LHC constraints on $W'$, $Z'$ that couple mainly to third generation fermions

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Abstract: We use the results of CMS and ATLAS searches for resonances that decay to $\tau\nu$ or $tb$ and $\tau^+\tau^-$ or $t\bar{t}$ final states to constrain the parameters of non-universal $W'$ and $Z'$ gauge bosons that couple preferentially to the third generation. For the former we consider production from $c\bar{c}$ annihilation and find very weak constraints on the strength of the interaction and only for the mass range between 800 and 1100 GeV from the $pp \rightarrow \tau h p_{\text{miss}}$ channel. The constraints on the latter are much stronger and arise from both $t\bar{t}$ and $\tau^+\tau^-$ production. Treated separately, we find that the weak constraints on the $W'$ still permit an explanation of the $R(D^{(*)})$ anomalies with a light sterile neutrino whereas the stronger constraints on the $Z'$ exclude significant light sterile neutrino contributions to the $K \rightarrow \pi\nu\bar{\nu}$ rates. Within specific models the masses of $W'$ and $Z'$ are of course related and we briefly discuss the consequences.
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1 Introduction

The CMS and ATLAS experiments have both searched for exotic resonances that single out the third generation. In particular CMS has reported a result from an integrated luminosity of $35.9 \text{ fb}^{-1}$ at $\sqrt{S} = 13 \text{ TeV}$ on searches for a $W'$ that decays into a tau-lepton and a neutrino [1] while ATLAS has reported results for the same channel with $36.1 \text{ fb}^{-1}$ at $\sqrt{S} = 13 \text{ TeV}$ [2]. In both cases the analysis was carried out with benchmark models for the $W'$ in which production through $u\bar{d}$ annihilation is assumed. This is inadequate for truly non-universal models where the couplings to the first generation quarks can be suppressed by many orders of magnitude. We reinterpret these searches by comparing the experimental results to cross-sections obtained from $c\bar{b}$ annihilation production of the $W'$. ATLAS has also reported a search in the top-bottom final state with $36.1 \text{ fb}^{-1}$ at $\sqrt{S} = 13 \text{ TeV}$ [3] which is not yet competitive with the $\tau\nu$ channel.

In the same manner, searches for non-universal $Z'$ bosons have also been reported in the $\tau^+\tau^-$ channel by CMS with $2.2 \text{ fb}^{-1}$ at $\sqrt{S} = 13 \text{ TeV}$ [4] and in the $t\bar{t}$ channel by ATLAS with $36.1 \text{ fb}^{-1}$ at $\sqrt{S} = 13 \text{ TeV}$ [5]. The models studied in this cases also assumed couplings of the $Z'$ to first generation fermions and we reinterpret those results for models in which the $Z'$ is dominantly produced from $b\bar{b}$ annihilation.

After obtaining the allowed parameter space for the coupling and mass of the new gauge bosons we revisit the viability of these scenarios as sources for large deviations in flavour observables. Taking the $W'$ on its own, we find that in combination with a light sterile neutrino, this is still a viable explanation for the $R(D^{(*)})$ anomalies. On the other hand, the constraints on the $Z'$ rule out significant enhancements to $K \to \pi\nu\bar{\nu}$ modes through the addition of light sterile neutrinos that couple to the $Z'$. We comment on connections between the two sets of bounds within the context of a specific model.

2 The model

Our starting point will be the non-universal LR model of [6, 7]. To single out the third generation we augment the SM gauge group with a second $SU(2)$ under which only the third generation right handed fermions are charged. The gauge group is then $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with gauge coupling constants $g_3, g_L, g_R$ and $g$, respectively. In the weak interaction basis, the first two generations of quarks $Q^{1,2}_L, U^{1,2}_R, D^{1,2}_R$ transform as $(3, 2, 1)(1/3), (3, 1, 1)(4/3)$ and $(3, 1, 1)(-2/3)$, and the leptons $L^{1,2}_L, E^{1,2}_R$ transform as $(1, 2, 1)(-1)$ and $(1, 1, 1)(-2)$. The third generation, on the other hand, transforms as $Q^3_L (3, 2, 1)(1/3), Q^3_R (3, 1, 2)(1/3), L^3_L (1, 2, 1)(-1)$ and $L^3_R (1, 1, 2)(-1)$. These assignments provide universality violation. The third family has, in addition to the SM fermions, a sterile neutrino which we denote by $N_R$. It appears as the partner of the $\tau_R$ in the right-handed doublet $L^3_R$. 

