Dilepton bounds on left-right symmetry at the LHC run II and neutrinoless double beta decay

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In the light of the new 13 TeV dilepton data set with $3.2\,\text{fb}^{-1}$ integrated luminosity from the ATLAS collaboration, we derive limits on the Z' mass in the context of left-right symmetric models and exploit the complementarity with dijet and $lljj$ data, as well as neutrinoless double beta decay. We keep the ratio of the left- and right-handed gauge coupling free in order to take into account different patterns of left-right symmetry breaking. By combining the dielectron and dimuon data we can exclude Z' masses below 3 TeV for $g_R = g_L$, and for $g_R \sim 1$ we rule out masses up to ~ 4 TeV. Those comprise the strongest direct bounds on the Z' mass from left-right models up to date. We show that in the usual plane of right-handed neutrino and charged gauge boson mass, dilepton data can probe a region of parameter space inaccessible to neutrinoless double beta decay and $lljj$ studies. Lastly, we present a stringent indirect bound on the lifetime of neutrinoless double beta decay using dilepton data. Our results prove that the often ignored dilepton data in the context of left-right models actually provide important complementary limits.

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I. INTRODUCTION

Left-Right (LR) symmetric models based on the gauge group $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ gauge symmetry [1–3] are compelling extensions of the Standard Model (SM), in particular because they address parity violation at the weak scale and active neutrino masses via the seesaw mechanism. Albeit, the scale at which parity is restored is not predicted, leaving room for a large range of gauge boson masses (Z_R and $W_R^{\pm}$) which set the scale of symmetry breaking. In general, the main collider search strategies for the gauge bosons are based on dilepton, diboson, and dilepton plus dijet data. Besides collider searches for those gauge bosons a multitude of studies in the context of meson [4–6], flavor [7–9] and neutrinoless double beta decay data [10–17] have set important limits in TeV scalar LR symmetric models.

Those studies often assume that the left- and right-handed gauge couplings are identical, i.e. $g_R = g_L$, and that the charged gauge boson is lighter than the neutral one. In particular, in the context of minimal left-right symmetric models this relation reads $M_{Z'} = 1.7 M_{W_R}$ for $g_R = g_L$. Since in principle, those gauge bosons share similar production cross sections at the LHC, the best way to constrain a LR symmetry is by performing W_R searches in the light of the above mass relation. Another motivation is the fact that the W_R mass is straightforwardly connected to the $SU(2)_R$ gauge coupling and left-right symmetry breaking, $M_{W_R} = g_R v_R$.

However, W_R searches based on $lljj$ studies lose sensitivity for sufficiently heavy right-handed neutrinos, $M_N \gtrsim M_{W_R}$. Moreover, there are many ways to successfully break the left-right symmetry down to the Standard Model yielding either $g_R \neq g_L$ or $M_{Z'} \ll M_{W_R}$, or both.

Therefore, in this work we remain agnostic as to how precisely the left-right symmetry is broken and perform an independent Z' search with LHC constraints and show that actually the use of dilepton data from the LHC offers an interesting avenue to probe left-right models. Indeed, as long as neutral gauge bosons couplings to charged leptons are not suppressed, neutral gauge boson searches based on dilepton data are rather promising and give rise to the most stringent limits on their masses [18–35].

Along this line, using 8 TeV centre-of-mass energy, ATLAS and CMS collaborations with integrated luminosity $\mathcal{L} = 20 - 21$ fb^{-1} [36, 37] in the dilepton channel have found no evidence for new resonances, and consequently 95% confidence level lower limits on the mass of the sequential and other Z' bosons were placed. In the context of left-right models recent limits based on the 8 TeV data were derived in [38]. Most recently both ATLAS and CMS collaborations have presented their results based on run II which 13 TeV centre-of-mass energy and $2 - 3$ fb^{-1} of integrated luminosity in [39]. In what follows we will use ATLAS results since they have more luminosity. Using $\mathcal{L} = 3.2$ fb^{-1} of data, the collaboration performed resonance searches for dilepton invariant masses above 500 GeV, and used its invariant mass spectrum as the discriminating variable. No statistical fluctuation above SM expectations has been found and 95% C.L. bounds were obtained, ruling out the sequential Z' with masses below 3.4 TeV. In the light of this new data set we update existing limits on the Z' gauge boson of left-right models.

