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Lepton Number Violating Muon Decay and the LSND Neutrino Anomaly

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Abstract

We show that lepton number violating muon decays, $\mu^+ \to e^+ + \overline{\nu_e} + \overline{\nu_i}$ ($i = e, \mu$ or τ), can consistently explain the neutrino anomaly reported by the LSND experiment. Two effective operators in the Standard Model are identified which lead to just such decays and no other processes. The scale of new physics Λ must be relatively low, $\Lambda \leq 500$ GeV. Extensions of the Standard Model which realize these effective operators are presented. Since new physics affects only the decay of the muon, and not of $\pi^\pm$, our scenario predicts a null result for $\overline{\nu}_\mu - \overline{\nu}_e$ oscillation searches at the Fermilab mini–BOONE experiment. Models which realize these effective operators, while consistent with all available data, can be tested in the near future through (i) discovery of new scalar particles with masses below about 500 GeV, (ii) small but observable deviations in $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \nu\nu\gamma$ cross sections, (iii) observable corrections to the muon $g-2$, and (iv) lepton number violating Z^0 decays with branching ratios of order 10^{-7}.

1 Introduction

Evidence for neutrino flavor oscillations have been mounting over the years. A variety of solar neutrino experiments [1, 2, 4, 3, 5] which have consistently detected fewer ν_e's from the sun than expected now seem to converge on the large angle MSW solution as the preferred explanation for the discrepancy [6]. The deficit in the flux of atmospheric muon neutrinos [7] and especially the observed zenith angle dependence are compelling evidences in favor of $\nu_\mu - \nu_\tau$ oscillations. The LSND collaboration observes an anomaly in the flux of $\overline{\nu}_e$ detected [8], which can be interpreted as evidence for $\overline{\nu}_\mu - \overline{\nu}_e$ oscillations.

As it turns out, it is not possible to explain all of these observations in terms of neutrino oscillations with just three flavors of neutrinos ($\nu_e,\ \nu_\mu$ and ν_τ). The reason is that the characteristic oscillation length scales inferred from the three types of experiments are quite different having no overlap: $\lambda_\odot \sim 200$ km, $\lambda_{atm} \sim 6000$ km and $\lambda_{LSND} \sim 60$ m. The oscillation length is given by $\lambda = (4E)/\Delta m^2$ where $\Delta m^2_{12} = m_1^2 - m_2^2$ etc, with m_i being the mass of the ith neutrino mass eigenstate, and where E denotes the neutrino energy. In three neutrino oscillation schemes there are only two independent mass–splittings, which therefore excludes a simultaneous explanation of all three observations.

Two approaches have been adopted in the literature to address this conundrum. In the first, one of the three observations is simply discarded. In the second approach, a fourth "sterile" neutrino (ν_s) – sterile so that it does not affect the number of neutrinos that couples to the Z^0 bososn – is introduced. Both of these approaches are not very satisfactory. The first one is clearly without justification. The second, introduction of a sterile neutrino, has some serious theoretical difficulties, in addition to a possible problem with the standard Big Bang Nucleosynthesis. Its lightness cannot be explained in any simple way, unlike that of the "active" neutrino which follows very naturally from the seesaw mechanism [9]. Even taking a light sterile neutrino for granted, some potential experimental difficulties have emerged over the last year. When the recent SNO results on solar neutrinos are combined with the results of SuperKamiokande, the allowed parameter space is tightly constrained for oscillations involving a sterile neutrino. In fact, a two–flavor $\nu_e - \nu_s$ oscillation scenario no longer provides a good fit to the solar neutrino data. Atmospheric neutrino oscillation results from SuperKamiokande also disfavor oscillations of ν_μ with a ν_s. Somewhat more involved four neutrino oscillation schemes would be necessary, conforming to either a (3+1) [10] scheme or a mixed 2+2 scheme [11]. Although both appear to be viable presently, neither gives a really satisfactory global fit to all the data [12]. There is also a proposal to account for the LSND results in the three neutrino framework by invoking CPT violation [13].

