



Left–right model with TeV fermionic dark matter and unification



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ABSTRACT

The ingredients for a model with a TeV right-handed scale, gauge coupling unification, and suitable dark matter candidates lie at the heart of left–right symmetry with broken D-parity. After detailing the contents of such a model, with $SU(2)_R$ self-conjugate fermions at the right-handed scale aiding in unification of couplings, we explore its dark matter implications and collider signatures.

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1. Introduction

These are indeed exciting times for particle physics as the Large Hadron Collider (LHC) at CERN is all set to run at its machine configuration of $\sqrt{s} = 14$ TeV. With experiments at this highest energy facility in a hunt for new physics at TeV scales, it is no surprise that the community is particularly focussed on models with phenomenological signatures in the $\mathcal{O}(\text{TeV})$ range. Of the various models that try to explain natural phenomena beyond the scope of the standard model (SM), those based on left–right (LR) symmetry [1–4] have withstood the tests of time as they extend the SM electroweak sector in well motivated ways. These models explain the origin of parity violation and at the same time gauge the global $U(1)_{(B-L)}$ symmetry inherent in SM and in the process explain the smallness of the neutrino mass.

Hypothesised primarily in the context of visible sector physics, LR models do not have any *de facto* dark matter (DM) candidate built into their bare bones structure. However, the group theoretic configuration of LR symmetry has the provision of a naturally arising discrete symmetry, remnant after the spontaneous breaking of $U(1)_{(B-L)}$ [5–10], which facilitates the building of a plethora of DM models [11–16].

The LR gauge symmetry and particle content, along with gauge coupling unification (GCU), can be embedded in $SO(10)$ “grand unified theories” (GUTs) [17,18] having numerous desired features such as quark–lepton unification, unification of the SM interactions, and explanation of the arbitrary $U(1)_Y$ assignment of the SM, among others. However, in models with the left–right symmetry breaking scale $M_R \sim \mathcal{O}(\text{TeV})$, and a minimal scalar sector, GCU

is impossible [19–24]. To achieve unification one either needs to add scalar multiplets redundant to their primary function of symmetry breaking and mass generation, or larger symmetries intermediate between the Left–Right symmetry (LRS) and GUT scales. These modifications end up introducing additional scalar fine tunings and a degree of arbitrariness.

In this letter, we show that the three requirements of $\mathcal{O}(\text{TeV})$ right-handed breaking scale, unification of LRS couplings, and the presence of a suitable dark matter candidate can be achieved with a single stroke by the careful appraisal of fermion masses in a class of left–right models where the exact $L \leftrightarrow R$ symmetry is spontaneously broken at a scale different from the one where the right-handed gauge symmetry is broken [25,26]. While focussing on model mechanics, we discuss dark matter phenomenology and show that though its direct detection prospects are not bright, the collider signatures of the model are testable.

2. Model

The left–right symmetry is defined by the gauge group, $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{(B-L)}$, and a discrete $SU(2)_L \leftrightarrow SU(2)_R$ symmetry, \mathcal{P} . Under this, the SM quarks, leptons, and a right-handed (RH) neutrino of one family transform as:

$$l_L \equiv (1_C, 2_L, 1_R, -1_{(B-L)}); l_R \equiv (1_C, 1_L, 2_R, -1_{(B-L)});$$

$$q_L \equiv (3_C, 2_L, 1_R, 1/3_{(B-L)}); q_R \equiv (3_C, 1_L, 2_R, 1/3_{(B-L)}); \quad (1)$$

with $(B-L)$ being normalised by the relation:

$$Q_{em} = T_{3R} + T_{3L} + \frac{B-L}{2}. \quad (2)$$

The scalar sector is given by:

$$\Phi \equiv (1_C, 2_L, 2_R, 0_{(B-L)}); \eta \equiv (1_C, 1_L, 1_R, 0_{(B-L)});$$

$$\Delta_R \equiv (1_C, 1_L, 3_R, 2_{(B-L)}); \Delta_L \equiv (1_C, 3_L, 1_R, 2_{(B-L)}) . \quad (3)$$

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Under \mathcal{P} the multiplets transform as:

$$\begin{aligned} l_L &\leftrightarrow l_R; & q_L &\leftrightarrow q_R; & \Delta_L &\leftrightarrow \Delta_R; \\ \Phi &\leftrightarrow \Phi^\dagger; & \eta &\leftrightarrow -\eta. \end{aligned} \quad (4)$$

The scalar sector is modified to accommodate spontaneous breaking of \mathcal{P} at a scale $M_{\mathcal{P}}$, where the \mathcal{P} odd gauge singlet, η , acquires a vacuum expectation value (vev), v_η . Thus, symmetry breaking takes place in three steps. The first being the breaking of \mathcal{P} , followed by the breaking of $SU(2)_R \otimes U(1)_{(B-L)}$ to SM by the vev , v_R , of Δ_R , and finally electroweak symmetry breaking is achieved through the $vevs$ k_1 and k_2 of the bi-doublet Φ , with $\sqrt{k_1^2 + k_2^2} = 246$ GeV. We show that the other mass scales of the model are $M_R \sim \mathcal{O}(\text{TeV})$ and $M_{\mathcal{P}}$ at the GUT scale.

The gauge bosons related to $SU(2)_R \otimes U(1)_{(B-L)}$ breaking, W_R^\pm and Z' , acquire mass at M_R , and for $(M_W/M_{W_R})^2 \ll 1$ are given by:

$$M_{W_R} = \frac{g_R}{\sqrt{2}} v_R; \quad M_{Z'} = \frac{\sqrt{2}}{\cos\phi} M_{W_R}, \quad (5)$$

with

$$\sin\phi = \frac{g_L}{g_R} \tan\theta_W,$$

where θ_W is the weak mixing angle. For $(M_W/M_{W_R})^2 \ll 1$, W_L - W_R mixing is negligible. The physical states of the bi-doublet other than the SM Higgs are constrained to be $\geq \mathcal{O}(10 \text{ TeV})$ from lepton flavour violation limits [27], and the scalars from Δ_L are all heavy at $M_{\mathcal{P}}$ [25,26]. There are no stringent constraints on the masses of the Δ_R scalars and they can be lighter than M_{W_R} and even $\mathcal{O}(100 \text{ GeV})$. Here, for simplicity we take them to be heavier than M_{W_R} .

$U(1)_{(B-L)}$ being broken by a scalar with $(B-L) = 2$, leaves behind a remnant \mathbb{Z}_2 symmetry, defined by: $\mathcal{Z} \equiv (-1)^{3(B-L)}$ [9]. LRS fermions (scalars) have odd (even) $3(B-L)$ and hence are odd (even) under \mathcal{Z} . As a result, fermions with even $3(B-L)$ are forbidden to decay only to SM fermions and/or bosons, and hence the lightest one of them is stable. If this state is neutral, then subject to relic density and direct/indirect detection constraints, it can be taken to be a dark matter candidate.

