

## Review Article

# Heavy Chiral Fermions and Dark Matter

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Dark matter presents perhaps one of the most compelling direct indications of new physics beyond the standard model with three generations of fermions. In this paper, we survey several scenarios for dark matter in association with a fourth generation of chiral matter. The surveyed scenarios include stable heavy neutrino dark matter, composite dark matter consisting of stable heavy quarks, heavy quarks as mediators between the dark and visible sectors, and the four-generation standard model with the minimal addition of a stable real scalar field. We discuss the basic properties of the models, direct search constraints on their dark matter, and their collider phenomenology, as well as the possible effects of dark matter on the searches for a Higgs boson in the presence of four generations. We also comment on the potential implication of the recent observation of a Higgs-like new particle at the LHC.

## 1. Introduction

In recent years, an ever-increasing collection of measurements have been performed and produced data which support the inference that dark matter exists in our Universe. They include the observations of velocities of various astronomical objects and the detailed mapping of the cosmic microwave background radiation [1]. In spite of all this evidence, the identity of the basic constituents of most dark matter has so far remained a mystery, as they are not of any known type of matter. Nevertheless, there are some basic properties that candidates for dark matter need to possess. They must be stable on cosmological time scales, interact very weakly with electromagnetic radiation, and have the right relic density. Furthermore, analyses of structure formation in the Universe suggest that dark matter consists mainly of cold (i.e., nonrelativistic) particles [1] (for reviews on the nature of, and search strategies for, dark matter, see also [2–4]).

Among the considerable variety of dark matter (DM) candidates, the most popular at present are the so-called weakly interacting massive particles (WIMPs). While the standard model (SM) does contribute weakly interacting

stable particles in the form of neutrinos, their being very light precludes them from being abundant enough to be the dominant component of the observed relic density. Many models for new physics have been proposed that contain suitable WIMP candidates, including supersymmetry with  $R$ -parity, universal extra dimensions with Kaluza-Klein parity, and little Higgs models with  $T$ -parity. Alternatively, it is possible that the DM candidate naturally yields the correct relic density, but does not have a weak-scale mass or weak interactions. Such a WIMP-less possibility can occur in models which possess sequestered (hidden) sectors with conserved quantum numbers.

In this paper, we will give an overview of some scenarios for DM in conjunction with heavy chiral quarks and leptons, as well as their respective motivations, cosmology, and collider phenomenology. The considered scenarios are

- (1) a sequential fourth generation with a stable heavy neutrino,
- (2) a sequential fourth generation with stable heavy quarks,

- (3) heavy chiral quarks acting as mediators between the SM sector and a hidden sector, and
- (4) a sequential fourth generation plus the simplest DM candidate.

We will here briefly describe the models, before continuing to give a more in-depth survey of their properties in the following sections.

The first scenario involves a sequential fourth generation with a neutrino that is heavy and stable. This possibility is natural, as it builds on the existing SM structure, and also fairly economical in that it retains neutrinos as the only source of weakly interacting stable matter in the universe. To guarantee the stability of the heavy neutrino, one may introduce a  $Z_2$  symmetry under which the neutrino is odd, whereas the SM particles are even, and which may originate from an extra gauge group spontaneously broken at some high scale [5, 6]. If the couplings of the fourth neutrino to the  $Z$  boson are comparable to those of the light neutrinos, the fourth neutrino can make up at most a few tenths of the observed DM abundance and moreover direct searches for DM impose severe constraints [7–10]. However, if the fourth neutrino is mostly right-handed, it may get around these restrictions and saturate the relic density [11].

The second scenario again involves a sequential fourth generation, but with DM that is predominantly due to a (quasi-)stable heavy anti-up-type quark  $\bar{U}$  [12–14]. These stable antiquarks form baryons with charge  $-2$ , which are captured by  ${}^4\text{He}$  immediately after nucleosynthesis. The resulting “atoms” play the role of DM in structure formation and other observables.

