A tale of two models of lepton number violation

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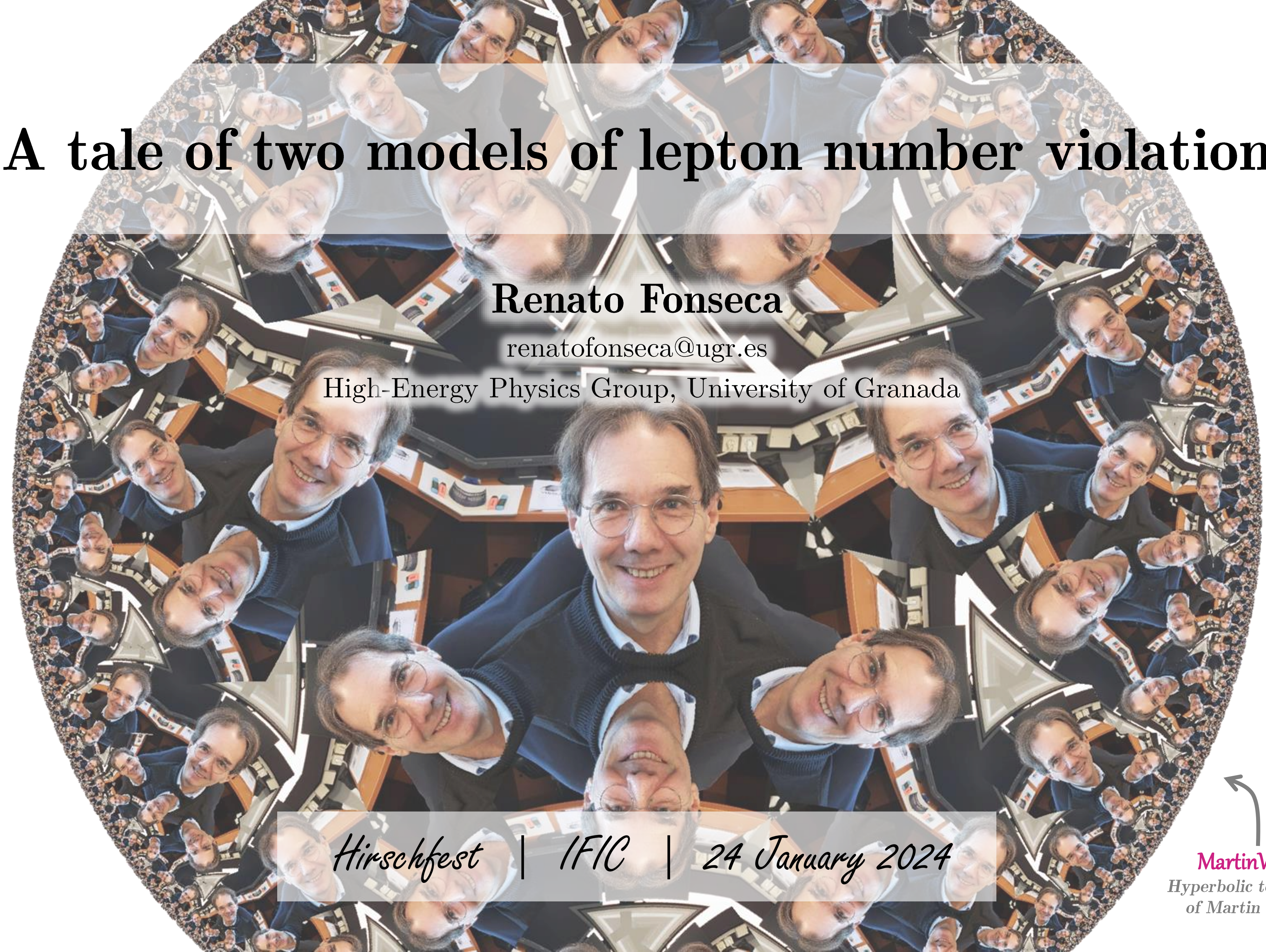

MartinWorld
Hyperbolic tessellation of Martin at work.

My 11 papers with Martin

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You may know Martin as a model killer, but he is also a model builder

I will therefore highlight this part of his research with two examples

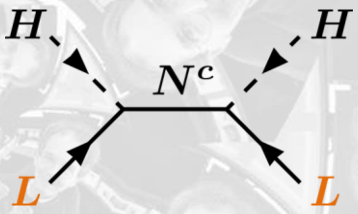
Lepton number violation

$\Delta L = 2$ and $\Delta B = 0$

Lepton number violation (LFV) brings to mind Majorana neutrino masses, neutrinoless double beta decay, and events with jets plus two same-sign charged lepton at the LHC

$LLHH$

Generated via the type-I seesaw mechanism (for example)



Minkowski (1977) Gell-Mann, Ramond, Slansky (1979) Mohapatra, Senjanovic (1980) Schechter, Valle (1980)

$(A, Z) \rightarrow (A, Z \pm 2) + 2e^{\mp}$

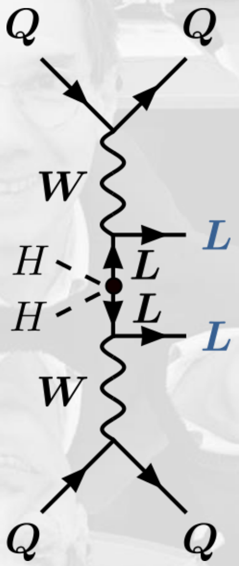
Operators:

$QQ\overline{QQ}LLHH$

+others

Note that $0\nu 2\beta$ can be induced in many other ways

Bonnet, Hirsch, Ota, Winter (2012)



$pp \rightarrow jets + \ell^{\pm}\ell'^{\pm}$

In left-right symmetric models for example:

Keung, Senjanović (1983)

Lepton number violation

$\Delta L = \pm 1$ and $\Delta B = 1$

But let us not forget that **lepton number can be violated by one unit**. However $Z_2(B+L)$ invariant implies that that **baryon number must also be violated**.