As mentioned above, a popular and often considered process to constrain left-right symmetry is neutrinoless double beta decay [40]. Here the most straightforward approach is to consider the right-handed analog of the standard light neutrino exchange mechanism, which is sensitive to the W_R mass and the right-handed neutrino masses. The LHC analog of this diagram is the production of two like-sign leptons and two jets, $eejj$. Several papers have studied the LHC constraints [41] of this final state and obtained the corresponding limits on the parameter space in comparison to the double beta decay constraints [11–17]. We point out here that Z' mass limits can within many LR models be translated into W_R mass limits, which therefore provides indirect limits on the parameter space relevant for double beta decay. These limits are moreover essentially independent on the right-handed neutrino mass and complementary to other limits. Depending on the breaking scheme of the left-right symmetry and the ratio of gauge boson couplings, they probe part of parameter space outside the one reachable by LHC $eejj$ searches and double beta decay, and are stronger than the ones from dijet data.

We start this letter by discussing some aspects of left-right symmetry before providing the Z' mass limits by newest LHC dilepton data and then making the comparison to direct limits on the double beta decay parameter space.

II. LEFT-RIGHT SYMMETRY

Left-right models rely on the gauge group $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ and have quite interesting features: (i) they naturally incorporate baryon and lepton number; (ii) generate neutrino masses through type I+II seesaw mechanisms; (iii) might appear in unification theories such as SO(10) and E(6); (iv) they restore C and/or P (charge conjugation and parity) at high energy scales, thus addressing their violation at the electroweak scale, which is arguably the most striking motivation for a gauge left-right symmetry. Within this context we address two different exemplary symmetry breaking patterns.

A. Scalar Content A

In case there is a left-right discrete symmetry in the model, the fields transform under parity and charge conjugation as follows: P: $Q_L \leftrightarrow Q_R, \phi \leftrightarrow \phi^\dagger, \Delta_{L,R} \leftrightarrow \Delta_{R,L}$; and C: $Q_L \leftrightarrow Q_R^c, \phi \leftrightarrow \phi^T, \Delta_{L,R} \leftrightarrow \Delta^*_{R,L}$. The full fermion and scalar content of the model is

$$\begin{aligned} Q_L &= \begin{pmatrix} u_L \\ d_L \end{pmatrix}, Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}, \\ l_L &= \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, l_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix}, \end{aligned} \tag{1}$$

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & \delta^+_{L,R}/\sqrt{2} \end{pmatrix}. \tag{2}$$

Notice that in this most often considered left-right model ϕ is a bidoublet which transform as $(2, 2^*, 0)$ under $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ in order to generate fermion masses, and $\Delta_{L,R}$ are scalar triplets with $B - L = 2$.

While typically $g_L = g_R$ is assumed as a consequence of a discrete left-right symmetry such as parity or charge conjugation, this is actually not necessary. For instance, by using so-called D-parity instead, which is broken by the vev of a total gauge singlet field, one can easily depart from $g_L = g_R$ at low energies, see [15, 38, 42–46] for explicit realizations. In short, one decouples in such theories the breaking of the discrete and gauge left-right symmetries, consequently the left- and right-handed scalar fields have different masses early on, and the gauge couplings run differently resulting in $g_L \neq g_R$ at low scales.