The third scenario is inspired by so-called WIMPlless models, where DM resides in a sequestered (hidden) sector [15–19]. In such models, any interactions with the SM sector must come about due to mediators, particles charged under both the hidden and SM sectors. An interesting possibility is that these mediators carry the SM quantum numbers of a pair of chiral quarks, as well as some hidden-sector quantum number(s). Such quark mediators would give rise to sufficient cross-section for DM detection in direct search experiments as well as abundant production at the LHC.

Finally, in the fourth scenario, the SM with four sequential generations (SM4) is slightly expanded by incorporating a real gauge-singlet scalar field which acts as the WIMP candidate [20]. This is the most economical extension of the SM4 with WIMP DM in the case of all the fourth-generation fermions being unstable. Its minimality is reflected in the small number of parameters in its DM sector, which makes it highly testable with recent and ongoing experiments.

The rest of the paper is organized as follows. Section 2 gives details on the scenarios, including their motivation, and cosmological and astrophysical phenomenology. In Section 3, we present the collider phenomenology of the different scenarios. We discuss in Section 4 some of the possible impacts of the DM under consideration on Higgs searches in the SM4. We also comment on the potential implication of the recent observation at the LHC of a new

particle compatible with the Higgs boson in the three-generation case (SM3). We finally discuss similarities and differences of the models and present our conclusions in Section 5.

## 2. Cosmology and Dark Matter Detection

The four scenarios presented here, despite the common features of dark matter and heavy chiral fermions, all have quite different motivation and phenomenology. We will therefore present the models in four separate subsections and will defer the discussion on similarities and differences to Section 5.

*2.1. Scenario 1: A Stable Heavy Neutrino.* In the presence of the fourth generation, it is natural and economical to regard its neutral member as a potential WIMP candidate. The lower limit, at 95% confidence level (CL), on the mass of a stable fourth-generation neutrino with SM coupling strength is 45.0 (39.5) GeV if it is a Dirac (Majorana) fermion [1]. (In the Majorana case, if the fourth neutrino is the lighter member of a pair of Majorana neutrino eigenstates with masses originating from both Dirac and Majorana contributions, the lower limit can be relaxed to 33.5 GeV [21].) As it turns out, such a neutrino cannot be a primary candidate for DM because its annihilation cross-section is generally large and leads to relic abundance that is too small to account for the observed DM density [7]. Moreover, constraints from experiments looking directly for DM interacting with nuclei rule out the fourth-generation neutrino with SM couplings as the leading component of the DM in our galactic halo. Specifically, for a stable fourth-generation Dirac neutrino dominating the halo DM, the spin-independent cross-section of the neutrino elastically scattering off a nucleus is much higher than the upper bounds from the direct searches, which excludes masses up to the TeV level. In the Majorana neutrino case, the spin-dependent cross-section is also too large over a comparable, but smaller, mass range. For a heavier neutrino, the cross-sections may agree with the data, but in the higher-mass region perturbative unitarity may be violated [7]. These restrictions can be lessened if the stable heavy neutrino is not assumed to saturate the local halo DM.

It is instructive to review the situation in the context of a specific example in light of recent results from the Higgs and DM direct searches. We adopt the model of [10] in which the four generations of fermions are sequential with respect to the SM gauge group and a right-handed neutrino state is added to each generation. The neutrino DM is made stable by a  $Z_2$  symmetry which arises naturally after the spontaneous breaking of an extra Abelian gauge group,  $U(1)_F$ . All the quarks and leptons carry  $U(1)_F$  charges,  $\mathcal{Q}_i^q$  and  $\mathcal{Q}_i^\ell$ , respectively, for  $i = 1, \dots, 4$ , but the Higgs doublet does not. These charges are chosen to be  $\mathcal{Q}_{1,2,3}^q = \mathcal{Q}_q = -\mathcal{Q}_4^q/3$  and  $\mathcal{Q}_{1,2,3}^\ell = \mathcal{Q}_\ell = -\mathcal{Q}_4^\ell/3$ , with  $\mathcal{Q}_q = \mathcal{Q}_\ell$ . One can deduce from these charge assignments that flavor-changing neutral currents at tree level and gauge anomalies are absent. The model also contains extra scalar fields  $\phi_a$  and  $\phi_b$ , which are singlets under the SM gauge group and carry the  $U(1)_F$  charges

