Violation of lepton number in 3 units[eee]

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[eee] Based on "*RF, Martin Hirsch and Rahul Srivastava, Phys. Rev. D 97, 075026*"

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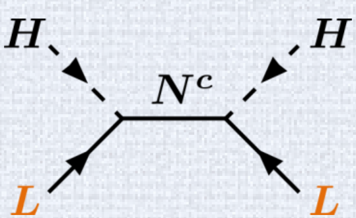
Lepton number violation

$\Delta L = 2$ 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)

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

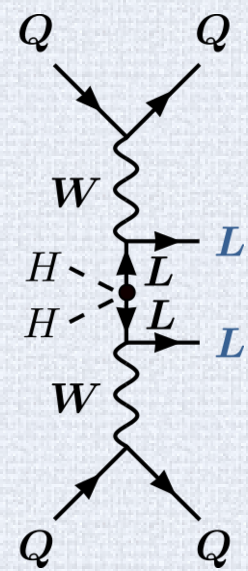
Operators:

$QQ\overline{QQ}LLHH$

+others

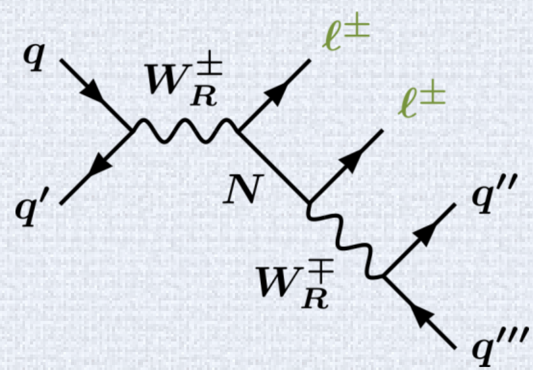
Note that $0\nu 2\beta$ can be induced in many other ways

Bonnet, Hirsch, Ota, Winter (2012)



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

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

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

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

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

$$\frac{1}{\Lambda^2}\left[\begin{array}{c} QQQL \\ \overline{u^c}Q\overline{Qe^c} \\ \overline{u^c}\overline{d^c}QL \\ u^c u^c d^c e^c \end{array}\right. \quad \frac{1}{\Lambda^3}\left[\begin{array}{c} \left(\partial d^c\right) d^c d^c \overline{e^c} \\ d^c d^c Q \left(\partial \overline{L}\right) \end{array}\right. \quad \tau\left(p\right) \sim \left[\Gamma\left(p\right)\right]^{-1} \sim \left(\frac{m_p^5}{\Lambda^4}\right)^{-1}$$

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

Very heavy mediators
(and/or tiny couplings)

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)

$$E_{sphaleron} \sim \frac{m_W}{\alpha_W} \sim 9 \text{ TeV} \qquad q + q \to 7\overline{q} + 3\overline{\ell} + \underbrace{n_W}_{\text{dozens}} W + n_h h \qquad \left(n_W, n_h \sim \alpha_W^{-1} \right)$$

see talk by Carlos Tamarit

What about $\Delta L = 3$?

Perturbative $\Delta L = 3$ beyond the SM?

What processes should we look for? Neutrinoless triple beta decay violates the Lorentz symmetry (9 fermions). So we must search for other processes.

Valid possibilities:

High energies

$$pp \to \ell\ell\ell + \cdots$$

Durieux, Gerard, Maltoni, Smith (2013)

Low energies

Note that baryon number must also be violated but not necessarily in 3 units. If $\Delta B = \pm 1$ nucleon decay becomes a possibility (and perhaps a concern)

Something to keep in mind:

Nature does not care about a physicist's preferences. However, it is worth noting that experimentally lepton number cannot be tagged in neutrinos, so ideally we would like to have access to the above type of processes where all leptons are charged

Is proton decay a concern?

No

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

What is the relevant operator?

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What is the relevant operator?

eee ___ ___ ___

3 charged leptons

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$eeeuuu\bar{d}$

3 charged leptons

quarks for charge conservation

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3 charged leptons

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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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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, $\Delta L = 3$

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

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

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, $\Delta L = 3$

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

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

+others

dim 12, $\Delta L = -3$

(more operators)

dim 13, $\Delta L = 3$

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

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

+others

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

Available data

There are few limits on proton decay modes into 4- and 5-body final states

$p \to \pi^0 e^+ \bar{\nu}\bar{\nu}$
$p \to \pi^- \pi^- e^+ e^+ e^+$

$$\tau \left[p/n \to e^+ \left(\mu^+\right) + \text{any}\right] > 0.6(12) \times 10^{30} \text{ years}$$