The relevant aspect of this class of models for what follows is the fact that it induces Z'-fermions couplings

$$\frac{g_R}{\sqrt{1-\delta\tan^2\theta_W}}\overline{f}\,\gamma_\mu\left(g_V^f - g_A^f\gamma^5\right)\,f\,Z^\mu\,, \tag{3}$$

with the couplings determined by

$$\begin{aligned} g_V^f &= \frac{1}{2}\left[\left\{\delta\tan^2\theta_W\left(T_{3L}^f - \mathrm{Q}^f\right)\right\} + \left\{T_{3R}^f - \delta\tan^2\theta_W \mathrm{Q}^f\right\}\right] \\ g_A^f &= \frac{1}{2}\left[\left\{\delta\tan^2\theta_W\left(T_{3L}^f - \mathrm{Q}^f\right)\right\} - \left\{T_{3R}^f - \delta\tan^2\theta_W \mathrm{Q}^f\right\}\right] \end{aligned}$$

where $T^f_{3L,3R} = \pm 1/2$ for ${}^{\mathrm{up}}_{\mathrm{down}}$-fermions, $\delta = g_L^2/g_R^2$, and Q^f being the corresponding electric charge. In general the neutral current depends on how the left-right gauge symmetry is broken. Therefore, the Z'-fermion coupling strength is subject to the spontaneous symmetry breaking pattern. We will get back to that further. Another interesting outcome of this class of models is the mass relation

$$\frac{M_{Z_R}}{M_{W_R}} = \frac{\sqrt{2}g_R/g_L}{\sqrt{(g_R/g_L)^2 - \tan^2\theta_W}}\,. \tag{4}$$

Setting $g_L = g_R$, we find $M_{Z_R} \simeq 1.7 M_{W_R}$, with $M_{W_R} = g_R v_R$, where v_R is the scale at which the left-right gauge symmetry is broken to the Standard Model. This mass relation has profound implications, since it clearly shows that bounds on the mass of the charged gauge boson imply stronger ones on the Z' mass. Thus, as far as constraining the gauge boson masses are concerned, W_R searches should be the primary target. Although, collider searches for W_R rely mainly on dilepton plus dijet data that are subject to large background. Hence, it is worthwhile performing an independent collider study of the Z' gauge boson in left-right models because it predicts a clean signal based on dilepton data. Moreover, in case a signal consistent with a W_R is observed at the LHC a corresponding dilepton excess can be expected using the mass relation Eq. (4).

B. Scalar Content B

In general terms, as already in the model treated above, g_R may be different from g_L at low energy scale. In addition, the mass relation in Eq. (4) depends also on the spontaneous symmetry breaking pattern. It has been proposed in [42, 47], that if one evokes a D-parity breaking with the following scalar particle content,

$$\begin{aligned} \phi &= \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix},\ \Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & \delta^+_{L,R}/\sqrt{2} \end{pmatrix} \\ \Omega_{L,R} &= \begin{pmatrix} \omega^0 & \omega^+/\sqrt{2} \\ \omega^-/\sqrt{2} & -\omega^0 \end{pmatrix}, \end{aligned} \tag{5}$$

(the fermion sector is unchanged from the previous model) one can actually get $M_{W_R} \gg M'_Z$ and $g_R \neq g_L$. The two additional triplet scalars $\Omega_{L,R}$, which transform with $B-L=0$, are required in order to break the LR symmetry in two steps: (i) $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \rightarrow SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L}$ through the vev of neutral field of the triplet Ω_R which sets the W_R mass; (ii) $U(1)_R \otimes U(1)_{B-L} \rightarrow U(1)_Y$, by the vev of neutral field of the triplet Δ_R determining the Z_R mass. Its coupling to fermions is the same as in Eq. (3). The additional scalar fields above are needed to break the SM to electromagnetism as usual. Taking the vev of Ω_R to be at very high energy scales, the masses of the charged and neutral gauge bosons are uncorrelated, with $M_{W_R} \gg M_{Z_R}$. Thus, in this scenario, collider searches for neutral gauge bosons are more promising since the charged gauge boson is not attainable at the LHC.

