

$\Delta L = 3$ processes: Proton decay and the LHCRenato M. Fonseca,[†] Martin Hirsch,[‡] and Rahul Srivastava^{*}*AHEP Group, Institut de Física Corpuscular–C.S.I.C./Universitat de València,
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We discuss lepton number violation in three units. From an effective field theory point of view, $\Delta L = 3$ processes can only arise from dimension 9 or higher operators. These operators also violate baryon number, hence many of them will induce proton decay. Given the high dimensionality of these operators, in order to have a proton half-life in the observable range, the new physics associated to $\Delta L = 3$ processes should be at a scale as low as 1 TeV. This opens up the possibility of searching for such processes not only in proton decay experiments but also at the LHC. In this work we analyze the relevant $d = 9, 11, 13$ operators which violate lepton number in three units. We then construct one simple concrete model with interesting low- and high-energy phenomenology.

DOI: [10.1103/PhysRevD.97.075026](https://doi.org/10.1103/PhysRevD.97.075026)**I. INTRODUCTION**

The standard model conserves baryon (B) and lepton (L) number perturbatively. However, this is no longer true for nonrenormalizable operators [1] which might be generated in ultraviolet completions of the theory. For example, the only dimension 5 ($d = 5$) operator, the famous Weinberg operator associated to Majorana neutrino masses, violates lepton number by two units. On the other hand, at $d = 6$ there are various 4-fermion operators which violate baryon and lepton number by one unit [1–3], inducing proton decay to two-body final states.

Proton decay searches therefore concentrate on final states such as $p \rightarrow e^+\pi^0$ or $p \rightarrow K^+\bar{\nu}$. The former is expected to be dominant in ordinary GUTs, while the latter is expected to dominate in supersymmetric $SU(5)$ models [4]. However, all such searches have so far only provided lower limits on the proton half-life [4,5].

At the same time, searches for neutrinoless double beta decay have been negative so far (see for example [6,7] for a review of this topic). Neither do we have any other clear experimental signal of lepton number violation. Thus, we do not know whether neutrinos are Dirac or Majorana particles.

Given the absence of any experimental signal, it is therefore possible that some unknown symmetry exists

forbidding altogether such nonrenormalizable operators, or perhaps just the lowest order ones. Such a symmetry could be related to some particular combinations of lepton/quark flavors, as argued for example in [8], or to total lepton and baryon numbers. The possibility we discuss in this paper is that lepton number might actually be violated only in units of three: $\Delta L = 3$.

This implies that neutrinos must be Dirac particles, as Majorana mass terms would require violation of lepton number in two units. Another immediate consequence of this hypothesis is that proton decay final states must be at least three-body, while an unambiguous experimental signal establishing $\Delta L = 3$ requires three charged leptons: $p \rightarrow \pi^-\pi^-e^+e^+e^+$, i.e., a 5-body decay. It is not hard to see that $\Delta L = 3$ operators must involve at least 3 lepton and 3 quark fields, which means that they are suppressed by several powers of the new physics scale. For such high-dimensional operators, an observable rate of proton decay is achieved for a new physics scale in the (1–100) TeV range, depending on the dimension of the operator under consideration. This also opens up the possibility to actually observe violation of lepton number in three units at the LHC. In Sec. III we will discuss a concrete model realizing this idea.

It is worth mentioning that proton decay limits into 4- and 5-body final states rely on rather old bounds for inclusive decays. Hence, they would benefit substantially from an up-to-date dedicated search. In particular there is a lower limit of $0.6(12) \times 10^{30}$ years on the nucleon lifetime associated with $p/n \rightarrow e^+(\mu^+) + \text{anything}$ [5,9] which relies on experiments [10,11] done in the 1970s and early 1980s with exposures three to four orders of magnitude lower than the one achieved in Super-Kamiokande. Super-K has recently published some limits on 3-body decays [12]: $\tau(p \rightarrow e^+\nu\nu) > 1.7 \times 10^{32}$ and $\tau(p \rightarrow \mu^+\nu\nu) > 2.2 \times 10^{32}$ at 90% confidence level, but gives no limits

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on 4-body and 5-body decays. As neutrinos are missing energy, they may as well be antineutrinos, hence the quoted values apply both to $\Delta L = 1$ ($p \rightarrow \ell^+ \bar{\nu} \nu$) and $\Delta L = 3$ ($p \rightarrow \ell^+ \bar{\nu} \bar{\nu}$) decay modes. Nevertheless, we mention that in models with lepton number violation in three units, the decay channels with more particles in the final state (4 or more) might be the dominant ones, as we will discuss later. In this case one has to rely on the rather weak inclusive limits mentioned above.

