scale very high

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

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

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

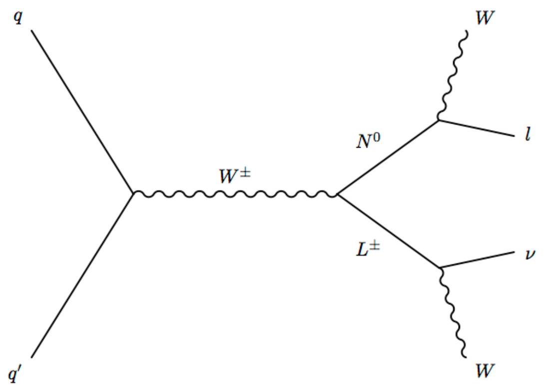
Type 2 and 3: Mediators have EW quantum numbers.

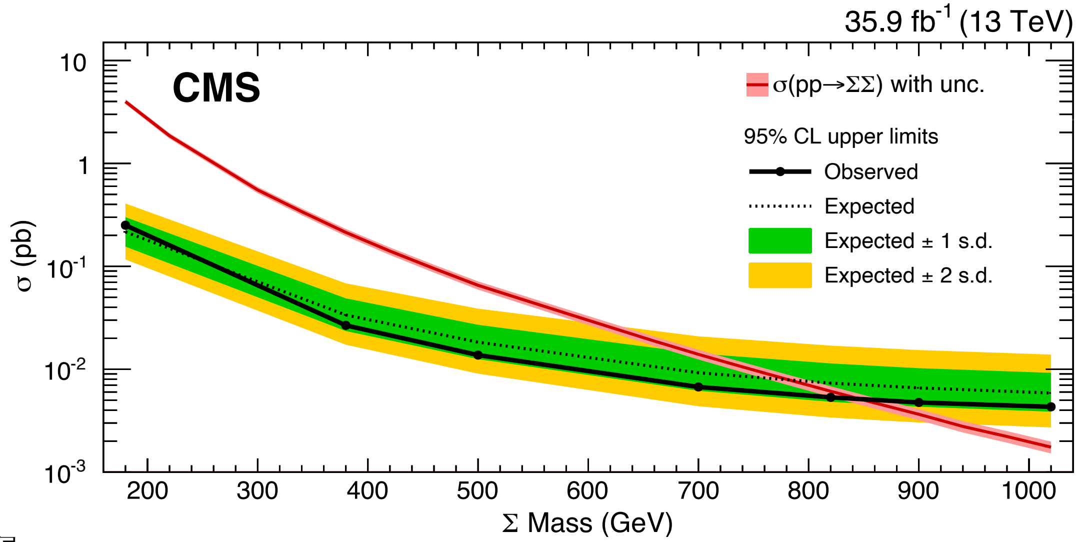
Better (but not great) prospects at colliders.

Example of search and bound: type 3 seesaw.

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

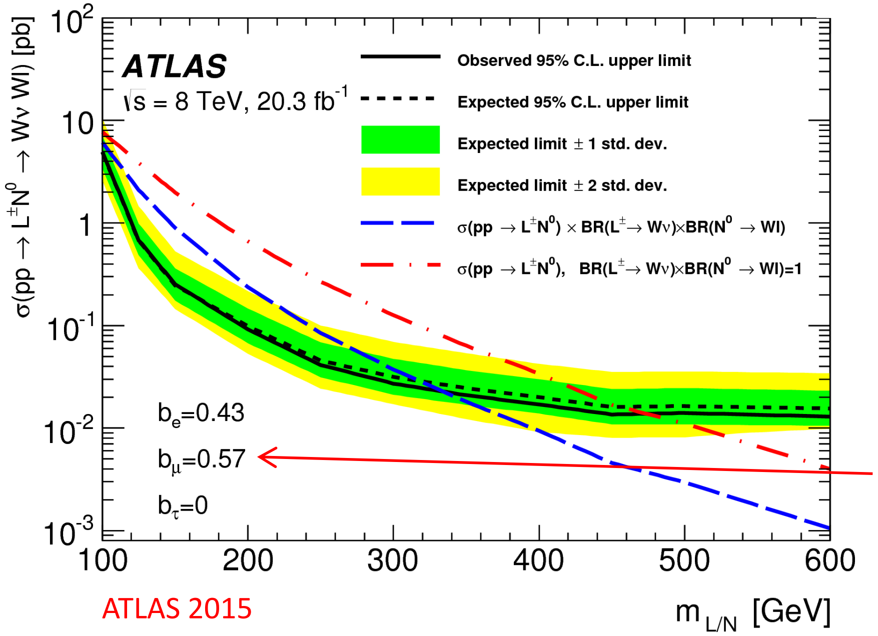
Heavy lepton EW pair production.





