Leptonic number violation signature arising from a $Z'$ model with non-diagonal leptonic couplings

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Abstract: Within the framework of a $Z'$ model with non-universal leptonic couplings, we analyze possible signatures of leptonic number violation effects at LHC. Results are described for leptonic energy distributions, both from its specific signature and events number, that could allow us to observe this class of models, under reasonable conditions at LHC.

Keywords: $Z'$, LFV
1 Introduction

Although the Standard Model (SM) has been successful in describing the physics at the Electroweak (EW) scale, and the particle content of the EW interactions can be considered completed with the recent Higgs boson discovery \cite{1, 2}, it is considered as the low energy limit of a more fundamental theory. So New Physics (NP) should exist at energy scales of a few TeV. Among the many models of physics beyond the SM, there exist a class of models that predict the presence of a structure like $SU(2)_1 \times SU(2)_2 \times U(1)_X$ at the scale of a few TeVs \cite{3, 4–7}. Such a gauge symmetry may have its origin from various grand unified theories, string-inspired models, and even dynamical symmetry breaking models, and little Higgs models. See, for example \cite{7} and references therein. In these class of models, there exist new gauge bosons. In particular, new neutral gauge bosons that are going to be searched in all present and future colliders \cite{7, 8}.

Usually, flavor-conserving $Z'$ bosons have been extensively studied \cite{6, 7}, while less attention has been given to the more general case of $Z'$ bosons as a primal source of Lepton Flavour Violation (LFV) processes. One of the features of such kind of models is the presence of a heavy $Z'$ gauge bosons with mass in the TeV scale, well within the reach of LHC \cite{9, 10}. Also there have been some work on a global EW fit that could prefers a $Z'$ which do not couple to the first leptonic and second quark generation \cite{10}, leading to family dependent fermionic couplings for a new $Z'$. That opens an opportunity windows for the search of $Z'$ contributions in the case of non-diagonal fermionic couplings. Following that work, the aim of our paper is to study leptonic number violation effects at LHC through the processes \( pp \to Z' \to l_i \bar{l}_j \) and \( pp \to Z' \to l_i \bar{l}_j h \).

The structure of the paper is the following: in section 2, we are going over the details of the model and the processes under consideration. We then describe the results for differential cross section distributions accordingly. Our conclusions are given in the final section.
2 Lepton number violation processes

In this paper we would focus in the feasibility of direct detection of a heavy $Z'$ gauge boson through the distinctivesignature of lepton number violation plus $h$ boson. We are, first, assuming that a $SU(2)_1 \times SU(2)_2 \times U(1)_X$ gauge structure represents the correct physics at the TeV scale [6]. Based on that assumption, we allow for the possibility that the fermion-$Z'$ couplings be non-universal, as in the model from Langacker-Plumacker [9]. This lead us to LFV effects, which we are going to focus; aswell as FCNC contributions which are not treated in the present paper. In order to scan the parameter space in a more efficient way, we parametrise the non-universal fermionic-$Z'$ coupling in an effectivelagrangian way (see for example [11]). Moreover, in order to restrict the number of unknown parameters, only the leptonic sector it is considered to be non-diagonal, while the quark sector couplings are considered to behave as SM-like.

The Feynman diagrams for the considered processes,

1. $pp \rightarrow Z' \rightarrow l_i \bar{l}_j X$ ,
2. $pp \rightarrow Z \rightarrow Z'h \rightarrow l_i \bar{l}_j h X$

are shown in the following figures.

![Figure 1. Feynman diagrams for the process 1.](image1)

![Figure 2. Feynman diagrams for the process 2.](image2)

In the following we will designate as Process 1 to $pp \rightarrow Z' \rightarrow l_i \bar{l}_j X$, while Process 2 will be used for $pp \rightarrow Z' \rightarrow l_i \bar{l}_j h X$. The leptonic energy distributions were done, as remarked already, by using an effective approach for the vertex $Z'l_i \bar{l}_j$, parametrised as $C_V \left(g_{Vij}^f - g_{Aij}^f \gamma_5\right) \gamma^\nu$. While the small vertex $ZZ'h$ is given by the Lorentz structure $C_{ZZ'h}g^{\mu\alpha}$. Given the non-universality of the fermionic couplings of the $Z'$, the $g_{Vij}^f$ and $g_{Aij}^f$ are matrices, generally with all its elements not null. For the sake of simplifying the number of free parameters to be considered, the quark-$Z'$ vertex was set both as diagonal in the flavour space and with its coupling equal as in the SM. The coefficient of the fermionic-$Z'$ coupling, $C_V = .8C_{SM}$, for definitiveness, and the coupling $C_{ZZ'h} = 0.01 - .001$, given the restrictions that arise usually from the $Z - Z'$ mixing.