We would like to mention that we are not the first to discuss $\Delta L = 3$ processes and proton decay into multi-particle final states (although the literature on this subject seems to be quite scarce). In [13] an operator analysis of $\Delta(B, L) = (1, \pm 3)$ was carried out, while the authors of [14] considered $\Delta L = 3$ LHC processes involving all generations. Three lepton proton decay modes resulting from $d = 9, 10$ operators have been discussed recently in [8]. However, all final states considered in this paper are $\Delta B = \Delta L = \pm 1$. In [15] 4-body and 5-body proton decays (all with $\Delta L = \pm 1$) have been discussed in the context of leptoquark (LQ) models. The only other paper, that we are aware of, that mentions a $\Delta L = 3$ proton decay is [16]. This paper discusses a $d = 17$ operator that appears in an extra-dimensional model with six spacetime dimensions. Finally, we note that one can also consider the reverse situation where baryon number is violated in three units, while lepton number is changed by one unit only [17].

The rest of this paper is organized as follows. In Sec. II we discuss $\Delta L = 3$ operators. After that, in Sec. III, we provide one example of a concrete model which generates $\Delta L = 3$ processes observable not only in proton decay experiments, but possibly also at the LHC. In Sec. IV we analyze the possible connection of $\Delta L = 3$ processes with Majorana/Dirac neutrinos. We then close with a short summary.

II. $\Delta L = 3$ OPERATORS

We start with a discussion on the effective operators which lead to lepton number violation in three units. It is well known that (a) baryon number B and lepton number L breaking has to occur in integer units and (b) $(\Delta B, \Delta L) = (\text{odd}, \text{odd})$ or $(\text{even}, \text{even})$. The reason why ΔB must be an integer is simply due to the fact that in order for an operator to be colorless, the number of quarks (triplets of $SU(3)_C$) minus the number of antiquarks (antitriplets) must be a multiple of 3. On the other hand, if the ΔB associated to a given operator is even (odd), then the number of quarks plus antiquarks is also even (odd), in which case Lorentz invariance requires the presence of an even (odd) number of leptons plus antileptons, hence ΔL will also be even (odd). Thus we have:

$$\Delta B + \Delta L = 0, \pm 2, \pm 4, \dots \quad (1)$$

As a consequence, lepton number violation in three units is only possible if baryon number is violated as well. The

simplest solution to consider is $\Delta B = \pm 1$; $\Delta B = \pm 3$ and more complicated possibilities involve at least 12 fermions (this is the case for some nonperturbative effects [18,19]). Furthermore, having ΔL and ΔB with the same sign leads to lower-dimensional operators, so in this sense, beyond the normal $\Delta(B, L) = (1, \pm 1)$ proton decay operators, the $\Delta(B, L) = (1, 3)$ operators are the next simplest ones.

In the absence of a symmetry, one usually expects that normal proton decay operators dominate over the higher-dimensional ones with $\Delta(B, L) = (1, \pm 3)$. Perhaps the simplest way to explain the nonobservation of simpler decay final states is to invoke the presence of a $Z_3(L)$ symmetry. However, note that one could as easily eliminate the $|\Delta L| = 1$ operators and keep the $\Delta L = \pm 3$ ones with other discrete Z_n symmetries involving baryon number as well. In fact, continuous symmetry groups $U(1)_{3B \mp L}$ will work equally well.

Let us consider from now on the sign of ΔB to be positive. A $\Delta L = \pm 3$ operator necessarily involves at least 6 standard model fields—3 quarks and 3 (anti)leptons—thus the lowest order operator must be 9-dimensional [13]. While there are dozens of $d = 9$ operators, only two of them violate L by three units ($\Delta L = +3$). These are

$$\mathcal{O}_9^1 = \overline{u^c} \overline{u^c} \overline{u^c} \overline{e^c} LL, \quad (2)$$

$$\mathcal{O}_9^2 = \overline{u^c} \overline{u^c} QLLL. \quad (3)$$

However, neither leads to proton decay, since both of these operators have the $\overline{u^c}$'s contracted in an antisymmetric fashion, hence two up-type quarks of different generations are necessary.¹

At $d = 10$ one finds for the first time a single $\Delta L = -3$ operator [13] that can induce proton (and neutron) decay,

$$\mathcal{O}_{10} = \overline{d^c} \overline{d^c} \overline{d^c} \overline{L} \overline{L} \overline{L} H^* \quad (4)$$

which is nonzero only for two or more generations of either d^c or L . From electric charge conservation, one can infer that it will induce processes with two neutrinos, such as $n \rightarrow e^- \nu \nu \pi^+$ and $p \rightarrow e^- \nu \nu \pi^+ \pi^+$.²

At $d = 11$, including derivatives, there are already 14 $\Delta L = 3$ operators.³ All of them contain either two derivatives, two Higgs fields, or one derivative and one Higgs. For example:

¹On the other hand, accelerator experiments such as the LHC could probe these operators. Note also that the operator in Eq. (2) requires two different L generations.