$\mathcal{Q}_a = -2\mathcal{Q}_\ell$  and  $\mathcal{Q}_b = 6\mathcal{Q}_\ell$ , respectively. Accordingly, the mass-generating terms for the neutrinos can be expressed as

$$\begin{aligned} \mathcal{L}_Y^{\nu} = & -Y_{kl}\bar{\nu}_{kR}\tilde{H}^\dagger L_{lL} - \frac{1}{2}Y'_{kl}\bar{\nu}_{kR}(v_{lR})^c\phi_a^\dagger \\ & -Y_4\bar{\nu}_{4R}\tilde{H}^\dagger L_{4L} - \frac{1}{2}Y'_4\bar{\nu}_{4R}(v_{4R})^c\phi_b^\dagger + \text{H.c.}, \end{aligned} \quad (1)$$

where  $k, l = 1, 2, 3$  are summed over,  $\tilde{H}^\dagger (L_{lL})$  represents the Higgs (left-handed lepton) doublet, and  $(v_{iR})^c$  denotes the charge conjugate of the right-handed neutrino  $\nu_{iR}$ . Thus when the vacuum expectation values (VEVs) of  $\phi_{a,b}$  become nonzero,  $\langle\phi_{a,b}\rangle = v_{a,b}/\sqrt{2}$ , they break  $U(1)_F$ , causing the associated gauge boson  $Z'$  to get mass given by  $M_{Z'}^2 \propto \mathcal{Q}_a^2 v_a^2 + \mathcal{Q}_b^2 v_b^2$ , and simultaneously the right-handed neutrino fields gain Majorana mass terms. It follows that, after electroweak symmetry breaking, each generation ends up with two Majorana mass eigenstates. Those in the fourth generation are denoted here by  $\chi_1$  and  $\chi_2$ , with masses satisfying  $m_1 < m_2$  and the DM candidate  $\chi_1$  being lighter also than the fourth-generation charged lepton.

The relic density  $\Omega_1$  of  $\chi_1$  is related to the cross-section at freeze-out of  $\chi_1$  annihilation into all possible SM4 final states. Assuming that  $m_1 < m_{Z'}$ , one calculates the contributions of diagrams mediated by the Higgs or  $Z$  boson in the  $s$  channel and by  $\chi_{1,2}$  or the fourth charged-lepton  $e_4$  in the  $t$  channel. In Figure 1 we display the resulting ratio  $r_\Omega = \Omega_1/\Omega_{\text{DM}}$ , where  $\Omega_{\text{DM}}$  is the observed total DM density [1], for various values of  $m_1$  and the  $\chi_1$ - $\chi_2$  mixing angle  $\theta$ , as the  $\chi_1$  couplings to the Higgs,  $W$ , and  $Z$  bosons depend on  $\theta$ , which varies from 0 to  $\pi/4$ . In the numerical work,  $\mathcal{Q}_\ell$  is set to unity, the  $e_4$  mass to  $m_{e_4} = m_1 + 50$  GeV, consistent with constraints from electroweak precision data [22, 23], and the Higgs mass to  $m_h = 115$  GeV, outside the 120–600 GeV zone excluded by LHC data at 95% CL [24, 25]. Hence in this model the stable fourth-generation neutrino can constitute up to about half of the total DM density. However, restraints from direct searches for DM may reduce this fraction significantly.