Nucleon decay

The proton is very stable. **Upper limits on its mean partial lifetime** depend on the decay channel

$$\tau\left(p \to e^+ \pi^0\right) > 8.2 \times 10^{33} \text{ years (90\% C.L.)}$$

Nishino et. al. [Super-Kamiokande] (2009)

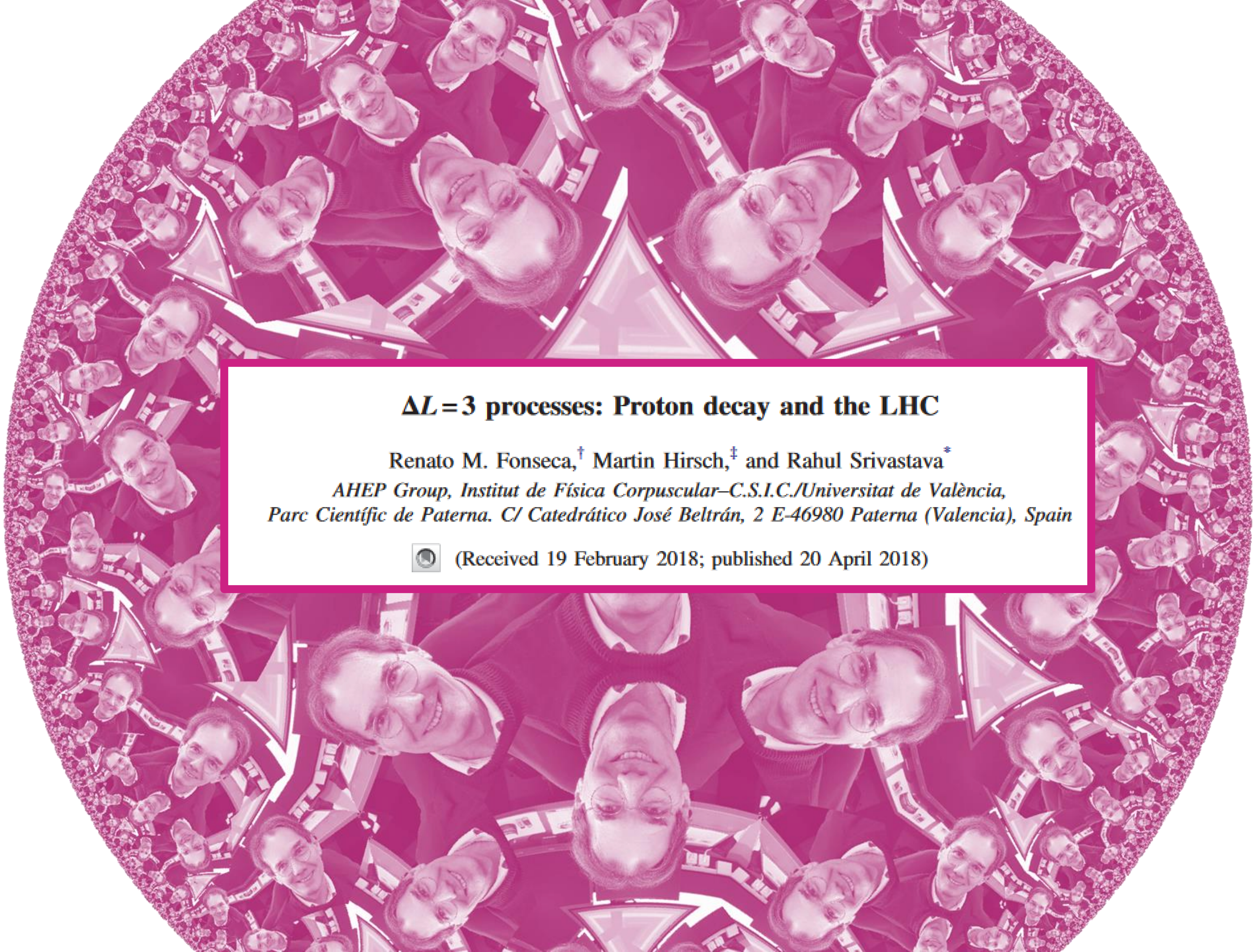
Dimension 6 ($L = -B = -1$) and 7 ($L = B = 1$) induce these processes

$$\frac{1}{\Lambda^2}\left[\begin{array}{c} QQQL \\ \overline{u^c}QQ\overline{e^c} \\ \overline{u^c}\overline{d^c}QL \\ u^c u^c d^c e^c \end{array}\right. \qquad \frac{1}{\Lambda^3}\left[\begin{array}{l} (\partial d^c)\, d^c d^c \overline{e^c} \\ d^c d^c Q\left(\partial \overline{L}\right) \end{array}\right.$$

$$\tau(p) \sim \left[\Gamma(p)\right]^{-1} \sim \left(\frac{m_p^5}{\Lambda^4}\right)^{-1}$$

$$\Rightarrow \Lambda \gtrsim 10^{16} \text{ GeV}$$

Very heavy mediators
(and/or tiny couplings)



$\Delta L = 3$ processes: Proton decay and the LHC

Renato M. Fonseca,[†] Martin Hirsch,[‡] and Rahul Srivastava[*]
AHEP Group, Institut de Física Corpuscular–C.S.I.C./Universitat de València,
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(Received 19 February 2018; published 20 April 2018)

What about $|\Delta L| = 3$?

We do not know if lepton number can be violated in 1 or 2 units **BUT ...**

$U(1)_B$ and $U(1)_L$ are anomalous in the Standard Model. Transitions between vacua with different B and L are possible

t'Hooft (1976)

(this is a consequence of the axial anomaly: the divergence of the axial current does not vanish for massless fermions)

Bell, Jackiw (1969)
Adler (1969)

instantons and sphalerons:

$$\Delta B = \Delta L = N_{\text{families}}$$

Belavin et al. (1975)
t'Hooft (1976)
Klinkhamer, Manton (1984)

Hence the SM is $Z_3(L)$ invariant

It would certainly be extremely interesting to observe these processes at colliders (note that, in theory, all relevant parameters are known)

$$E_{sphaleron} \sim \frac{m_W}{\alpha_W} \sim 9 \text{ TeV}$$

$$q + q \rightarrow 7\bar{q} + 3\bar{\ell} + \underbrace{n_W}_{\text{dozens}} W + n_h h$$

$(n_W, n_h \sim \alpha_W^{-1})$

What about perturbative violation of lepton number in 3 units, at low energies

For $\Delta B = \pm 1$ nucleon decay becomes possible

Is proton decay a concern?

Not really

Let us estimate the proton decay lifetime
as a function of the new physics scale

What is the relevant operator?

