Eur. Phys. J. C (2014) 74:3107
DOI 10.1140/epjc/s10052-014-3107-9

THE EUROPEAN
PHYSICAL JOURNAL C

Letter

Testing right-handed currents at the LHC

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Received: 4 August 2014 / Accepted: 26 September 2014 / Published online: 15 October 2014

Abstract The CMS Collaboration has published two different searches for new physics that contain possible hints for excesses in $eejj$ and $e\nu jj$ final states. Interpreting those hints as a possible signal of a right-handed gauge boson W_R with mass 2–2.5 TeV may have profound implications for our understanding of the gauge structure of nature and Grand Unification, the scalar sector accessible at the LHC, neutrino physics, and the baryon asymmetry of the Universe. We show that this interpretation is, indeed, consistent with all existing constraints. However, before making premature claims we propose a number of cross-checks at the LHC14 that could confirm or falsify this scenario. Those include searches for a Z_R resonance and the related new scalar sector around 6–7 TeV. Additionally, large effects in top-quark spin-asymmetries in single top production are possible.

1 Introduction

In dedicated searches for right-handed currents [1] the CMS Collaboration at the LHC at CERN claims to see a 2.8σ deviation from the Standard Model in the channel

$$pp \to 2j + ee,$$

which is peaked around an invariant mass of the 4 objects of 2–2.5 TeV. The corresponding excess has not been observed in the $pp \to 2j + \mu\mu$ channel. At the same time, 2.4σ and 2.6σ excesses in the final states $2j + ee$ and $2j + e\nu$, respectively, have also been observed in searches for leptoquarks [2] in which other kinematical variables ($j\ell$ invariant masses) have been reconstructed. It is intriguing to argue that both excesses may have the same new physics origin.

In the pair production of leptoquarks [2], one expects to see no clear peak in the four particle invariant mass distribution, disfavouring leptoquarks as an explanation for the excess observed in [1]. Nevertheless, the peak may be explained in leptoquark models with colorons [3].

In this work we argue that the simplest and most natural common explanation for the the observed excesses could be the s-channel resonant production of right-handed gauge bosons W_R [4–13], with right-handed gauge coupling $g_R \sim 0.6 g_L$. The excess in $eejj$ [1] is then produced by the subsequent decay of the W_R to a heavy right-handed electron neutrino and an electron. The right-handed neutrino is unstable and undergoes a 3-body decay to two light jets and another electron, so the decay chain is:

$$W_R \to N_R + e, \qquad N_R \to e + 2j.$$

Within this model it can be easily explained why the W_R only decays to electrons and not to muons, if the right-handed muon neutrino is not kinematically accessible.[1] Indeed, as explained below, the natural mass scale of the symmetry breaking sector is 2–3 times the W_R mass, so that such a mass hierarchy not entirely unexpected.[2] At the same time, the produced W_R-bosons are also expected to decay hadronically through the decay chain

$$W_R \to tb/tq \to \ell\nu bb/\ell\nu bq,$$

where the decay rates to different quark flavours b, s, d depend on the unknown values of the right-handed CKM matrix V_R^{CKM}. Since the search [2] does not make use of b-tagging, it is sensitive to all the above final states, explaining the excess.

If this interpretation is correct, the discovery of right-handed currents and the associated physics at energies acces-

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[1] One has to also assume that the mixing between the right handed electron neutrino and the right handed muon or tau neutrino is not significant. Otherwise muonic final states would still be expected even with the assumed mass hierarchy.

[2] While this work was under preparation, similar claims for the W_R properties were put forward in [14]. However, that paper does not consider the $e\nu jj$ excess nor study other tests of the W_R scenario that are the purpose of this work.

sible at the LHC would completely change our presently favoured picture of particle physics.

The asymmetric nature of elementary particle interactions has been a long-standing puzzle, dating back to the original discovery of parity violation in kaon decays. In the Standard Model this asymmetry is represented by the absence of weak couplings to right-handed fermions. At the same time, the peculiar anomaly free chiral representations of fermions in the Standard Model point to a unifying structure at a higher energy scale.

These observations led Pati and Salam [15] to propose the first model of partial unification based on the gauge group $SU(4) \times SU(2)_L \times SU(2)_R$ that is left-right symmetric. Soon after that the left-right symmetric model based on $SU(3)_{\rm QCD} \times U(1)_{B-L} \times SU(2)_L \times SU(2)_R$ was formulated [16–18]. The latter can naturally explain the smallness of active neutrino masses that are suppressed by the high $SU(2)_R \times U(1)_{B-L}$ breaking scale [19]. Consequently, the baryon asymmetry of the Universe can be generated via leptogenesis [20].