In summary, left-right models predict the existence of new neutral and charged gauge bosons and their mass relation is subject to the scalar content of the model. If the neutral gauge boson is heavier than the charged one, our results play a complementary role since a W_R signal at the LHC should be accompanied by a dilepton resonance. If the neutral gauge boson is lighter than the charged one, our limits are crucial and the most restrictive direct limits on the Z' mass. Moreover, the left- and right-handed gauge couplings can be different from each other, and should be left as free parameter. Hence, in an attempt of remaining agnostic regarding the precise scalar content and the spontaneous symmetry breaking pattern chosen, we base our results on the Z'-fermions couplings in the context of Eq. (3) and varying in particular the gauge coupling g_R.

III. DILEPTON LIMITS

Dilepton data (ee, $\mu\mu$) is a promising data set in the search for new physics in several theories which possess neutral gauge bosons with sizable couplings to leptons[1]. At the LHC, in particular, the high selection efficiencies and well understood background naturally poses this channel as a golden channel since a heavy dilepton resonance is a new physics smoking gun. Up to date, the most sensitive heavy neutral gauge bosons searches were carried out by both ATLAS and CMS collaborations [36, 37]. ATLAS collaboration has obtained 95% C.L. limits on the sequential Z' boson at 8 TeV centre-of-mass energy with $\mathcal{L} = 20$ fb^{-1} ruling out masses below 2.90 TeV, combining ee and $\mu\mu$ data. With the LHC run II data at 13 TeV with $\mathcal{L} = 3.2$ fb^{-1} unprecedented sensitivities were reached in [39].

The most relevant background contributions arise from the Drell-Yan processes. Additional background sources come from diboson and top-quark production. Due to misidentification of jets as electrons also known as jet-fake rate, multi-jet and W+jets channels are also background to dielectron searches. We have taken the background estimations from [39]. As for the signal, we simulated $pp \rightarrow Z' \rightarrow e^+e^-$, $\mu^+\mu^-$ plus one jet (in order to account for extra isolated dilepton events with the presence of one jet which are identified as dilepton events) using MadGraph5 [49] for invariant masses above 500 GeV as analyzed in [39]. We have used the CTEQ6L parton distribution functions [50] and taken into account jet hadronization QCD radiation with Pythia and imposed the same isolation requirements as the ATLAS collaboration. As for detector effects, we adopted a flat 70% signal efficiency, which is reasonable as shown in Fig. 1 of [36]. The dimuon data efficiency lies around 40%, resulting into a slight overestimation of our combined limits, but it lies within the 2σ error bar reported by ATLAS collaboration. Following the procedure in [39], the signal events were selected by applying the following cuts:

- $E_T(e_1) > 30\,\text{GeV}, E_T(e_2) > 30\,\text{GeV}, |\eta_e| < 2.5,$
- $p_T(\mu_1) > 30\,\text{GeV}, p_T(\mu_2) > 30\,\text{GeV}, |\eta_\mu| < 2.5,$
- $500\,\text{GeV} < M_{ll} < 6000\,\text{GeV},$

where M_{ll} is the invariant mass of the lepton pair, which is the most important signal-to-background discriminating variable for this kind of analysis.

By looking at the differential cross section in terms of the invariant mass distribution of the lepton pairs (see Fig. 1), one can clearly see the pronounced peak when the invariant mass matches the mass of the neutral gauge boson. In the left-right models, the cross section suddenly increases near the Z' mass, featuring a narrow resonance. One could do a similar plot for the number of events and notice that there is negligible SM background for invariant masses above 2 TeV (see table 2 of [39]). Hence, in the light of no event observed for large invariant masses one can place robust limits on the Z' mass. In Fig. 2 we present the limits on the g_R vs. $M_{Z'}$ mass plane enforcing the signal cross section not to exceed at 95% C.L. the observed one using Fig. 3-c of [39]. For instance, for $g_R/g_L = 1$ the limit is $M_{Z'} > 3230$ GeV, whereas for $g_R/g_L = 1$ (0.6)