In order to consider the future behaviour of LHC, we have considered both cases of $\sqrt{s} = 8$, and 14 TeV center of mass (CM) energy. We analyse some interesting differential
distributions for the final particles, as a way to disentangle the most interesting signatures that allow us a direct path to found the Z' signal at LHC. Given the different possibilities for the detection of the Higgs boson, we use the \( \gamma \gamma \) decay case, and consider the Process 2 as \( pp \rightarrow Z' \rightarrow l_i \bar{l}_j \gamma \gamma X \).

3 Results for LFV Processes

This section will show the obtained results for several differential distributions of the corresponding cross sections for Processes 1 and 2. We will focus in the signal at the resonance, since we have found that give us the maximum signal for the processes under study.

For the Process 1, namely \( pp \rightarrow Z' \rightarrow l_i \bar{l}_j \), a Drell-Yan-like process, we calculate both the differential cross section with respect to the reduced partonic energy, \( \tau \), as well as the expected number of events for the \( l_i \bar{l}_j \) invariant mass.

Figure (3) shows the differential cross section as a function of the reduced partonic energy, the ratio of the quark CM energy vs \( pp \) CM energy. Because LHC has a strong limit on SM-like fermionic coupling for sequential models of \( Z' \), we use in our analysis masses of 2, 2.5 and 3 TeV for the \( Z' \). The figure at the left corresponds to the case \( \sqrt{s} = 8 \) TeV, while the right figure corresponds to \( \sqrt{s} = 16 \) TeV. In the plots involving \( \tau \), a cut was made at \( 10^{-3} \). The library LHAPDF v 5.8.8 was used to define the corresponding PDFs, with CTEQ 6 [12].

![Figure 3. Process 1: Differential cross section vs. reduced partonic energy, at \( \sqrt{s} = 8 \) (left), and 16 TeV (right). We present the plots for \( M_{Z'} = 2, 2.5, \) and 3 TeV.](image)

We can appreciate the signal is only relevant near the resonance \( Z' \) peak, and that happens at low values for \( \tau \), both for \( \sqrt{s} = 8, 16 \) TeV.

Figure (4) shows the same differential distribution, but in this case we contrast the effects at \( \sqrt{s} = 8 \), and at 16 TeV, for a \( Z' \) of mass 2.5 (left), and 3 (right) TeV, correspondingly. So we can expect a \( 10^{-2} \) factor for the 16 TeV case, compared with the 8 TeV case.

In order to quantify if this kind of models can give us an observable number of events, we assume reference values from LHC. For the number of events, we take into consideration the electron and muon detection eficency, taking nominally the same numbers for both ATLAS and CMS [13, 14]. The reported luminosity for the 8 TeV run is 23.269 fb\(^{-1}\) [15]. We have
used a luminosity of 60-100 $fb^{-1}$ for a 14 TeV LHC CM energy because the experimental expectatives at that energies [16]. Also in Ref. [17] have been pointed that the possibilities for $Z'$ discovering at a future LHC relies in that levels of luminosity.

The expected number of events for the cases of $M_{Z'} = 2$ (left), 2.5 (center), and 3 (right) TeV is shown in Fig. (5). The LHC CM energy assumed were 8, and 16 TeV. We take the leptonic invariant mass as the variable, $e$ and $\mu$ are considered for the final leptonic states.

Meanwhile, the figure(6) presents the same distribution as figure (5), but in this case we compare the values for the different $Z'$ masses that we have used, for each of the cases $\sqrt{s} = 8$ (left), and 16 (right) TeV. We can see that only around the resonance, it is the cross section above $10^{-2}\ fb^{-1}$ which is considered a measurable signal. Further studies are needed for off-
Figure 6. Process 1: Differential distribution for the number of events (left scale) vs. leptonic invariant mass, and differential cross section (right scale) vs. leptonic invariant mass for the cases of $\sqrt{s} = 8$ (left), and 16 (right) TeV. For each graph we compare the cases of $M_{Z'}=2, 2.5, \text{and } 3$ TeV. The conditions for the luminosity are specified in the text.

resonance signals.

The results shown in figs. (3-6) were obtained with a particular set of values for the several unknown parameters. And even when in the literature there exist some boundings for some of them [9, 18], as we stated above, we prefer an effective lagrangian approach. Thenceforth, we are allowed to let run these parameters.

Figure 7. Process 1: Differential cross section as a function of $\tau$, with the variation on $g_V$ and $g_A$, for the $e - \mu$ decay mode. We take $M_{Z'}=2$ TeV for $\tau = 0.1$ (left), 0.2 (center), and 0.3 (right); the first row correspond to $\sqrt{s} = 8$, while the second row for 16 TeV.
Figures (7-9) detail the dependence on the non-diagonal fermionic couplings, $g_V$ and $g_A$, for the $e-\mu$ decay mode of $Z'$. These plots correspond to $M_{Z'} = 2$ (fig. (7)), 2.5 (fig. (8)), and 3 (fig. (9)) TeV. We plotted the dependence of the differential distribution for the cross section with respect to $\tau$, but fixing it at .1 (left), .2 (center), and .3 (right) in each of the figures. The fixing was made taking into account the results shown in Figs. (3-4). The graphs display the corresponding dependence in the $g_V, g_A$ parameter space, for each one of the signaled cases. We also present the differences between $\sqrt{s} = 8$ (first line) and 16 (second line) TeV, in each of figures (7-9).