Fermions in self-conjugate representations of $SU(2)_L \otimes SU(2)_R$, $X_L \oplus X_R \equiv (1_C, (2m+1)_L, 1_R, 0_{(B-L)}) \oplus (1_C, 1_L, (2m+1)_R, 0_{(B-L)})$, typify this scenario with $m \in \mathbb{N}$. Each multiplet consists of a Majorana fermion and m pairs of Dirac fermions and their antiparticles with electric charges 1 to m . Thus, these multiplets must be assigned $B=L=0$.

The left-right symmetric bare mass and Yukawa terms of these multiplets for a general case of n_g such 'generations' is given by:

$$\begin{aligned} \mathcal{L}_{X_M} &= \frac{\mathcal{M}_i}{2} \left(\overline{X_L^i} X_L^i + R \leftrightarrow L \right) \\ &+ \frac{h_i}{2} (v_\eta + \eta) \left(\overline{X_L^i} X_L^i - R \leftrightarrow L \right) + h.c., \end{aligned} \quad (6)$$

where summation over $i = 1, \dots, n_g$ is implicit. The negative signs pertaining to interactions of X_R^i with η are according to eq. (4). Because the multiplets can always be rotated into a diagonal basis, we can do away with the cross terms without any loss of generality. From eq. (6), we see that the breaking of \mathcal{P} enforces a separation of the masses of the multiplets transforming under $SU(2)_L$ and $SU(2)_R$ with the corresponding masses given by:

$$M_i^L = \mathcal{M}_i + h_i v_\eta; \quad M_i^R (= M_i) = \mathcal{M}_i - h_i v_\eta. \quad (7)$$

With $\mathcal{M}_i \sim h_i v_\eta$, X_L^i multiplets remain heavy at $M_{\mathcal{P}}$ and the X_R^i become light with the exact mass scale dependent on the couplings. We want to underscore that in general for $(1_C, (2m+1)_L, 1_R, 0_{(B-L)}) \oplus (1_C, 1_L, (2m+1)_R, 0_{(B-L)})$ fermion multiplets, the mass scale of either one will be at the larger of \mathcal{M}_i and $h_i v_\eta$ while the other can be tuned to be at lower values. During the evolution of the Universe the superheavy $SU(2)_L$ multiplets are Boltzmann suppressed and annihilate and co-annihilate rapidly to lighter states through their couplings to W_L and Z .

The framework being discussed can lead to a variety of DM models, which we label as (m, n_g) , with the DM particle(s) completely separated from the SM and interacting only with the RH sector. For the rest of the letter we focus on the (1, 2) case as this model simultaneously provides a suitable DM sector, gauge coupling unification, and $\mathcal{O}(\text{TeV})$ M_R .

3. Gauge coupling unification

With the self-conjugate $SU(2)_R$ generations of an $(m, n_g) \equiv (1, 2)$ model, i.e., the model with a pair of $(1_C, 3_L, 1_R, 0_{(B-L)}) + (1_C, 1_L, 3_R, 0_{(B-L)})$, in the TeV range, the gauge couplings unify with $M_{\mathcal{P}} = M_U$. The LR gauge group is a subgroup of $SO(10)$ and with GCU we can embed the model in an $SO(10)$ unified theory. The LRS multiplets of the model belong in the following $SO(10)$ representations:

$$\begin{aligned} &(3_C, 2_L, 1_R, 1/3_{(B-L)}) + (\bar{3}_C, 1_L, 2_R, -1/3_{(B-L)}) \\ &+ (1_C, 2_L, 1_R, -1_{(B-L)}) + (1_C, 1_L, 2_R, 1_{(B-L)}) \subseteq 16_F; \\ &(1_C, 2_L, 2_R, 0_{(B-L)}) \subset 10_H; \\ &(1_C, 3_L, 1_R, 2_{(B-L)}) + (1_C, 1_L, 3_R, 2_{(B-L)}) \subset 126_H; \\ &(1_C, 1_L, 1_R, 0_{(B-L)}) \subset 210_H; \\ &(1_C, 3_L, 1_R, 0_{(B-L)}) + (1_C, 1_L, 3_R, 0_{(B-L)}) \subset 45_F; \end{aligned} \quad (8)$$

where the subscripts F and H denote whether the multiplets contain fermions or scalars, respectively. There is an element of the $SO(10)$ algebra, 'D' [28], which in the case that all the couplings of the lagrangian are real, plays the role of the parity symmetry \mathcal{P} . $\eta \subset 210_H$ is odd under 'D'.

The fermion triplets reside in 45-plets. The $SO(10)$ symmetric mass term for which is:

$$\mathcal{L}_{\text{Mass}} = -\frac{\mathcal{M}_{1,2}}{2} \overline{45_F^{1,2C}} 45_F^{1,2} + h.c., \quad (9)$$

with $\mathcal{M}_{1,2} \sim M_U = M_{\mathcal{P}}$. Under the Pati-Salam [1,2] symmetry, $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$, 45_F is decomposed as: $45 \supset (15_4, 1_L, 1_R) + (6_4, 2_L, 2_R) + (1_4, 3_L, 1_R) + (1_4, 1_L, 3_R)$. Since $(15_4, 1_L, 1_R)$ and $(6_4, 2_L, 2_R)$ transform identically under $SU(2)_L$ and $SU(2)_R$, they have masses at $\mathcal{M}_{1,2}$, while $(1_4, 3_L, 1_R)$ and $(1_4, 1_L, 3_R)$ are split according to the previous discussion. As for the scalars, all submultiplets not required to be either at the right-handed or the electroweak scale are at the unification scale according to the minimal fine-tuning principle of the extended-survival hypothesis [29,30].

In Fig. 1, we show the running of the inverses of the fine structure constants ($\alpha = g^2/(4\pi)$), as obtained from 2-loop perturbation theory. As inputs at the Z-pole, $M_Z = 91.1876(21)$, we take $\alpha_s = 0.1181(11)$, $\sin^2\theta_W = 0.23129(5)$, and $\alpha_{EM} = 1/128$ [31]. We find that when $\alpha_s(M_Z)$ and $\sin^2\theta_W$ are varied over their 1σ allowed ranges the unification scale varies between $(0.81-1.05) \times 10^{16}$ GeV and the unification coupling comes out to be, $g_U = 0.53$. The $SU(2)_R$ breaking scale lies between 3.78–9.40 TeV, with the

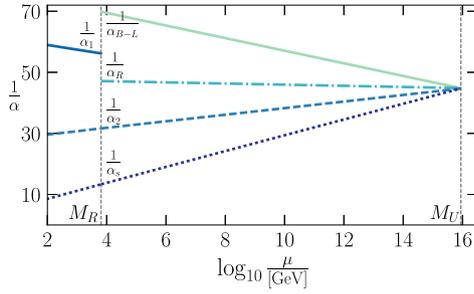


Fig. 1. 2-loop running of the inverse of the gauge couplings α_i with mass scale, μ .