Learned, Reines, Soni (1979)

Super-Kamiokande: no 4,5-body decay limits

Some 3-body decay limits can be used to set limits on $\Delta L = 1$ and $\Delta L = 3$ processes:

$$\tau \left(p \to e^+ \nu\nu\right) > 1.7 \times 10^{32} \text{ years}$$
$$\tau \left(p \to \mu^+ \nu\nu\right) > 2.2 \times 10^{32} \text{ years}$$

Takhistov et al. [Super-Kamiokande](2014)

An up-to-date dedicated search could improve the 4 and 5 body decay limits significantly; $\tau \left(p \to 4, 5 \text{ bodies}\right) \gtrsim 10^{35}$ years does not seem unrealistic with Hyper-Kamiokande

So far I have discussed the possibility (in abstract) **that perhaps leptons can only be created or destroyed in groups of 3**

Who knows? Nature is mysterious ….

I will now present a specific model **(out of many!) where this happens**

A specific model

Field content (on top of the SM fields):

$N, N^c = (1,1,0)$ Left- and right-handed Weyl fermions (3 pairs)

$S_u = (\overline{3}, 1, -2/3)$ Scalar

$S_d, S_d' = (\overline{3}, 1, 1/3)$ Scalar (two copies are needed)

$Z_3(L)$ symmetry

$\psi \to \exp(2\pi i L/3)\,\psi$

N^c, S_u, S_d, S_d' $L=-1$

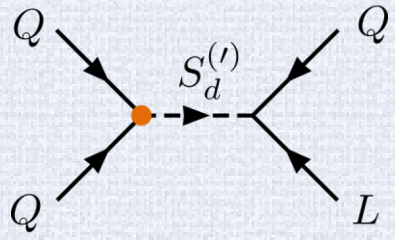
N $L=1$

SM fields $L(L) = -L(e^c) = 1$

$L(Q, u^c, d^c) = 0$

Without the discrete lepton symmetry, proton decay would impose stringent bounds on the couplings of the new scalars

For example, $S_d^{(\prime)}$ is both a leptoquark and a diquark



$\mathcal{O} = QQQL$

A specific model

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

Some remarks

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

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- The μ term is critical: in the limit $\mu \to 0$ both B and L are conserved

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- 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.

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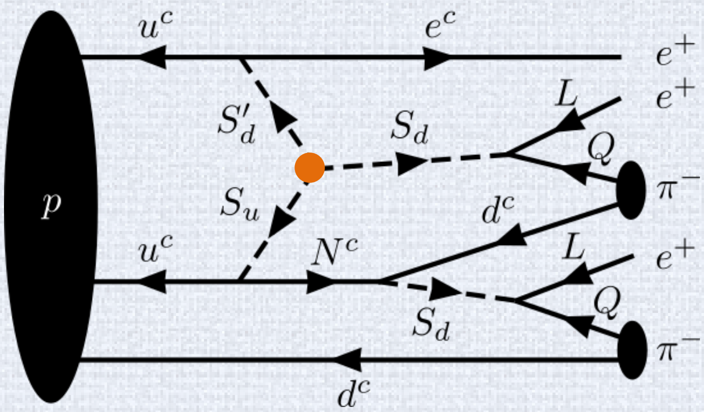
- A $Z_3(L)$ symmetry was used, but it can be shown that the Lagrangian is $U(1)_{3B-L}$ invariant (*B*=-1, *L*=3 processes are therefore absent)