²Final states with muons instead of electrons, and/or kaons instead of pions, are allowed in all cases we discuss in this paper.

³The counting we present here refers to the number of gauge and Lorentz invariant field combinations; it does not take into account different contractions of the same fields nor different applications of the derivative operator.

$$\mathcal{O}_{11}^1 = \partial\bar{u}^c \bar{u}^c QLLL, \quad (5)$$

$$\mathcal{O}_{11}^2 = \partial Q\bar{u}^c \bar{u}^c LL\bar{e}^c H. \quad (6)$$

\mathcal{O}_{11}^1 induces both proton and neutron decay of the type $p \rightarrow e^+ \bar{\nu} \bar{\nu}$, $p \rightarrow \pi^- e^+ e^+ \bar{\nu}$ and $n \rightarrow \pi^- \pi^- e^+ e^+ \bar{\nu}$. From the Super-Kamiokande limit on $p \rightarrow \ell^+ \nu \nu$ [12] we estimate very roughly a lower limit on the scale of \mathcal{O}_{11}^1 of order (7–13) TeV for couplings of order $\mathcal{O}(1)$.⁴ We defer the discussion of \mathcal{O}_{11}^2 to Sec. III.

There are more $\Delta L = -3$ operators at dimension $d = 12$ which we will not discuss in detail. Importantly, all of the operators discussed so far, with $d \leq 12$, involve neutrinos, making it impossible to tag lepton number experimentally. In other words, it is not possible to be certain that lepton number is violated in three units unless all the leptons are charged. One can easily see from electric charge conservation alone that 8 fermions are needed to form such an operator:

$$eeeeuuu\bar{d}(H \text{ or } \partial). \quad (7)$$

The need for a derivative or a Higgs boson is seen once the full standard model group is taken into consideration. There are many operators at $d = 13$ of this type; we show here only two examples:

$$\mathcal{O}_{13}^1 = \partial\bar{u}^c \bar{u}^c \bar{u}^c \bar{u}^c d^c \bar{e}^c \bar{e}^c \bar{e}^c, \quad (8)$$

$$\mathcal{O}_{13}^2 = \partial\bar{u}^c \bar{u}^c d^c QQ\bar{e}^c LL. \quad (9)$$

Note that \mathcal{O}_{13}^1 requires two lepton generations, leading to decays of the form $p \rightarrow e^+ e^+ \mu^+ \pi^- \pi^-$. The operator \mathcal{O}_{13}^2 , on the other hand, can yield decays involving just one generation of quarks and fermions: $p \rightarrow e^+ e^+ e^+ \pi^- \pi^-$, $p \rightarrow e^+ e^+ \bar{\nu} \pi^-$, $p \rightarrow e^+ \bar{\nu} \pi^0$, and also $n \rightarrow e^+ e^+ e^+ \pi^- \pi^-$, $n \rightarrow e^+ e^+ \bar{\nu} \pi^-$, $n \rightarrow e^+ \bar{\nu} \pi^-$. From simple phase space arguments one expects the 4-body decay modes to dominate over the other ones. However, at least in principle, the final state with three positrons can have a half-life short enough to be observed in (future) proton decay searches. We will discuss this in the context of one concrete ultraviolet completion for operator \mathcal{O}_{13}^2 in the next section.

III. A SIMPLE MODEL FOR $\Delta L = 3$ WITH CHARGED LEPTONS

Many ultraviolet complete models generating $\Delta L = 3$, $d = 13$ operators can be constructed. Here, for illustration

⁴Any realistic ultraviolet completion of this operator will, however, have to obey also low-energy bounds on the couplings, which might lead to quite stringent limits on some couplings, and correspondingly weaker limits on the scale of the operator, depending on the model. For a discussion in one concrete model see the next section.

and to facilitate definite quantitative discussions, we will discuss one simple example. In our model, proton decay is induced by a $d = 13$ operator which is generated at tree-level, but the model also provides a $d = 11$ 1-loop contribution to this process. The $d = 11$ loop contribution, as we will discuss shortly, is suppressed compared to the $d = 13$ tree level contribution which is the dominant contribution to proton decay. This illustrative model is also chosen for its minimality of particle content while still being able to potentially provide a clear $\Delta L = 3$ signal both in proton decay and at the LHC.