$SU(2)_R$ coupling, $g_R = 0.52$. Fig. 1 has been drawn using the central value. The $U(1)$ couplings of the theory are normalised according to GUT (canonical) normalisation, resulting in the matching condition at M_R :

$$\frac{1}{g_Y^2} = \frac{3}{5} \frac{1}{g_R^2} + \frac{2}{5} \frac{1}{g_{(B-L)}^2} + \frac{1}{20\pi}. \quad (10)$$

In between M_R and M_U the particles flowing in the loops and hence contributing to the β -coefficients are Φ , Δ_R , l_L , l_R , q_L , q_R as in traditional D-parity broken models, and the pair of dark sector $SU(2)_R$ triplets $X_R^{1,2}$. The system of running equations are given by [32,33]:

$$\frac{\partial g_i}{\partial \log \mu} = \frac{a_i}{16\pi^2} g_i^3 + \sum_j \frac{b_{ij}}{(16\pi^2)^2} g_i^3 g_j^2. \quad (11)$$

The 1-loop β -coefficients a_i and the 2-loop β -coefficients, b_{ij} , for the couplings of the SM are readily available [33], the same for the LRS stage are given in eq. (12). Since the only additions on top of the usual LRS particle content are the self-conjugate $SU(2)_R$ triplets which transform trivially under the other symmetries, the only change in the β -coefficients are for the $SU(2)_R$ coupling for the 1-loop case and the diagonal coefficient corresponding to $SU(2)_R$ for the two loop case.

$$a_i \equiv \begin{bmatrix} B-L & 2R & 2L & 3C \\ \frac{11}{2} & \frac{1}{3} & -3 & -7 \end{bmatrix}$$

$$b_{ij} \equiv \begin{bmatrix} \frac{61}{2} & \frac{81}{2} & \frac{9}{2} & 4 \\ \frac{27}{2} & \frac{208}{3} & 3 & 12 \\ \frac{3}{2} & 3 & 8 & 12 \\ \frac{1}{2} & \frac{9}{2} & \frac{9}{2} & -26 \end{bmatrix} \begin{matrix} B-L \\ 2R \\ 2L \\ 3C \end{matrix}. \quad (12)$$

In principle, a complete treatment of 2-loop RGE running should take into account threshold effects [34,35] at all the symmetry breaking scales. However, in this work we do not include threshold effects, as in demanding exact unification of the couplings, we are establishing GCU for a more restricted case. Threshold corrections introduce more parameters to the model and hence such situations are bound to follow suit.

We next estimate the lifetime of the proton in our model. In non-supersymmetric GUTs, scalar induced $d = 6$ and the $d > 6$ operators contributing to proton decay are generally highly suppressed in comparison to the gauge induced $d = 6$ operators [36–38], and here we concentrate only on the latter. The decay rate of the proton in the $p \rightarrow e^+ \pi^0$ channel is expressed as [36, 39]:

$$\Gamma(p \rightarrow e^+ \pi^0) = \frac{m_p g_U^4}{16\pi f_\pi^2 M_U^4} R_L^2 (A_{SL}^2 + A_{SR}^2) |\alpha_H|^2 (1 + D + F)^2, \quad (13)$$

where $m_p = 938.3$ MeV [31] is the mass of the proton, $f_\pi = 130.41(23)$ MeV [40] is the pion decay constant, $\alpha_H = -0.0118(0.0021)$ GeV³ denotes the relevant hadronic matrix element, $D = 0.8(2)$ and $F = 0.47(1)$ are chiral lagrangian parameters calculated from lattice gauge theory [41–43], g_U is the unified coupling constant, M_U the unification scale. $R_L = 1.46$ is the two-loop long range running effect on the effective proton decay operator, corresponding to running from M_Z to m_p , while $A_{SL(R)}$ is the short range left-(right-) handed short range renormalisation factor of the proton decay operator corresponding to running from M_U to M_Z [44]. $A_{SL(R)}$ is a function of the anomalous dimensions and β -coefficients of the running couplings, and also the values of the couplings at the symmetry breaking scales and are taken to be $A_{SL} \simeq A_{SR} = 2.0$ [45–49]. We set the masses of the leptoquark gauge bosons to be degenerate and at M_U . Further, the flavour matrices associated with baryon and lepton flavour changing currents have been set to unity [50,51].

With $M_U = 10^{15.97}$ GeV we get from eq. (13) a proton decay lifetime in this channel, $\tau_{p \rightarrow e^+ \pi^0} \sim 1.5 \times 10^{35}$ years, which is larger than the present bound of $\tau_{p \rightarrow e^+ \pi^0} = 1.6 \times 10^{34}$ years [52], but testable at the Hyper-Kamiokande experiment [53], which is expected to probe lifetimes $\sim 2 \times 10^{35}$ yrs. As indicated by eq. (13), this value is extremely sensitive to the unification scale M_U . Still, we have checked that for the above chosen values of the parameters, $\tau_{p \rightarrow e^+ \pi^0}$ remains below the Hyper-Kamiokande projection with M_U varying between its allowed range, i.e., $(0.81-1.05) \times 10^{16}$ GeV. However, extreme choices of the different parameters may make the model not falsifiable even by this experiment.

The mass scales, predicted by unification, are particularly ingratiating for neutrino seesaw masses. In minimal LR models, the left-handed neutrino has both type-I and type-II seesaw [54–57] contributions. $L \leftrightarrow R$ symmetry breaking induces a nonzero $SU(2)_L$ triplet νv [58]:

$$\nu_L \simeq \frac{v_R}{v_\eta} \frac{\mathcal{O}(k_i^2)}{2M_{\eta\Delta}}. \quad (14)$$

Here $M_{\eta\Delta}$ is the dimensionful coefficient of the $\eta\Delta\Delta$ type term in the potential. The left- and right-handed neutrino masses are given by [59–61]:

$$M_{\nu_R} = f v_R, \quad M_{\nu_L} = f v_L + \frac{v^2}{v_R} y f^{-1} y^T. \quad (15)$$

f is the Yukawa coupling matrix of the leptons with the triplet scalars $\Delta_{L,R}$ while y is the Yukawa matrix of the neutrinos with the bidoublet Φ . From the values of the symmetry breaking scales as given above, we see that the left-handed neutrino gets a mass of the order of 0.1 eV, with $f \sim \mathcal{O}(1)$, when the Yukawa matrix y is set at the order of that of the up quark, in the spirit of quark-lepton unification.¹ The seesaw is predominantly type I.