~~DISCRETE18~~
CONTINUOUS18

Proton decay

5-body



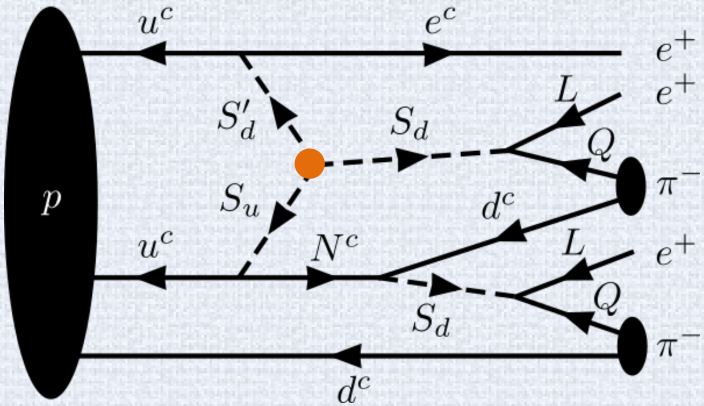
All decay particles visible

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

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

Proton decay

5-body



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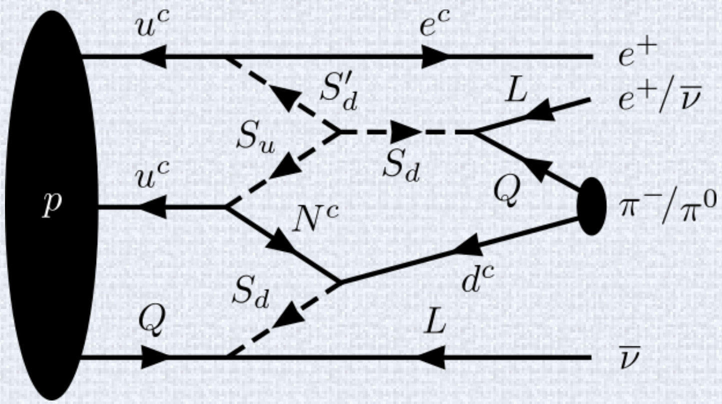
4-body

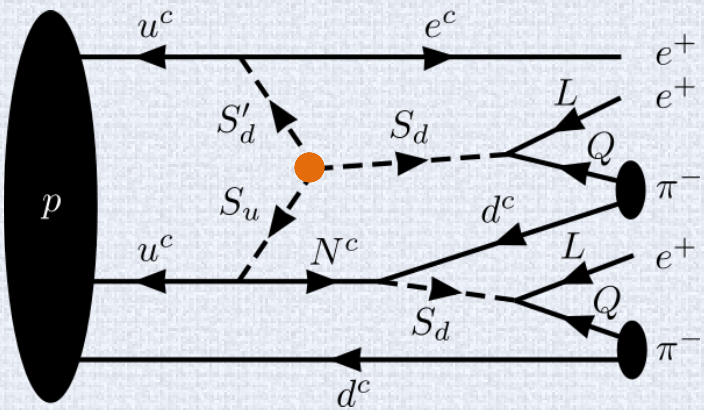


At least one neutrino is undetected

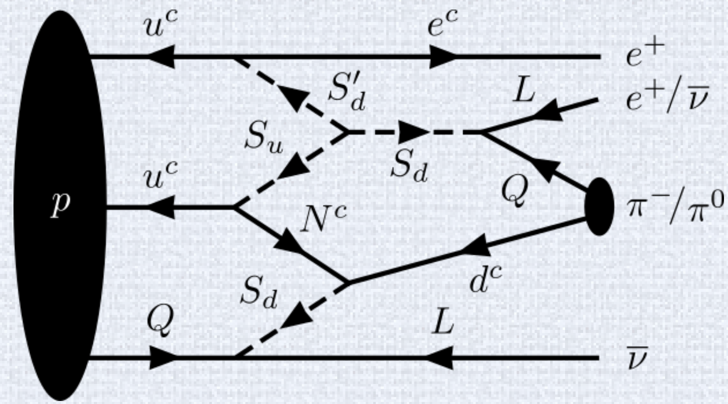
4-body decay enhanced over the 5-body decay

Proton decay

5-body



4-body



5-body

$$\mathcal{A} \sim \frac{Y_1 Y_2 Y_3 Y_4^2 \mu \langle p \rangle}{m_N^2 m_{S_u}^2 m_{S_d}^4 m_{S'_d}^2}$$

$$\tau^{-1}\left(p \to 3e^+ 2\pi^-\right) \sim \frac{\overbrace{J_0}^{\sim 0.1}}{\underbrace{f(5)}_{\sim 10^{-7}}} \mathcal{A}^2 \frac{m_p^{15} \overbrace{\langle \pi^- | \mathcal{O} | p \rangle^2}^{0.2\ \text{GeV}^2}}{\underbrace{f_\pi^2}_{0.13}}$$