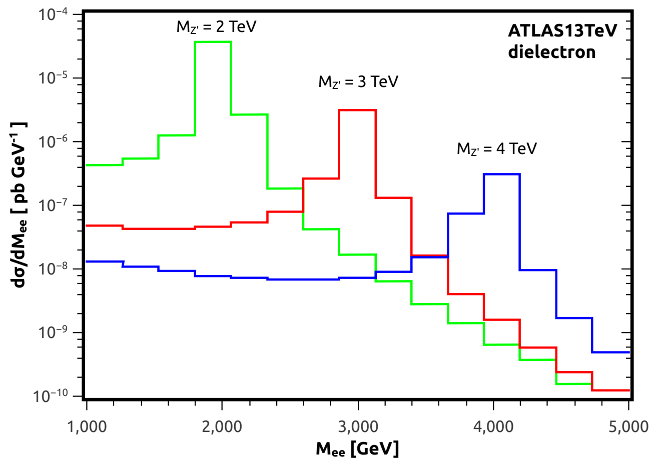

FIG. 1: Differential cross section for the dielectron channel at 13 TeV. The p_T and E_T cuts given in Sec. III were applied to the figure.

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[1] See [48] for a good review of LEP-II bounds on gauge bosons. In particular, note that the LEP-II limit on our Z' bosons is 667 GeV for $g_R = g_L$.

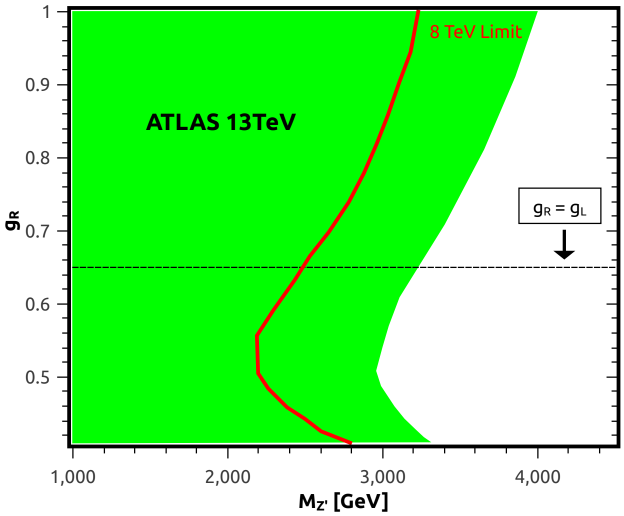

FIG. 2: 13 TeV LHC bounds on the Z' mass in the context of left-right symmetric models for different g_R values. In particular, for $g_R = g_L$ (dashed line) we find $M_{Z'} \geq 3230$ GeV. Notice that the Z'-fermion coupling strength does not always grow with g_R because of the presence of extra $1/g_R^2$ factors in the vector/axial couplings, explaining the shape of the figure. Those limits are subject to 2σ errors as reported by ATLAS.

the limit is $M_{Z'} > 4000$ (3300) GeV. Using the mass relation between $M_{Z'}$ and M_{W_R} from Eq. (4), these limits translate into $M_{W_R} > 1900$ GeV $(g_R/g_L = 1)$, $M_{W_R} > 2666$ GeV $(g_R = 1)$, and $M_{W_R} > 1100$ GeV $(g_R/g_L = 0.6)$.

The presence of right-handed neutrinos might degrade the limits by 1-2% due to branching ratio subtraction into charged leptons. Hence, our limits are essentially independent on the right-handed neutrino mass, in contrast to limits on W_R bosons from $eejj$ data, which will be of importance when we now continue to discuss the connection to double beta decay.