¹ Grand unification implies the same Yukawa couplings for up-type quarks and the neutrinos. However, the contributions to the masses in the two sectors can be the same, for the $(1_4, 2_L, 2_R) \subset 10_H$, or unequal and of opposite sign, for $(15_4, 2_L, 2_R) \subset 126_H$. For the second and the third generation a fine-tuned cancellation between the two contributions (at the level of 1 in 10^5 for the third generation) is needed to keep the Type I seesaw neutrino masses in the desired range.

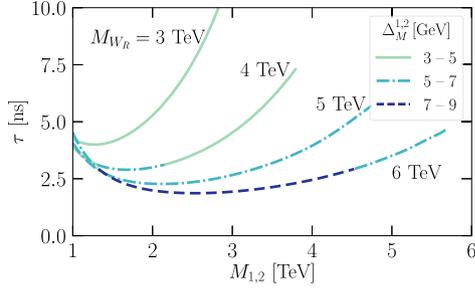


Fig. 2. The decay time of $\chi_{1,2}^\pm$ as a function of its mass for different choices of M_{W_R} . Linestyles distinguish different mass splittings between the charged and neutral states of the multiplet.

4. Dark matter phenomenology

The triplets, $X_R^{1,2}$, each contribute a singly-charged Dirac fermion–anti-fermion pair ($\chi_{1,2}^\pm$), and a Majorana fermion ($\chi_{1,2}^0$). The charged and neutral states are mass degenerate at tree level, with mass $M_{1,2}$. At one-loop order, gauge interactions induce the mass splitting, $\Delta_M^{1,2} = M_{\chi_{1,2}^\pm}^{1,2} - M_{\chi_{1,2}^0}^{1,2}$ [62–64].

The interaction lagrangian for the constituents of the triplets, $X_R^{1,2}$, for the LR stage is given by:

$$\mathcal{L}_{\text{int}} = -g_R \left(\overline{\chi_i^+} W_R^+ \chi_i^0 + h.c. \right) - e \overline{\chi_i^+} A \chi_i^+ - g_R \cos \phi_0 \overline{\chi_i^+} Z' \chi_i^+ + e \tan \theta_W \overline{\chi_i^+} Z \chi_i^+ \quad (i = 1, 2), \quad (16)$$

where e is the electromagnetic coupling. Presence of charged heavy fermions during big bang nucleosynthesis (BBN) would imply the existence of atom-like bound states, in the present epoch, containing such particles [65,66]. The non-observance of such entities in deep sea water searches [67–71] rules out their existence. This implies positive $\Delta_M^{1,2}$, large enough to produce a lifetime for the charged states smaller than the time at BBN ~ 1 s.

In Fig. 2 we plot the decay time of $\chi_{1,2}^\pm$ as a function of its mass for different M_{W_R} near M_R . The intra-multiplet mass splitting, $\Delta_M^{1,2}$, calculated using expressions in [13,14], is indicated by the line-styles of the curves, i.e., short-dashed, long-dashed, or solid. Notice that for each curve $\Delta_M^{1,2}$ changes with $M_{1,2}$. We find that the lifetime of the charged states for all masses near M_{W_R} is $\mathcal{O}(\text{ns})$, and the mass splitting is $\mathcal{O}(\text{GeV})$. Hence the heavy charged states of our model decay well before BBN. As the mass difference is tiny with respect to the masses themselves, $\chi_2^\pm \rightarrow \chi_1^0 \chi_{1,2}^\pm$ decay is forbidden from kinematics. Of course the same argument also applies the other way round. Hence, although we have a single stabilising \mathbb{Z}_2 , we end up with two component ($\chi_{1,2}^0$) dark matter.

The behaviour of dark matter relic density for this model is illustrated in Fig. 3. The allowed regions in the M_1 – M_2 plane are those points which fall on the ellipse-like or semi-circle-like plots. We show only the region for which $M_1 < M_2$. The allowed values with $M_1 > M_2$ can be readily obtained by a reflection. In the inset of Fig. 3 we exhibit the relic density as a function of the dark matter mass for $M_{W_R} = 4$ TeV. The observed value of the relic density, $\Omega h^2 = 0.1198 \pm 0.0015$ [72], is indicated by the dashed horizontal straight line. As noted, in the model under discussion, there are two dark matter candidates, χ_1^0 and χ_2^0 . In the inset, for simplicity, they have been taken to be degenerate. The dips in the curve reflect resonant $\chi_i^\pm \chi_i^0 \rightarrow W_R^\pm$ or $\chi_i^+ \chi_i^- \rightarrow Z'$ production. Without these dips, the relic density in this model would have been about an order of magnitude larger than the observed limit. The points where the curves agree with the observation are near the two resonant dips. In Fig. 3 the closed ellipse-type curves with an asterisk in the middle correspond to regions where the dark matter candidate χ_2^0 is near the Z' resonance (i.e., $M_2 \simeq M_{Z'}/2$) while

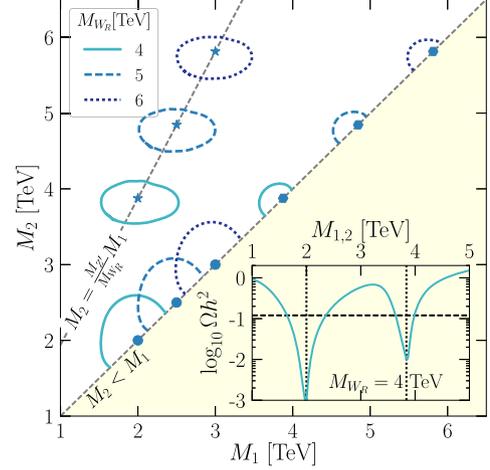


Fig. 3. The points in the M_1 – M_2 plane consistent with the measured dark matter relic density lie on the curves (see text). Only the solutions with $M_2 > M_1$ are displayed. Plots are shown for different M_{W_R} . Inset: The dark matter relic density as a function of its mass for $M_{W_R} = 4$ TeV. The curve is for the case when the two dark matter candidates are degenerate.

χ_1^0 is close to the W_R resonance point (i.e., $M_1 \simeq M_{W_R}/2$). The semicircle-like curves with a dot (hexagon) within correspond to the situation where the dark matter particles χ_1^0 and χ_2^0 are near degenerate and also close in mass to $M_{W_R}/2$ ($M_{Z'}/2$). We have kept the lower bound of $M_{1,2} > 547$ GeV, as set by recent searches for heavy singly charged particles [73,74]. For these relic density computations we have utilized the MicrOMEGAS 4.3 [75] package. The model file was written using FeynRules 2.0 [76], modifying the version in [77] to our needs.