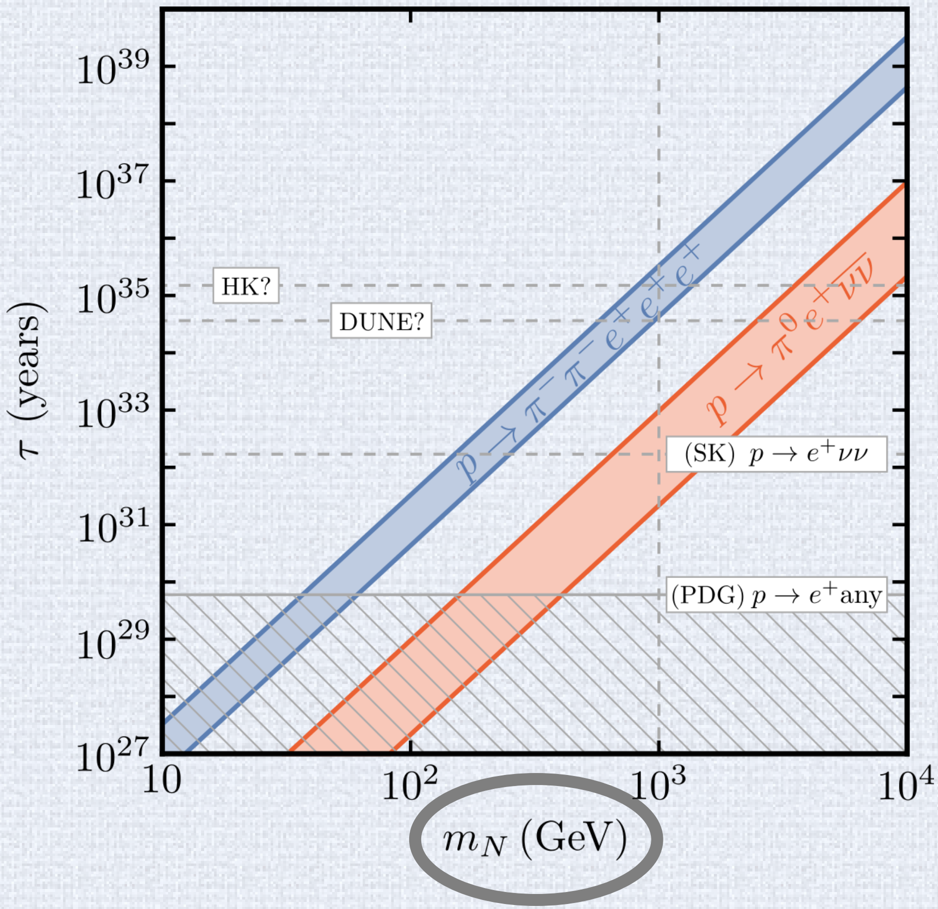
4-body

$$\tau^{-1}\left(p \to 2e^+ \overline{\nu} \pi^-\right) \sim \underbrace{f(5)/f(4)\, J_0 m_p^2 / f_\pi^2}_{\sim 10^3} \tau^{-1}\left(p \to 3e^+ 2\pi^-\right)$$

Rough estimates!

Proton decay

Benchmark scenario



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

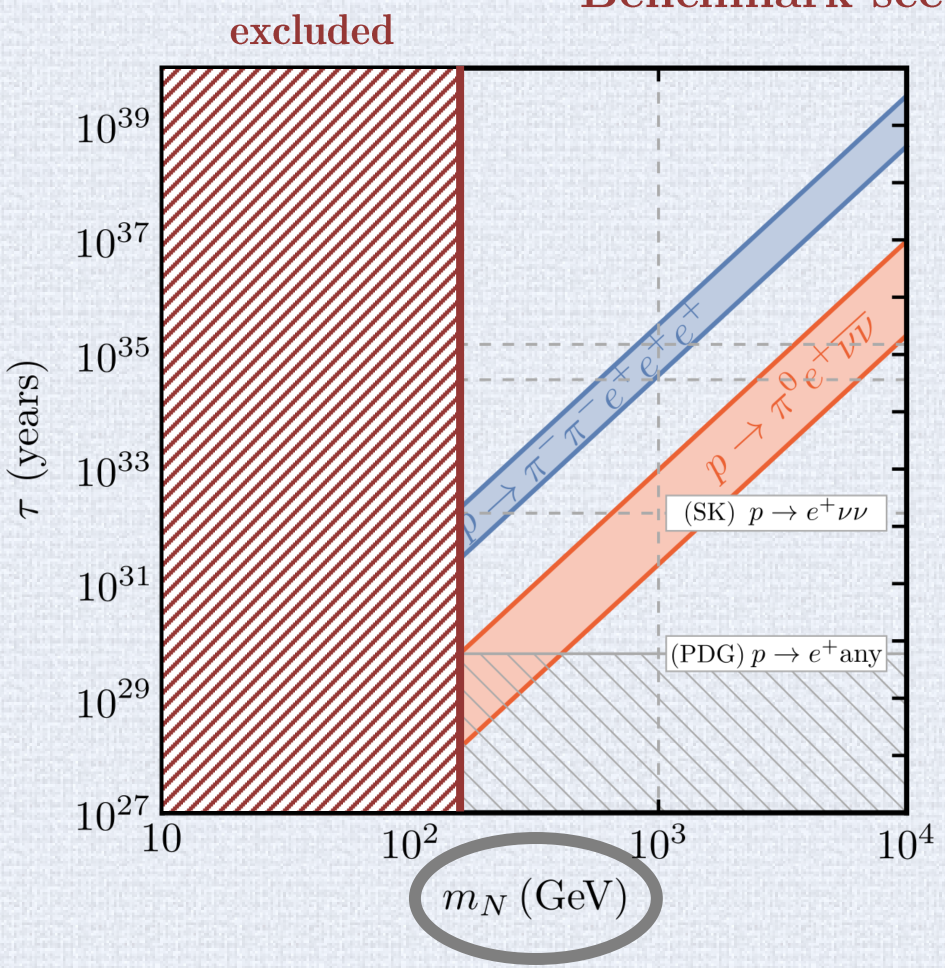
All parameters fixed except the right handed neutrino mass scale

