Phenomenologies of Exotic Particles in the Lepton Sector

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Abstract

By considering all new interaction terms in the lepton sector that are renormalizable and SM gauge invariant, but with only ***one*** exotic particle appearing per term, we identify those couplings which have been rarely studied. For these new processes, we have begun investigating their contributions to the FCNC effects. Using the available low-energy experimental data, constraints can then be placed on the interaction strength involving these exotic leptons.

Introduction

Of the many ways to construct new renormalizable couplings involving exotic particles, we've opted to look at the minimal form $Y_{\rm exotic}\,({\rm SM\ particle})\cdot({\rm SM\ particle})\cdot({\rm exotic\ particle})$,

where $Y_{\rm exotic}$ is the coupling strength. Hence, in the lepton sector, five types of new interaction terms are allowed:

$$\text{(i)}\ \ L_L\times L_L\times({\rm new})\ ,\ \ \text{(ii)}\ \ L_L\times \ell_R\times({\rm new})\ ,\ \ \text{(iii)}\ \ \ell_R\times\ell_R\times({\rm new})\ ,$$
$$\text{(iv)}\ \ L_L\times\phi\times({\rm new})\ ,\ \ \text{(v)}\ \ \ell_R\times\phi\times({\rm new})\ .$$

Many of the resulting "(new)" particles have been studied due to other motivations. We summarize their status in the table on the right (NB. $Q=I_3+Y$).

However, not much work has been done on these exotic triplet and doublet fermions

(new)	spin	$SU(2)_L$	$U(1)_Y$	type	studied in
Φ_i	0	2	1/2	(ii)	multi-Higgs doublet
χ_0	0	1	−1	(i)	dilepton/Babu-Zee
Δ	0	3	−1	(i)	dilepton/Type-II seesaw
ξ_0	0	1	2	(iii)	dilepton/Babu-Zee
ν_R	1/2	1	0	(iv)	Type-I seesaw
Σ_R	1/2	3	0	(iv)	Type-III seesaw
L'_L	1/2	2	−1/2	(v)	4th generation leptons
ℓ'_R	1/2	1	−1	(iv)	4th generation leptons
$E_{R,L}$	1/2	3	−1	(iv)	– – not much – –
$\tilde{L}_{L,R}$	1/2	2	−3/2	(v)	
Z'_μ	1	1	0	(i) & (iii)	GUT or dilepton gauge boson models
X_μ	1	2	−3	(ii)	
W'_μ	1	3	0	(i)	

Model with Exotic Triplets

In this current work, we shall only concentrate on the exotic triplet fermions with $Y = -1$. We introduce to the SM two sets of new triplet fields (RH and LH) and write them in a 2×2 representation

$$E_{R,L}=\begin{pmatrix} E^-_{R,L}/\sqrt{2} & E^0_{R,L}\\ E^{--}_{R,L} & -E^-_{R,L}/\sqrt{2}\end{pmatrix}\sim(1,3,-1)\ .$$

The interaction Lagrangian of interest is

$$\mathcal{L}^E={\rm Tr}\left[\overline{E}_R i\not{D} E_R\right]+{\rm Tr}\left[\overline{E}_L i\not{D} E_L\right]+{\rm Tr}\left[\overline{E}_R M_E E_L+h.c.\right]$$
$$-\left[L_L Y_E E_R\phi+L_L Y_\ell\phi\,\ell_R+L_L Y_\nu\phi^c\,\nu_R+h.c.\right]\ ,$$

where we have only included a neutrino Dirac mass term but ***not*** a Majorana mass (i.e. no seesaw) for simplicity. To study the mixing between SM leptons and components of the exotic triplets, it is convenient to package the mass terms in an analogous way that is used to analyse the triplet seesaw setup [1],

$$\mathcal{L}^{\rm mass}=-\begin{pmatrix}\overline{\nu}_R & \overline{E^0_R}\end{pmatrix}\begin{pmatrix} m_D^\dagger & 0\\ vY_E^\dagger/\sqrt{2} & M_E\end{pmatrix}\begin{pmatrix}\nu_L\\ E^0_L\end{pmatrix}-\begin{pmatrix}\overline{\ell}_R & \overline{E^-_R}\end{pmatrix}\begin{pmatrix} m_\ell & 0\\ -vY_E^\dagger/2 & M_E\end{pmatrix}\begin{pmatrix}\ell_L\\ E^-_L\end{pmatrix}\ ,$$

where v denotes the Higgs VEV.

Preliminary Results

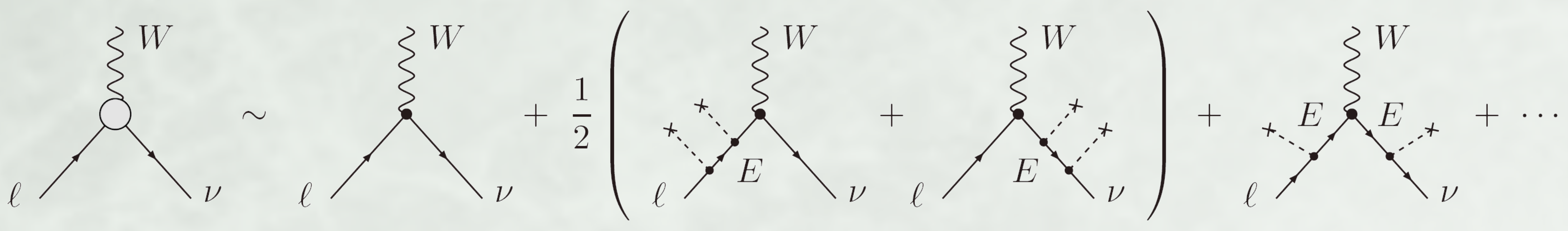
Because of the mixing between the exotic triplets and SM leptons induced by the coupling Y_E, the diagonalization matrix for transforming into the neutrino mass eigenbasis is now ***non-unitary*** in general. Such non-unitary effect will give rise to a new source of tree-level FCNC in the lepton sector. We can parameterize this by defining the 3×3 matrix