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$\underline{eee}$ ______ ______

3 charged leptons

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$eee\,uuu\bar{d}$ ______

3 charged leptons

quarks for charge conservation

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$$\underbrace{eee}\underbrace{uuu\bar{d}}\underbrace{(H \text{ or } \partial)}$$

- 3 charged leptons
- quarks for charge conservation
- Under the full SM gauge group a derivative/Higgs is needed

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Dimension 13 operator: suppressed by a factor $c \sim 1/\Lambda^9$

Usual dim 6 proton decay ($c \sim 1/\Lambda^2$)

$$\left[\tau_{1/2}(p)\right]^{-1} \sim \Gamma(p) \sim m_p^5 c^2$$

$$\sim 10^{32}\left(\frac{m_p}{\Lambda}\right)^4 \text{y}^{-1} \Rightarrow \Lambda \gtrsim 10^{16}\text{ GeV}$$

CURRENT case ($c \sim 1/\Lambda^9$)

$$\left[\tau_{1/2}(p)\right]^{-1} \sim \Gamma(p) \sim m_p^{19} c^2$$

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3 charged leptons — quarks for charge conservation — Under the full SM gauge group a derivative/Higgs is needed

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May show up at the LHC!

$|\Delta L| = 3$ operators

Note:

Operators which create/destroy 3 charged leptons must have dimension 13 or higher. However, there are lower dimensional ones involving neutrinos

This is important: even if Nature is $Z_3(L)$ invariant and as a consequence the proton decays necessarily into 3 (anti)leptons, we may not be able to verify this if the main decay modes contain (anti)neutrinos in the final state

(colliders would be the only way)

So, let us look at the lowest dimensional $|\Delta L| = 3$ operators (and $\Delta B = 1$)

dim 9, $\Delta L = 3$

$$\mathcal{O}_9^1 = \overline{u^c}\,\overline{u^c}\,\overline{u^c}\,\overline{e^c} L L$$

$$\mathcal{O}_9^2 = \overline{u^c}\,\overline{u^c} Q L L L$$

no proton decay

dim 10, $\Delta L = -3$

$$\mathcal{O}_{10} = \overline{d^c}\,\overline{d^c}\,\overline{d^c}\,\overline{L}\,\overline{L}\,\overline{L} H^*$$

dim 11, $\Delta L = 3$

$$\mathcal{O}_{11}^1 = \partial\partial \overline{u^c}\,\overline{u^c} Q L L L$$

$$\mathcal{O}_{11}^2 = \partial Q \overline{u^c}\,\overline{u^c} L L \overline{e^c} H$$

+others

dim 12, $\Delta L = -3$

(more operators)

dim 13, $\Delta L = 3$

$$\mathcal{O}_{13}^1 = \partial \overline{u^c}\,\overline{u^c}\,\overline{u^c}\,\overline{u^c} d^c \overline{e^c}\,\overline{e^c}\,\overline{e^c}$$

$$\mathcal{O}_{13}^2 = \partial \overline{u^c}\,\overline{u^c} d^c Q Q \overline{e^c} L L$$

+others

With a $U(1)_{3B-L}$ symmetry, proton decay is induced by operators of dim 11 or higher

A specific model

Besides these model independent considerations, in our paper we have a particular example, with rough estimates for the proton decay rate and production rate of the new particles (which mediate B and L violation) at the LHC

$$N, N^c = (1,1,0)$$
$$S_u = (\overline{3}, 1, -2/3)$$
$$S_d, S_d' = (\overline{3}, 1, 1/3)$$

all $L = -1$
except $L(N) = 1$

$$\mathscr{L} = \mathscr{L}_{SM} + Y_\nu L N^c H + Y_1 \overline{u^c}\,\overline{N^c} S_u + Y_2 N^c d^c S_d^* + Y_3 \overline{e^c u^c} S_d' + Y_4 Q L S_d + \mu S_u S_d S_d' + m_N N N^c + \cdots$$

Some remarks

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Besides these model independent considerations, in our paper we have a particular example, with rough estimates for the proton decay rate and production rate of the new particles (which mediate B and L violation) at the LHC

$$N, N^c = (1,1,0)$$
$$S_u = (\overline{3}, 1, -2/3)$$
$$S_d, S_d' = (\overline{3}, 1, 1/3)$$

all $L=-1$ except $L(N)=1$

$$\mathscr{L} = \mathscr{L}_{SM} + Y_\nu L N^c H + Y_1 \overline{u^c}\,\overline{N^c} S_u + Y_2 N^c d^c S_d^* + Y_3 \overline{e^c u^c} S_d' + Y_4 QLS_d + \mu S_u S_d S_d' + m_N N N^c + \cdots$$

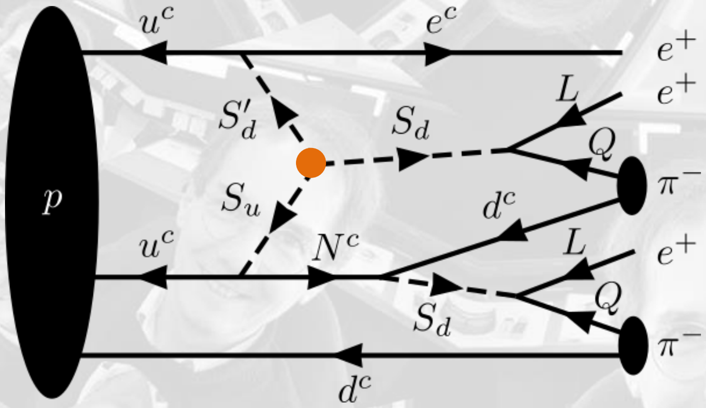
Some remarks

- The μ term is critical: in the limit $\mu \to 0$ both B and L are conserved
- Neutrinos are Dirac particles (as expected, since Majorana masses are forbidden by the $Z_3(L)$ symmetry)
- Note that S_d and S_d' have the same quantum numbers, hence they can have the same couplings. However, the product of leptoquark couplings to both L- and R-handed fermions is more constrained than each coupling individually, hence we assume that each scalar couples to either $\overline{e^c u^c}$ or QL (this arrangement can be achieved automatically by complicating the model). We consider this scenario to lower the leptoquark masses and enhance the proton decay rate.
- A $Z_3(L)$ symmetry was used, but it can be shown that the Lagrangian is $U(1)_{3B-L}$ invariant (*B=-1*, *L=3* processes are therefore absent)

Proton decay

(I will not discuss LHC phenomenology)

5-body



All decay particles visible

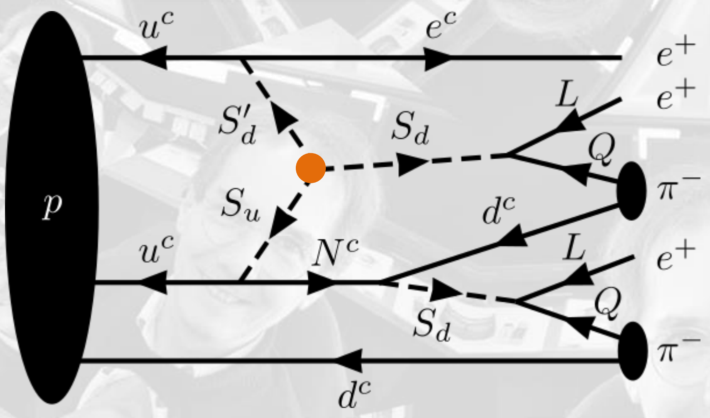
3 shower-like Cherenkov rings
+
2 nonshower-like rings