The purpose of this paper is to provide a simultaneous solution to the three neutrino anomalies without introducing a sterile neutrino. It will be achieved by small non–standard interactions of the leptons instead. Since the flavor conversion probabilities are of order unity for both the solar and the atmospheric neutrino experiments, we shall focus on non–standard lepton interactions explaining the LSND anomaly, which calls for a smaller probability: $P_{\overline{\nu}_\mu \to \overline{\nu}_e} = (0.264 \pm 0.067 \pm 0.045)\%$ [8]. Specifically, we shall show that lepton number violating ($\Delta L = 2$) muon decays can account for the LSND events. The new decay mode of the muon is

$$\mu^+ \to e^+ + \overline{\nu}_e + \overline{\nu}_i \ , \tag{1}$$

where $\overline{\nu}_i$ stands for any one of $\overline{\nu}_e$, $\overline{\nu}_\mu$ or $\overline{\nu}_\tau$. Consistent gauge models will be presented where such decays occur with the desired strength.

It is crucial that the non–standard decays of the muon are lepton number violating [14]. Attempts to explain the LSND data in terms of lepton number conserving four–fermion interaction [15, 16] will lead to inconsistencies with other experiments. One can make an $SU(2)_L$ transformation on such effective operators which would invariably generate lepton number violating processes such as $\mu \to 3e$ decay, muonium–antimuonium transition, $\tau \to \mu ee$ decay, etc, which are highly constrained by experiments [14, 15]. In contrast, the $\Delta L = 2$ processes that we find will not admit an $SU(2)_L$ transformation to generate one of these highly forbidden processes, primarily because there is no charged current counterpart to the anomalous muon decays.[1] Since the new physics affects only $\mu^\pm$ decays, and not that of $\pi^\pm$, our interpretation of the LSND results would predict that no oscillation signal should be seen at the Fermilab mini–BOONE experiment. We have identified two $\Delta L = 2$ effective operators which are invariant under the Standard Model symmetries that can induce the decay of Eq. (1) without generating any other effects. These effective operators can be realized from underlying renormalizable theories which are extensions of the Standard Model involving additional scalar multiplets. The masses of these scalar bosons are bounded by about 500 GeV, in order that the signal at LSND is significant. Since the scale of new physics, Λ, is relatively low, the particles at the scale Λ do not decouple entirely and have an impact on low energy observables. We highlight the processes that would succumb to the new physics most easily. They include small but observable deviations in $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \nu\nu\gamma$ cross sections, observable corrections to the muon $g-2$, and lepton number violating Z^0 decays with branching ratios of order 10^{-7}.

2 Lepton number violating muon decay

The decay $\mu^+ \to e^+ + \overline{\nu}_e + \overline{\nu}_i$ with $i = e\ \mu$ or τ, if allowed by the theory, can explain the LSND neutrino anomaly. Recall that the usual μ decay $\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e$ has no $\overline{\nu}_e$ which the LSND detector registers. The new decay of μ^+ produces $\overline{\nu}_e$, which will then be detected. The branching ratio for the new decay should be about $(1.5 - 3) \times 10^{-3}$, as can be inferred from the LSND analysis of the $\overline{\nu}_\mu - \overline{\nu}_e$ oscillation probability.

We have found two effective operators invariant under the symmetries of the Standard Model [17] that can induce the desired $\Delta L = 2$ muon decays. They are

$$\mathcal{O}_1 \ = \ \frac{1}{\Lambda^5}(\overline{\Psi}_\mu e_R \Phi)(\Psi_e^T C^{-1} \Psi_i \Phi\Phi)$$

[1] We shall see shortly that the anomalous muon decay is mediated by neutral current.

$$\mathcal{O}_2 = \frac{1}{\Lambda^5}(\overline{\mu}_R \Psi_e \Phi^\dagger)(\Psi_e^T C^{-1} \Psi_i \Phi\Phi) \ . \tag{2}$$

Here $\Psi_\mu = (\nu_\mu,\ \mu)_L^T$, $\Psi_e = (\nu_e,\ e)_L^T$, etc denote the left–handed lepton doublets, while e_R, μ_R denote the right–handed singlets. Φ is the Standard Model Higgs doublet with its hypercharge normalized to be $+1/2$.