$$\lambda\equiv\frac{v^2}{8}\,Y_E\,\frac{1}{M_E^2}\,Y_E^\dagger\ .$$

Hence, to order $v^2 M_E^{-2}$, the charged and neutral currents become

$$\mathcal{L}^{CC}=\frac{g}{\sqrt{2}}\,\overline{\nu}\,W^+P_L\,N^\dagger\,\ell+h.c.\ ,$$
$$\mathcal{L}^{NC}=\frac{g}{\cos\theta_w}\left\{\overline{\ell}\,\not{Z}\left[P_L\left(-\frac{1}{2}NN^\dagger+\sin^2\theta_w\right)+P_R\sin^2\theta_w\right]\ell\right.$$
$$\left.+\overline{\nu}\,\not{Z}\,P_L\left(\frac{1}{2}\,(N^\dagger N)^{-2}\right)\nu\right\}\ ,$$

where $N\equiv(1-\lambda)U_{\rm PMNS}$ is a non-unitary mixing matrix.



Pictorial visualization of the modified W-vertex to order λ.

An important consequence of this is the modification of the Fermi constant, G_F, as extracted from muon decay.

To leading order, the correction to G_F is given by

$$G'_F=G_F\sqrt{1-2\lambda_{ee}-2\lambda_{\mu\mu}}\ ,\qquad {\rm with}\qquad G_F^2\equiv g^4/32M_W^4\ .$$

Furthermore, constraints on the elements of λ can be obtained by considering various tree-level W and Z processes and using the experimental data from [2]:

W **decays**

$$\frac{(1-2\lambda)_{\alpha\alpha}}{\sqrt{1-2\lambda_{ee}-2\lambda_{\mu\mu}}}\simeq\frac{\Gamma(W\to\ell_\alpha\nu_\alpha)\,6\sqrt{2}\,\pi}{G'_F M_W^3}=\begin{cases}1.012\pm0.032\ ; & \alpha=e\\ 0.995\pm0.034\ ; & \alpha=\mu\\ 1.059\pm0.037\ ; & \alpha=\tau\end{cases}$$

Z **decays (invisible)**

$$\frac{3+8\sum_\alpha\lambda_{\alpha\alpha}}{\sqrt{1-2\lambda_{ee}-2\lambda_{\mu\mu}}}\simeq\frac{\Gamma(Z\to{\rm inv})}{\Gamma_{\nu\nu}(1+\rho_{\rm loop})}=2.984\pm0.009\ .$$

Z **decays (charged leptons)**

decay process	constraint
$Z\to e^\pm\mu^\mp$	$\lvert\lambda_{e\mu}\rvert<1.4\times10^{-3}$
$Z\to e^\pm\tau^\mp$	$\lvert\lambda_{e\tau}\rvert<3.4\times10^{-3}$
$Z\to \mu^\pm\tau^\mp$	$\lvert\lambda_{\mu\tau}\rvert<3.8\times10^{-3}$

lepton → 3 leptons

LFV process	constraint	LFV process	constraint
$\mu^-\to e^+e^-e^-$	$\lvert\lambda_{e\mu}\rvert<6.3\times10^{-7}$	$\tau^-\to\mu^-e^+e^-$	$\lvert\lambda_{\mu\tau}\rvert<8.7\times10^{-5}$
$\tau^-\to e^+e^-e^-$	$\lvert\lambda_{e\tau}\rvert<2.8\times10^{-4}$	$\tau^-\to e^+\mu^-\mu^-$	$\lvert\lambda_{\mu e}\rvert\lvert\lambda_{\mu\tau}\rvert<2.5\times10^{-4}$
$\tau^-\to\mu^+\mu^-\mu^-$	$\lvert\lambda_{\mu\tau}\rvert<2.7\times10^{-4}$	$\tau^-\to\mu^+e^+e^-$	$\lvert\lambda_{e\mu}\rvert\lvert\lambda_{e\tau}\rvert<2.4\times10^{-4}$
$\tau^-\to e^-\mu^+\mu^-$	$\lvert\lambda_{e\tau}\rvert<1.0\times10^{-4}$		

These constraints on the elements of λ will in turn lead to restrictions on the entries for Y_E and M_E .

Summary & Further Work

We have presented some preliminary analyses on a special type of exotic triplet leptons which minimally couple to SM particles. In particular, we concentrated on their effects on FCNC at tree-level, and constraints were derived using experimental data. The analysis of other interesting processes involving these triplets that are still in progress include: $\mu\to e\gamma$, modification to muon g–2, as well as μ-e conversion in atomic nuclei.

References

[1] A. Abada *et al.* JHEP **0712**:061, 2007 [arXiv:0707.4058 [hep-ph]]

[2] C. Amsler *et al.* (Particle Data Group), Phys. Lett. **B667**, 1 (2008) and 2009 partial update for the 2010 edition.

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