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

(favors an enhanced proton decay rate)

Proton decay

Benchmark scenario



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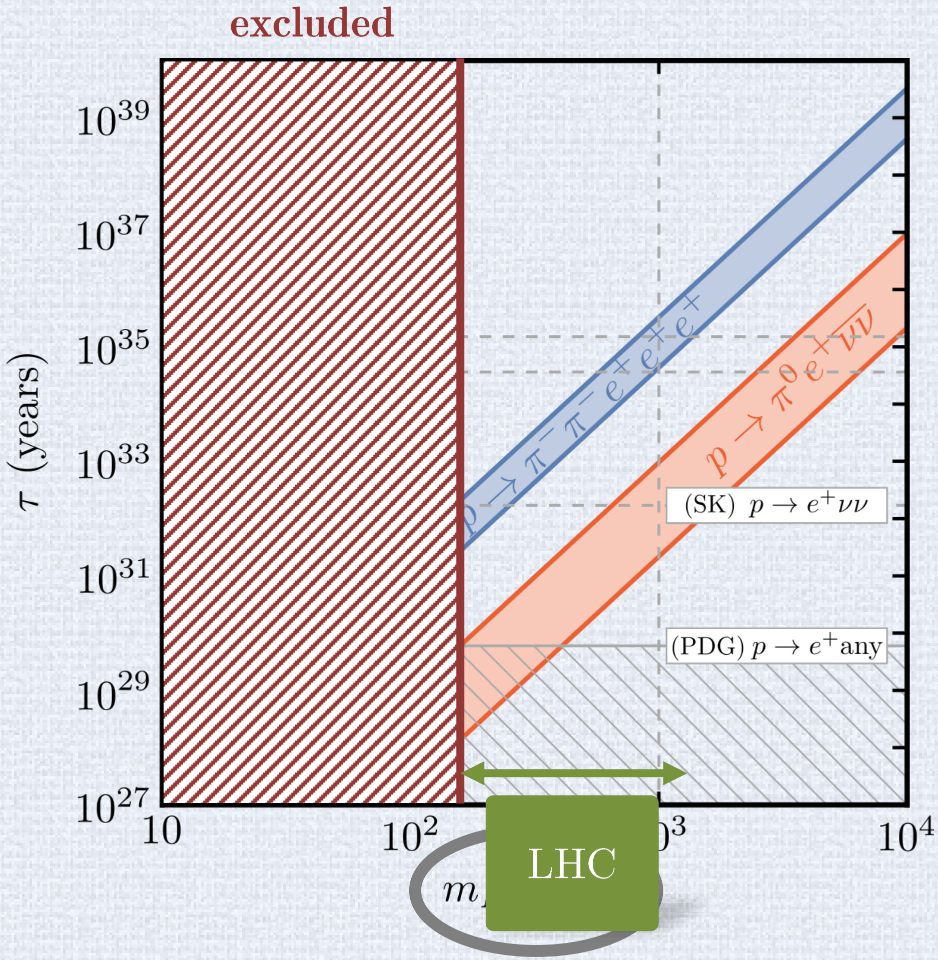