CMS 2017

Flavour democratic BR choice



ATLAS 2015

Benchmark BR

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, νDFSZ+VISHν)

Langacker, Peccei, Yanagida 1986
Shin 1987
Salvio 2015, 2019
Ballesteros+ 2017a, 2017b, 2019
RV+ 1988; Clarke, RV 2016
Sopov, RV 2022

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

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

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

4. Tree-level low-scale seesaw models

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

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

The triplet scalars are not needed. Doublets suffice.

SO(10) level:

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

126 can be replaced by 16.

Putting in mass scales: $\begin{bmatrix} 0 & m & m_L \\ m & 0 & m_R \\ m_L & m_R & \mu \end{bmatrix}$

Inverse seesaw: $m_L = 0$ and $\mu \ll m \ll m_R$

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

Light neutrino mass:

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

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.

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

Akhmedov+ 1996
Malinksý, Ramão, Valle 2005

Light neutrino mass:

$$\boxed{m_\nu \sim \frac{m m_L}{m_R}}$$

$m_L=0$ 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 ~ 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?

For discovery prospects for ν-mass and leptogenesis-related heavy neutral leptons see e.g. talks by A. Golutvin (SHiP) & N. Valle (FCC-ee), and the theory papers (very incomplete, sorry!):

Drewes+ 2024; Drewes+ 2022; Hernández+ 2022; Klarić+ 2021; Drewes+ 2017; Hernández+ 2016; Canetti+ 2013

5. Radiative or loop-level models

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

Systematic model-building and classification procedure.

Two complementary approaches:

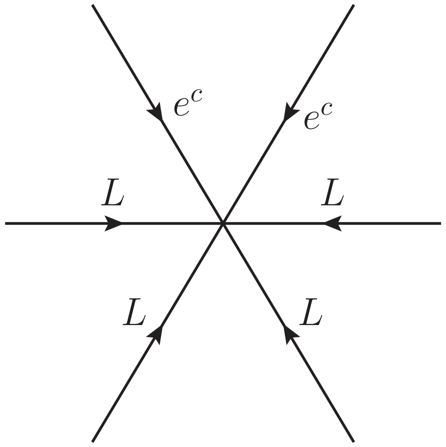
(Generalised) Weinberg operators $\frac{\lambda}{M^{1+2n}} LLHH(H^\dagger H)^n$ Valencia group: Hirsch, Cepedello et al (many papers)

Non-Weinberg operators → ν self-energy graphs with both SM particles and exotics

Babu, Leung 2001
de Gouvêa, Jenkins 2008
Melbourne group:
Bigaran, Gargalionis, RV et al
(many papers)

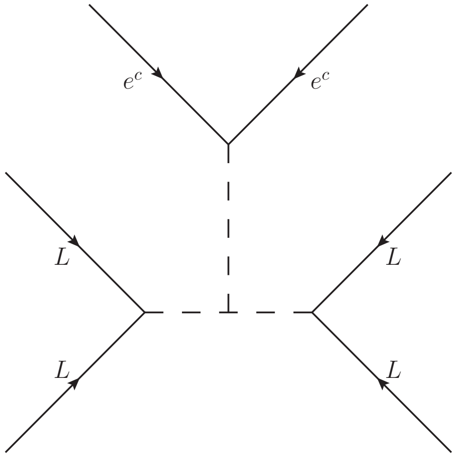
Talks by Vatsyayan, Santos Leal, Mohanta, Cárcamo Hernández, Sadhukhan, De Melo, Fridell. (Apologies if I missed any!)