Since  $\chi_1$  can only contribute to a fraction of the observed relic density, it is reasonable to expect that  $\chi_1$  also contributes to a fraction,  $r_\rho$ , of the local halo DM density,  $\rho_0$ . This implies that the spin-independent and spin-dependent cross-sections  $\sigma_n^{\text{SI}}$  and  $\sigma_n^{\text{SD}}$ , respectively, of  $\chi_1$  elastically scattering off a nucleon need to be rescaled as  $\tilde{\sigma}_n^{\text{SI,SD}} = r_\rho \sigma_n^{\text{SI,SD}}$  for comparison with experiment. Under the assumption that the local density of  $\chi_1$  is proportional to its cosmic density,  $r_\rho = r_\Omega$ , we show in Figure 2 the predictions of  $\tilde{\sigma}_n^{\text{SI,SD}}$  for various values of  $m_1$  and  $\theta$ . These graphs illustrate how the parameters of this model may affect its predictions which can be probed by ongoing and future DM direct detection experiments. Given the formidable challenges in observing neutral stable particles at the LHC, the DM direct searches may have an edge in the quest for fourth-generation neutrino DM due to its potentially sizable couplings to  $h$  and  $Z$ .

We turn now to another model which, like the first one, has four sequential generations with right-handed neutrinos and an extra Abelian gauge group,  $U(1)'$ . However,

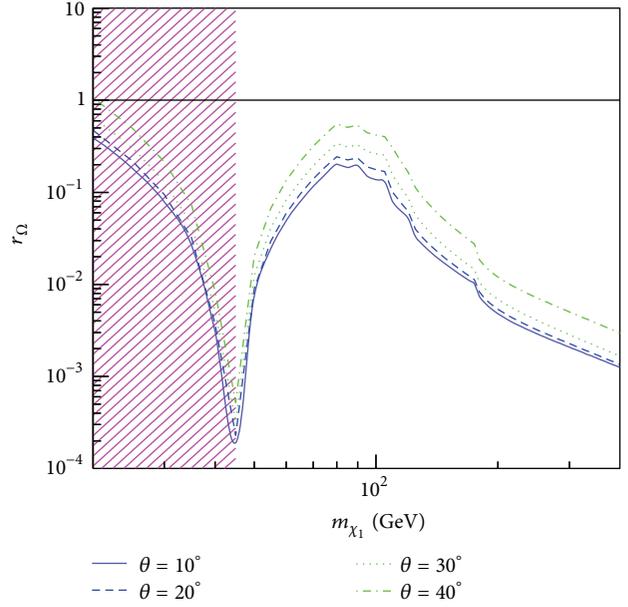


FIGURE 1: Relative relic density  $r_\Omega$  of stable fourth-generation neutrino  $\chi_1$  as a function of its mass for mixing angle values  $\theta = 10^\circ$  (solid),  $20^\circ$  (dashed),  $30^\circ$  (dotted), and  $40^\circ$  (dot-dashed). The shaded region is excluded by LEP-2 data [1] in the case of  $\chi_1$  being a Dirac fermion. Plot from [10].

the fermions have charge assignments under this new gauge group that are different from those in the first model. As proposed in [11], their  $U(1)'$  charges are  $\mathcal{Q}_{1,2,3,4}^f = 1/3$ ,  $\mathcal{Q}_{1,2,3}^\ell = 0$ , and  $\mathcal{Q}_4^\ell = -4$ . This implies that the charge operator of  $U(1)'$  is  $\mathcal{Q} = B - 4L_4$ , where  $B$  and  $L_4$  represent the baryon and fourth-generation lepton numbers, respectively. Another difference lies in the scalar sector which contains, besides the Higgs doublet  $H$ , one SM-singlet scalar field  $S$  and one Higgs triplet  $T$ , both of which carry the charge  $\mathcal{Q} = 8$  and couple to the fourth-generation leptons, but not to the other fermions, giving rise to a fourth-generation neutrino mass matrix of the form [11]

$$M_{\nu_4} \sim \begin{pmatrix} y_T v_T & y_D v_H \\ y_D v_H & y_S v_S \end{pmatrix}, \quad (2)$$

where  $y_{D,S,T}$  are Yukawa couplings and  $v_{H,S,T}$  denote the VEVs of  $H$ ,  $S$ , and  $T$ , respectively. By requiring that  $y_T v_T > y_S v_S \gg y_D v_H$ , one can ensure that the lighter Majorana mass eigenstate,  $\chi$ , is mostly right-handed, while the heavier one is predominantly left-handed. In that case, the couplings of  $\chi$  to the Higgs and  $Z$  bosons become suppressed, allowing  $\chi$  to overcome the obstacles faced by  $\chi_1$  in the previous model.