IV. CONNECTION WITH NEUTRINOLESS DOUBLE BETA DECAY AND W_R SEARCHES

Left-right symmetric models give rise to several contributions to neutrinoless double beta decay ($0\nu\beta\beta$) [10, 40]. Focusing on the purely right-handed neutrino exchange, one finds applying the current bound from KamLAND-Zen of 2.6×10^{25} yrs for the decay of ^{136}Xe [51] the following constraint:

$$\left(\frac{g_R}{g_L}\right)^4 \frac{|V_{ei}^2|}{M_{N_i} M_{W_R}^4} \leq 0.1 - 0.2 \text{ TeV}^{-5} \,, \qquad (6)$$

where M_{N_i} are the right-handed neutrino masses and V is the right-handed analog of the PMNS matrix U, assumed here for definiteness to be equal to U. Assuming the right-handed contribution to be the dominant mechanism of the decay, the pink region in Figs. 3–5 is ruled out. Also given in those figures is the region from CMS and ATLAS $eejj$ searches [41, 52],

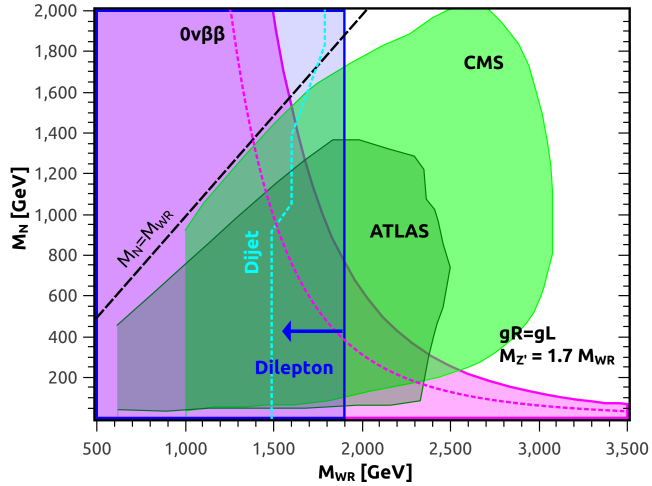

FIG. 3: Complementary among neutrinoless double beta decay, W_R and Z' searches at the LHC for $g_R/g_L = 1$.

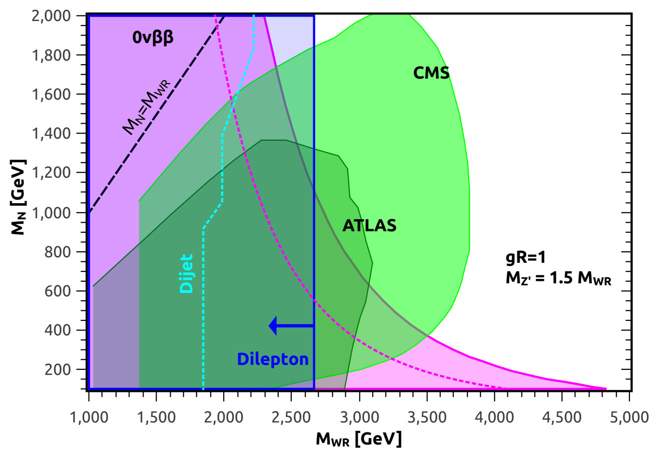

FIG. 4: Complementary among neutrinoless double beta decay, W_R and Z' searches at the LHC for $g_R = 1$, i.e. $g_R/g_L = 1.54$.

the strongest constraints being obtained for centre-of-mass energy of 8 TeV with integrated luminosity of 19.7 fb^{-1} from the CMS collaboration [41]. No excess beyond SM expectations is observed and 95% C.L. limits were derived ruling out masses up to 3 TeV as shown in Figs. 3–5 in the M_N vs. M_{W_R} plane (the limits on M_{W_R} are similar to the ones from meson physics [4–6]).

Note that those limits are applicable to the $M_{W_R} > M_N$ regime and assume the branching ratio $W_R \to lN$ to be 100%, where $l = e, \mu$. Moreover, for small $M_N \ll M_{W_R}$ the detector efficiencies are rather poor, explaining the shape in Fig. 3. Assuming that the narrow width approximation is valid and the efficiency remains for different values of g_R, one can naively rescale the limits for different g_R/g_L values. The branching ratio remains the same, but the production cross section goes with g_R^2/g_L^2. Thus, we can translate that shift in the production cross section into a rescaling of the bound on the W_R as presented in Figs. 4 and 5. We emphasize that