In our construction, we make a simple extension of the standard model by adding left-handed fermions $N, N^c \equiv F_{1,1,0}$ and two types of scalars $S_u \equiv S_{\bar{3},1,-2/3}$ and $S_d \equiv S_{\bar{3},1,1/3}$. For reasons discussed below, we will need two copies of this last field, S_d and S'_d , three generations of N , and six of N^c .⁵ Here, S and F stand for scalars and (left-handed) Weyl fermions, and the subscripts indicate the transformation properties/charges of the fields under the standard model gauge group, following the order $SU(3)_C \times SU(2)_L \times U(1)_Y$.

The Lagrangian contains the following pieces:

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{\text{SM}} + Y_\nu LN^c H + Y_1 \bar{u}^c \bar{N}^c S_u + Y_2 N^c d^c S_d^* \\ & + Y_3 \bar{e}^c \bar{u}^c S'_d + Y_4 QLS_d + \mu S_u S_d S'_d + m_N N N^c \\ & + \dots, \end{aligned} \quad (10)$$

where the dots stand for additional terms which are irrelevant to the following discussion. We do not consider terms such as NN , $N^c N^c$, LNH , $\bar{u}^c \bar{N} S_u$, $N d^c S_d^*$, $d^c d^c S_u$, $u^c d^c S_d$, QQS_d^* and similar terms with $S_d \rightarrow S'_d$, as they are forbidden by $Z_3(L)$ symmetry under which each field has a charge ω^L , ω being the cubic root of 1, and L the field's lepton number. It is straightforward to check that $L(S_d) = L(S'_d) = L(S_u) = L(N^c) = -L(N) = -1$.

The term proportional to μ couples three colored triplets, thus two copies of S_d are needed. In the limit of $\mu \rightarrow 0$ the model conserves both B and L and the proton is completely stable, hence μ can be seen as the source of lepton and baryon number violation. Note that the mass term for the N , N^c fermions is of the Dirac-type, hence it does not violate L .

At this point, it is necessary to briefly discuss the need for the additional $Z_3(L)$ symmetry. As mentioned earlier, the gauge quantum numbers of the scalar S_d allow a term $Y_5 QQS_d^*$. This coupling, however, together with Eq. (10), induces proton decay via a tree-level $d = 6$ operator with $\Delta(B + L) = 2$, $\Delta(B - L) = 0$ at an unacceptable rate. It

⁵A truly minimal setup would postulate only three copies of N^c and one of N . In this case, two of the N^c then pair off with the active neutrino of the SM, to generate the two mass splittings observed in oscillation experiments, while the third N^c forms a vectorlike pair with N .

follows that the product of Y_5 with other couplings must be very small; indeed, we estimate that⁶

$$Y_4 Y_5 \lesssim 10^{-24} \left(\frac{m_{S_d}}{1 \text{ TeV}} \right)^2, \quad (11)$$

and similarly for the product $Y_3 Y_5$. This motivates strongly the introduction of a symmetry under which L and S_d/S'_d are odd while Q is even, to forbid the unwanted term. There are different ways to do this and a simple $Z_3(L)$ or $Z_4(B+L)$ is sufficient (in our model, both cases lead to an accidental $U(1)_{3B-L}$).

A similar, but quantitatively much less important concern is that S_d/S'_d can have simultaneous coupling to $\overline{e^c u^c}$ and QL , since these scalars transform in the same way under all symmetries. Constraints from meson decays limit the product of these couplings roughly to [20,21]

$$Y_3 Y_4 \lesssim 2 \times 10^{-5} \left(\frac{m_{S_d}}{1 \text{ TeV}} \right)^2. \quad (12)$$

Constraints on Y_3 and Y_4 individually are much weaker. From the constraints discussed in [20,21], we estimate:

$$\begin{aligned} Y_3 &\lesssim 0.26 \left(\frac{m_{S_d}}{1 \text{ TeV}} \right), \\ Y_4 &\lesssim 0.27 \left(\frac{m_{S_d}}{1 \text{ TeV}} \right). \end{aligned} \quad (13)$$

Thus, in order to maximize the proton decay rate it is preferable that each scalar couples to either $\overline{e^c u^c}$ or QL , but not both. This can be achieved by introducing another discrete symmetry which would eliminate the unwanted couplings, as we will explain in the next section. Also for simplicity we assume that all of the leptoquarks, namely S_u , S_d , and S'_d , couple preferentially to first generation quarks and leptons only. However, this requirement is not essential and can be relaxed.