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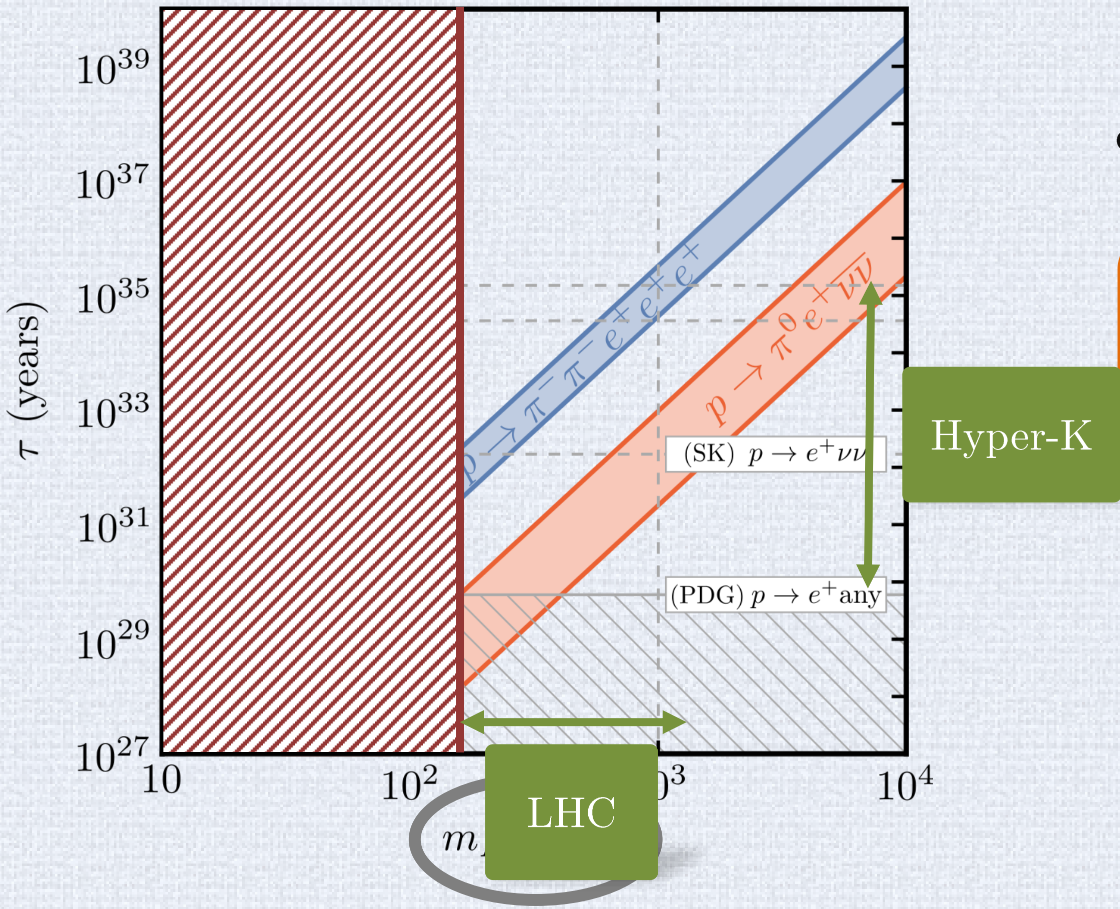

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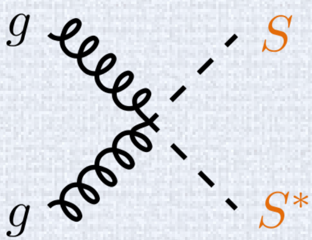
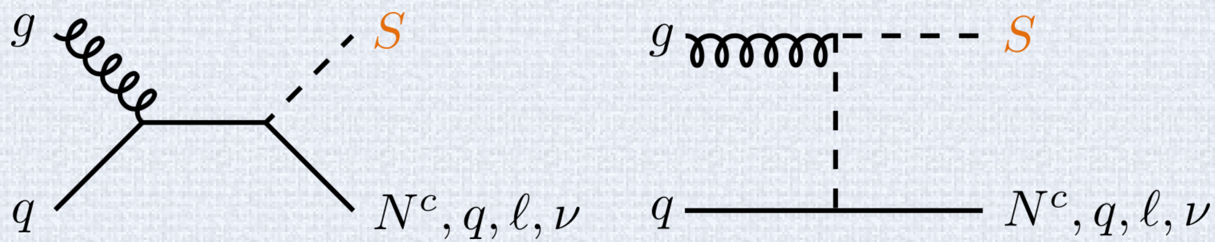
Phenomenology at the LHC

Production of the scalar leptoquarks $S = S_u, S_d^{(\prime)}$ in the model:

See talk by Norbert Neumeister



Pair production via gluon-gluon scattering



Single production in association with a fermion (SM one or heavy neutrino)

Pair production: for 2 TeV mass, ~30 events with 3000 fb^{-1}

Single production: cross section can be larger than the one of pair production (it depends on the value of the Yukawa couplings)

Doršner, Greljo (2018)
(and references cited there)

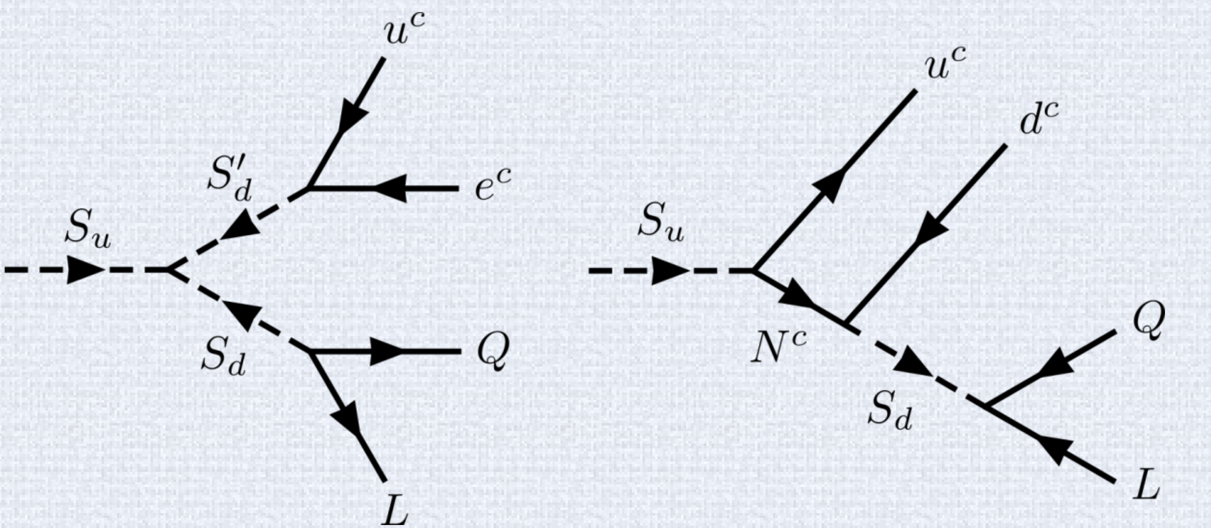
Decay

S_u or $S_d^{(\prime)}$?
Which one is more interesting?

To establish that lepton number is violated one must observe the leptoquarks decay into a varying number of leptons

The branching ratios of S_u are more balanced, hence we should look for lepton number violation there

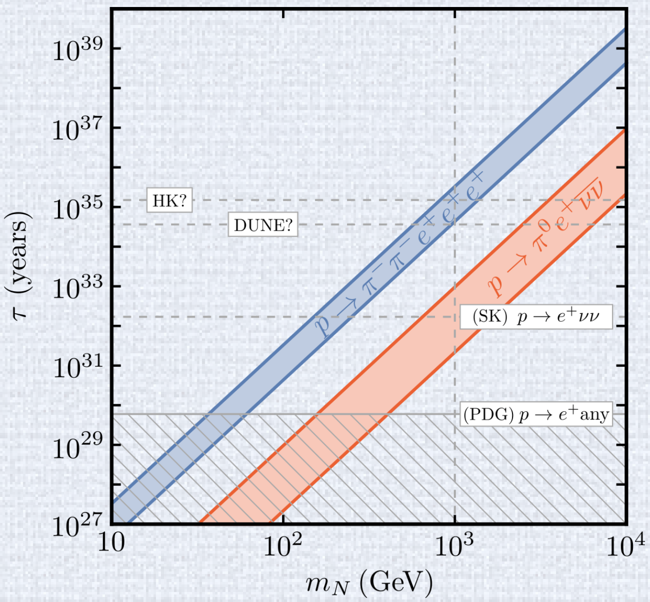
Phenomenology at the LHC



$$\text{Br}(S_u \to (S_d^*)^\star + (S_d'^*)^\star \to 2e^- + 2j) \simeq \text{Br}(S_u \to (N^c)^\star + u^c \to e^+ + 3j)$$

Under the assumption that $m_{S_u} < m_{S_d} + m_{S'_d}$, N^c should be produced off-shell in order to have similar branching ratios for the two decay channels

What about dim 11 proton decay?



