Production and decay rates of excited leptons in a left-right symmetric scenario

Piyali Banerjee* and Urjit A. Yajnik†

Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India

Abstract

We merge two leading Beyond Standard Model scenarios, namely compositeness and left-right symmetry, and probe the resulting collider signatures in the leptonic case. The constraints on composite models for fermions leave open the possibility of vector like excitations of Standard Model (SM) fermions. Here we consider the possibility of low scale left-right gauge symmetry $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$, with the simplifying assumption that the right like excited sector of fermions is significantly heavier than the excitations of the left chiral fermions. It is found that the right handed currents still contribute to observable processes, and alter the existing bounds on the scale of compositeness. The cross section times branching ratio of the photon decay channel is strongly depressed, bringing down the exclusion limit of the mass of excited electrons from about 2 TeV to below 1 TeV. On the other hand, cross section times branching ratio of the Z decay channel is significantly enhanced and remains greater than that of the photon channel. We thus propose analyzing the Z decay channel in existing collider data in order to search for signature of left-right symmetry as well as excited leptons with masses above 1 TeV.

* banerjee.piayali3@gmail.com
† yajnik@iitb.ac.in
I. INTRODUCTION

One way around the conceptual problems faced by the Higgs mechanism operating at scales much lower than the Planck scale, is to conjecture, as has been done in many works, that the observed spectrum of particles arises as a set of composites of some more fundamental particles. If this is true then in particular, there would be excited states heavier than known fermions, with some correspondence to, and decay channels into, known particles. Such models have been considered early in the development of electroweak theory, [1–4, 8–10] from theoretical motivations, and also subsequently, from a phenomenological point of view in response to emerging experimental signatures [11–17]. Signatures of excited leptons have been searched for at the DESY Hadron Electron Ring Accelerator (HERA) and the CERN Large Electron Positron collider (LEP) [18, 19], the Fermilab Tevatron collider [20, 21], the CERN Large Hadron Collider (LHC) [22–24], and are proposed for the next linear colliders [25, 26]. Up to now, no signal has been observed for excited states [27], but with higher centre-of-mass energy and more data we would be able make the search more robust.

The confirmation of small neutrino masses in the past decade [28–31] has raised the possibility that the spectrum of matter is after all symmetric between the two handedness states, and the maximal parity violation of Weak forces is only a low energy effect. Chirality already incorporated in the Standard Model (SM) however continues to be the underlying principle on which building blocks of matter are organized, with the advantage of universal source of masses from spontaneous symmetry breaking. While the question of grand unification seems to have got postponed with the absence of proton decay at expected energies, we may take the Left-Right symmetric model (LRSM) as a natural extension of the SM. The Left-Right symmetric model [32, 33] treats both left- and right-handed fermions as doublets, and possesses the potential to provide an elegant explanation of neutrino masses [34] through the see-saw mechanism [35–37]. Additionally the model gauges the $B - L$ quantum number [38], the only anomaly free quantum number of the the SM left ungauged.

The scale of parity breakdown is as yet unknown. The see-saw mechanism [36, 37], while providing an elegant qualitative explanation, is unable to predict the parity breaking energy scale due to wide variation in the fermion masses across the generations. The scale of the parity breakdown, equivalently that of the right handed Majorana neutrinos is usually
pegged high, $10^{14}$ GeV. However this is subject to the choice of the "pivot" mass, which is often pegged at the electroweak scale. If the pivot mass is that of the lighter charged fermions, it is equally well possible to have the appearance of the right handed gauge forces at as low as TeV scale [39]. The current experimental constraints on $Z'$ mass are as low as the TeV scale [40]. However the existing models of excited fermions, based on the SM, have not attempted to address the incorporation of non-zero neutrino masses. So it is natural to attempt combining these two models to address the above inadequacies of SM. We thus have two new scales appearing beyond the SM, the scale $M_R$ which determines the mass of $W_R$ and $Z_R$ bosons, and hence the mass $m_{Z'}$ of new neutral gauge boson $Z'$, and separately, a scale $\Lambda$, which determines the mass $m_{l^*}$ of the composite fermions.

Any model of excited fermions is strongly constrained, [41] [11] firstly by the absence of any structure for the fermions upto currently accessible energies, and secondly by the anomalous magnetic moments $g-2$ as well the electric dipole moments of the leptons. The contribution of vector like fermionic states to $g-2$ is however significantly suppressed and therefore such excited states remain light enough to be accessible to current and near future accelerators without contradicting the other data.