But Super(Hyper)-K and DUNE cannot distinguish electrons from positrons

Proton decay

(I will not discuss LHC phenomenology)

5-body



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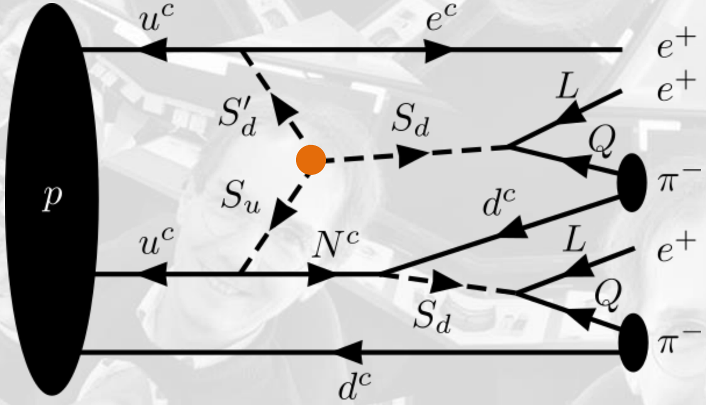

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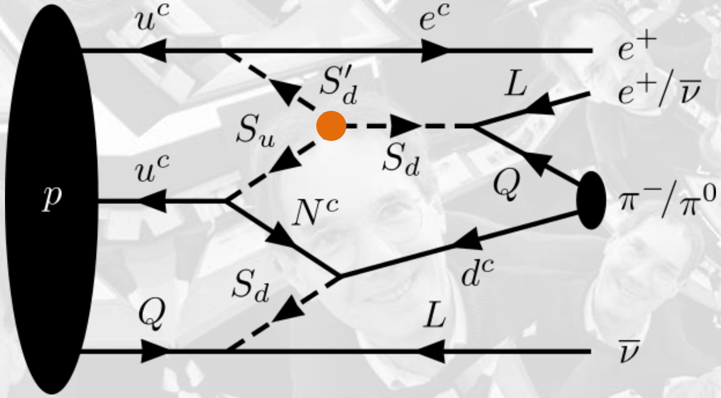
+
2 nonshower-like rings

But Super(Hyper)-K and DUNE cannot distinguish electrons from positrons

4-body

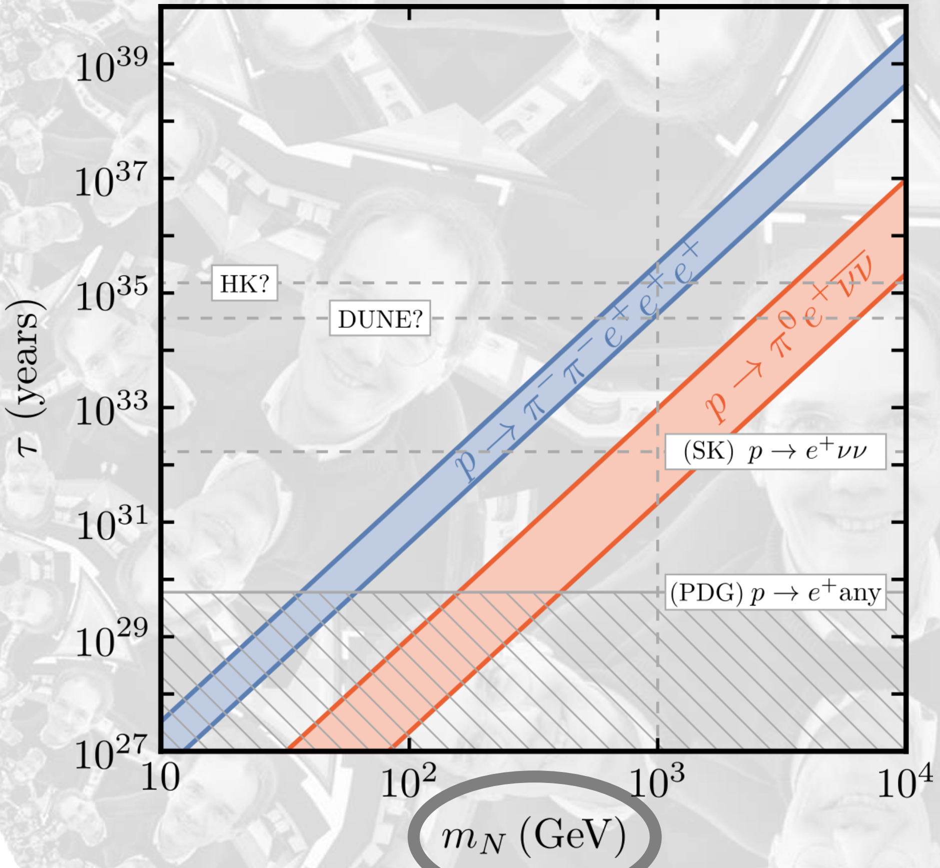


At least one neutrino is undetected

4-body decay enhanced over the 5-body decay

Proton decay

Benchmark scenario



Right-handed neutrino masses
(the only parameter left free)