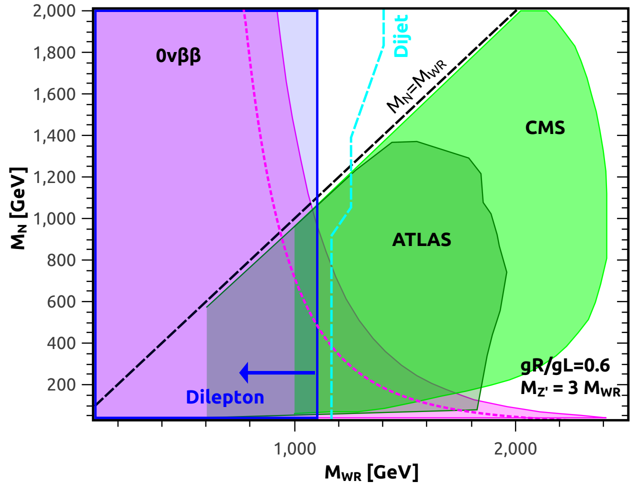

FIG. 5: Complementary among neutrinoless double beta decay, W_R and Z' searches at the LHC for $g_R/g_L = 0.6$.

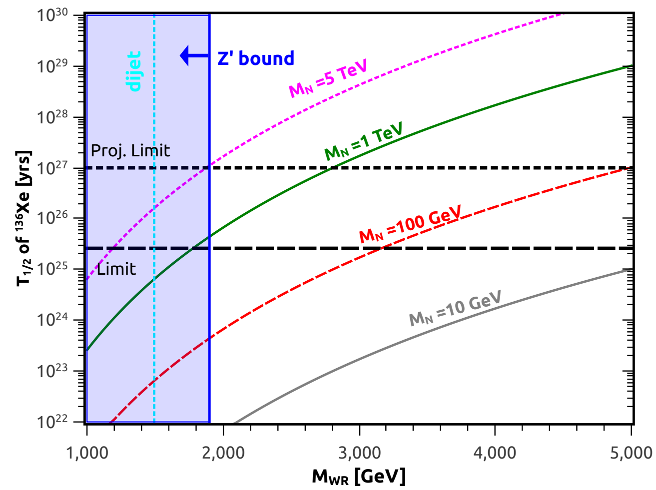

FIG. 6: Indirect limits on the half-life of ^{136}Xe from dilepton and dijet searches at the LHC for $g_R/g_L = 1$. In particular, for $M_N = 5$ TeV, where no bound from $eejj$ searches is applicable, dilepton resonances provide the most restrictive limits on the half-life of ^{136}Xe.

the new bounds on the W_R mass are approximate, and certainly overestimated in the regions which $M_{W_R} \sim M_N$ or $M_{W_R} \gg M_N$, but satisfactory to our reasoning. In Figs. 4 and 5, ATLAS and CMS limits were rescaled from $g_R/g_L = 1$ to $g_R = 1$ and $g_R/g_L = 0.6$, respectively. We also include in the figure the (partly in analogy to the $eejj$ limits rescaled) bounds on W_R as obtained by dijet data from Ref. [53][2]. For other studies regarding W_R searches see [54, 55].

As already mentioned, Z' searches based on dilepton data are essentially not sensitive to the right-handed neutrino masses. Therefore, relating the Z' mass limits via Eq. (4) to W_R mass limits allows to set indirect constraints on the parameter range. This method allows to enter parameter space not probed by W_R studies and neutrinoless double beta decay, as one can see in Figs. 3–5. In particular, the bound on the Z' mass is important for low right-handed neutrino masses and if the right-handed neutrino lives in the neighborhood of M_{W_R} (keeping in mind that vacuum stability prohibits the mass of the right-handed neutrino to be much heavier than the W_R [56, 57]).