Historic example: Zee-Babu model



$$O_9 = LLLe^cLe^c$$

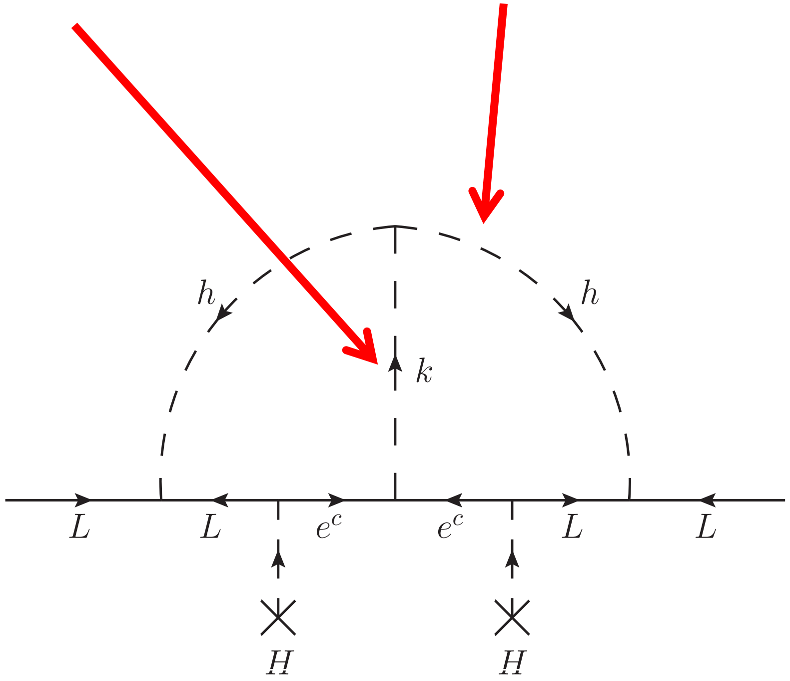
Effective op



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.

Rich phenomenological implications.

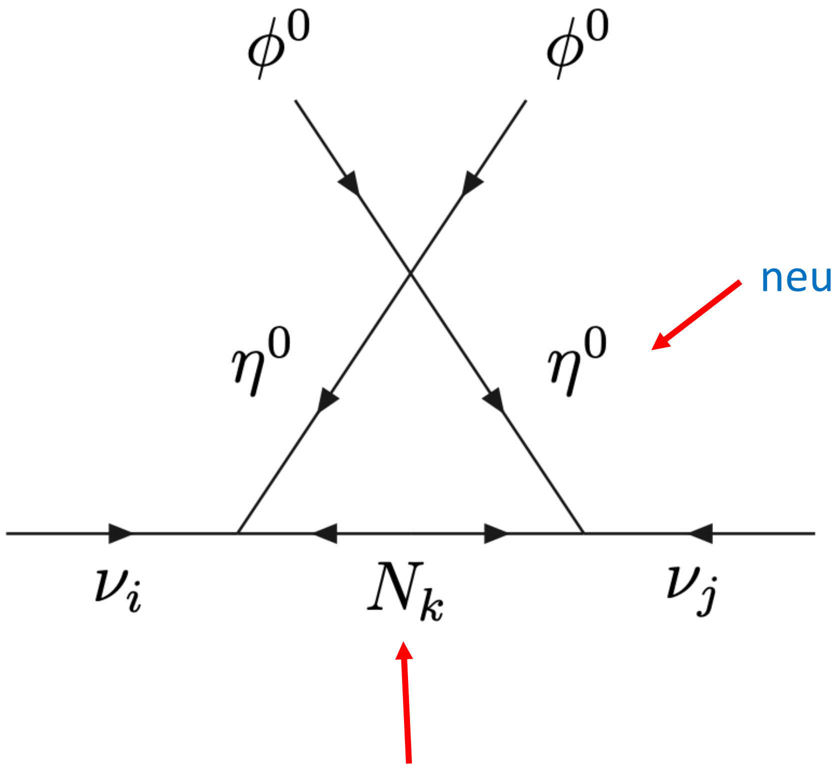
Connections with many other areas e.g.