Does proton decay need to proceed through a dimension 13 operator (where potentially all leptons can be tagged)?

An operator analysis shows that there are already d=11 operators which cannot be forbidden on symmetry grounds

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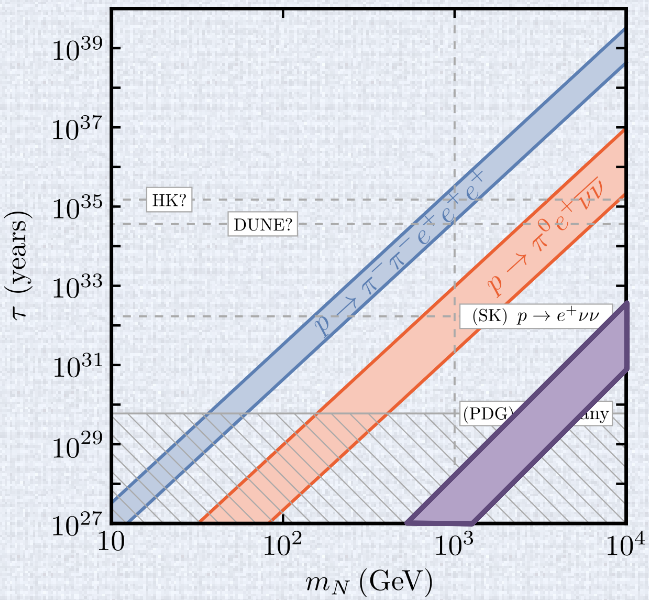

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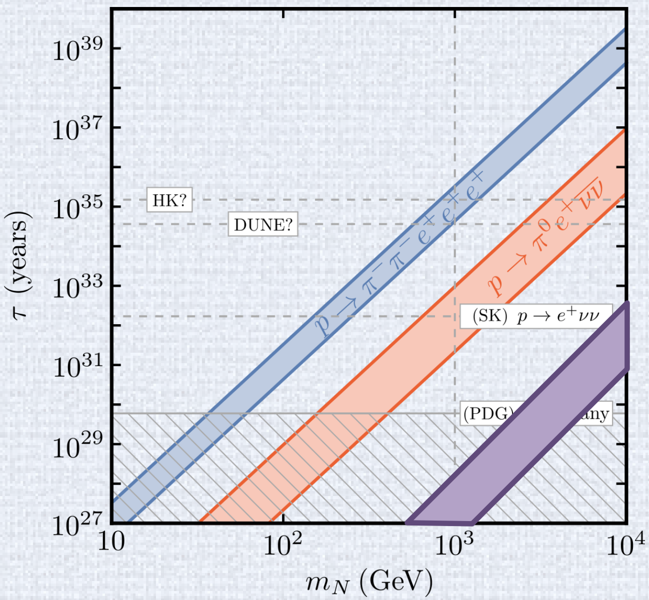

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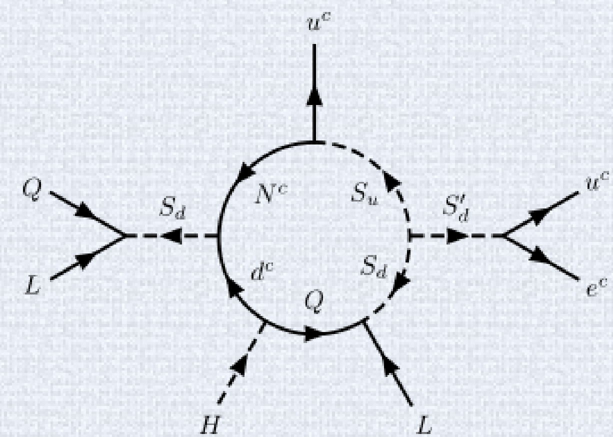
Do they appear in the model? Yes but ...



$$\partial Q \overline{u^c}\,\overline{u^c} L L \overline{e^c} H$$

Is it a significant contribution for proton decay?

Enhancements: (1) lower dimensional operator,
(2) bigger phase space (3-body decays)

Suppressions: (1) loop process,
(2) first/second generation Yukawa couplings
(3) smallness of neutrino masses (in some cases)

Overall:

Subdominant

e^- e^- e^- Summary e^- e^- e^-

Lepton number violation in 1 or 2 units has been studied extensively

However, it is plausible that the laws of Nature are such that leptons can only be created or destroyed in 3 units

That is would be interesting. TeV-scale mediators lead to a slow but potentially observable proton decay rate

TeV particles? Then colliders can also probe this possibility

Thank you