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Limits on the left-right symmetry scale and heavy neutrinos from early LHC data

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We use the early Large Hadron Collider data to set the lower limit on the scale of left-right symmetry, by searching for the right-handed charged gauge boson W_R via the final state with two leptons and two jets, for 33 pb^{-1} integrated luminosity and 7 TeV center-of-mass energy. This signal is kinematically observable for right-handed neutrino lighter than W_R. In the absence of a signal beyond the standard model background, we set the bound $M_{W_R} \gtrsim 1.4$ TeV at 95% C.L.. This result is obtained for a range of right-handed neutrino masses of the order of few 100 GeV, assuming no accidental cancellation in right-handed lepton mixings.

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I. INTRODUCTION

For more than three decades, the left-right (LR) symmetric gauge theories [1] have been one of the most popular extensions of the standard model (SM), introduced originally for the sake of understanding the breakdown of parity in weak interactions. These theories played a profound role in the development of neutrino mass. They required nonvanishing neutrino mass long before it was to be confirmed experimentally and, moreover, they led to the seesaw mechanism [2,3], nowadays a well-established framework of small neutrino mass.

The question is, at which scale does the LR symmetry get restored, or equivalently, what is the mass of the right-handed charged gauge boson W_R? In the minimal model, there exist strong theoretical limits [4] on the scale of the theory from $K_L - K_S$ mass difference . This limit depends on the choice between two possible discrete left-right symmetries: parity ($\mathcal{P}$) and charge conjugation ($\mathcal{C}$). In the case of $\mathcal{P}$, the limit is $M_{W_R} \gtrsim 3$ TeV, whereas in the case of $\mathcal{C}$ it is somewhat lower: $m_{W_R} \gtrsim 2.5$ TeV [5].

The seesaw version of the theory offers a particularly exciting signal in the form of the lepton-number breaking channel of a same-sign lepton pair and two jets without missing energy [6], intimately related with the Majorana nature of neutrino mass. Dedicated studies of both, ATLAS and CMS, show that the LHC running at 14 TeV can reach $M_{W_R} \lesssim 2(4)$ TeV with a luminosity of 0.1(30) fb^{-1} [7,8].

Moreover, the LR scale may well be required to lie in the Large Hadron Collider (LHC) energy region. The point has to do with the neutrinoless double beta decay, which has been claimed to have been observed [9]. One possible source of this process is a Majorana neutrino mass, but if cosmology keeps pushing down the sum of neutrino masses, and if this claim is to be confirmed, new physics behind neutrinoless double beta decay would be a must. LR symmetry plays that role naturally [10], and this would require the LR scale to be in the TeV region. One could have a profound interplay between high energy collider experiments and low energy neutrinoless double beta decay [11].

In spite of the short period of running and a fairly low luminosity, the sensitivity achieved by both ATLAS and CMS collaborations, allows one to already set relevant updated bounds on a number of new particles and their interactions. For example, in case the right-handed neutrinos are very light, or equivalently, neutrinos being the Dirac particles, the right-handed charged boson decays leptonically in the manner often associated with the nomenclature $W' \to \ell\nu$. Recently, the CMS collaboration established the generic bound for such particles $M_{W'} \gtrsim 1.4$ TeV, for the same couplings of W and W' [12,13].

Inspired by this, we investigate carefully the analogous limit in the Majorana case of the LR theory, by using the available LHC data. This theoretically preferred scenario, which requires heavy right-handed neutrinos, leads at this stage to a very similar bound, $M_{W_R} \gtrsim 1.4$ TeV at 95% confidence level (CL) for a large portion of parameter space. In particular, this applies to right-handed (RH) heavy neutrinos in the LHC accessible region, $m_N = \mathcal{O}(100)$ GeV and generic RH lepton flavor mixing angles.

This lower bound would go to 2.2 TeV for $\sqrt{s} = 7$ TeV, and a luminosity of 1 fb^{-1}.

II. THE GENERIC GAUGE STRUCTURE

The minimal LR symmetric theory is based on the gauge group $\mathcal{G}_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ (suppressing color), with corresponding gauge couplings g_L, g_R and g_X, and a symmetry between the left and right sectors. Quarks and leptons come in LR symmetric representations $q_{L,R} = (u, d)_{L,R}$ and $\ell_{L,R} = (\nu, e)_{L,R}$.