At freeze-out temperature, the charged states, $\chi_{1,2}^\pm$, did not have enough time to decay to the neutral ones, and hence annihilation and co-annihilation of all the triplet states contribute to the net annihilation cross section $\langle \sigma v \rangle$. Near the W_R resonance, $\langle \sigma v \rangle$ is saturated by co-annihilation of $\chi_{1,2}^\pm$ with $\chi_{1,2}^0$ and around the Z' resonance by both co-annihilation and annihilation of $\chi_{1,2}^\pm$. As the neutral $\chi_{1,2}^0$ have no interaction with the Z' or Z , it can only annihilate to a W_R pair through the t -channel exchange of $\chi_{1,2}^\pm$. This channel, however, opens up only when $M_{1,2} \gtrsim M_{W_R}$, and even then it accounts for a minute fraction of the total $\langle \sigma v \rangle$. g_R is essentially fixed from the running of gauge couplings and is no more a free parameter while calculating cross sections. Furthermore, the relic density constraint fixes a narrow range for $M_{1,2}$ given M_{W_R} . The scale of M_{W_R} itself is fixed by gauge coupling unification. This makes the model remarkably predictive and free of parameters which can be altered at will. Thus, falsifying the model is quite straightforward.

Present and proposed DM direct detection experiments such as LUX, LZ, XENONIT [78–80], are all based on detecting elastic scattering of WIMP DM candidates with nucleons. The dark matter candidates of this model, $\chi_{1,2}^0$, do not have any neutral current interactions, neither do they couple to the Higgs boson. Their only possible interaction with nucleons (\mathcal{N}) are through charged current processes, $\chi_i^0 \mathcal{N}^0 \rightarrow \chi_i^- \mathcal{N}^+$ or $\chi_i^0 \mathcal{N}^+ \rightarrow \chi_i^+ \mathcal{N}^0$. At the direct detection experiments, the \mathcal{N} is initially at rest and the DM kinetic energy alone is not large enough to surmount the $\mathcal{O}(\text{GeV})$ mass difference between the $\chi_{1,2}^\pm$ and $\chi_{1,2}^0$. Therefore, an on-shell $\chi_{1,2}^\pm$ in the final state is disallowed from kinematic considerations. An off-shell $\chi_{1,2}^\pm$ decaying to $\chi_{1,2}^0$ and ($l \nu_l$) or pions through W_R^* is in principle possible but highly suppressed due to lack of available phase space and $\mathcal{O}(\text{TeV})$ masses in the propagators. Neutral current NLO cross sections for $\chi_i^0 \mathcal{N} \rightarrow \chi_i^0 \mathcal{N}$, involving W_R and

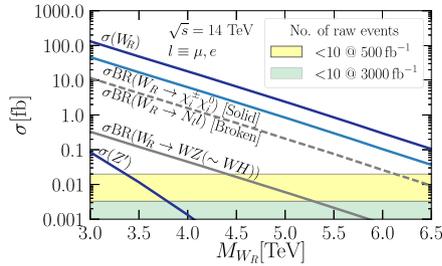


Fig. 4. Cross section times branching fraction for production of W_R and Z' and their subsequent decays into different channels, as labelled, at $\sqrt{s} = 14$ TeV. The thick lines represent total cross sections. The deeply (lightly) shaded regions delimit the cross sections for which the total number of raw events drops below 10 at 3000 (500) fb^{-1} .

$\chi_{1,2}^\pm$ in the loop are naturally negligible. A detailed discussion in case of $SU(2)_L$ triplets and a possible way of circumventing the difficulty in detection can be found in [64]. In the absence of any annihilation channels at tree level, the DM parameter region is not constricted by indirect detection [81,82] constraints.

5. Collider studies

As noted previously, the dark matter relic density constraint restricts the masses of $\chi_{1,2}^\pm$ and $\chi_{1,2}^0$ to near $M_{W_R}/2$ or $M_{Z'}/2$. The $\chi_{1,2}^\pm$ particles, if produced, for example, through W_R or Z' decay, will be observed as tracks in the CMS and ATLAS pixel detectors and silicon trackers. These particles will typically be at sub-relativistic velocities and can be distinguished from SM charged particles from the higher rate of ionization energy loss (dE/dx). For most of the allowed mass region, the final state particles have $0.3 < \beta\gamma (= p/M) < 1.5$ and hence the average energy loss with distance travelled can be modelled by the Bethe-Bloch distribution. Given a lifetime of $\mathcal{O}(\text{ns})$ for $\chi_{1,2}^\pm$, as can be seen from Fig. 2, we find their decay lengths to be of the order ~ 0.1 – 1 m. The charged particles will hence decay almost exclusively in the trackers of CMS and ATLAS. The only decay mode of $\chi_{1,2}^\pm$ is to $\chi_{1,2}^0$, and the mass difference being $\sim \mathcal{O}(\text{GeV})$, the associated jets will be too soft to be reconstructed for a displaced vertex analysis. Hence, the signal of the charged particles will be the observation of disappearing tracks.² An energetic initial state radiation jet can be effectively used as a trigger for the event. The neutral states will obviously be missed completely. The charged particle decay length and $\beta\gamma$ are also favourable for detection at the MoEDAL detector [84] at LHC. If observed, the masses of the particles can be calculated from information about average energy loss and reconstructed transverse momentum as measured from the curvature of the charged tracks in the magnetic fields [85,86].

The vindication of TeV scale $SU(2)_R$ breaking will be the discovery of the W_R and the heavy neutrino, in the $lljj$ channel, the event topology being given by: $pp \rightarrow W_R \rightarrow N_l l \rightarrow lljj$ [87]. If the neutrino is a Majorana particle as predicted by the LRS model, one should observe equal same-sign and opposite-sign final states. We ask to what extent this signal is affected by the presence of the self-conjugate triplets $\chi_{1,2}$? In Fig. 4 we show the cross section times branching fractions of W_R production and its subsequent decays in different channels.³ For this purpose, leading order cross sections were calculated in CalcHep 3.4 [89] using the CTEQ6L1 parton distribution functions [90], and multiplied by

² For a recent discussion of the sensitivity of the LHC detectors to such disappearing charged tracks, see for example, [83].

³ The possibility of detecting a virtual heavy W_R signal through much lighter RH 'neutrino jets' has recently been examined in [88].

the corresponding K-factors, as obtained from [91]. For the sake of comparison, we have chosen the DM multiplets to be mass degenerate and having the smallest mass as allowed by relic density constraints and taken $M_{N_i} = M_{\chi_{1,2}^\pm}$.