Additionally, there are constraints from direct searches at the LHC. For both S_d and S'_d , standard leptoquark searches apply. Limits on these states depend on the lepton and quark generations they couple to. We are mostly interested in first generation lepto-quarks, and for this case, searches from CMS [22] and ATLAS [23] establish a lower limit of roughly $m_{S_d} \sim m_{S'_d} \sim 1 \text{ TeV}$. For S_u , as discussed below, in order to have a clear signature of $\Delta L = 3$ process at LHC, final states should always be 4-body, hence constraints are slightly less stringent, but in any case we expect them not to be significantly below 1 TeV.

Figure 1 shows the tree-level Feynman diagram for proton decay in our model. The parton level amplitude is given approximately by the expression

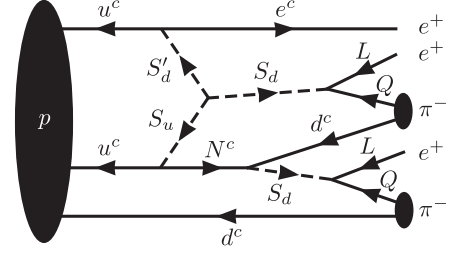


FIG. 1. Proton decay $p \rightarrow \pi^- \pi^- e^+ e^+ e^+$ induced by a $d = 13$ operator in our model. Diagrams permuting the 4 external up-quarks are equally allowed. Note the presence of the trilinear coupling $\mu S_u S_d S'_d$ in the diagram.

$$\mathcal{A} \sim \frac{Y_1 Y_2 Y_3 Y_4^2 \mu \langle p \rangle}{m_N^2 m_{S_u}^2 m_{S_d}^4 m_{S'_d}^2}, \quad (14)$$

where $\langle p \rangle$ is the mean parton momentum involved in the process. Very roughly $\langle p \rangle \sim \mathcal{O}(m_p)$.

A simple estimate of the mean proton lifetime associated to this decay mode is given by

$$\tau^{-1}(p \rightarrow 3e^+ 2\pi^-) \sim \frac{J_0}{f(5)} \mathcal{A}^2 \frac{m_p^{15} W^2}{f_\pi^2}, \quad (15)$$

where $f(n) \equiv 4(4\pi)^{2n-3} (n-1)! (n-2)!$ takes care of the phase space volume available to the decay products,⁷ $f_\pi = 0.13 \text{ GeV}$ is the pion decay constant, $W = \langle \pi^- | \mathcal{O} | p \rangle \sim 0.2 \text{ GeV}^2$ [24] is the QCD form factor involved in single pion decay, and $J_0 \approx 0.1$ is a numerical factor [25]. Without taking into account form factors, one would replace $J_0 W^2 / f_\pi^2$ by m_p^2 in Eq. (15).

These two estimates for the lifetime associated to $p \rightarrow e^+ e^+ \mu^+ \pi^- \pi^-$ are shown in Fig. 3 as two lines which form the upper and lower limits of the blue band. Note that due to LHC constraints, none of the scalars can be light. However, there are practically no constraints on the mass of N^c , hence we show the estimated lifetime as a function of the mass of this field.

By switching the $SU(2)_L$ components of the Q and L fields, it is possible to use the operator shown in Fig. 1 to induce the 4-body decays $p \rightarrow \pi^- e^+ e^+ \bar{\nu}$ and $p \rightarrow \pi^0 e^+ \bar{\nu} \bar{\nu}$ —see Fig. 2. The associated lifetimes are given by the expression in Eq. (15) but without a factor $J_0 m_p^2 / f_\pi^2$ and with the larger phase-space factor $1/f(4)$ replacing $1/f(5)$, implying that the 4-body decay is roughly a factor of 10^3 faster than the 5-body one. This is shown in Fig. 3 as the upper limit of the orange band, while the lower limit corresponds to a naive power counting estimate of the lifetime, obtained by substituting W^2 by m_p^4 . The difference between the proton lifetime in decay modes

⁶We assume all couplings to be real without loss of generality.

⁷For $n = 2, 3, 4, 5$, this factor is close to 5×10^1 , 2×10^4 , 2×10^7 and 3×10^{10} .