Note that both $\mathcal{O}_1$ and $\mathcal{O}_2$ are non–renormalizable operators of dimension 9, and hence are suppressed by fifth power of Λ which characterizes the scale of new physics. As we shall see, these operators will arise from integrating out scalar fields which have lepton number violating interactions. Operator $\mathcal{O}_1$ has a unique $SU(2)_L$ contraction, owing to Bose symmetry in the Φ field. Although $(\overline{\Psi}_\mu e_R \Phi)$ in $\mathcal{O}_1$ contracts to form an $SU(2)_L$ singlet, it will not induce a $\overline{\mu}_L e_R$ mass term (see below). Similarly, no $d = 5$ neutrino mass term will arise from these operators. Note also that there is a unique Lorentz contraction of fermionic fields in $\mathcal{O}_1$, if we limit ourselves to obtaining these operators by integrating out scalar fields. Similar remarks apply to operator $\mathcal{O}_2$ as well. In this case, there is a minor variant, obtained by contracting $(\overline{\mu}_R \Psi_i \Phi^\dagger)$ rather than $(\overline{\mu}_R \Psi_e \Phi^\dagger)$, which is somewhat different for the case when $i \neq e$.

When the vacuum expectation value $\langle \Phi^0 \rangle = v$ is inserted in Eq. (2), it would generate the four–fermion operators

$$\begin{aligned}
\mathcal{O}_1 &\sim \frac{v^3}{\Lambda^5}(\overline{\mu}_L e_R)(\nu_e^T C^{-1} \nu_i) \\
\mathcal{O}_2 &\sim \frac{v^3}{\Lambda^5}(\overline{\mu}_R e_L)(\nu_e^T C^{-1} \nu_i) \ .
\end{aligned} \tag{3}$$

These operators will lead to the decay $\mu^+ \to e^+ + \overline{\nu}_e + \overline{\nu}_i$. The branching ratio for the L–violating μ^+ decay is given by

$$Br(\mu^+ \to e^+ \overline{\nu}_e \overline{\nu}_i) = \left[\frac{v^3}{4\sqrt{2} G_F \Lambda^5}\right]^2 \ . \tag{4}$$

Inserting the numerical value of $v \sim 246$ GeV, and demanding that the branching ratio for this decay is in the range $Br(\mu^+ \to e^+ \overline{\nu}_e \overline{\nu}_i) = (0.0015 - 0.0025)$, we find that the scale $\Lambda \simeq (360 - 340)$ GeV. Since Λ is not very large, the particles that have masses of order Λ will not entirely decouple and will affect low energy observables.

An important point about operators $\mathcal{O}_1$ and $\mathcal{O}_2$ of Eq. (2) is that they induce only the terms given in Eq. (3) and nothing more. This is because of the $\Delta L = 2$ nature of these operators and the fact that there is only one Higgs scalar in the theory. This proves that the effective operators of Eq. (2) generate the desired interactions that can explain the LSND events, and nothing else. Unlike in the case of $\Delta L = 0$ muon decays, there is no conflict with processes such as $\mu \to 3e$, $\tau \to \mu ee$, etc.

KARMEN experiment [18] has set severe limits on lepton number violating decays of the muon. These limits however, depend sensitively on the assumed decay distribution. The anomalous muon decay arising from Eq. (2) in our models has a different distribution compared to that of the usual (V-A) decay of the muon. We find that operators

$\mathcal{O}_1$ and $\mathcal{O}_2$ lead to the prediction $\rho = 0$ for the Michel parameter for the $\Delta L = 2$ decay. (The other decay asymmetry parameters for the L–violating μ decay are found to be: $\eta = 0,\ \xi = -3/4$, and $\delta = 0$ [19].) The limit from KARMEN for the branching ratio for the decay $\mu^+ \to e + \overline{\nu}_e + \overline{\nu}_i$ corresponding to the case where $\rho = 0$ is Br $\leq (0.0015 - 0.002)$ [20]. This limit is somewhat weaker than KARMEN's published limit corresponding to the case of $\rho = 3/4$ [21]. Thus, the KARMEN results appear to be just about consistent with LSND observations, in our interpretation of the data. A joint analysis of the LSND and the KARMEN data in our framework will be desirable.