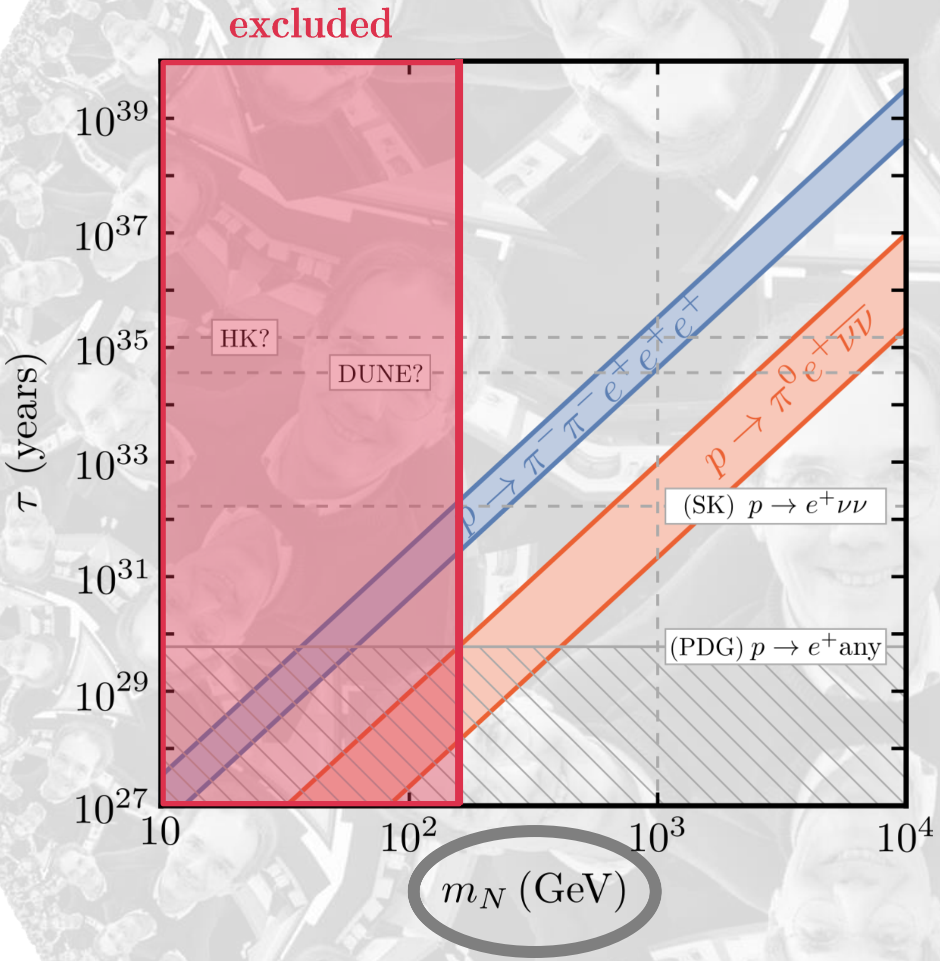
All parameters fixed except the right-handed neutrino mass scale

Yukawa couplings: ~1
Scalar masses: 1 TeV
μ : 10 TeV

(favors an enhanced proton decay rate)

Proton decay

Benchmark scenario



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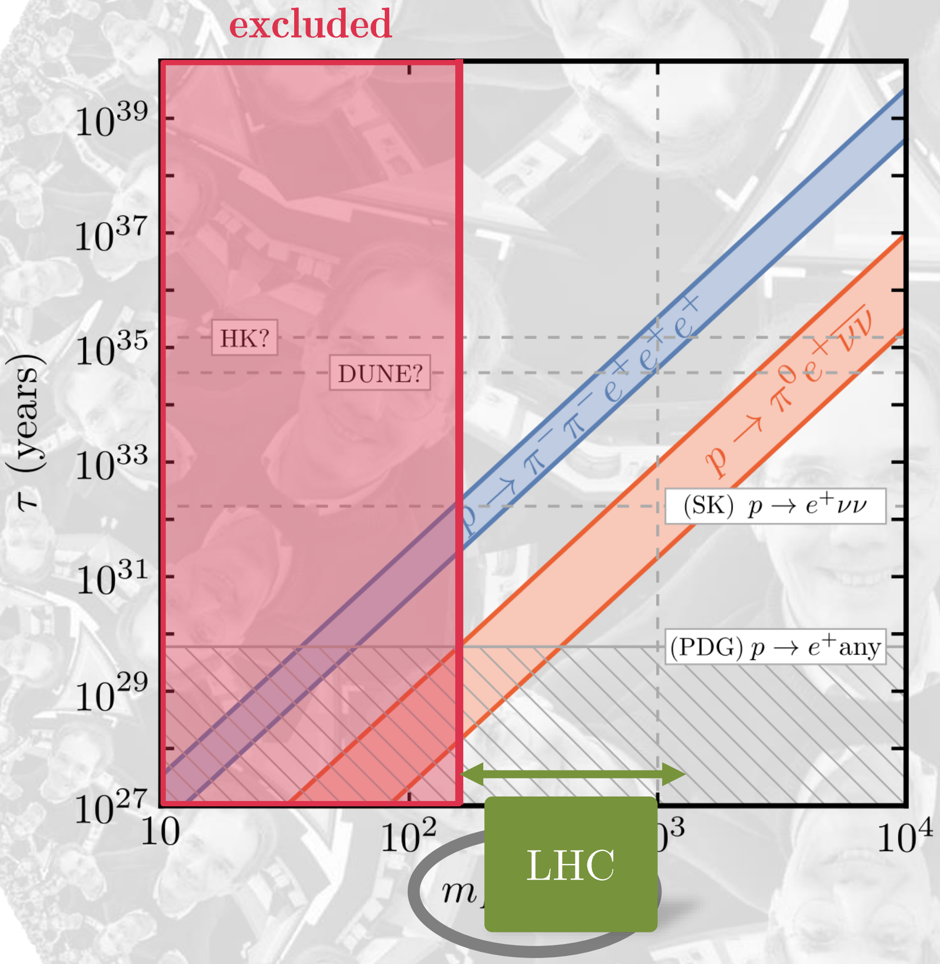