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Since the new right-handed gauge bosons must be heavier than the $W$ and $Z$, we separate the symmetry breaking scales of $SU(2)_L$ and $SU(2)_R$, introducing two Higgs multiplets $H_L (1, 2, 1)(-1)$ and $H_R (1, 1, 2)(-1)$ with respective vevs $v_L$ and $v_R$. An additional bi-doublet $\phi (1, 2, 2)(0)$ scalar with vevs $v_{1,2}$ is needed to provide mass to the fermions. Since both $v_1$ and $v_2$ are required to be non-zero for fermion mass generation, the $W_L$ and $W_R$ gauge bosons of $SU(2)_L$ and $SU(2)_R$ will mix with each other. In terms of the mass eigenstates $W, Z$ and $W', Z'$, the mixing can be parametrized as

$$W_L = \cos \xi_W W - \sin \xi_W W' \quad W_R = \sin \xi_W W + \cos \xi_W W'$$

$$Z_L = \cos \xi_Z Z - \sin \xi_Z Z' \quad Z_R = \sin \xi_Z Z + \cos \xi_Z Z'$$  \hspace{1cm} (1)$$

The model can provide potentially large contributions to amplitudes that involve third generation fermions when $g_R > g_L$, where the new gauge bosons interact very weakly with the first two generations. The dominant gauge boson-fermion interactions in this limit are given by

$$L_W = -\frac{g_R}{\sqrt{2}} \bar{U} R \gamma^\mu V_R D_R (\sin \xi_W W^\mu \mu + \cos \xi_W W'^\mu) + \text{h. c.,}$$

$$L_Z = \frac{g_L}{2} \tan \theta_W \cot \theta_R (\sin \xi_Z Z^\mu + \cos \xi_Z Z'^\mu) \left( \bar{d}_R V_{Rbd} \bar{V}_{Rb}^d \gamma^\mu d_R - \bar{u}_R V_{Rtu}^{u*} V_{Rtj}^u \gamma^\mu u_R \right)$$

$$+ \frac{g_R}{2} (\bar{\tau} \gamma_\mu P_R \tau - N_R \gamma_\mu P_R N_R) Z'_\mu$$ \hspace{1cm} (2)$$

where $U = (u, c, t)$, $D = (d, s, b)$, $V_{KM}$ is the Kobayashi-Maskawa mixing matrix and $V_R \equiv (V_{Rij}) = (V^{u,d}_{Rij})$ with $V_{Rij}^{u,d}$ the unitary matrices which rotate the right handed quarks $u_{Ri}$ and $d_{Rj}$ from the weak to the mass eigenstate basis. To extract the large $g_R$ limit from the expressions in [6, 7] we used

$$\cot^2 \theta_R = \left( \frac{g_R}{g_L} \cot \theta_W \right)^2 - 1 \implies g_L \tan \theta_W \cot \theta_R \approx g_R.$$ \hspace{1cm} (3)$$