All new phenomena in the model will arise from particles with masses of order Λ. To see these additional new effects, we have to generate operators of Eq. (2) from renormalizable Lagrangian densities. We now turn to this task.

3 Gauge models for Lepton number violating muon decays

We shall now present renormalizable gauge models that induce the effective operators of Eq. (2). These models are obtained by extending the scalar sector of the Standard Model. The new interaction Lagrangian for the first model which induces $\mathcal{O}_1$ is given by

$$\begin{aligned} \mathcal{L}_1 &= h_{\mu e} \overline{\Psi}_\mu e_R H + f_{ei} \Psi_e^T C^{-1} \Psi_i \Delta \\ &+ \mathcal{M}_0 H^\dagger \chi \Phi + \lambda' \Delta \chi \Phi^\dagger \Phi^\dagger + H.C. \end{aligned} \tag{5}$$

Here $\Delta(3,1),\ \chi(3,0)$ and $H(1,1/2)$ are scalar fields (their $SU(2)_L \times U(1)_Y$ quantum numbers are as indicated) which do not acquire any vacuum expectation value.

Figure 1 will induce the effective operator $\mathcal{O}_1$ from Eq. (5). Notice that the intermediate scalar particles are electrically neutral, so the anomalous muon decay is a neutral current process. It is not possible to make an $SU(2)_L$ transformation in Fig. 1 to convert some of the external fermions, without also transforming the external Higgs field to its charged component, which of course is unphysical.

The strength of the effective four–fermion coupling arising from Fig. 1, in the approximation of small scalar mixing, is

$$G_{\rm eff} = \frac{h_{\mu e} f_{ei} \lambda' \mathcal{M}_0 v^3}{(m_{\chi^0}^2 m_{H^0}^2 m_{\Delta^0}^2)} \ . \tag{6}$$

If all the mass parameters are equal and if $h_{\mu e}, f_{ei}$ and λ' are equal to one, LSND data would require the scalar masses to be in the range $(340 - 360)$ GeV. Actually, we can make this statement more precise. Let us denote the scalar mass–squared matrix involving the mixing of $(H^0, \chi^0, \Delta^{0*})$ to be $\mathcal{M}^2$. Let K be the unitary matrix that diagonalizes $\mathcal{M}^2$: $K^\dagger \mathcal{M}^2 K = diag.(M_1^2,\ M_2^2,\ M_3^2)$ with $M_1 \leq M_2 \leq M_3$. Then by making use of the

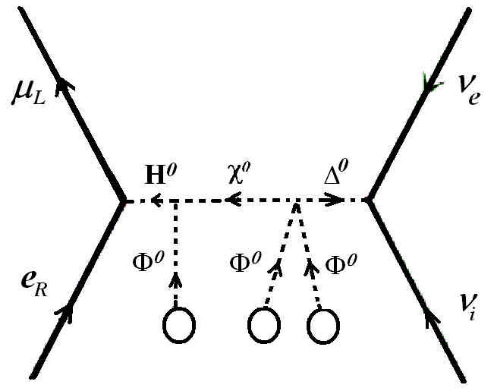

Figure 1: Scalar exchange inducing lepton number violating decay $\mu^+ \to e^+ + \overline{\nu}_e + \overline{\nu}_i$ through operator $\mathcal{O}_1$.

unitarity of K and the fact that $(\mathcal{M}^2)_{13} = 0$, we can write down the branching ratio to be

$$Br(\mu^+ \to e^+ \overline{\nu}_e \overline{\nu}_i) = \frac{|h_{\mu e} f_{ei}|^2 |K_{12} K_{32}^*|^2}{32 M_1^4 G_F^2} \left(1 - \frac{M_1^2}{M_2^2}\right)^2 \left(1 - \frac{M_2^2}{M_3^2}\right)^2 . \qquad (7)$$

Noting that $|K_{12}K_{32}^*| \leq 1/2$, and demanding that Br is in the range $(0.0015 - 0.002)$, we obtain an upper limit on the lightest neutral scalar mass M_1: $M_1 \leq (442 - 412)$ GeV. If $|K_{12}K_{32}^*|$ is less than $1/2$, M_1 will have to be even lighter. The heavier masses M_2 and M_3 cannot be very much larger, or else the mixing angle $|K_{12}K_{32}^*|$ will be suppressed. We estimate $M_{2,3}$ to be not larger than M_1 by about a factor of 2. While these limits hold for the neutral scalars, their charged partners should also have comparable masses. Any splitting between the masses of the neutral and charged scalars will be $SU(2)_L$–breaking, and is limited by the electroweak ρ parameter.