Incorporating Left-Right symmetry in this setting requires doubling up the entire spectrum of the excited fermions, one set connected to the left chiral fermions and another connected to the right chiral fermions. To keep the discussion simple in this initial investigation we assume the heavy vector like fermions to be doublets only under the SM $SU(2)_L$, and ignore the spectrum that may be associated to the $SU(2)_R$ of the LRSM. This may actually be a valid approximation in the full fledged model if the $SU(2)_R$ related vector like heavy spectrum is naturally heavier than the left like. This circumstance could have the same underlying physics as that which suppresses the right handed currents at low energies. With above reasoning, in this paper we work in the simplified framework where the excited fermion spectrum to be explored is coupled directly only to the SM $SU(2)_L$. Nevertheless, the $l^*$ sector leaves its stamp on the search strategies for Left-Right symmetry. This is because in LRSM, the observed $Z$ boson is an admixture of $Z_L$ and $Z_R$ and the signal for $Z'$ bosons would have to be modified if this excited lepton sector exists. In the following we shall assume the hierarchy $\Lambda \gtrsim m_{l^*} > m_{Z'} > m_Z$.

This paper is organised as follows. In Sec. II we introduce the effective Lagrangian describing the interaction of excited leptons with left right symmetric fermions. We then
analyze the various production and decay rates of $l^*$ for different $Z'$ and $W'$ mass, and the last section contains a summary and conclusions.

II. EXTENSION TO LEFT-RIGHT SYMMETRIC CASE

The $SU(2)_L \times U(1)_Y$ invariant effective Lagrangian that describes the interaction between an ordinary lepton $l$, a gauge boson $V(=W, Z, \gamma)$, and an excited lepton $l^*$ is introduced as follows [13][15][22]:

$$\mathcal{L}_{\text{trans}} = \frac{1}{2\Lambda} \bar{l}_R \sigma^{\mu\nu} \left[ g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu} + g f^\tau \frac{\tau}{2} \cdot W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] l_L + \text{H.c.} \quad (1)$$

in a notation that parallels [22]. Here $\Lambda$ is the compositeness scale, and the $G$, $W$ and $B$ denote the field strengths of the colour and electroweak sectors. $f$ and $f_0$ are the transition magnetic moments arising from the compositeness dynamics. Further, an underlying assumption of excited fermions hypothesis is that no mixing of generations is triggered by the excitation physics. In this paper we shall refers to this as the Standard Model based or SM based approach, and compare specific calculations to the results of [22], referred to as BSZ.

Left-right symmetric extension of the SM ensures parity symmetry while retaining the highly desirable chiral nature of the fermionic spectrum. The extension entails that we add a right handed neutrino state to each generation of the spectrum, and together with this, the SM fermions have additional quantum numbers under an extended gauge group $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ which displayed for one generation are

$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, 1, -1) \quad l_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \sim (1, 1, 2, -1) \quad (2)$$

Similar changes to the quarks sector are required, but not relevant to this study. The corresponding electric charge formula becomes left-right symmetric, $Q_{\text{electric}} = T^3_L + T^3_R + \frac{1}{2}(B-L)$. To this list of particles, we add, for each generation, excited leptons, being a pair of doublets, taken together forming a vector like representation of $SU(2)_L$

$$l^*_L = \begin{pmatrix} \nu^*_L \\ e^*_L \end{pmatrix} \sim l^*_R = \begin{pmatrix} \nu^*_R \\ e^*_R \end{pmatrix} \sim (1, 2, 1, -1) \quad (3)$$

There should also exist a similar set of vector like excited leptons with charges $(2, 1, 1, -1)$. As explained in the Introduction, we postpone this study for the future, assuming for the
purpose of this paper that the $SU(2)_R$ excited fermions are too heavy to affect experimental signatures.

We therefore propose the generalisation of the effective Lagrangian of Eq. (1) to the left-right symmetric case in the form

$$L_{\text{trans}} = \frac{1}{2\Lambda} f_l^* q^{\mu\nu} \left[ g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu} + g_1 f_1 \frac{\tau}{2} \cdot W^L_{\mu\nu} + g_2 f_2 \frac{\tau}{2} \cdot W^R_{\mu\nu} + g'' f'' \frac{B - L}{2} B^{B-L}_{\mu\nu} \right] l_R + \text{H.c.} \right)$$

Here $W^L_{\mu\nu}$ and $W^R_{\mu\nu}$ are the field strength tensors of $SU(2)_L$ and $SU(2)_R$ gauge fields respectively and $B^{B-L}_{\mu\nu}$ is the field strength tensor of $U(1)_{B-L}$. $g_1$, $g_2$ and $g''$ are the $SU(2)_L$, the $SU(2)_R$ and the $U(1)_{B-L}$ gauge couplings respectively. $f_1$, $f_2$ and $f''$ are the new couplings that arise due to compositeness in the theory. Consistent with the original left-right symmetry philosophy we assume $g_1 = g_2$, in turn equal to $g$ of Eq. (1).