For the model to be phenomenologically viable, both $\xi_W$ (from $B \to X s \gamma$ [6]) and $\xi_Z$ (from $Z \to \tau \tau$ [7]) are required to be very small and we will ignore them for the remainder of this study. The mixing angles in $V_{Rij}^{u,d}$ control the size of tree-level flavor changing neutral currents of the $Z'$ and are also severely constrained [8, 9]. These constraints can be satisfied in a simple manner with the ansatz described in Ref. [10], which we summarize for the purposes of this study into the conditions $V_{Rbd}^d = \delta_{bj}$, $V_{Rti}^{u*} \sim 1$, $V_{Rtc}^{u} \sim V_{cb}$. When this ansatz is combined with $g_R > g_L$ the couplings reduce to

$$L_{W'} = -\frac{g_R}{\sqrt{2}} \left( \bar{t}_R \gamma^\mu t_R + \bar{c}_R \gamma^\mu c_R + N_R \gamma_\mu P_R \tau \right) W'^\mu + \text{h. c.,}$$

$$L_{Z'} = \frac{g_R}{2} \left( \bar{b}_R \gamma^\mu b_R - \bar{\tau} \gamma^\mu \tau_R - V_{cb} \bar{\tau} \gamma^\mu \tau_R - V_{cb} \bar{\tau} \gamma^\mu \tau_R \right) Z'^\mu$$

$$+ \frac{g_R}{2} (\bar{\tau} \gamma_\mu P_R \tau - N_R \gamma_\mu P_R N_R) Z'_\mu$$ \hspace{1cm} (4)$$

Eq. 4 defines the simplified model used in this study.
2.1 Resonance width and branching ratios

The couplings of the $W'$ in the limit discussed above translate into a width

$$\frac{\Gamma_{W'}}{M_{W'}} = (1 + N_c) \frac{g_R^2}{48\pi}. \quad (5)$$

The second term, proportional to $N_c$, corresponds to the top-bottom channel for which we assume $M_{W'} \gg M_t$ and the first term to the $\tau N_R$ channel where we assume that the sterile neutrino is light, $M_{W'} \gg M_{N_R}$. Defining perturbative unitarity by the condition that the width to mass ratio be smaller than 1/2, results in

$$g_R \lesssim 4.34 \text{ or } \left(\frac{g_R}{g_L}\right) \lesssim 6.7 \quad (6)$$

which is within the range that has been previously discussed. In this large $g_R$ limit, one also finds that

$$B(W' \to \tau N_R) \approx \frac{1}{3} \frac{4P_{W'}}{1 + P_{W'}}. \quad (7)$$

where we have now included a phase space factor

$$P_{W'} = \left(1 - \frac{M^2_{N_R}}{M^2_{W'}}\right) \left(1 - \frac{M^2_N}{2M^2_{W'}} - \frac{M^4_{N_R}}{2M^4_{W'}}\right) \quad (8)$$

resulting in

$$B(Z' \to \tau\tau) \approx \frac{1}{7 + P_{Z'}}. \quad (11)$$
The region of parameter space that is of interest for this study has \( g_R >> g_L \) and from Eq. 5 and Eq. 9 we see this corresponds to relatively fat resonances as can be seen in Figure 1. Assuming that the resonances are much larger than both the top-quark and the sterile neutrino masses, the figure shows the ratio \( \Gamma/M \) for both \( W' \) and \( Z' \) as a function of \( g_R/g_L \). The dashed horizontal line marks the limit we use for perturbative unitarity.

Figure 1: \( \Gamma/M \) for both \( W' \) and \( Z' \) as a function of \( g_R/g_L \). The horizontal dashed line is adopted as the boundary for perturbative unitarity.

3 Signatures at the LHC

For our numerical study to recast the LHC constraints we implement the Lagrangian of Eq.(4) in FEYNRULES [11, 12] to generate a Universal Feynrules Output (UFO) file, and then feed this UFO file into MG5_aMC@NLO [13]. We have used the PDF4LHC15_nlo_mc set of parton distribution functions including for the \( b \)-quark.