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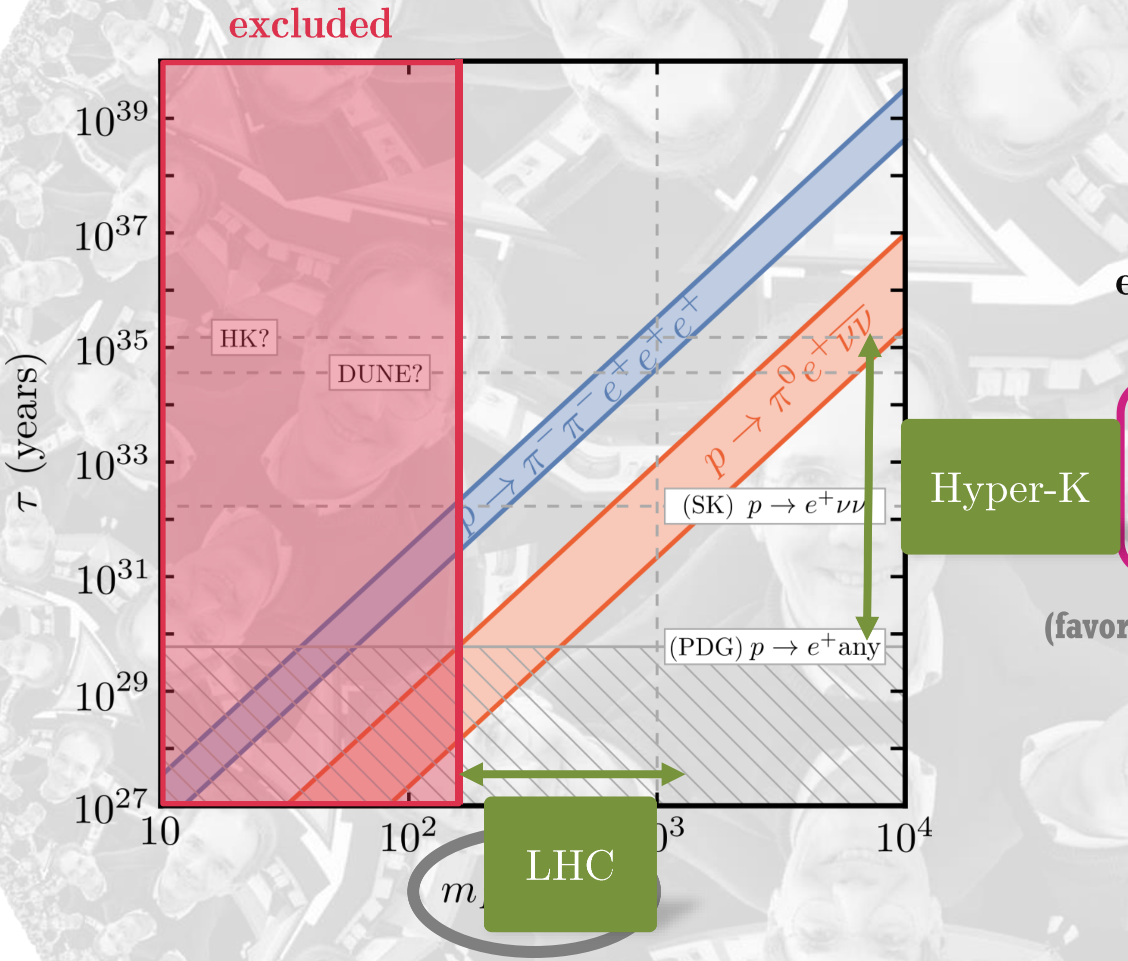

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A flipped 331 model

PUBLISHED: *August 1, 2016*

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331 models

$$SU(3)_C \times \underbrace{SU(3)_L \times U(1)_X}_{\supset\ SU(2)_L \times U(1)_Y}$$

The SM hypercharge is a combination of the X charge with the 8th generator of $SU(3)_L$

$$Y = \beta T_8 + X$$

Interestingly, the β parameter can take several different values

The SM doublet of leptons L must be promoted to a triplet of $SU(3)_L$ and the charge of the third component depends on this β.

$$\psi_\ell = \begin{pmatrix} \nu_L \\ \ell_L \\ N^c \end{pmatrix} \quad \beta = -1/\sqrt{3}$$

Singer, Valle, Schechter (1980)

$$\psi_\ell = \begin{pmatrix} \nu_L \\ \ell_L \\ \ell^c \end{pmatrix} \quad \beta = -\sqrt{3}$$

Pisano, Pleitez (1992), Frampton (1992)

$$\psi_\ell = \begin{pmatrix} \nu_L \\ \ell_L \\ E^- \end{pmatrix} \quad \beta = 1/\sqrt{3}$$

Pleitez (1996), Özer (1996)

$$\psi_\ell = \begin{pmatrix} \nu_L \\ \ell_L \\ E^{--} \end{pmatrix} \quad \beta = \sqrt{3}$$

We called it model X in RF, Hirsch (2016)

To avoid fractionally charged particles, one cannot go beyond these values

331 models

Importantly, 331 models are said to predict 3 generations. Here's why:

In order to cancel the $(SU(3)_L)^3$ anomaly, one needs as many triplets of this group as anti-triplets

Left-handed leptons: 3 triplets
Left-handed quarks:
2x3=6 <u>anti-triplets</u> and 1x3=3 <u>triplets</u>

One generation of quarks is different from the other two under the 331 group

Name	331 representation	SM group decomposition	# flavors
ψ_ℓ	$\left(\mathbf{1},\mathbf{3},-\frac{1}{2}-\frac{1}{2\sqrt{3}}\beta\right)$	$\left(\mathbf{1},\widehat{\mathbf{2}},-\frac{1}{2}\right)+\left(\mathbf{1},\widehat{\mathbf{1}},-\frac{1}{2}-\frac{\sqrt{3}}{2}\beta\right)$	3
ℓ^c	$(\mathbf{1},\mathbf{1},1)$	$\left(\mathbf{1},\widehat{\mathbf{1}},1\right)$	3
ℓ_X	$\left(\mathbf{1},\mathbf{1},\frac{1}{2}+\frac{\sqrt{3}}{2}\beta\right)$	$\left(\mathbf{1},\widehat{\mathbf{1}},\frac{1}{2}+\frac{\sqrt{3}}{2}\beta\right)$	3
Q_{12}	$\left(\mathbf{3},\overline{\mathbf{3}},\frac{1}{6}+\frac{1}{2\sqrt{3}}\beta\right)$	$\left(\mathbf{3},\widehat{\mathbf{2}},\frac{1}{6}\right)+\left(\mathbf{3},\widehat{\mathbf{1}},\frac{1}{6}+\frac{\sqrt{3}}{2}\beta\right)$	2
Q_3	$\left(\mathbf{3},\mathbf{3},\frac{1}{6}-\frac{1}{2\sqrt{3}}\beta\right)$	$\left(\mathbf{3},\widehat{\mathbf{2}},\frac{1}{6}\right)+\left(\mathbf{3},\widehat{\mathbf{1}},\frac{1}{6}-\frac{\sqrt{3}}{2}\beta\right)$	1
u^c	$\left(\overline{\mathbf{3}},\mathbf{1},-\frac{2}{3}\right)$	$\left(\overline{\mathbf{3}},\widehat{\mathbf{1}},-\frac{2}{3}\right)$	3
d^c	$\left(\overline{\mathbf{3}},\mathbf{1},\frac{1}{3}\right)$	$\left(\overline{\mathbf{3}},\widehat{\mathbf{1}},\frac{1}{3}\right)$	3
J_{12}	$\left(\overline{\mathbf{3}},\mathbf{1},-\frac{1}{6}-\frac{\sqrt{3}}{2}\beta\right)$	$\left(\overline{\mathbf{3}},\widehat{\mathbf{1}},-\frac{1}{6}-\frac{\sqrt{3}}{2}\beta\right)$	2
J_3	$\left(\overline{\mathbf{3}},\mathbf{1},-\frac{1}{6}+\frac{\sqrt{3}}{2}\beta\right)$	$\left(\overline{\mathbf{3}},\widehat{\mathbf{1}},-\frac{1}{6}+\frac{\sqrt{3}}{2}\beta\right)$	1
ϕ_1	$\left(\mathbf{1},\mathbf{3},\frac{1}{2}-\frac{1}{2\sqrt{3}}\beta\right)$	$\left(\mathbf{1},\widehat{\mathbf{2}},\frac{1}{2}\right)+\left(\mathbf{1},\widehat{\mathbf{1}},\frac{1}{2}-\frac{\sqrt{3}}{2}\beta\right)$	1
ϕ_2	$\left(\mathbf{1},\mathbf{3},\frac{1}{\sqrt{3}}\beta\right)$	$\left(\mathbf{1},\widehat{\mathbf{2}},\frac{\sqrt{3}}{2}\beta\right)+\left(\mathbf{1},\widehat{\mathbf{1}},0\right)$	1
ϕ_3	$\left(\mathbf{1},\mathbf{3},-\frac{1}{2}-\frac{1}{2\sqrt{3}}\beta\right)$	$\left(\mathbf{1},\widehat{\mathbf{2}},-\frac{1}{2}\right)+\left(\mathbf{1},\widehat{\mathbf{1}},-\frac{1}{2}-\frac{\sqrt{3}}{2}\beta\right)$	1