Those models are in good accordance with the Grand Unification paradigm since they can be embedded into the (left-right symmetric) $SO(10)$ gauge group,

$$\begin{aligned} &SO(10)\\ &\quad\supset SU(4) \times SU(2)_L \times SU(2)_R\\ &\quad\supset SU(3)_{\rm QCD} \times U(1)_{B-L} \times SU(2)_L \times SU(2)_R\\ &\quad\supset SU(3)_{\rm QCD} \times SU(2)_L \times U(1)_Y\\ &\quad\supset SU(3)_{\rm QCD} \times U(1)_{\rm QED}. \end{aligned}$$

Combining the Standard Model fermions plus right-handed neutrinos into a complete **16** representation of $SO(10)$ guarantees the absence of gauge anomalies, and is also motivated by String Theory arguments. The $SO(10)$ symmetry breaking down to QCD and QED may occur in different chains via different intermediate scales. In the simplest left-right symmetric models with one intermediate scale the gauge coupling unification implies a very high scale of $SU(2)_R$ breaking [21], in agreement with small neutrino masses and leptogenesis. In more involved models, in which the discrete left-right symmetry and the $SU(2)_R$ breaking occur at different scales [22], the $SU(2)_R$ breaking scale can be as low as the TeV scale [14].

The scenario described above is appealing both phenomenologically and theoretically. However, no experimental evidence for the existence of right-handed currents has been obtained so far. Constraints from precision data [23,24] and from $K-\bar{K}$ and $B-\bar{B}$ systems require the W_R gauge boson to be heavier than about 2–3 TeV [25–29].[3] The Higgs sector of left-right symmetric models [31–33] offers additional tests of this scenario. The most promising of those at the LHC is the search for doubly charged Higgs boson [34]. Present experimental bounds on the mass of this particle from the LHC [35,36] are all below the TeV scale. Therefore the right-handed symmetry breaking scale 6–7 TeV indicated by the LHC [1], as discussed below Eq. (5), is safely above the existing constraints.

In the following we will propose and study additional tests of the right-handed currents and the associated physics at the LHC. This includes searches for new resonances related to the extended gauge and Higgs sectors as well as new observables, such as asymmetries, that are sensitive to right-handed currents. Clearly, our motivation is to point out that powerful cross-checks of this scenario can and should be carried out at the LHC. We take a bottom up approach and study the above described physics as model independently as possible just relying on group theory and on the LHC results. Nevertheless we show that some quantitatively robust conclusions can be drawn which allow further tests of this scenario at the LHC.

2 Gauge coupling strength

From group theory arguments and from the observed strength of the strong and hypercharge interactions we can find a simple estimate for the expected strength of the W_R coupling. At the scale of $SU(4) \to SU(3)_{\rm QCD} \times U(1)_{B-L}$ symmetry breaking the gauge couplings should be identical. We can represent the $SU(4)$ generators by 4×4 matrices in 3+1 block diagonal form:

$$T_i^{\rm QCD} = \frac{1}{2}\begin{pmatrix} \lambda_i & 0 \\ 0 & 0 \end{pmatrix}, \quad T^{B-L} = \sqrt{\frac{3}{2}}\begin{pmatrix} 1/6 & 0 \\ 0 & -1/2 \end{pmatrix}. \tag{1}$$

Here λ_i represent the Gell-Mann matrices, and the normalization constant has been chosen such that ${\rm tr}(T_i T_j) = \frac{1}{2}\delta_{ij}$. From this argument we find that, at the scale of $SU(4)$ symmetry breaking,

$$g_{B-L} = \sqrt{\frac{3}{2}}\, g_3. \tag{2}$$

Furthermore, it is easy to see that at the scale of $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ symmetry breaking,

$$\frac{1}{g_Y^2} = \frac{1}{g_R^2} + \frac{1}{g_{B-L}^2}. \tag{3}$$

From this simple mix of top-down and bottom-up argument [8], neglecting the logarithmic running between the two scales, we can see that if $g_{B-L} \geq 1$ as suggested by Eq. (2), the right-handed gauge coupling must be aproximately equal to the hypercharge coupling:

[3] These bounds are subject to large uncertainties in low energy hadronic matrix elements and can also be relaxed by giving up assumed exact left-right symmetry $g_L = g_R$, $V_L^{CKM} = V_R^{CKM}$ [30].

$$g_R \approx 0.6\, g_L. \tag{4}$$

Curiously, as was also pointed out in [14], this value fits very well to the observed signal strength associated with the $eejj$ excess [1]. Indeed, the CMS result excludes the W_R with $g_R = g_L$ as an explanation for the excess, as the predicted signal strength in that case is larger than what is observed.