3.1 \( W' \)

We begin with the right-handed \( W' \) with couplings as in Eq. 4. Single production of this \( W' \) at the LHC is then dominated by \( c\bar{b} \) (\( b\bar{c} \)) annihilation as the couplings to \( u,d \) quarks are zero in this approximation. The dominant decays would be into \( \tau N_R \) if kinematically allowed, and into \( t\bar{b}(b\bar{t}) \). Searches for \( W' \) bosons in both of these channels have been carried out: by CMS in the \( \tau_h + p_T^{\text{miss}} \) final state with 35.9 fb\(^{-1} \) at 13 TeV [1], and by ATLAS in the \( t\bar{b}(b\bar{t}) \) final state with 36.1 fb\(^{-1} \) at 13 TeV [3].

The parameter region of interest corresponds to fat resonances (see Figure 1) and consequently the narrow width approximation is not expected to be reliable. We compute the cross-section
\(\sigma(pp \to \tau N_R)\) with MadGraph, allowing contributions well outside the resonance width but working with an energy independent width. The calculation defined in this way corresponds purely to new physics and the cross-section scales approximately as \(g_R^2\). The use of an energy independent width for fat spin zero resonances is known to overestimate the cross-section in the vicinity of the resonance [14, 15]. We multiply \(\sigma(pp \to \tau N_R)\) by the branching ratio for hadronic tau decay, approximately 0.65, in order to compare our results with Figure 5 of [1] (CMS). We expect this calculation to overestimate the cross-section due to the use of an energy independent width and to our neglect of detector effects, in this sense our limits will be conservative. The use of the specific final state with the sterile neutrino removes interference terms with the SM that could occur in more general models.

Our results for \(\sigma(pp \to W' \to \tau h_{T}^{\text{miss}})\) are presented in Figure 2. The left panel illustrates our cross-sections for values \(g_R/g_L = 5.4, 6.1, 6.5\) as the solid, dashed and dotted blue lines. These model calculations are superimposed on the CMS limit: 95%cl observed (solid), expected (dashed), 1\(\sigma\) (green) and 2\(\sigma\) (yellow) taken from Figure 5 of [1]. The result exhibits an interesting behaviour: the largest value of \(g_R/g_L\) shown corresponds to \(g_R = 4.24\) and is near the perturbative unitarity limit. The cross-section in this case lies within the expected 1\(\sigma\) exclusion for any value of \(M_{W'}\) below about 1 TeV. However, it lies above the CMS observed 95% CL bound only for the range \(826 \lesssim M_{W'} \lesssim 1100\) GeV. Taken at face value this means that both light and heavy resonances are allowed at the 95% CL. The dashed curve corresponds to \(g_R = 3.96\) and constitutes a limiting case: it barely touches the CMS observed 95% CL bound at \(M_{W'} \approx 990\) GeV. Values of \(g_R \lesssim 3.96\) are therefore allowed for any value of \(M_{W'}\). The right panel shows the allowed region in \(M_{W'} - g_R\) parameter space, the area below the blue line. The boundary, labelled \(g_R^{\text{max}}\), is obtained from the intersection between the \(\sigma(pp \to W' \to \tau h_{T}^{\text{miss}})\) curve in the model and the CMS observed 95% CL bound. This line then represents the constraints from this process for the narrow window between \(3.96 \lesssim g_R \lesssim 4.34\) (where we reach the perturbative unitarity limit). This perturbative unitarity limit, as well as \(g_R = 3.96\) (the lowest value that is constrained by the CMS data) are shown as horizontal dashed lines. The ATLAS results [2] are currently less restrictive than CMS and do not change this picture.

The other important decay channel in the model is \(W'^{\pm} \to t \bar{b}\), which becomes the dominant one for a heavy sterile neutrino. It can be constrained in principle from the cross-section \(\sigma(pp \to W'^{\pm} \to t \bar{b})\). The current ATLAS result from 36.1 fb\(^{-1}\) at \(\sqrt{S} = 13\) TeV (combination of semileptonic and hadronic searches) does not yet constrain this model as illustrated in Figure 3 where we show the model prediction for \(g_R = 4.24\) (near its perturbative unitarity bound) in blue.
Figure 2: Left panel: $\sigma(pp \to W'^\pm \to \tau\nu)$ for $g_R = 3.53, 3.96, 4.24$ ($g_R/g_L = 5.4, 6.1, 6.5$) solid, dashed and dotted blue lines respectively, superimposed on the CMS results: 95% CL observed (solid), expected (dashed), $1\sigma$ (green) and $2\sigma$ (yellow) (Figure 5 of [1]). The right panel shows the maximum value of $g_R$ allowed by the CMS observed 95% CL bound for a given $W'$ mass. The horizontal dashed lines mark the strongest constraint and the perturbative unitarity limit on $g_R$.