Ψ_i in Eq. (5) can be Ψ_e, Ψ_μ or Ψ_τ. Consider the case when $\Psi_i = \Psi_e$. In this case, the Lagrangian of Eq. (5) conserves two combinations of leptons numbers, viz., $(L_e + 3L_\mu)$ and L_τ. A Z_3 subgroup of electron number is also preserved. It is not required that these symmetries be broken, so they may be used to prevent rare processes at undesirable rates.[2]

If $\Psi_i = \Psi_\mu$ in Eq. (5), then muon and tau lepton numbers are unbroken. Also unbroken is a Z_2 subgroup of electron number. If $\Psi_i = \Psi_\tau$, then $(L_e + 2L_\mu)$ and $(L_\mu + L_\tau)$ are unbroken, as is Z_2 subgroup of L_e. These symmetries guarantee that potentially dangerous lepton number violating processes remain small.

The scalar fields Δ, χ and H carry lepton number symmetries (or a discrete subgroup of these symmetries), so that they do not acquire VEVs. This can be ascertained by choosing the mass–squared of these scalars to be positive. The lepton number symmetries

[2]We have in mind a scenario where the solar and the atmospheric neutrino oscillations arise from neutrino masses and mixings induced by the seesaw mechanism. Lepton flavor violation that arises from the seesaw mechanism is too tiny to be observable in any processes other than neutrino oscillations themselves.

will forbid possible tadpole contributions to their VEVs. Thus, these new interactions do not induce neutrino masses at all. The only source of neutrino mass in these models is through the seesaw mechanism.

One may worry about the compatibility of the lepton number symmetries present in Eq. (5) and the neutrino oscillation data, which calls for the breaking of all such symmetries. We shall present a concrete example to demonstrate the consistency. Consider Eq. (5) with $\Psi_i = \Psi_\mu$. Let us impose L_μ and L_τ symmetries as well as a Z_2 subgroup of L_e. Under these symmetries the scalar fields $(H,\ \chi,\ \Delta)$ have charges $(1,0)_-$, $(1,0)_-$ and $(-1,0)_-$ respectively. The charged lepton mass matrix as well as the Dirac neutrino mass matrix will be diagonal due to these symmetries. Neutrino mixings can still arise from the superheavy Majorana mass matrix of the ν_R fields. The charges of $(\nu_{eR},\ \nu_{\mu R},\ \nu_{\tau R})$ under these symmetries are $\{(0,0)_-;\ (1,0)_+;\ (0,1)_+\}$ respectively. If scalar fields with charges $(0,0)_+$, $(0,-1)_-$, $(-1,-1)_+$ and $(0,-2)_+$ are introduced and given large vaccum expectation values, all neutrino flavors will mix with one another. These superheavy scalars will have no couplings to the $(H,\ \chi,\ \Delta)$ fields and thus will not spoil the symmetry, except through small neutrino mass terms.

The exchange of the new scalars with masses of order 500 GeV can lead to new processes. We list below the most significant of these.

1. The effective Michel parameter ρ in μ decay is modified in our scenario: ($\rho = 0.7485$). The deviation from 3/4 arises because of the rare μ decay mode we have introduced here to explain the LSND data. Currently the uncertainty in the measurement of ρ is ± 0.0026, but the TWIST experiment at TRIUMF [22] will have a sensitivity of 10^{-4} in ρ, which can test this scenario. There will also be a small shift in G_F extracted from μ decay by $(0.15 - 0.2)\%$, compared to the Standard Model value. Such a shift is currently consistent with radiative corrections in muon decay (parametrized by Δr), which has an uncertainty of about 0.2% arising from the ± 5 GeV uncertainty in the top quark mass alone.