At this point, it is sufficient to assume that this gauge symmetry is broken down to the SM at a scale M_R. If $g_L \approx g_R$, the Tevatron sets a rough bound (to be discussed below more carefully) $M_R \gtrsim$ TeV. This is enough to ensure a

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small mixing angle between left and right gauge bosons, which for all practical purposes is taken to be zero in what follows.

The physical gauge fields consist of the usual the SM states and the new ones: $W_R^{\pm}$ and Z_{LR}, with the following interactions

$$\frac{g_R}{\sqrt{2}} W^+_{R\mu}[\bar{u}_R \gamma^\mu d_R + \bar{\nu}_R \gamma^\mu \ell_R] + \text{H.c.}, \qquad (1)$$

where we suppress the family indices, together with the flavor mixing indices, and $\frac{g_R}{\sqrt{1-\tan^2\theta_W g_L^2/g_R^2}} Z^\mu_{LR} \bar{f} \gamma_\mu [T_{3R} + \tan^2\theta_W \frac{g_L^2}{g_R^2}(T_{3L} - Q)] f$, where θ_W is the usual weak mixing angle. It is easy to show that there is a lower limit on $g_R > g_L \tan\theta_W$. All of this is independent of the choice of the Higgs sector, responsible for the symmetry breaking. What does depend on the choice of the Higgs sector, is the ratio of Z_{LR} and W_R masses, just as in the SM.

Before delving into the Higgs swamp, let us discuss the generic limits on the new gauge boson masses, most of which depend crucially on the nature of the right-handed neutrinos. There is one limit on the mass of W_R which depends only on the value of g_R and the right-handed quark mixing, from the $W_R \to tb$ channel. Tevatron gives this bound for the same left and right parameters: $M_{W_R} \gtrsim 885$ GeV [14].

The limit on Z_{LR} mass depends only on g_R and for equal left and right couplings, and the present limit set by $Z_{LR} \to \mu^+\mu^-$ and ee channel: $M_{Z_{LR}} \gtrsim 1050$ GeV [15].

III. THE MAJORANA CONNECTION

We start first with the seesaw scenario in which the right-handed neutrinos are heavy Majorana particles that we denote N in what follows. In a reasonable regime 10 GeV $\lesssim m_N \lesssim M_{W_R}$, this opens an exciting lepton-number violating channel [6] $W_R \to \ell^\pm \ell^\pm jj$, which allows one to probe higher values of M_{W_R} [7,8]. After being produced through the usual Drell-Yan process, W_R decays into a charged lepton and a right-handed neutrino N. Since N is a Majorana particle, it decays equally often into another charged lepton or antilepton, together with two jets. Ideally, one would like to study both same-sign lepton pairs, for the sake of lepton-number violation, and any-sign lepton pair for the sake of increasing the sensitivity of the W_R search.

Such a final state with any-sign lepton pair was used recently by the CMS collaboration to search for pair production of scalar leptoquarks, for both electron and muon lepton flavors [16]. We thus use these data to impose an improved limit on the masses of W_R and N [17].

We perform a Monte Carlo simulation, using MADGRAPH [18], PYTHIA [19] to generate the events for the process $pp \to n\ell n' j (n, n' \geq 2)$ and do the showering, including the K-factor of 1.3 to account for the NNLO QCD corrections [20]. We simulate the CMS detector using both PGS and DELPHES which give essentially the same result. We also use the CTEQ6L1 parton distribution functions (PDF). We summarize in Table I the cuts used in this Letter, taken from the CMS papers [16]. For jet clustering, we employ the FASTJET package [21], using the anti-k_T algorithm with $R = 0.5$ for jet reconstruction. The lepton isolation cut makes our exclusion less efficient in the region of light N, roughly below 50 GeV. The reason is that the lepton and jets coming from the boosted N decay become too collimated and finally merge into a single jet with a lepton inside. However, when N is heavier, this cut becomes less relevant.