A flipped 331 model

In our paper we pointed out that one can make a valid model where the lepton generators are different, and the quarks are all the same

Any SM model must meet two requirements:

1. Extra fermions should not be introduced, unless they are vector-like under the SM group; i.e. they must either be in a real representation of $SU(3)_C \times SU(2)_L \times U(1)_Y$, or come in pairs of complex conjugated representations.
2. Gauge anomalies should cancel.

(Concerns only the fermions; that's the hard part. The scalar sector is not a problem)

The key is to have one of the three left-handed leptons in a sextet

$$(\mathbf{1},\mathbf{6},x) \rightarrow \underbrace{\left(\mathbf{1},\widehat{\mathbf{3}},x+\frac{1}{\sqrt{3}}\beta\right)}_{\text{Not in the SM; should be vector-like, i.e hypercharge =0}} + \underbrace{\left(\mathbf{1},\widehat{\mathbf{2}},x-\frac{1}{2\sqrt{3}}\beta\right)}_{\text{One of the 3 generations of left-handed doublets}} + \underbrace{\left(\mathbf{1},\widehat{\mathbf{1}},x-\frac{2}{\sqrt{3}}\beta\right)}_{\text{Easy to take care of}}$$

Not in the SM; should be vector-like, i.e hypercharge =0

One of the 3 generations of left-handed doublets

Easy to take care of

$$x = -\frac{1}{3}$$

$$\beta = \frac{1}{\sqrt{3}}$$

Gauge anomaly cancellation

Compared to a triplet (**3**), how much does a sextet (**6**) contribute to the $(SU(3)_L)^3$ anomaly?

It contributes as much as 7 triplets

7 = weird number, unrelated to the number of families and/or colors

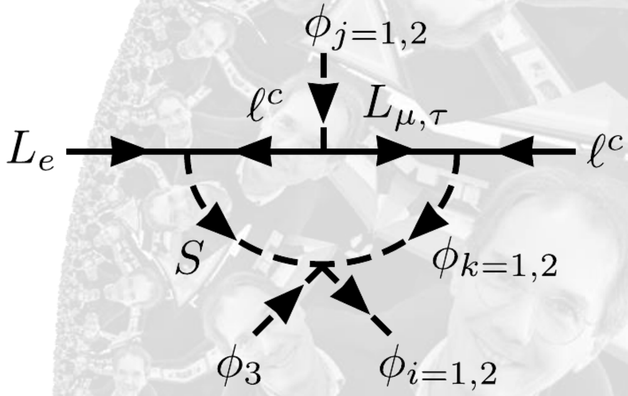
However, it turns out to be perfect: If leptons sit in the representations 6+3+3 then they count as 9 triplets; quarks can then be in 3x3 anti-triplets

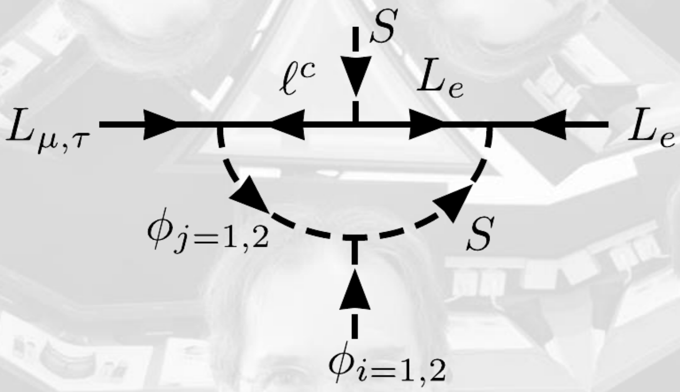
Non-sequential quarks

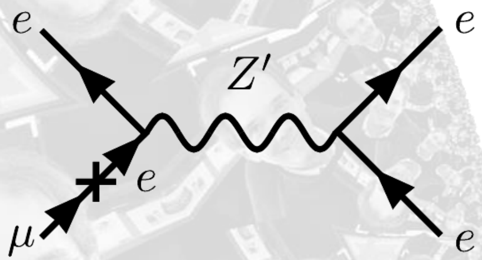
Sequential quarks

Name	331 rep.	SM group decomposition	Components	# flavors
L_e	$(\mathbf{1},\mathbf{6},-\frac{1}{3})$	$(\mathbf{1},\hat{\mathbf{3}},0)+(\mathbf{1},\hat{\mathbf{2}},-\frac{1}{2})+(\mathbf{1},\hat{\mathbf{1}},-1)$	$\begin{pmatrix}\Sigma^+ & \frac{1}{\sqrt{2}}\Sigma^0 & \frac{1}{\sqrt{2}}\nu_e\\ \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^- & \frac{1}{\sqrt{2}}\ell_e\\ \frac{1}{\sqrt{2}}\nu_e & \frac{1}{\sqrt{2}}\ell_e & E_e\end{pmatrix}$	1
$L_{\alpha=\mu,\tau}$	$(\mathbf{1},\mathbf{3},-\frac{2}{3})$	$(\mathbf{1},\hat{\mathbf{2}},-\frac{1}{2})+(\mathbf{1},\hat{\mathbf{1}},-1)$	$(\nu_\alpha,\ell_\alpha,E_\alpha)^T$	2
ℓ_α^c	$(\mathbf{1},\mathbf{1},1)$	$(\mathbf{1},\hat{\mathbf{1}},1)$	ℓ_α^c	6
Q_α	$(\mathbf{3},\overline{\mathbf{3}},\frac{1}{3})$	$(\mathbf{3},\hat{\mathbf{2}},\frac{1}{6})+(\mathbf{3},\hat{\mathbf{1}},\frac{2}{3})$	$(d_\alpha,-u_\alpha,U_\alpha)^T$	3
u_α^c	$(\overline{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	$(\overline{\mathbf{3}},\hat{\mathbf{1}},-\frac{2}{3})$	u_α^c	6
d_α^c	$(\overline{\mathbf{3}},\mathbf{1},\frac{1}{3})$	$(\overline{\mathbf{3}},\hat{\mathbf{1}},\frac{1}{3})$	d_α^c	3