3 Scalar sector, neutrino masses, leptogenesis

If the gauge group just above the TeV scale is $U(1)_{B-L} \times SU(2)_L \times SU(2)_R$ as we assume here, the minimal Higgs sector that breaks $U(1)_{B-L} \times SU(2)_R$ down to the hypercharge must contain at least one right-handed triplet with $Y = 2$ which gives mass to the W_R, to right-handed neutrinos N_i and to itself via its VEV. Usually the Higgs sector is taken to be left-right symmetric [31–33] containing also a left triplet with very small VEV. In the latter scenario the Standard Model neutrinos receive mass contributions from two sources, from the usual seesaw mechanism involving heavy neutrinos and at tree level from the left-handed triplet VEV. If the latter dominates, the doubly charged triplet component branching fractions to same-charge leptons must follow the measured neutrino mass matrix [37]. Searches for doubly charged Higgses at the LHC14 provide good tests of this model.

According the the LHC result, the right-handed electron neutrino N_e is somewhat lighter than $N_{\mu,\tau}$. In this case flavoured [38] resonant [39–41] leptogenesis from the degenerate $N_{\mu,\tau}$ pair is possible if either a μ or τ asymmetry is generated. The latter are not washed out by N_e, producing the observed baryon asymmetry. However, according the the LHC results [1], only one same-charge lepton pair was observed out of 14 signal events. If the heavy neutrino N_e was of Majorana type, this ratio should have been 50:50 [42]. This sets strong constraint on the nature of N_e favouring (pseudo) Dirac heavy neutrinos [43] suggesting that the most minimal model, perhaps, is not realised in nature. This implies a non-minimal Higgs sector that, perhaps, can be tested at the LHC14. This type of model building is beyond the scope of this paper.

4 Experimental tests and existing limits

4.1 Resonances

In addition to the search described in [1], other direct searches that are sensitive to W_R production have been performed by the ATLAS and CMS collaborations.

If the W_R is produced at the LHC, it will decay to 2 jets and appear as a dijet resonance, $W_R \to jj$. The strongest limit on this decay was found by ATLAS using 20.3 fb^{-1} at 8 TeV [44], excluding a "Sequential Standard Model" (SSM) W' with a mass of 2.45 TeV at 95 % CL.

In that model the coupling of the W_R to the SM fermions is assumed equal to that of the left handed W. In our model the value is smaller, so to estimate the constraint on this model we simply rescale the production cross section of the W_R, and hence the signal strength, by g_R^2/g_L^2. The branching ratio of the W_R to dijets is roughly similar to that of the sequential W', since all of the couplings are just rescaled with the common factor. If the mass of the W' is at the 2 TeV range, one can in first approximation treat all the final state fermions as massless, and then the branching ratios are roughly $\frac{3}{4}$ to hadrons and $\frac{1}{4}$ to leptons. In our case 2 of the leptonic channels are not available, since the right handed muon and tau neutrinos are assumed to be heavier than the W_R. Therefore the signal strength of the open channels need to be rescaled by a factor of $\frac{6}{5}$. Thus, if the W_R coupling is reduced to $g_R \approx 0.6 g_L$ the mass exclusion limit drops to $M(W_R) \gtrsim 2$ TeV.

For simplicity we have assumed here that the right handed CKM matrix is equal to the left handed one, and therefore does not affect the consideration of the different branching ratios. If this is not the case, and especially if the V_{11}-element is not close to maximal, the signal strength will be suppressed by the lower production cross section and thus the limits will be weaker.

Also the process $W_R \to tb, tj$ has been searched for at the LHC. In this channel there are two relevant searches from ATLAS [45] and CMS [46]. The 95 % CL exclusion limits from those two searches for a W_R with $g_R = g_L$ are 1.84 TeV and 1.85 TeV, respectively.

The CMS collaboration has compared the four particle invariant mass spectrum of the $pp \to eejj$ process to the Standard Model and to a W_R model with different masses for the W_R and the right-handed neutrino N_R [1]. In order to further test this scenario, two easy steps could be taken in the analysis of this final state:

1. In addition to the W_R mass, the mass of the right-handed neutrino can be reconstructed by measuring the invariant mass of the ℓjj-system. Depending on the mass splitting between the W_R and the heavy neutrino, the lepton from the original W_R decay is usually expected to be more energetic. Therefore a first attempt can be to use the lepton with less p_T in the reconstruction. If the $W_R \to \ell + N_R$ hypothesis holds, a clear peak in the N_R mass distribution should be seen in signal events.
2. The p_T distribution of the harder electron in the event should be examined. Again, if the W_R decay hypothesis is correct, a clear peak near $M_{W_R} - M_N$ should be visible.