**Figure 8.** Process 1. Differential cross section with respect to $\tau$ in function of $g_V$ and $g_A$, for the $e-\mu$ decay mode. We take $M_{Z'} = 2.5$ TeV for $\tau = 0.1$ (left), 0.2 (center), and 0.3 (right); the first row correspond to $\sqrt{s} = 8$, while the second row for 16 TeV.

For the second process, which we called Process 2, $pp \to Z \to Z'h \to l_i\bar{l}_j h X$, we repeat the procedure for the first process, with the corresponding changes. We directly introduce the branching ratio of the Higgs boson into $\gamma\gamma$, as coming from ATLAS and CMS limits [1, 2]. And even when the signal is rather small still is at the measureable level as at the peak as can be seen in fig. (10). These plots show the differential distribution with respect to $\tau$, the reduced partonic energy, and $x_{l_i}$, the usually defined $i$-lepton scaled energy ($x_{l_i} = E_{l_i}/2\sqrt{s}$). In our case we take $i = e$

When the branching ratio of the Higgs decaying into a pair of photons is factored to the differential cross sections, it is assumed that there is no contribution arising from a new $W'$ nor from new exotic fermions in the loop-level process $H \to \gamma\gamma$. This can be show to be a plausible consideration by a seasoned choice of quantum numbers for the fermion or because the existence of only an extra $U(1)'$ at the TeV level. Of course there is the necessity of supression for the contribution coming from the charged Higgs sector. Still it is possible to construct an specific model in which that it is allowed and plausible. For the case of $M_{Z'} = 2.5 - 3$
Figure 9. Process 1. Differential cross section vs. $\tau$ in function of $g_V$ and $g_A$, for the $e - \mu$ decay mode of the $Z'$. We take $M_{Z'} = 3$ TeV for $\tau = 0.1$ (left), 0.2 (center), and 0.3 (right); the first row correspond to $\sqrt{s} = 8$, while the second row for 16 TeV.

Figure 10. Process 2: Differential cross section in dependence to $\tau$ and electron reduced energy, for $M_{Z'} = 2$ (left), and 2.5 (center), and 3 (right) TeV. The first row of graphs correspond to $\sqrt{s} = 8$ while the second row correspond to the 16 TeV case.

TeV, and a low value of $g''$, the coupling coming from the extra $SU(2)$ or $U(1)$, we can have an expectation value of the extra Higgs fields, that which generate the $Z'$ mass, of the order of 5-6 TeV. In this way we found that the contribution of the charged Higgs sector is suppressed in the $H \rightarrow \gamma \gamma$ decay.

Figs. (11-13) show us the variation of the differential cross section, as a function of $\tau$, on the values of the non-diagonal $g_V$ and $g_A$, in the case of $e - \mu$ decay of $Z'$. 


Figure 11. Process 2: Differential cross section with respect $\tau$ as a function of $g_V$ vs. $g_A$, for the $e-\mu$ decay mode of the $Z'$. We take $M_{Z'}=2$ TeV for $\tau = 0.1$ (left), 0.2 (center), and 0.3 (right); the first row correspond to $\sqrt{s} = 8$, while the second row for 16 TeV.

Figure 12. Process 2: Dependence of the differential cross section with respect to $g_V$ vs. $g_A$, for the $e-\mu$ decay mode of the $Z'$. We take $M_{Z'}=2.5$ TeV for $\tau = 0.1$ (left), 0.2 (center), and 0.3 (right); the first row correspond to $\sqrt{s} = 8$, while the second row for 16 TeV.

4 Conclusions

In this paper we have studied the possible signatures of the leptonic number violation vertex ($Z' l_i \bar{l}_j$), as coming from $G(221)$ models with non-universal couplings [9], at LHC. The case
Figure 13. Process 2: Dependence of the differential cross section with respect to $g_V$ vs. $g_A$, for the $e - \mu$ decay mode of the $Z'$. We take $M_{Z'} = 3$ TeV for $\tau = 0.1$ (left), 0.2 (center), and 0.3 (right); the first row correspond to $\sqrt{s} = 8$, while the second row for 16 TeV.

$e\mu$ it is shown to be the most characteristic signal, since the cases with a final $\tau$ could be more difficult to reconstruct from its decay products. We have shown that the $e\mu$ signal could be feasible to be found at LHC, under reasonable expectations and conditions, in a foreseeable future. Our results could be shown to be of the same order of magnitude for similar processes studied in previous papers [18].

From the several energy distributions that we have shown, we can conclude that a possible leptonic number violation through a $Z'$, Drell-Yan-like, could be expected to be found in the case of a $Z'$ discovery. The events differential distribution together with its distinctive leptonic signature make this kind of processes feasible to be found, if the nature has chosen this structure at the TeV scale. as we hope.

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