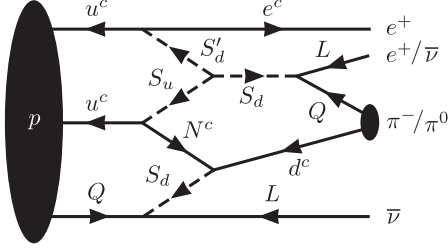


FIG. 2. Proton decay into four bodies, $p \rightarrow \pi^- e^+ e^+ \bar{\nu}$ and $p \rightarrow \pi^0 e^+ \bar{\nu} \bar{\nu}$, induced by the same $d = 13$ operator as in Fig. 1.

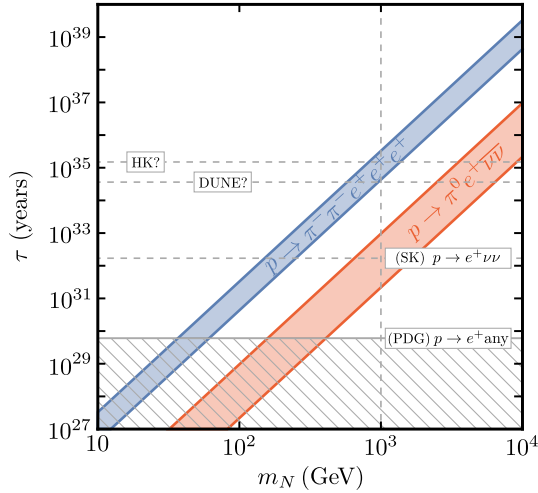


FIG. 3. Proton decay lifetime as function of m_N , for $\mu = 10$ TeV, $m_{S_u} = m_{S_d} = m_{S'_d} = 1$ TeV, $Y_1 = Y_2 = 1$, $Y_3 = 0.26$ and $Y_4 = 0.27$. The figure also shows existing constraints from proton decay searches, for the chosen benchmark point. Inclusive searches exclude m_N smaller than ~ 150 GeV. Also, for reference, are shown the current Super-Kamiokande limits on three body decay mode $p \rightarrow e^+ \bar{\nu} \bar{\nu}$, which is currently the most stringent limit for a three body decay mode. Note, however, that this limit does not apply to our case. We have also shown the expected reach of the Hyper-Kamiokande and DUNE experiments for two body decay modes.

$p \rightarrow \pi^- e^+ e^+ \bar{\nu}$ and $p \rightarrow \pi^0 e^+ \bar{\nu} \bar{\nu}$ is negligible and so only the latter mode is shown in Fig. 3.

As mentioned earlier, there are currently no limits on 4- and 5-body decays from Super-Kamiokande, hence the current bounds on the processes $p \rightarrow \pi^- \pi^- e^+ e^+ e^+$ and $p \rightarrow \pi^0 e^+ \bar{\nu} \bar{\nu}$ are rather weak ($\sim 10^{30} - 10^{31}$ years). Hyper-Kamiokande [26] is expected to be able to probe 2-body proton decay modes up to 10^{35} years. Thus, one should not exclude the possibility of a five orders of magnitude improvement in the experimental reach on $\Delta L = 3$ decay modes. In this context we mention also the DUNE experiment [27], although its mass is smaller than the one of Hyper-Kamiokande. Note however that neither of these experiments has charge discrimination, hence they will not be able to unambiguously check that lepton number is being violated in 3 units.

In our model, the decays involving neutrinos dominate, hence they should probably be seen first in events with 3 Cherenkov rings (with at least two being of shower-type) associated to an invariant mass below m_p . However, it is conceivable that Hyper-Kamiokande or DUNE can also observe the rarer mode with three charged leptons in the final state, given that this mode involves a clean signal with 3 shower- plus 2 nonshower-type Cherenkov rings, and a reconstructed mass equal to m_p .

We now turn to a brief discussion of $\Delta L = 3$ phenomenology at the LHC. The new scalars of our model can be produced either in pairs (through gluon-gluon fusion), in association with N^c , or in association with a standard model lepton (in the case of S'_d). Production cross sections for these leptoquark states at LHC have been calculated several times in the literature, most recently at next-to-leading order in [28], for example. If the leptoquark masses are around 1 TeV one expects that the current run of the LHC will find at least some hints. However, even for a leptoquark with 2 TeV of mass, one expects roughly a pair production cross section of 10^{-2} fb, or 30 events in 3000 fb^{-1} before cuts. Thus, LHC signatures for $\Delta L = 3$ processes are possible. Associated production cross sections are larger for small N^c masses and large couplings, given current constraints up to $(1 - 2)$ fb for the fields S_u and S_d , S'_d , assuming couplings equal to 1. However, associated production cross sections scale like Y_i^2 and thus could conceivably be much smaller.