2. The neutral component H^0 from the scalar H can mediate the process $e^+e^- \to \mu^+\mu^-$. The total cross section as well as the forward–backward asymmetry measured away from the Z^0 pole give useful constraints. The most stringent one arises from LEP experiments run at $130 \leq \sqrt{s} < 189$ GeV. L3 collaboration has quoted lower limits on contact interaction [23] at these energies. The exchange of H^0 induces the following effective contact interaction:

$$\mathcal{L} = -\frac{|h_{\mu e}|^2}{2m_{H^0}^2}(\overline{\mu}_L \gamma_\mu \mu_L)\overline{e}_R \gamma^\mu e_R) \ . \tag{8}$$

   This corresponds to the case of $\eta_{LR} = -1$ and all other $\eta_{ij} = 0$ in the notation of Ref. [23]. The limit on compositeness scale $\Lambda_- > 1.9$ TeV [23] implies

$$m_{H^0}/|h_{\mu e}| \geq 379\ GeV \ . \tag{9}$$

The constraints from forward–backward asymmetry measurements, which have uncertainty of a few % will be satisfied once Eq. (9) is met.

The exchange of Δ^{++} partner of Δ^0 will also contribute to the process $e^+e^- \to \ell^+\ell^-$. The effective Lagrangian for this process is

$$\mathcal{L} = \frac{|f_{ei}|^2}{2m_{\Delta^{++}}^2}(\overline{e}_L\gamma_\mu e_L)(\overline{\ell}_{iL}\gamma^\mu \ell_{iL}) \ . \tag{10}$$

The constraint on Λ_+ is $\Lambda_+ > \{3.8,\ 7.3,\ 3.9\}$ TeV for $\ell_i = (e,\ \mu,\ \tau)$ [23]. This would lead to the following limits:

$$\frac{m_{\Delta^{++}}}{|f_{ee}|} > 758 \text{ GeV}, \quad \frac{m_{\Delta^{++}}}{|f_{e\mu}|} > 1456 \text{ GeV}, \quad \frac{m_{\Delta^{++}}}{|f_{e\tau}|} > 778 \text{ GeV} \ , \tag{11}$$

corresponding to ℓ_i being e, μ, or τ. Since Δ^{++} cannot be split much in mass from Δ^0, explaining the LSND result at the suggested rate would require f_{ei} to be somewhat smaller than one and simultaneously one of the neutral scalar masses to be lower than about 300 GeV (see Eqs. (6) and (7)).

3. The charged member H^+ from H scalar will mediate the process $e^+e^- \to \nu\nu\gamma$. This process has been studied at LEP as a way to count the number of light neutrino species. L3 collaboration quotes $N_\nu = 3.05 \pm 0.11 \pm 0.04$ from single photon measurements carried out at 130 GeV $\leq \sqrt{s} \leq$ 189 GeV [24]. (Measurements very close to the Z^0 pole are less useful for our purpose.) Using the 3 sigma limit we obtain (following the procedure outlined in Ref. [25])

$$m_{H^0}/|h_{\mu e}| \geq 375 \ GeV \ . \tag{12}$$

   We see that the predicted deviation from the Standard model is in the observable range, once the LSND data is explained.

4. The neutral H^0 will contribute to the anomalous magnetic moment of the muon. The shift in a_μ compared to the Standard model prediction is given by $\delta a_\mu \simeq |h_{\mu e}|^2(m_\mu/m_{H^0})^2/(24\pi^2) \simeq 47 \times 10^{-10}|h_{\mu e}|^2(100 \text{ GeV}/m_{H^0})^2$. This is in the experimentally interesting range for $|h_{\mu e}|$ being order one and $m_{H^0} = (100 - 300)$ GeV, as needed by the LSND data.

5. Δ^+ can mediate $e^+e^- \to \nu\nu\gamma$ for the case where $\Psi_i = \Psi_e$, with a branching ratio very close to the current limits. In the case where $\Psi_i = \Psi_\mu$, there is new contribution to ordinary muon decay from the exchange of Δ^+. We obtain $m_{\Delta^+}/|f_{e\mu}| \geq 525$ GeV using $\delta(\Delta r) \leq 0.003$. This limit, for the case where $\Psi_i = \Psi_\mu$, while consistent, will force some of the other scalars to be lighter than 400 GeV.