The dominant decay mode of W_R is obviously to two jets. As can be seen from Fig. 4 the decay $W_R^\pm \rightarrow \chi_i^\pm \chi_i^0$ is a few times larger than the subdominant but often searched for leptonic decays ($l \equiv e, \mu$). Nonetheless, the leptonic branching remains substantial and we find that a W_R with mass ~ 6.5 TeV can still be discovered by the ATLAS and CMS collaborations in this channel with $\sqrt{s} = 14$ TeV and an integrated luminosity of 3000 fb^{-1} . Indirect detection of a heavier W_R with masses up to ~ 8 TeV is possible in the studies of K and B meson decays at LHCb [27] where this model has no distinction from the canonical LRS model. Another promising mode for the detection of W_R is the di-boson channel ($W_R \rightarrow WZ$ or $W_R \rightarrow WH$). The branching ratios are almost the same for these two channels. However, due to the suppressed W_L – W_R mixing, they are small, see Fig. 4, and as M_{W_R} approaches 6 TeV this channel becomes unfeasible. Note that as the masses of the triplet fermions are related to the mass of the W_R boson from relic density constraints, and since the $\chi_{1,2}^\pm$ do not interact with the SM particles, the detection of W_R or Z' without detection of these will essentially falsify the model.

With $M_{Z'} \sim 1.94 \times M_{W_R}$, the discovery potential of Z' is bleak at the LHC. For W_R masses above 3.5 TeV, the Z' becomes too heavy to be detected at LHC-II as can be seen from Fig. 4. For HL-LHC luminosities of 3000 fb^{-1} , the sensitivity increases slightly.

6. Conclusion

In this work we have presented a model which rests on left–right symmetry, is amenable to gauge coupling unification, and provides suitable dark matter candidates. Aided by two distinct discrete symmetries inherent to the left–right symmetric theory the stability of dark matter and the scales of symmetry breaking are ensured. The model is falsifiable at both the GUT scale and the LRS breaking scale at the Hyper-Kamiokande experiment and the LHC respectively. The model predicts a 'desert' between the LRS and GUT scales. In the absence of multiple symmetry breaking thresholds, the variable parameters of the model viz. the $SU(2)_R$ coupling, g_R , and scale of the W_R mass are essentially fixed from unification. The Dark Matter candidates satisfy the relic density constraint aided by resonant enhancements of the cross section and hence allowed masses are intertwined with $M_{W_R}/2$ and $M_{Z'}/2$. Their direct detection in ongoing and planned experiments is unlikely. Nonetheless, with a very small leeway for the parameters to vary, the model is remarkably predictive, making falsification or vindication more or less straightforward at colliders.

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References

- [1] J.C. Pati, A. Salam, Is baryon number conserved?, Phys. Rev. Lett. 31 (1973) 661.
- [2] J.C. Pati, A. Salam, Lepton number as the fourth color, Phys. Rev. D 10 (1974) 275; Phys. Rev. D 11 (1975) 703 (Erratum).
- [3] R.N. Mohapatra, J.C. Pati, "Natural" left–right symmetry, Phys. Rev. D 11 (1975) 2558.
- [4] G. Senjanovic, R.N. Mohapatra, Exact left–right symmetry and spontaneous violation of parity, Phys. Rev. D 12 (1975) 1502.
- [5] L.M. Krauss, F. Wilczek, Discrete gauge symmetry in continuum theories, Phys. Rev. Lett. 62 (1989) 1221.