Comapring dijet and dilepton data for different g_R/g_L ratios, we see that for both $g_R = g_L$ and $g_R = 1$, dilepton data surpasses the current dijet limits. The dilepton data might lose in sensitivity to the dijet data if there is a large mass splitting in the gauge boson relation $M_{Z'} > M_{W_R}$, be it from the ratio g_R/g_L or in models as described in Sec. IIA. We emphasize again that in case one breaks left-right symmetry such that the W_R are much heavier than the Z' and thus disconnected, then both jj and $eejj$ data yield weak limits.

In Fig. 6 we use our bound on the Z' mass to constrain the half-life for double beta decay. We plot the half-life for ^{136}Xe assuming different values for a right-handed neutrino mass. We also exhibit the dijet and current (projected) $0\nu\beta\beta$ decay limits. The curves from top to bottom are for $M_N = 5$ TeV, $M_N = 1$ TeV, 100 GeV and 10 GeV, respectively. In particular, for $M_N = 5$ TeV there is no bound from $eejj$ searches on the W_R mass, since $M_N > M_{W_R}$, and only those stemming from dijet and dilepton resonances apply. It is visible that dilepton data from LHC provides an exciting opportunity to indirectly probe neutrinoless double beta decay, i.e., lepton number violation, specially in the regime of heavy right-handed neutrino masses.

We stress that in the left-right model the W_R mass is determined by the vev of the triplet scalar Δ_R. Large W_R masses might require the quartic couplings in the scalar potential to be non-perturbative. After including 1-loop effects and renormalization of the scalar sector, the authors in [57] found that $M_N \leq 7.3 M_{W_R}$ is allowed without ruining stability or perturbativity of the model. Thus, the region of parameter space with $M_N > M_{W_R}$ is indeed theoretically allowed. If left-right models with two doublets are considered instead of the triplet scalar a similar logic should apply, concretely reaffirming that for heavy right-handed neutrinos, dilepton data offers a promising search strategy to grasp left-right symmetry in nature.

As a note we emphasize that the $eejj$ limits obtained in the context of left-right models with no $W - W_R$ mixing are equivalent to those right-handed neutrino searches which are parametrized in terms of the Lagrangian $\theta \frac{g}{\sqrt{2}} \bar{l}(1+\gamma_5) N W$, with $\theta = 10^{-4}$ being the mixing angle between W and W_R such as in [58, 59]. Thus our conclusions are also applicable to those studies focused on right-handed neutrino searches at the LHC.

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[2] The behavior of the dijet limit is explained by the change in the branching ratio $W_R \to jj$ when $M_N > M_{W_R}$.

V. CONCLUSIONS

We have performed a collider study of the Z' gauge boson in the context of left-right symmetry models motivated by the 13 TeV dilepton data set with 3.2 fb^{-1} integrated luminosity from the ATLAS collaboration and exploited the complementarity with neutrinoless double beta decay, dijet and W_R searches. Leaving the right-handed gauge coupling free, we set limits of up to 4 TeV on $M_{Z'}$, while the limit for the canonical $g_R = g_L$ case is $M_{Z'} > 3.2$ TeV. Our findings are nearly independent of the right-handed neutrino masses, as opposed to $eejj$ and double beta decay constraints.

In the context of minimal left-right models one has $M_{Z'} > M_{W_R}$, with the proportionality factor of order one depending on the Weinberg angle and the ratio of left-and right-handed gauge couplings. This naively indicates that the most promising way to constrain the left-right symmetry is by searching for W_R bosons at the LHC. However, as the relation between the gauge boson masses depends on model details and can in fact even be $M_{Z'} \ll M_{W_R}$, Z' searches in the context of left-right symmetry should be pursued too. In addition, comparing W_R and Z' properties is an important consistency check of possible signals in the future. There is yet another motivation for our limits, namely in the context of the complementarity of LHC and neutrinoless double beta decay results: if a direct relation between $M_{Z'}$ and M_{W_R} exists, we have pointed out that Z' limits constrain the parameter space relevant for double beta decay in an indirect manner, reaching areas of parameter space not accessible by dijet and $eejj$ searches depending on the ratio of gauge couplings.

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