However the effective couplings $f_1$, $f_2$, $f''$ above are constrained by their potential contribution to the anomalous magnetic moment form factors of the known leptons at one-loop level. One approach to calculating the loop contribution is to introduce a dipolar form factor for the excited leptons, given by $\frac{A^4}{(q^2 - \Lambda^2)^2}$ [5, 6], where $q^2$ is the virtual photon mass squared. Let $\frac{2-2}{2}$ denote the anomalous magnetic moment of the muon. Let $m$, $M$ denote the masses of ordinary and excited muons respectively, and $\Lambda$ the compositeness scale. Under the parameter regime $m \ll M \leq \Lambda$, $M$ of the order $\Lambda$, our calculation gives us a constraint on $f_1$, $f_2$ and $f''$ described by the equation

$$(f_1 + f_2 + f'')^2 \frac{mM}{\Lambda^2} \cdot I(M^2/\Lambda^2) \leq \frac{(g - 2)\pi}{\alpha}$$

(5)

Above, $I$ is a function of $M^2/\Lambda^2$ only. When $M$ is of the order of $\Lambda$, $I$ is of the order of $10^{-1}$. In particular, when $M = \Lambda$, $I(1) = 7/45$. Since we consider $\Lambda$ at the TeV scale, $m/M$ is of the order $10^{-4}$. Using the best value of $g - 2$ and $\alpha$ known currently [7], the right hand side of the above expression turns out to be $2.066 \times 10^{-6}$. This constrains $f_1 + f_2 + f''$ to be around 0.5 for our range of parameters.

The partial widths for the electroweak decay channels [22] are now given, neglecting ordinary quark masses, by the formulae

$$\Gamma(f^* \rightarrow f\gamma) = \frac{1}{16\pi} C_\gamma^2 \frac{m^*}{\Lambda^2},$$

$$\Gamma(f^* \rightarrow fV) = \frac{1}{8\pi} C_V^2 \frac{m^*}{\Lambda^2} \left(1 - \frac{m^2}{m^*} \right) \left(2 + \frac{m^2}{m^*} \right).$$

(6)
where \((V = W, W', Z, Z')\) and

\[
\begin{align*}
C_\gamma &= T_3 f_1 + f_2 T_3 + f'' \frac{B - L}{2}; \\
C_Z &= f_1 T_3 \cos^2 \theta_W - f_2 T_3 \sin^2 \theta_W + f' \frac{B - L}{2}; \\
C_W &= \frac{L}{\sqrt{2}}; \\
C_{Z'} &= f_2 T_3 \cot \theta_R + f'' \tan \theta_R \frac{B - L}{2}; \\
C_{W'} &= \frac{L}{\sqrt{2}}.
\end{align*}
\]

(7)

where \(\theta_W\) is the weak mixing angle and

\[
\sin^2 \theta_R = \frac{2 \sin^2 \theta_W}{1 + \sin^2 \theta_W}.
\]

(8)

is the angle mixing \(T_{3R}\) and \(B - L\) giving rise to right handed neutral currents.

We study the decay rates of the excited leptons in the context of above interaction, and try to identify how the signals get modified compared to the SM based approach. In the SM based approach, the excited lepton has available to it the decay channels \(l, \gamma; l, Z; \nu_l, W\). Extension to the left-right group leads to the possibility of two additional decay modes namely \(l, Z'; \nu_l, W'\). We study the effect on the production cross section of \(\mu^*\) of these additional two channels as a function of \(\mu^*\) mass \(m_{\mu^*}\) and compositeness scale \(\Lambda\). We also vary the \(Z'\) mass to see the effect on production cross-section times branching ratios (B.R.) of \(\mu^*\).

To carry out the main comparison, we have studied the case of \(\mu^*\). The contributions from \(e^*\) would be similar in principle, except for the difference in the input mass of the usual lepton. Since the effect of the mass of the usual leptons being negligible at the scale of the scattering we get similar results for \(e^*\) and \(\mu^*\).