- Dark matter e.g. scotogenesis
- Charged-lepton flavour violation
- Quark flavour physics
- Collider searches for exotics
- Anomalous magnetic moments
- CPV and electric dipole moments

Dark matter connection e.g. scotogenesis

Ma 2006
Many subsequent papers

Talks: e.g. Mohanta,
Cárcamo Hernández,
Sadhukhan, De Melo



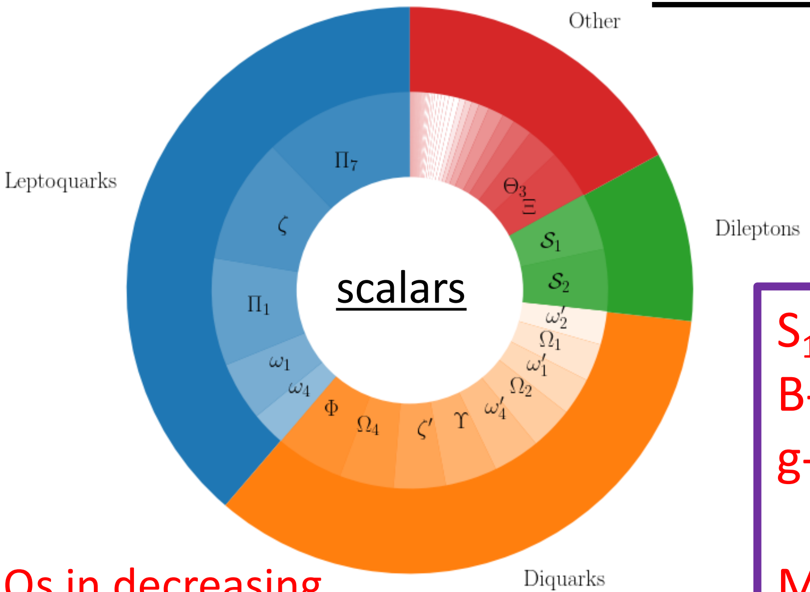
neutral component of inert scalar doublet

Both are Z_2 odd DM candidates

heavy neutral Majorana fermions

Quantum numbers of the exotics

From survey by Gargalionis, RV 2021



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, R_2 of great interest for the B-meson $R_{D(*)}$ anomaly and g-2 and EDM of muon and electron.

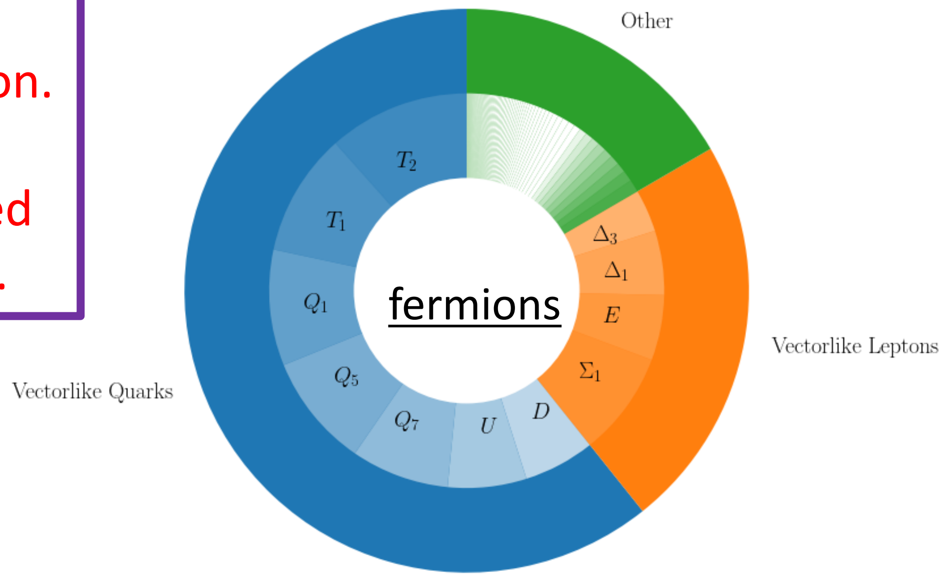
Most induce quark and/or charged lepton flavour BSM at some level.