Figure 3: $\sigma(pp \to W'^\pm \to \bar{t}b)$ for $g_R = 4.24$ shown as a blue line, superimposed on the ATLAS limit: 95% CL observed (solid), expected (dashed), $1\sigma$ (green) and $2\sigma$ (yellow) from Figure 8 of [3]). The data does not yet constrain the model.

3.2 $Z'$

The production mechanism for the $Z'$ is less model dependent than that of the $W'$ as the leading flavour diagonal couplings to fermions do not depend on unknown mixing angles. In the limit of Eq. 4 the dominant production at LHC is initiated by $b\bar{b}$ annihilation. The main final states of interest are $t\bar{t}$ and $\tau^+\tau^-$, a $b\bar{b}$ final state is also possible but its study is more difficult due to
QCD backgrounds

In Figure 4 we compare our $Z'$ production from $b\bar{b}$ annihilation followed by decay into di-tau pairs in all tau decay channels with the CMS result of Ref. [4]. On the left panel we superimpose the cross-sections $\sigma(pp \to Z' \to \tau^+\tau^-)$ for representative values $g_R = 2.5, 3, 3.5, 4$ shown in blue (with increasing values of $g_R$ from the leftmost curve) onto Figure 2e of [4]. We treat the fat resonance in the same manner as before: use an energy independent width and compute $\sigma(pp \to \tau^+\tau^-)$ allowing for contributions away from the resonance but not including interference with the SM. The right panel shows the maximum value $g_R$ can take for a given $M_{Z'}$ as determined by requiring the model cross-section to be below the 95% CL limit observed by CMS, and the dashed line marks the perturbative unitarity limit on $g_R$.

Figure 4: Left panel: we reproduce the 95% CL observed (solid), expected (dotted), 1σ (green) and 2σ (yellow) from CMS Figure 2e of [4] for the process $\sigma(pp \to Z' \to \tau^+\tau^-)$ and superimpose the cross-sections predicted in our model for representative values $g_R = 2.5, 3, 3.5, 4$ shown in blue (with increasing values of $g_R$ from the leftmost curve) that follow from Eq. 4. Right panel: upper limit on $g_R$ as a function of $M_{Z'}$ as read from the left panel.

In Figure 5 we compare $t\bar{t}$ production from $b\bar{b}$ annihilation through an intermediate $Z'$ with the ATLAS result shown in Figure 9 of [5]. The ATLAS figure is split into a resolved and boosted analysis by the vertical line at 1200 GeV. The shape of the observed limit makes it difficult to interpret the constraints this result imposes on our model. Taken at face value, $g_R$ cannot exceed the value for which the prediction intersects the 95%CL observed ATLAS limit (solid black line in the left panel) and this is depicted on the right panel. The figure suggests that masses below about 1500 GeV are excluded for the parameter region with $g_R >> g_L$, although strictly speaking there remains a window near 1 TeV with no meaningful constraints. For masses above 2.2 TeV $g_R \lesssim 3$ is allowed and for masses above 2.8 TeV all values of $g_R \lesssim 4.34$ (in the perturbative region) are allowed.

\footnote{Hadron colliders constraints on this type of $Z'$ produced from light-quark annihilation were studied in Refs. [16, 17].}
4 Flavour Physics consequences

4.1 $R(D)$ and $R(D^*)$

A $W'$ in conjunction with a light sterile neutrino has been proposed as a possible explanation of the $R(D)$ [18–20] and $R(D^*)$ [18–23] measurements [24–28]. To address the viability of this explanation we examine the allowed parameter space in the $g_R - M_{W'}$ plane with the specifics of Ref. [25].