The symmetry breaking $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ has the same structure as the electroweak symmetry breaking in the Standard Model, so one also expects to find an uncharged Z_R boson. Parametrically, the gauge boson masses are of the order

$$M_{W_R}^2 \approx g_R^2\, f^2, \qquad M_{Z_R}^2 \approx (g_R^2 + g_{B-L}^2)\, f^2, \tag{5}$$

where f is the symmetry breaking scale and the exact coefficients depend on the details of the Higgs sector. If $g_{B-L}^2 \gtrsim 1$, the mixing angle between the gauge groups is close to maximal. The Z_R boson mass is expected to be close to the symmetry breaking scale f, which is approximately 6–7 TeV if the W_R lives at 2–2.5 TeV. Scalar states associated with the Higgs mechanism will also naturally be expected at or near this scale. The Z_R couplings are close to $B-L$ because of the large mixing angle, such that the predominant decay channels of the Z_R are to leptons. If such a Z_R can be produced at the LHC14, a signal in the dilepton channels could be visible.

The dilepton signal $Z_R \to \ell^+\ell^-$ is also the most significant existing limit for the Z_R. ATLAS [47] and CMS [48] have performed searches for this signature. The exact exclusion limits depend on the Z_R charges but lie in the ballpark between 2.5 and 3 TeV. Also the search for contact interactions utilizing dileptons [49] is potentially sensitive to the Z_R. A limit of 18.3 TeV for the contact interaction scale is reported, but this assumes a strong coupling $g^2 \sim 4\pi$. In our case $g^2 \sim \mathcal{O}(10^{-1})$, so the signal strength that is proportional to g^4 is suppressed by a factor of $\mathcal{O}(10^{-4})$ with respect to reference [49]. Thus the expected mass of 6–7 TeV is clearly in the allowed region.

4.2 Asymmetries and indirect searches

Finally, there are indirect limits on the W_R model from electroweak precision (EWP) measurements, most importantly $e^+e^- \to e^+e^-$ scattering at LEP II. Contributions to EWP observables are dominated by Z_R exchange, while the contributions from W_R and the Higgs sector are of secondary importance. The details depend on the Higgs sector, but in the limit of $g_R \approx g'$ the limit on the $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ symmetry breaking scale f becomes approximately 3 TeV, implying $M(W_R) > 0.9$ TeV. For a more complete discussion of EWP limits on W_R models we refer the reader to [8,23,24].

Because of the coupling of the W_R to light quarks and to top+bottom, there will also be a t-channel contribution to single top production, competing with the left-handed W-exchange [50], as shown in Fig. 1. Since the coupling is about 0.6 times the left-handed coupling and the W_R-mass is a factor of 25 higher than the W-mass, we would at first expect this contribution to be insignificant. However, if the mixing in the right-handed sector between 1st and 3rd generations is much stronger than in the left-handed sector, there could be a clear signal, because in that case the process can be initiated by two light quarks, and is therefore not suppressed by the PDF of the initial state b-quark.

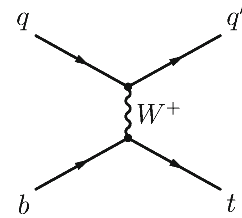

Fig. 1 The t-channel diagram contributing to *single top* production. In the SM, only *left*-handed tops are produced via the exchange of W_L. In the presence of W_R, also *right*-handed top quarks can be singly produced. If the CKM element between the first and third generation in the *right*-handed sector is not negligible, the process can also be initiated by two light quarks, avoiding the suppression from the initial state b-quark PDF

Angular distributions in single top decay might then show deviations from Standard Model expectations, because a significant component of right-handed top quarks could be produced, contrary to the SM case [51]. Searching for asymmetries [52,53], i.e. relations of cross sections such as $\sigma(pp \to t_L + j)/\sigma(pp \to t + j)$, can be an efficient way to observe the presence of new physics [54–58], as these measurements are free of systematic uncertainties such as the overall cross section normalization.

5 Conclusions

Recent experimental searches performed at the LHC show $\sim 3\sigma$ excesses compatible with right-handed currents mediated by a W_R-boson with a mass of 2–2.5 TeV. The coupling strength of this W_R appears to be about what is expected from theoretical arguments. Many details of this model have already been discussed, e.g. in [8]. Further tests are needed to confirm or falsify the W_R hypothesis. Among those tests are simple kinematic distributions, and asymmetries which could be measured in single top production at the LHC.

Acknowledgments This work was supported by grants MTT60, MJD435, IUT23-6, and by EU through the ERDF CoE program.

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