Most interesting for us is S_u production, as it can be used to experimentally probe $\Delta L = 3$ violation at the LHC. The scalar S_u , once produced, has two decay modes which are shown in Fig. 4. Given that we know neither the masses nor the couplings involved, we can not predict which of these two decays will be dominant. However, in order to observe violation of lepton number in three units, both channels should have similar branching ratios for the following reason. Gluon-gluon fusion actually produces a pair of scalars S_u and S_u^* . Thus, if one of the two channels in Fig. 4 dominates, one either has the final state $2e^+ 2e^-$ plus jets (through S_d) or $e^+ e^-$ plus jets (through the diagram with N^c). If, on the other hand, one of the two scalars decays through a diagram involving S'_d 's while the other decays through the diagram with N^c , the final state can be $3e^+$ plus jets (or $3e^-$ plus jets). One can easily convince oneself that

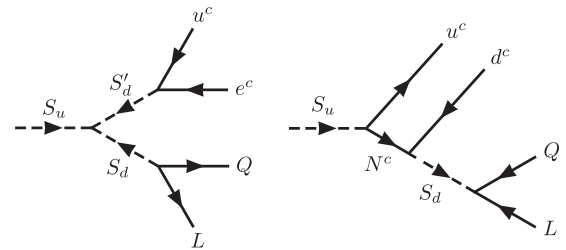


FIG. 4. Feynman diagrams for S_u decay at the LHC.

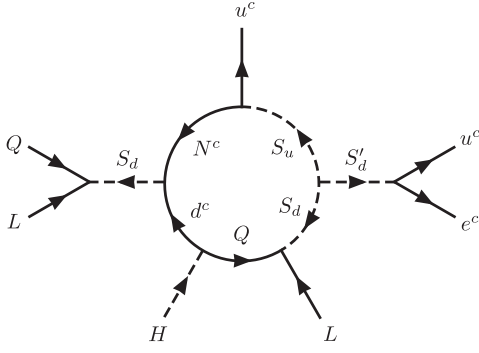


FIG. 5. Loop generation of the dimension 11 operator $\partial Q \bar{u}^c \bar{u}^c L L \bar{e}^c H$ in our model. This leads to $p \rightarrow e^+ \bar{\nu} \bar{\nu}$, for example.

this gives a sizable event number only if $\text{Br}(S_u \rightarrow (S_d^*)^* + (S_d'^*)^* \rightarrow 2e^- + 2j) \simeq \text{Br}(S_u \rightarrow (N^c)^* + u^c \rightarrow e^+ + 3j)$. Here, the stars “ \star ” indicate that the intermediate state might be off-shell. Given the lower limits on the mass of S_d, S_d' , this most likely requires that N^c to be heavy too: $m_{N^c} \gtrsim m_{S_u}$. If this is not the case, the 2-body decay $\text{Br}(S_u \rightarrow N^c + u^c)$ will dominate over the channel with S_d . However, in this region of parameter space where N^c is rather heavy, we expect that the proton decay lifetime into $3e^+ 2\pi^-$ is rather long—see Fig. 3. Thus, the LHC and proton decay experiments test complementary parts of the parameter space of the model (heavy versus light N^c).

The operator discussed so far is 13-dimensional: $\partial Q Q \bar{u}^c \bar{u}^c d^c L L \bar{e}^c$. As mentioned in the Introduction, there are lower dimensional operators which also break lepton number in three units. Hence, they are allowed by all symmetries of our model. Indeed in our model one can generate both dimension 9 and 11 operators with $\Delta L = 3$; we provide one example in Fig. 5. However, these are suppressed by the smallness of neutrino masses, the smallness of first/second generation Yukawa couplings,⁸ and/or loop factors. Hence, they are not as important as the $d = 13$ operator in Figs. 1 and 2.

With small changes to the model we have presented, it is also possible to build the operator in Eq. (8) involving only right-handed fermions, instead of operator (9). This simply requires that S_d and S_d' both have a coupling only to $\bar{e}^c \bar{u}^c$ (and not QL). The practical effect of this change is that the proton decay mode into three charged leptons would become the dominant mode.

⁸Proton decay only involves first generation up quarks and first or second generation down quarks and leptons. Note also that the only two $d = 9$ operators—see Eqs. (2) and (3)—necessarily require two up-quark generations.