The required $W'$ would have a mass near 1 TeV, and Figure 2 suggests that the largest coupling allowed in this region is approximately $g_R = 4$. For this parameter point the resonance width is $\Gamma_{W'}/M_{W'} = 42\%$, still within the perturbative regime. The production of this resonance occurs from $cb$ annihilation and therefore it scales quadratically with the mixing angle $V_{uR}^{cb}$. To obtain the constraints of the previous section we used $V_{uR}^{cb} = V_{cb} \approx 0.042$ from the ansatz of [10]. Clearly the constraints disappear if this mixing angle is smaller, but in that case the model is no longer a candidate to explain the charged B anomalies. The figure of merit to explain the latter is the product of the couplings $g_{bc}$ ($W'bc$ coupling) and $g_{\tau\nu}$ ($W'\tau\nu$ coupling) divided by the square of the $W'$ mass.

Ref. [29] argues that this explanation for $R(D)$ and $R(D^*)$ is ruled out because fitting these quantities requires $|g_{bc}g_{\tau\nu}^{e^2}|/M_{W'} = (0.6 \pm 0.1)$ TeV$^{-2}$, which is ruled out by their recasting of the same CMS constraints we use in Figure 2. Our study of $pp \rightarrow W' \rightarrow \tau N_R$ is in rough agreement with [29] but we find that this process is still consistent with explaining $R(D)$ and $R(D^*)$ at the 1σ level as can be seen in Figure 6. The figure shows the 1σ and 3σ contours from the
HFLAV average from Spring 2019 [30] as well as the SM point. Superimposed on that result, the
contribution of our $W'$ is shown as the narrow black band. The width of the band is controlled
by the smallness of the allowed $W - W'$ mixing and the position along the band by the mass of
the $W'$ for $g_R = 4$. The plot shows that the value $M_{W'} = 900$ GeV lies approximately on the 1σ
HFLAV contour. The point $g_R = 4, M_{W'} = 900$ GeV, corresponds to $|g_{bc}g_{\tau\nu}^*/M_{W'}^2| \approx 0.42$ TeV$^{-2}$

which is outside the 1σ range quoted in Ref. [29]. However, the HFLAV fits to $R(D)$ and $R(D^*)$
(particularly for the former) are now lower than they were in 2018 and as a result, our model is
compatible with these measurements, as illustrated in Figure 6.

4.2 $K \to \pi \nu \bar{\nu}$

These rare modes can receive contributions from a non-universal $Z'$ both tree and one-loop level
as detailed in [8, 25]. The tree-level contributions depend on FCNC couplings of the $Z'$ and are
severely constrained by B mixing measurements. The one-loop contributions include penguins
where the $Z'$ couples to the top-quark and the sterile neutrino that are potentially large but
quite model dependent. Their overall strength is determined by the ratio

$$r_{Z'}^2 = \left(\frac{g_R M_Z}{g_L M_{Z'}}\right)^2.$$  \(12\)

In order for these NP contributions to enhance the SM rates by factors of two, it was found in [25]
that $r_{Z'}$ needs to be of order 1. From Figure 4 we see that for values of $g_R$ near its unitarity limit
$r_{Z'} \lesssim 0.24$, about a factor of 4 smaller than the previous bound from LEP. With this new limit,
it is no longer possible to have a large enhancement over the SM in the rare modes $K \to \pi \nu \bar{\nu}$ in
this type of models.
5 Summary and Discussion

The constraints that can be placed on $W'$ and $Z'$ masses at the LHC by the different processes we considered in this paper are summarised in Figure 7. The best constraint on the $W'$ arises from $Z' \to t\bar{t}$ $W' \to \tau\nu$ $Z' \to \tau^+\tau^-$.