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
$\widetilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	$\overline{d}^C_R e_R$	-2
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$\overline{Q}^C L$, $\overline{u}^C_R e_R$	-2

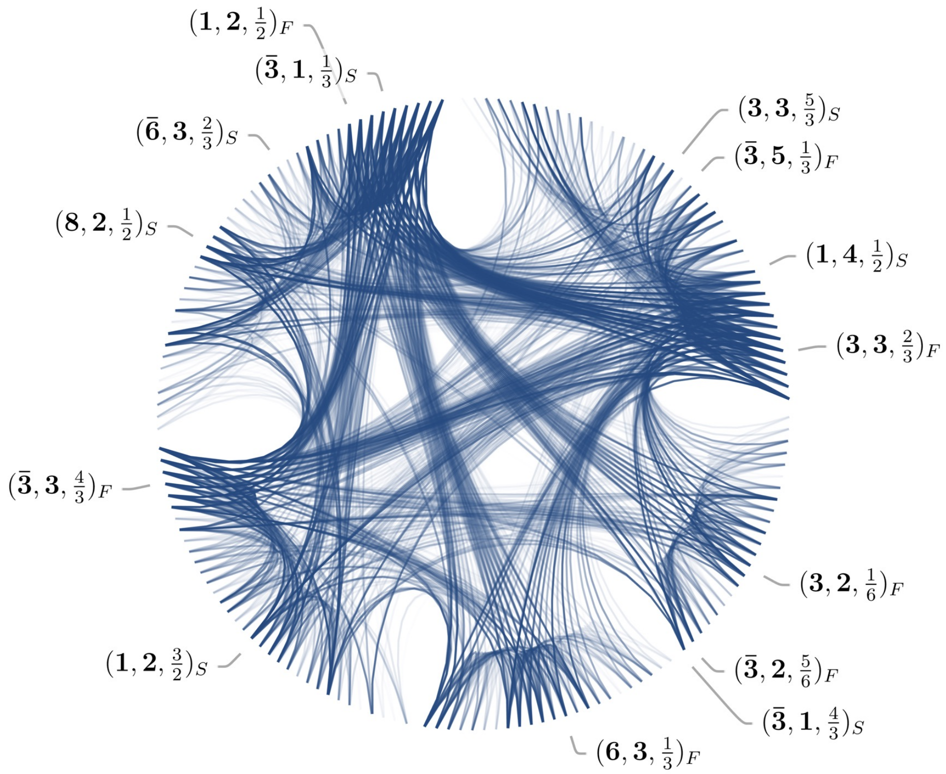
Table from Doršner+ 2020



Very relevant for collider searches.

Which exotics often occur together?

From survey by Gargalionis, RV 2021



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.

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6. Closing remarks

- We know neutrinos have tiny masses, but not what Lagrangian 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.
- The νMSM, inverse and linear seesaws are interesting lower-energy alternatives.
- Radiative models have much New Physics: charged-fermion flavour effects, g-2 contributions, and collider search targets for exotica.

Reasonable things to hope for:

Positive neutrinoless double beta decay signal.
Low mass heavy neutral leptons.
Charged-lepton flavour violation.
Deviations in g-2.
Non-SM quark flavour effects.
Exotica at (future?) colliders.

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