Fermion masses and Z' FCNC







The electron is massless at tree level

So are two neutrinos

FCNC for leptons

$$\mathscr{L}_{\ell Z'} = i\left(\sqrt{3g_L^2 - g_Y^2}\, y_\alpha - \frac{3g_L^2}{\sqrt{3g_L^2 - g_Y^2}} x_\alpha\right) \bar{\ell}_\alpha \gamma^\mu \ell_\alpha Z'_\mu$$

$$x_e = -1/3 \qquad x_{\mu,\tau} = -2/3$$

Model killer or model builder?

Creator of worlds

Destroyer of worlds

And let's not forget the first paper …

(g − 2) anomalies and neutrino mass #1
Carolina Arbeláez (Santa Maria U., Valparaiso), Ricardo Cepedello (Valencia U.), Renato M. Fonseca (Charles U.), Martin Hirsch (Valencia U.) (Jul 21, 2020)
Published in: *Phys.Rev.D* 102 (2020) 7, 075005 • e-Print: 2007.11007 [hep-ph]
pdf DOI cite claim reference search 37 citations

Systematic classification of three-loop realizations of the Weinberg operator #3
Ricardo Cepedello (Valencia U.), Renato M. Fonseca (Charles U.), Martin Hirsch (Valencia U.) (Jul 2, 2018)
Published in: *JHEP* 10 (2018) 197, *JHEP* 06 (2019) 034 (erratum) • e-Print: 1807.00629 [hep-ph]
pdf DOI cite claim reference search 42 citations

High-dimensional neutrino masses #4
G. Anamiati (Valencia U.), Oscar Castillo-Felisola (Santa Maria U., Valparaiso and CCTVal, Valparaiso), Renato M. Fonseca (Charles U.), J.C. Helo (CCTVal, Valparaiso and La Serena U.), M. Hirsch (Valencia U.) (Jun 19, 2018)
Published in: *JHEP* 12 (2018) 066 • e-Print: 1806.07264 [hep-ph]
pdf DOI cite claim reference search 45 citations

$\Delta L \geq 4$ lepton number violating processes #5
Renato M. Fonseca (Valencia U.), Martin Hirsch (Valencia U.) (Apr 27, 2018)
Published in: *Phys.Rev.D* 98 (2018) 1, 015035 • e-Print: 1804.10545 [hep-ph]
pdf DOI cite claim reference search 7 citations

$\Delta L = 3$ processes: Proton decay and the LHC #6
Renato M. Fonseca (Valencia U., IFIC), Martin Hirsch (Valencia U., IFIC), Rahul Srivastava (Valencia U., IFIC) (Feb 13, 2018)
Published in: *Phys.Rev.D* 97 (2018) 7, 075026 • e-Print: 1802.04814 [hep-ph]
pdf DOI cite claim reference search 18 citations

Quasi Dirac neutrino oscillations #7
G. Anamiati (Valencia U., IFIC), R.M. Fonseca (Valencia U., IFIC), M. Hirsch (Valencia U., IFIC) (Oct 17, 2017)
Published in: *Phys.Rev.D* 97 (2018) 9, 095008 • e-Print: 1710.06249 [hep-ph]
pdf DOI cite claim reference search 26 citations

Gauge vectors and double beta decay #8
Renato M. Fonseca (Valencia U. and Valencia U., IFIC), Martin Hirsch (Valencia U. and Valencia U., IFIC) (Dec 13, 2016)
Published in: *Phys.Rev.D* 95 (2017) 3, 035033 • e-Print: 1612.04272 [hep-ph]
pdf DOI cite claim reference search 6 citations

Lepton number violation in 331 models #9
Renato M. Fonseca (Valencia U., IFIC), Martin Hirsch (Valencia U., IFIC) (Jul 21, 2016)
Published in: *Phys.Rev.D* 94 (2016) 11, 115003 • e-Print: 1607.06328 [hep-ph]
pdf DOI cite claim reference search 35 citations

A flipped 331 model #10
Renato M. Fonseca (Valencia U., IFIC), Martin Hirsch (Valencia U., IFIC) (Jun 3, 2016)
Published in: *JHEP* 08 (2016) 003 • e-Print: 1606.01109 [hep-ph]
pdf DOI cite claim reference search 51 citations

SU(5)-inspired double beta decay #11
Renato M. Fonseca (Valencia U., IFIC), Martin Hirsch (Valencia U., IFIC) (May 22, 2015)
Published in: *Phys.Rev.D* 92 (2015) 1, 015014 • e-Print: 1505.06121 [hep-ph]

Supersymmetric SO(10)-inspired GUTs with sliding scales #12
Carolina Arbelaez (Lisbon, CFTP), Renato M. Fonseca (Lisbon, CFTP), Martin Hirsch (Valencia U., IFIC), Jorge C. Romao (Lisbon, CFTP) (Jan, 2013)
Published in: *Phys.Rev.D* 87 (2013) 7, 075010 • e-Print: 1301.6085 [hep-ph]

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Renato M. Fonseca (Valencia U., IFIC), Martin Hirsch (Valencia U., IFIC), Rahul

A flipped 331 model

only scanned a finite (though large) set of possible variants. Note, that these are variants, not configurations. As in the case of class-I practically any variant can be made by several possible anomaly-free configurations. The exhaustive list of variants ($m_{PS} = 10^{15}$ GeV) contains a total of 105909 possibilities and can be found in [25].

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This one.

Model killer and model builder!

Creator of worlds

Destroyer of worlds

**You've been very successful at both, as required by the Scientific Method.
I wish you many more successful and joyful years of research.**

Model killer and model builder!

Creator of worlds

Destroyer of worlds

Happy 60.47th birthday!