Figure 7: Largest allowed coupling $g_R$ as a function of $M_{W'}$ from CMS studies of $pp \to \tau h p_{T}^{miss}$ (dashed blue line) compared to ATLAS studies of $pp \to t\bar{t}$ (red dotted line) and to CMS studies of $pp \to \tau\tau$ (solid black line). The dashed horizontal line marks the perturbative unitarity limit.

The CMS studies of $pp \to \tau h p_{T}^{miss}$ and is shown as the dashed blue line in the figure. Its coupling to third generation fermions is allowed to be as large as its perturbative unitarity limit for almost all values of $M_{W'} \gtrsim 500$ GeV. In contrast the $Z'$ is much more constrained. The ATLAS studies of $pp \to t\bar{t}$ are shown as the red dotted line in the figure and overall they indicate significant bounds on the strength of the coupling. The CMS studies of $pp \to \tau^+\tau^-$, produce a constraint shown as a solid black line, and are even more restrictive, at least for $M_{Z'} < 2$ TeV. Combined, these two studies push potential $Z'$ bosons with couplings to third generation fermions stronger than 5 times electroweak couplings beyond 2 TeV.

The $W'$ is much less constrained than the $Z'$ because its production requires at least one fermion from the first two generations (in our model a charm quark). This also makes the results dependent on right-handed quark mixing angles, and suggests that future LHC studies on double resonance production may be able to better constrain this type of $W'$.

Considered independently, the LHC constraints on the $W'$ still allow the light sterile neutrino explanation for $R(D^{(*)})$, whereas those on the $Z'$ rule out sizeable enhancements to $K \to \pi\nu\bar{\nu}$ rates in the same scenario.

Within specific models the $W'$ and $Z'$ masses are related, but this relation depends on parameters of the scalar sector. For the models described in [6] the large number of parameters can be reduced for simplified cases as discussed in [7]. In that example, the vanishing of the gauge boson mixing parameters $\xi_W$ and $\xi_Z$ (at tree level) is accomplished with conditions on the
vevs, \( v_2 = 0 \) and \( v_L = v_1 \cot \theta_R \). Furthermore, the condition \( v_R \gg v_L, 1, 2 \) separates the scales of symmetry breaking and makes the right handed gauge bosons much heavier than the \( W \) and \( Z \) but still approximately degenerate in mass. To split the \( W_R \) and \( Z_R \) masses one needs to introduce additional scalar representations such as triplets \([6]\). In the \( g_R \gg g_L \) limit, a \( \Delta_R(1, 1, 3) \) scalar with a vev will lead to \( M_{Z_R}^2/M_{W_R}^2 = (v_R^2 + 4 v_{\Delta_R}^2)/(v_R^2 + 2 v_{\Delta_R}^2) \). However it will also provide a Majorana mass to the neutrinos. As a result, a large split between the \( W_R \) and \( Z_R \) masses achieved with \( v_{\Delta_R} \) comparable to \( v_R \) naturally leads to a heavy sterile neutrino which is then incompatible with a solution to \( R(D^{(*)}) \). This combination of conditions makes the light sterile neutrino explanation for \( R(D^{(*)}) \) contrived but not impossible within these models, as the scalar sector can always be augmented. For example a \( \phi_{3/2}(1, 1, 3/2) \) scalar, with a non-zero vev \( v_{3/2} \) results in \( M_{Z_R}^2/M_{W_R}^2 = (v_R^2 + 9 v_{3/2}^2)/(v_R^2 + 3 v_{3/2}^2) \). If \( v_{3/2} \) is of the same order as \( v_R \), \( M_{Z_R} \) can be much larger than \( M_{W_R} \). In conclusion, unless one has a very detailed model in mind, the LHC constraints on \( W' \) and \( Z' \) masses should be viewed as independent.

Acknowledgements

We are grateful to Ursula Laa for useful discussions. XGH was supported in part by the MOST (Grant No. MOST 106-2112-M-002-003-MY3).

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