For the simulation of the signal a customized version of the Pythia8 event generator [42] is used, following the model of [22]. Decays via contact interactions, not implemented in Pythia8, contribute between a few percent of all decays for \(\Lambda \gg m_{\mu^*}\) and 92% for \(\Lambda = m_{\mu^*}\) [22, 23]. However, in this study we are only interested in the new production cross section and the branching ratios (B.R.) as the outcome of the Lagrangian given by Eq. (4). So for all purpose we choose to neglect the correction for now.

III. RESULTS AND DISCUSSIONS

The total production cross section versus \(m_{\mu^*}\) for both SM based approach of [22] and for our LRSM based approach are shown for \(\mu^*\) in Fig. 1. We also show the variation of branching ratios for the different gauge decay modes as a function of \(m_{\mu^*}\) in both the approaches in
From the above plots we see that total production cross section, for a given \( m_{\mu^*} \), decreases in the left right symmetric scenario as compared to the BSZ theory. However the branching ratio of the \( \mu^* \rightarrow \mu, Z \) channel increases significantly, and in fact, the cross section times branching ratio of this channel is much higher in the left right symmetric theory. In fact, it is higher than even the cross section times branching ratio of the \( \mu^* \rightarrow \mu, \gamma \) channel for all masses of \( \mu^* \) and \( Z' \).

The cross section times branching ratio of the \( \mu^* \rightarrow \mu, \gamma \) channel is strongly depressed in the left-right symmetric theory as compared to the BSZ theory. This effect is even more pronounced when \( \Lambda = m_{\mu^*} \), which was the setting used by previous experiments to set limits on \( m_{\mu^*} \). Recently, the CMS experiment at the LHC has set the \( e^* \) and \( \mu^* \) mass limits at \( \sqrt{s} = 7 TeV \) with an integrated luminosity \( L_{\text{int}} = 5 fb^{-1} \), and excluded \( m_{\mu^*} < 1.9 \) TeV at 95% C.L. [21]. Our work shows that if excited leptons were coupled to a left-right symmetric extension of the SM, the excluded mass limit on excited leptons will come down significantly. We therefore focus our study in the region \( m_{\mu^*} > 850 \) GeV.

If excited leptons were coupled to a left-right symmetric extension of the SM, the \( l^* \rightarrow lZ \)
FIG. 2: Branching Ratio as function of $\mu^*$ mass, $\Lambda = 5000$ GeV, 14 TeV $pp$ beam. (a): BSZ, as in Ref. [22] (b-d): Left-right symmetric theory for $W'$ mass 800 GeV and $Z'$ mass 800, 1200 and 1800 GeV, $f_1 = f_2 = f''$.

channel, with its highest cross section times branching ratio, is the best channel to be probed in a future LHC scenario of 14 TeV beam energy. This channel with four lepton final states will have largest background contribution from SM direct production of $ZZ$ pairs where both the $Z$ bosons decay leptonically. For this background, we get a LO cross section of $93 fb$ with Pythia8. For an optimisitic scenario of $W'$ mass 800 GeV, $Z'$ mass 800 GeV and signal $l^* \to lZ \to ll'l'$ of about 5 fb, a $5\sigma$-significance can be easily obtained with around $100 fb^{-1}$ of data.
FIG. 3: Comparison of cross section times branching ratios of $l^*$ for photon and $Z$ channels in the BSZ of Ref. [22] as well as left-right symmetric theory, denoted by $l^*_LR$, as functions of $l^*$ mass, for 14 TeV $pp$ beam, $f_1 = f_2 = f''$. For left-right symmetric theory, $W'$ mass is fixed to 800 GeV. (a)-(c): $Z'$ masses values 800, 1200, 1800 GeV, $\Lambda = 5000$ GeV. (d): $Z'$ mass 800 GeV, $\Lambda = m_{\mu^*}$ GeV.

IV. SUMMARY AND CONCLUSIONS

The LHC has searched for (left handed) excited electrons and muons and ruled them out for masses below 1700 GeV. Their search strategy was just to look for an excess in the $l^* \rightarrow l\gamma$ channel. If excited leptons were coupled to a left-right symmetric extension of the SM, our results show that the cross section times branching ratio of this channel is depressed by a factor of more than two. This implies that the excess search carried out by Atlas would
only rule out excited electrons and muons having masses below 1000 GeV.

On the other hand, our results show that the cross section times branching ratio of the \( l^* \rightarrow lZ \) channel is enhanced in the left right symmetric scenario, and in fact, is significantly more than that of the \( l^* \rightarrow l\gamma \) channel. This implies that the Z channel becomes a promising candidate to search for left right symmetric excited leptons with masses above 1000 GeV. This channel was never explored in earlier experimental searches. It should be quite feasible to carry out this search with the current luminosity of the LHC and the data already collected.

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