- [6] L.E. Ibanez, G.G. Ross, Discrete gauge symmetry anomalies, *Phys. Lett. B* 260 (1991) 291.
- [7] L.E. Ibanez, G.G. Ross, Discrete gauge symmetries and the origin of baryon and lepton number conservation in supersymmetric versions of the standard model, *Nucl. Phys. B* 368 (1992) 3.
- [8] S.P. Martin, Some simple criteria for gauged R-parity, *Phys. Rev. D* 46 (1992) R2769, arXiv:hep-ph/9207218.
- [9] M. Kadastik, K. Kannike, M. Raidal, Dark matter as the signal of grand unification, *Phys. Rev. D* 80 (2009) 085020, arXiv:0907.1894 [hep-ph]; *Phys. Rev. D* 81 (2010) 029903 (Erratum).
- [10] M. Frigerio, T. Hambye, Dark matter stability and unification without supersymmetry, *Phys. Rev. D* 81 (2010) 075002, arXiv:0912.1545 [hep-ph].
- [11] Y. Mambrini, K.A. Olive, J. Quevillon, B. Zaldivar, Gauge coupling unification and nonequilibrium thermal dark matter, *Phys. Rev. Lett.* 110 (2013) 241306, arXiv:1302.4438 [hep-ph].
- [12] Y. Mambrini, N. Nagata, K.A. Olive, J. Quevillon, J. Zheng, Dark matter and gauge coupling unification in nonsupersymmetric SO(10) grand unified models, *Phys. Rev. D* 91 (2015) 095010, arXiv:1502.06929 [hep-ph].
- [13] J. Heeck, S. Patra, Minimal left–right symmetric dark matter, *Phys. Rev. Lett.* 115 (2015) 121804, arXiv:1507.01584 [hep-ph].
- [14] C. Garcia-Cely, J. Heeck, Phenomenology of left–right symmetric dark matter, *J. Cosmol. Astropart. Phys.* 1603 (2016) 021, arXiv:1512.03332 [hep-ph].
- [15] A. Berlin, P.J. Fox, D. Hooper, G. Mohlabeng, Mixed dark matter in left–right symmetric models, *J. Cosmol. Astropart. Phys.* 1606 (2016) 016, arXiv:1604.06100 [hep-ph].
- [16] P.S.B. Dev, R.N. Mohapatra, Y. Zhang, Naturally stable right-handed neutrino dark matter, arXiv:1608.06266 [hep-ph], 2016.
- [17] H. Georgi, The state of the art gauge theories, *AIP Conf. Proc.* 23 (1975) 575.
- [18] H. Fritzsch, P. Minkowski, Unified interactions of leptons and hadrons, *Ann. Phys.* 93 (1975) 193.
- [19] D. Chang, R.N. Mohapatra, J. Gipson, R.E. Marshak, M.K. Parida, Experimental tests of new SO(10) grand unification, *Phys. Rev. D* 31 (1985) 1718.
- [20] B. Brahmachari, U. Sarkar, K. Sridhar, Ruling out low-energy left–right symmetry in unified theories, *Phys. Lett. B* 297 (1992) 105.
- [21] N.G. Deshpande, E. Keith, P.B. Pal, Implications of LEP results for SO(10) grand unification, *Phys. Rev. D* 46 (1993) 2261.
- [22] S. Bertolini, L. Di Luzio, M. Malinsky, Intermediate mass scales in the non-supersymmetric SO(10) grand unification: a reappraisal, *Phys. Rev. D* 80 (2009) 015013, arXiv:0903.4049 [hep-ph].
- [23] J. Chakraborty, A. Raychaudhuri, GUTs with dim-5 interactions: gauge unification and intermediate scales, *Phys. Rev. D* 81 (2010) 055004, arXiv:0909.3905 [hep-ph].
- [24] T. Bandyopadhyay, B. Brahmachari, A. Raychaudhuri, Implications of the CMS search for W_R on grand unification, *J. High Energy Phys.* 02 (2016) 023, arXiv:1509.03232 [hep-ph].
- [25] D. Chang, R.N. Mohapatra, M.K. Parida, Decoupling parity and SU(2)–R breaking scales: a new approach to left–right symmetric models, *Phys. Rev. Lett.* 52 (1984) 1072.
- [26] D. Chang, R.N. Mohapatra, M.K. Parida, A new approach to left–right symmetry breaking in unified gauge theories, *Phys. Rev. D* 30 (1984) 1052.
- [27] S. Bertolini, A. Maiezza, F. Nesti, Present and future K and B meson mixing constraints on TeV scale left–right symmetry, *Phys. Rev. D* 89 (2014) 095028, arXiv:1403.7112 [hep-ph].
- [28] R. Slansky, Group theory for unified model building, *Phys. Rep.* 79 (1981) 1.
- [29] F. del Aguila, L.E. Ibanez, Higgs bosons in SO(10) and partial unification, *Nucl. Phys. B* 177 (1981) 60.
- [30] R.N. Mohapatra, G. Senjanovic, Higgs boson effects in grand unified theories, *Phys. Rev. D* 27 (1983) 1601.
- [31] C. Patrignani, et al., Review of particle physics, *Chin. Phys. C* 40 (2016) 100001.
- [32] M.E. Machacek, M.T. Vaughn, Two loop renormalization group equations in a general quantum field theory. 1. Wave function renormalization, *Nucl. Phys. B* 222 (1983) 83.
- [33] D.R.T. Jones, The two loop beta function for a $G(1) \times G(2)$ gauge theory, *Phys. Rev. D* 25 (1982) 581.
- [34] S. Weinberg, Effective gauge theories, *Phys. Lett. B* 91 (1980) 51.
- [35] L.J. Hall, Grand unification of effective gauge theories, *Nucl. Phys. B* 178 (1981) 75.
- [36] S. Bertolini, L. Di Luzio, M. Malinsky, Light color octet scalars in the minimal SO(10) grand unification, *Phys. Rev. D* 87 (2013) 085020, arXiv:1302.3401 [hep-ph].
- [37] S. Bertolini, L. Di Luzio, M. Malinsky, Seesaw scale in the minimal renormalizable SO(10) grand unification, *Phys. Rev. D* 85 (2012) 095014, arXiv:1202.0807 [hep-ph].
- [38] K.S. Babu, S. Khan, Minimal nonsupersymmetric SO(10) model: gauge coupling unification, proton decay, and fermion masses, *Phys. Rev. D* 92 (2015) 075018, arXiv:1507.06712 [hep-ph].
- [39] P. Nath, P. Fileviez Perez, Proton stability in grand unified theories, in strings and in branes, *Phys. Rep.* 441 (2007) 191, arXiv:hep-ph/0601023.
- [40] T. Blum, et al., Domain wall QCD with physical quark masses, *Phys. Rev. D* 93 (2016) 074505, arXiv:1411.7017 [hep-lat].
- [41] Y. Aoki, C. Dawson, J. Noaki, A. Soni, Proton decay matrix elements with domain-wall fermions, *Phys. Rev. D* 75 (2007) 014507, arXiv:hep-lat/0607002.
- [42] Y. Aoki, P. Boyle, P. Cooney, L. Del Debbio, R. Kenway, C.M. Maynard, A. Soni, R. Tweedie, Proton lifetime bounds from chirally symmetric lattice QCD, *Phys. Rev. D* 78 (2008) 054505, arXiv:0806.1031 [hep-lat].
- [43] Y. Aoki, E. Shintani, A. Soni, Proton decay matrix elements on the lattice, *Phys. Rev. D* 89 (2014) 014505, arXiv:1304.7424 [hep-lat].
- [44] T. Nihei, J. Arafune, The two loop long range effect on the proton decay effective Lagrangian, *Prog. Theor. Phys.* 93 (1995) 665, arXiv:hep-ph/9412325.
- [45] A.J. Buras, J.R. Ellis, M.K. Gaillard, D.V. Nanopoulos, Aspects of the grand unification of strong, weak and electromagnetic interactions, *Nucl. Phys. B* 135 (1978) 66.
- [46] J.T. Goldman, D.A. Ross, A new estimate of the proton lifetime, *Phys. Lett. B* 84 (1979) 208.
- [47] J.R. Ellis, D.V. Nanopoulos, S. Rudaz, GUTs 3: SUSY GUTs 2, *Nucl. Phys. B* 202 (1982) 43.
- [48] L.E. Ibanez, C. Munoz, Enhancement factors for supersymmetric proton decay in the Wess–Zumino gauge, *Nucl. Phys. B* 245 (1984) 425.
- [49] C. Munoz, Enhancement factors for supersymmetric proton decay in SU(5) and SO(10) with superfield techniques, *Phys. Lett. B* 177 (1986) 55.
- [50] P. Fileviez Perez, Fermion mixings versus $d = 6$ proton decay, *Phys. Lett. B* 595 (2004) 476, arXiv:hep-ph/0403286.
- [51] I. Dorsner, P. Fileviez Perez, How long could we live?, *Phys. Lett. B* 625 (2005) 88, arXiv:hep-ph/0410198.
- [52] K. Abe, et al., Search for proton decay via $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$ in 0.31 megaton-years exposure of the Super-Kamiokande water Cherenkov detector, *Phys. Rev. D* 95 (2017) 012004, arXiv:1610.03597 [hep-ex].
- [53] K. Abe, et al., Physics potentials with the second hyper-Kamiokande detector in Korea, arXiv:1611.06118 [hep-ex], 2016.
- [54] P. Minkowski, $\mu \rightarrow e \gamma$ at a rate of one out of 10^9 muon decays?, *Phys. Lett. B* 67 (1977) 421.
- [55] T. Yanagida, Horizontal symmetry and masses of neutrinos, *Conf. Proc. C* 7902131 (1979) 95.
- [56] R.N. Mohapatra, G. Senjanovic, Neutrino mass and spontaneous parity violation, *Phys. Rev. Lett.* 44 (1980) 912.
- [57] J. Schechter, J.W.F. Valle, Neutrino masses in SU(2) \times U(1) theories, *Phys. Rev. D* 22 (1980) 2227.
- [58] D. Borah, S. Patra, U. Sarkar, TeV scale left right symmetry with spontaneous D-parity breaking, *Phys. Rev. D* 83 (2011) 035007, arXiv:1006.2245 [hep-ph].
- [59] M. Magg, C. Wetterich, Neutrino mass problem and gauge hierarchy, *Phys. Lett. B* 94 (1980) 61.
- [60] G. Lazarides, Q. Shafi, C. Wetterich, Proton lifetime and fermion masses in an SO(10) model, *Nucl. Phys. B* 181 (1981) 287.
- [61] R.N. Mohapatra, G. Senjanovic, Neutrino masses and mixings in gauge models with spontaneous parity violation, *Phys. Rev. D* 23 (1981) 165.
- [62] H.-C. Cheng, B.A. Dobrescu, K.T. Matchev, Generic and chiral extensions of the supersymmetric standard model, *Nucl. Phys. B* 543 (1999) 47, arXiv:hep-ph/9811316.
- [63] J.L. Feng, T. Moroi, L. Randall, M. Strassler, S.-f. Su, Discovering supersymmetry at the Tevatron in wino LSP scenarios, *Phys. Rev. Lett.* 83 (1999) 1731, arXiv:hep-ph/9904250.
- [64] M. Cirelli, N. Fornengo, A. Strumia, Minimal dark matter, *Nucl. Phys. B* 753 (2006) 178, arXiv:hep-ph/0512090.
- [65] H. Goldberg, Constraint on the photino mass from cosmology, *Phys. Rev. Lett.* 50 (1983) 1419; *Phys. Rev. Lett.* 103 (2009) 099905 (Erratum).
- [66] J.R. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive, M. Srednicki, Supersymmetric relics from the Big Bang, *Nucl. Phys. B* 238 (1984) 453.
- [67] P.F. Smith, J.R.J. Bennett, A search for heavy stable particles, *Nucl. Phys. B* 149 (1979) 525.
- [68] P.F. Smith, J.R.J. Bennett, G.J. Homer, J.D. Lewin, H.E. Walford, W.A. Smith, A search for anomalous hydrogen in enriched D-20, using a time-of-flight spectrometer, *Nucl. Phys. B* 206 (1982) 333.
- [69] T.K. Hemmick, et al., A search for anomalously heavy isotopes of low Z nuclei, *Phys. Rev. D* 41 (1990) 2074.
- [70] P. Verkerk, G. Grynberg, B. Pichard, M. Spiro, S. Zylberajch, M.E. Goldberg, P. Fayet, Search for superheavy hydrogen in sea water, *Phys. Rev. Lett.* 68 (1992) 1116.
- [71] T. Yamagata, Y. Takamori, H. Utsunomiya, Search for anomalously heavy hydrogen in deep sea water at 4000-m, *Phys. Rev. D* 47 (1993) 1231.
- [72] P.A.R. Ade, et al., Planck 2015 results. XIII. Cosmological parameters, *Astron. Astrophys.* 594 (2016) A13, arXiv:1502.01589 [astro-ph.CO].
- [73] S. Chatrchyan, et al., Searches for long-lived charged particles in pp collisions at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* 07 (2013) 122, arXiv:1305.0491 [hep-ex].
- [74] V. Khachatryan, et al., Search for long-lived charged particles in proton–proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* 94 (2016) 112004, arXiv:1609.08382 [hep-ex].
- [75] G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov, micrOMEGAs4.1: two dark matter candidates, *Comput. Phys. Commun.* 192 (2015) 322, arXiv:1407.6129 [hep-ph].