The data and the SM background are taken from Ref. [16]. The main contributions to the background include the $t\bar{t}$ + jets and Z/γ^* + jets, and they can be suppressed efficiently by the appropriate cut on the invariant mass of the two leptons ($m_{ee} > 125$ GeV and $m_{\mu\mu} > 115$ GeV). We employ the Poisson statistics to get the exclusion plots. In order to get the most stringent bound, for each point in the $M_{W_R} - m_N$ parameter space, we choose the optimal cut on the S_T parameter (the scalar sum of the p_T of the two hardest leptons and the two hardest jets) from Table 1 of [16].

The resulting 95%CL limit $M_{W_R} \gtrsim 1.4$ TeV, the best up to date, holds for a large portion of parameter space, as shown in Fig. 1. One can see that this result holds for RH neutrino masses lying in a fairly natural energy scale 100 GeV–1 TeV. It turns out that both the electron and muon flavour channels give a similar exclusion in the parameter space.

In all honesty, this limit could be weakened by a judicial choice of RH leptonic mixing angles and phases; we opted here against such conspiracy. For example, in the case of an appealing type-II seesaw, left and right leptonic mixing angles are related to each other, and no suppression arises [11]. A careful study of the mixings, through *e.g.* flavor-changing $e\mu$ final state [15] will be published elsewhere.

Up to now, we have made an assumption that $g_R = g_L$, and the right-handed counterpart of the Cabibbo angle is the same as the left-handed one. This is actually true in the minimal version of the LR symmetric theory, but need not be so in general. One could easily vary the right-handed quark mixing parameters, but the presentation would become basically impossible with so many parameters and different PDF sets. We relax through the $g_R = g_L$

TABLE I. In both cases, we also demand at least two jets with $p_T > 30$ GeV and $|\eta| < 3$. Moreover, in the $\mu\mu jj$ case, at least one muon has to be within $|\eta| < 2.1$ and in the $eejj$ case, both electrons have to be separated from either jet by $\Delta R(e, j) > 0.7$.

channel	$p_T^{\min}(\ell)$	$\lvert\eta(\ell)\rvert^{\max}$	$\Delta R(\ell,\ell)^{\min}$	$m_{\ell\ell}^{inv}$	S_T
$eejj$	30 GeV	2.5	0.3	125 GeV	optimal
$\mu\mu jj$	30 GeV	2.4	0.3	115 GeV	optimal

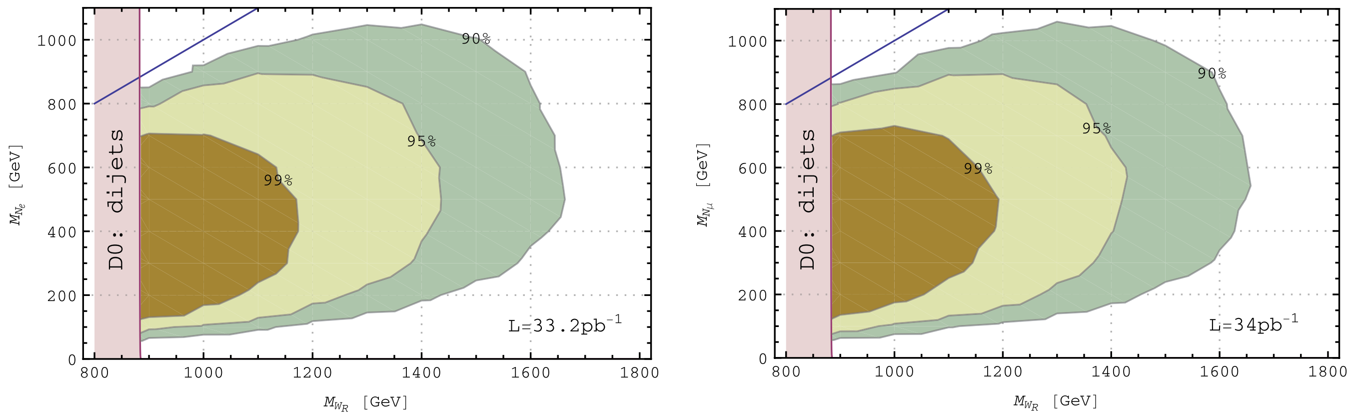

FIG. 1 (color online). Exclusion (90%, 95%, 99% CL) in the M_{W_R}–m_N plane from the $eejj$ (left) and $\mu\mu jj$ (right) channel. We assume no accidental cancellation in the RH lepton mixings. The 2σ lower bound $\sim$1.4 TeV is valid over a range of RH neutrino masses of order several hundred GeV.

assumption since this captures the essence of the impact when right and left are different. In the Fig. 2, in the shaded area, we plot the 95% CL exclusion region in the g_R/g_L versus M_{W_R} plane, for a fixed value $m_N = 500$ GeV. Clearly, with the increased g_R the production rate goes up and so does the limit on the mass of the right-handed gauge boson.