IV. COMMENT ON $\Delta L = 3$, DISCRETE SYMMETRIES, AND DIRAC NEUTRINOS

As we stated before, from simple dimensionality arguments, one expects that, if allowed by symmetries, $(\Delta B, \Delta L) = (1, \pm 1)$ processes will completely dominate over the higher dimensional $(\Delta B, \Delta L) = (1, \pm 3)$ processes. Thus, proton decay in $\Delta L = 3$ modes will be dominant only if the $\Delta L = 1$ mode is forbidden by some symmetry. As stated before, such a scenario can arise if the accidental $U(1)_L$ (or $U(1)_{B+L}$) symmetry of standard model is broken to a residual Z_3 (or Z_4) subgroup by the new physics involved in the process.

These symmetries force neutrinos to be Dirac particles, as Majorana mass terms with $(\Delta B, \Delta L) = (0, 2)$ are forbidden. After electroweak symmetry breaking, the relevant mass terms are $(Y_\nu)_{ik} \langle H \rangle \nu_i N_k^c + (m_N)_{jk} N_j N_k^c + \text{H.c.}$, where $i, j = 1, 2, 3$ and $k = 1, \dots, 6$. For $Y_\nu m_N^\dagger \approx \mathbf{0}$, the 3 left-handed ν states will not mix significantly with N^c , and the light neutrino masses and mixing angles will depend only on the matrix $Y_\nu Y_\nu^\dagger \langle H \rangle^2$. It is then possible to reproduce oscillation data with small Y_ν couplings. More elegant alternatives to this simple construction require additional fields, which can be used to explain the smallness of the observed neutrino masses through a Dirac seesaw mechanism [29,30].

Note that, in the absence of a $Z_3(L)$ symmetry (or an equivalent one), it will be possible to use the Majorana neutrino mass operator to convert $(\Delta B, \Delta L) = (1, \pm 3)$ operators into the $(\Delta B, \Delta L) = (1, \pm 1)$ standard proton decay. However, due to the smallness of neutrino masses, this does not imply that the 2-body decay rate of the proton will necessarily be large.

Finally, we would like to mention that the $Z_3(L)$ is insufficient to explain the absence of some couplings in our model. In particular, in order to avoid meson decay constraints and still maintain a sizable proton-decay rate, the two scalar S_d and S_d' which share the same quantum numbers must couple differently to QL and $\bar{e}^c \bar{u}^c$. We assumed that S_d couples mostly to the former fermions only, and S_d' to the latter. This arrangement can be achieved with the introduction of a second Higgs doublet field H' and an extra Z_2 symmetry such that the charge of e^c, S_d' and all $SU(2)_L$ doublets in the model is -1 . In this way, the terms $S_d' QL$ and $S_d \bar{e}^c \bar{u}^c$ are forbidden. Furthermore, quarks and leptons will couple to H and H' , respectively, hence both Higgs doublets need to acquire a non-zero vacuum expectation value. This will spontaneously break the Z_2 symmetry, generating $S_d' QL$ and $S_d \bar{e}^c \bar{u}^c$ couplings at loop level, which are not problematic phenomenologically.

V. CONCLUSIONS

Even if lepton number L is not a conserved quantity, it is still possible that all processes which violate it do so in

multiples of some number n . In this work we considered the possibility that leptons can only be created or destroyed in units of $n = 3$. This implies that there is a remnant $Z_3(L)$ symmetry and hence neutrinos are Dirac particles. The processes associated to this type of lepton number violation do not conserve baryon number B either. The case $\Delta(B, L) = (1, 3)$ which we considered is not only the simplest one, but it also leads to nucleon decay into three leptons. Given the high dimensionality of the relevant operators, proton and neutron decay life-time bounds are satisfied even for TeV mediator masses. There is the interesting possibility that both Hyper-Kamiokande and the LHC will be able to probe these scenarios. We have suggested a particular model implementing these ideas, where singlet fermions and three new scalar leptoquarks are added to the standard model. We showed by choosing a benchmark scenario with 1 TeV scalar masses and benchmark values of the couplings that such a scenario is feasible. In this case the nucleon decay modes visible at

Hyper-Kamiokande, and the LHC signatures will depend on the mass of the singlet fermions. For a TeV scale mass, it should be possible to observe events with 3 same sign leptons plus jets and no missing energy at LHC. For lower masses, proton decay into 4- and 5-body final state might be observable at DUNE or Hyper-Kamiokande.

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