- [76] A. Alloul, N.D. Christensen, C. Degrande, C. Duhr, B. Fuks, FeynRules 2.0 – a complete toolbox for tree-level phenomenology, *Comput. Phys. Commun.* 185 (2014) 2250, arXiv:1310.1921 [hep-ph].
- [77] A. Roitgrund, G. Eilam, S. Bar-Shalom, Implementation of the left–right symmetric model in FeynRules, *Comput. Phys. Commun.* 203 (2016) 18, arXiv:1401.3345 [hep-ph].
- [78] D.S. Akerib, et al., The Large Underground Xenon (LUX) experiment, *Nucl. Instrum. Methods, Sect. A* 704 (2013) 111, arXiv:1211.3788 [physics.ins-det].
- [79] D.C. Malling, et al., After LUX: the LZ program, arXiv:1110.0103 [astro-ph.IM], 2011.
- [80] E. Aprile, et al., Physics reach of the XENON1T dark matter experiment, *J. Cosmol. Astropart. Phys.* 1604 (2016) 027, arXiv:1512.07501 [physics.ins-det].
- [81] A. Abramowski, et al., Search for a dark matter annihilation signal from the Galactic Center halo with H.E.S.S., *Phys. Rev. Lett.* 106 (2011) 161301, arXiv:1103.3266 [astro-ph.HE].
- [82] A. Abramowski, et al., Search for photon-line-like signatures from dark matter annihilations with H.E.S.S., *Phys. Rev. Lett.* 110 (2013) 041301, arXiv:1301.1173 [astro-ph.HE].
- [83] R. Mahbubani, P. Schwaller, J. Zurita, Closing the window for compressed dark sectors with disappearing charged tracks, arXiv:1703.05327 [hep-ph], 2017.
- [84] N.E. Mavromatos, V.A. Mitsou, Physics reach of MoEDAL at LHC: magnetic monopoles, supersymmetry and beyond, in: 5th International Conference on New Frontiers in Physics Kolymbari, Crete, Greece, July 6–14, 2016, 2016, arXiv:1612.07012 [hep-ph].
- [85] M. Drees, X. Tata, Signals for heavy exotics at hadron colliders and supercolliders, *Phys. Lett. B* 252 (1990) 695.
- [86] M. Fairbairn, A.C. Kraan, D.A. Milstead, T. Sjostrand, P.Z. Skands, T. Sloan, Stable massive particles at colliders, *Phys. Rep.* 438 (2007) 1, arXiv:hep-ph/0611040.
- [87] W.-Y. Keung, G. Senjanovic, Majorana neutrinos and the production of the right-handed charged gauge boson, *Phys. Rev. Lett.* 50 (1983) 1427.
- [88] M. Mitra, R. Ruiz, D.J. Scott, M. Spannowsky, Neutrino jets from high-mass W_R gauge bosons in TeV-scale left–right symmetric models, *Phys. Rev. D* 94 (2016) 095016, arXiv:1607.03504 [hep-ph].
- [89] A. Belyaev, N.D. Christensen, A. Pukhov, CalcHEP 3.4 for collider physics within and beyond the standard model, *Comput. Phys. Commun.* 184 (2013) 1729, arXiv:1207.6082 [hep-ph].
- [90] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P.M. Nadolsky, W.K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, *J. High Energy Phys.* 07 (2002) 012, arXiv:hep-ph/0201195.
- [91] Qing-Hong Cao, Zhao Li, Jiang-Hao Yu, C.-P. Yuan, Discovery and identification of W' and Z' in $SU(2)_1 \times SU(2)_2 \times U(1)_X$ models at the LHC, *Phys. Rev. D* 86 (2012) 095010.