6. At a future linear collider running in the e^-e^- mode, it is possible to produce the doubly charged scalar Δ^{++} as an s-channel resonance in the process $e^- + e^- \to \ell^-\ell^-$, which will provide a spectacular signal.

7. In the dimension 9 operator of Eq. (4), if we insert VEVs to the external Higgs fields, it becomes a $d = 6$ operator. Then we can attach a Z^0 boson line on the effective four–fermion operator. That would lead to rare Z^0 decays such as $Z^0 \to e^+\mu^-\nu\nu$. A quick estimate gives the branching ratio for this decay to be of order $(10^{-7} - 10^{-8})$, which may be observable.

8. The Z^0 boson can decay into a virtual $H\bar{H}$ pair, which can lead to $Z^0 \to e^+e^-\mu^+\mu^-$ signal. This branching ratio is smaller than 10^{-6} .

3.1 Model for Operator $\mathcal{O}_2$

The gauge model that induces operator $\mathcal{O}_2$ in Eq. (2) can be obtained in analogous fashion. The Lagrangian of this model is taken to be

$$\begin{aligned} \mathcal{L}_2 &= h_{e\mu}\overline{\mu}_R\Psi_e H^\dagger + f_{ei}\Psi_e^T C^{-1}\Psi_i\Delta \\ &+ \mathcal{M}_0 H^\dagger\chi\Phi + \lambda'\Delta\chi\Phi^\dagger\Phi^\dagger + H.C. \end{aligned} \tag{13}$$

The main difference from $\mathcal{L}_1$ is that the helicities of e and μ have been switched. The diagram of Fig. 2 will induce the decay $\mu^+ \to e^+ + \bar{\nu}_e + \overline{\nu}_i$. The phenomenological implications of the model are very similar to Model 1. The only significant difference is that the exchange of H^+ now cannot induce the process $e^+e^- \to \nu\nu\gamma$, and so the constraint from that process would not apply.

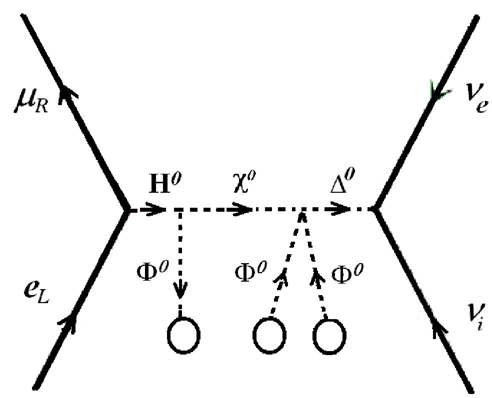

Figure 2: Scalar exchange inducing lepton number violating decay $\mu^+ \to e^+ + \overline{\nu}_e + \overline{\nu}_i$ through operator $\mathcal{O}_2$.

4 Conclusions

We have presented a class of models where the LSND neutrino anomaly can be explained in terms of the lepton number violating decay $\mu^+ \to e^+ + \bar{\nu}_e + \overline{\nu}_i$. There are two effective operators that can lead to this decay. These operators do not cause any problem with other rare processes such as $\mu \to 3e$, unlike the case of $\Delta L = 0$ decays. We have presented gauge models where these operators are derived from renormalizable interactions. All models predict the existence of additional scalar fields with masses below about 500 GeV. Observable deviations in the scattering processes $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \nu\nu\gamma$ and lepton number violating Z^0 decays are expected with strengths not much smaller than the current experimental limits.

Mini–BOONE experiment at Fermilab is expected to go on line in the near future. Our scenario predicts that mini–BOONE should see no signal. This is because the new interactions only affect $\mu^\pm$ decays in our scheme, and not $\pi^\pm$ decays. Hence, a null result in Mini-Boone does not invalidate the LSND results. The proposed ORLaND experiment [26] or experiments at a neutrino factory [27] using neutrinos from μ decays [19] can confirm or rule out the existence of such a lepton number violating decay mode; with the additional prediction that there be no L/E dependence. The TWIST experiment at TRIUMF [22] can test for the shift in the effective Michel parameter that is predicted in our model.

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