IV. THE DIRAC CONNECTION

In case the right-handed neutrinos are very light, they are treated as missing energy at the LHC and this case is equivalent to the case of Dirac neutrinos to which we now address our attention. This is actually the original version [1] of the LR symmetric theory, not popular anymore precisely since the neutrinos end up being Dirac particles. In this case the best limit comes from the recent CMS studies of $W' \to e\nu$ decay [12]: $M_{W_R} \gtrsim 1.36$ TeV and $W' \to \mu\nu$ decay [13]: $M_{W_R} \gtrsim 1.4$ TeV. Even with a low luminosity, LHC is already producing a better limit than the Tevatron one: 1.12 TeV [22].

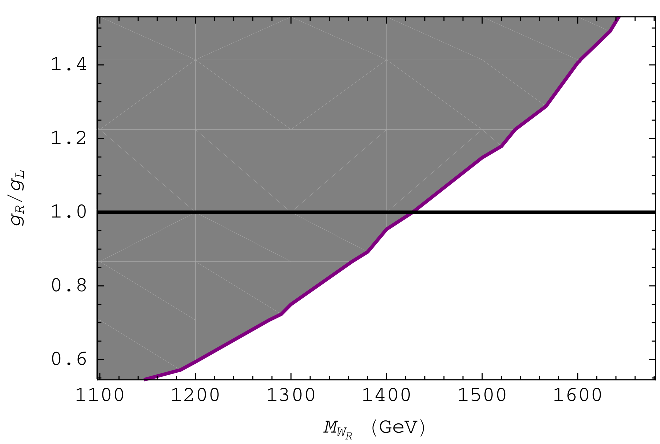

FIG. 2 (color online). Here, we vary the ratio g_R/g_L. The shaded region is the 95% CL exclusion on W_R mass for fixed value of the RH neutrino mass, chosen illustratively to be $m_N = 500$ GeV.

V. THE HIGGS CONNECTION

We discuss briefly the minimal models of Majorana and Dirac cases.

Majorana neutrino. The Higgs sector[1] consists of [2]: the $SU(2)_{L,R}$ triplets Δ_L and Δ_R. Besides giving a Majorana mass to N, a nonvanishing $\langle\Delta_R\rangle$ leads to the relation between the new neutral and charged gauge bosons

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

For $g_R \approx g_L$, one gets $M_{Z_{LR}} \approx 1.7 M_{W_R}$. In this case, one can infer the lower bound on $M_{Z_{LR}}$ from the lower bound on M_{W_R} in Fig. 1, and it exceeds the direct search result from [15]. For example, in the case of $m_N \sim 500$ GeV, the Z_{LR} with a mass below 2.38 TeV is excluded.

Dirac neutrino. In this case, the triplets are traded for the usual SM type left and right doublets, as in the original version of the LR theory [1]. For us, the only relevant change is the ratio of heavy neutral and charged gauge boson masses, which goes down by a $\sqrt{2}$.

VI. IMPROVED LIMITS FROM CMS DATA

The constraints from the recent CMS data are shown in Fig. 3, where the missing portion of the parameter space, not yet excluded by present data, is clearly seen. We use the BRIDGE [23] with MADGRAPH to calculate the average decay length of (boosted) N in the low mass region.

[1]There is also a bidoublet, which takes the role of the SM Higgs doublet, and we do not discuss it here. For a recent discussion of the limits on its spectrum and phenomenology, see [5].

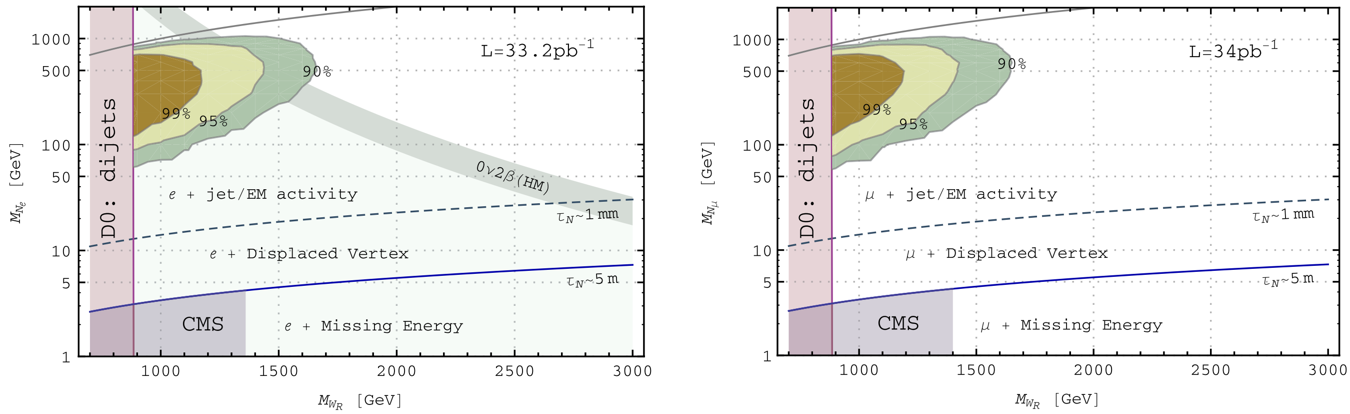

FIG. 3 (color online). Limits in the M_{W_R}–m_N parameter space. The elliptical regions correspond to Fig. 1, now shown in logarithmic scale. The excluded vertical region on the left is the D0 result from $W_R \to tb$ decay. The excluded lower trapezoid is the CMS missing energy result applicable for neglibly small m_N. For illustration in the left plot we also depict a (green) band where, ignoring leptonic mixings, the LR contribution to $0\nu\beta\beta$ decay saturates the HM claim [9].

We find that for $m_N \lesssim 3$–5 GeV, the average decay length exceeds the size of the detector, and is therefore regarded as missing energy.

The region above it, until about $m_N \lesssim 10$–15 GeV, corresponds to the displaced vertex regime and it has clear signatures for future discovery.

The white region further above unfortunately still requires published data or a dedicated analysis in order to set a bound on the W_R mass. This missing region can be easily filled with the data on the single lepton plus jet with electromagnetic activities (or a muon inside) [7].

VII. SUMMARY AND OUTLOOK

The direct limits on the scale of LR symmetry up to now have been much below the theoretical limit $M_{W_R} \gtrsim 2.5$ TeV [5], but with the advent of the LHC it is a question of (short) time that the experiment will finally do better.

Moreover, as discussed recently in [11], there is an exciting connection between the high energy collider and low energy experiments, with the LR scale possibly at the LHC reach. Motivated by this, we have used the existing CMS data to set a correlated limit on the mass of the right-handed charged gauge bosons and right-handed neutrinos. For reasonable values of right-handed neutrino masses, one gets $M_{W_R} \gtrsim 1.4$ TeV at 95% CL and 1.7 TeV at 90% CL. This is comparable to the recent CMS bound $M_{W_R} \gtrsim 1.36(1.4)$ TeV, applicable to Dirac neutrinos (and/or small Majorana RH neutrino masses). Although a coincidence, given the difference in background and cuts, it is reassuring that the limit seems quite independent of the nature of neutrino mass. As the luminosity increases up to $\mathcal{L} = 1\ \mathrm{fb}^{-1}$, expected by this summer, one could push the limit on M_{W_R} all the way up to 2.2 TeV. Also, using the data on the dilepton resonance search [15] (ignoring the jets), one can set a limit on W_R in a similar way as discussed in the present work.

There is a window for high values of m_N, when all of the right-handed neutrinos are much heavier than W_R. This less likely possibility, if true, will be covered by the limit from the future di-jet (or tb) data.

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