More specifically, the  $U(1)'$  charge assignments above imply that in the  $y_D v_H = 0$  limit  $\chi$  has only an axial-vector coupling to the  $Z'$  boson which in turn has only vectorial couplings to the quarks. As a consequence, the cross-sections of the  $\chi$ -nucleon scattering vanish, thereby automatically satisfying the direct search bounds. On the other hand, the  $\chi$  annihilation cross-section is nonzero and can yield relic density of the right amount, especially if the  $\chi$  mass is not far from

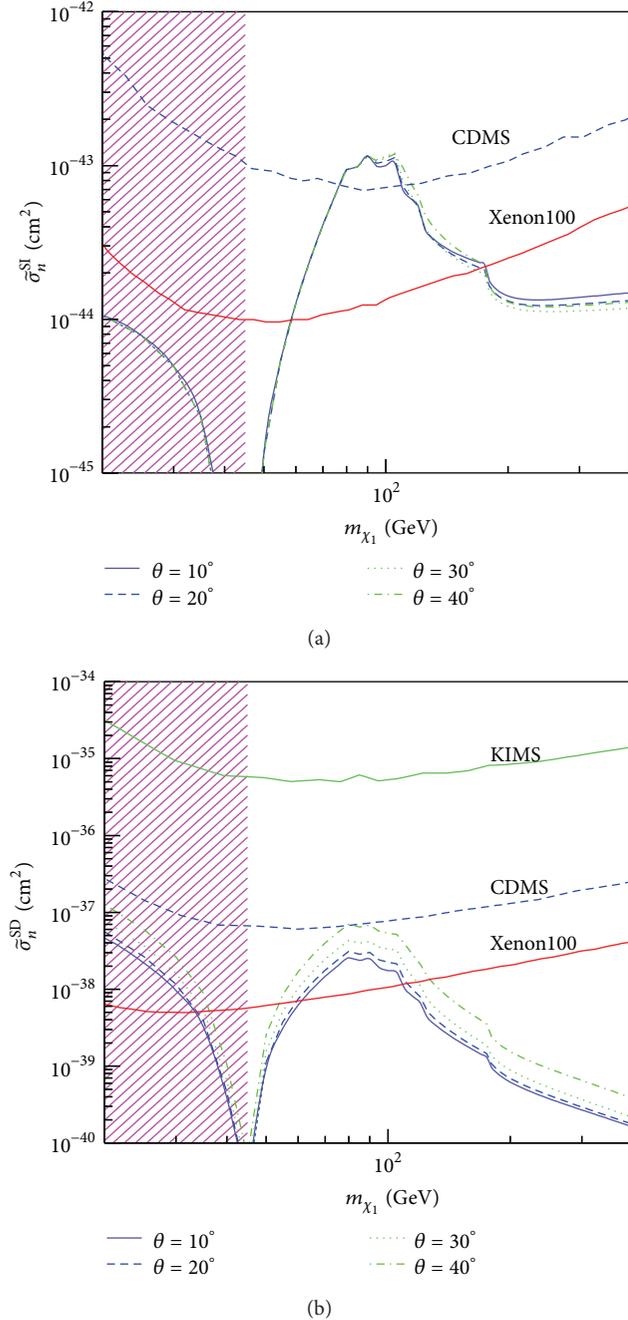


FIGURE 2: (a) Rescaled spin-independent cross-section  $\tilde{\sigma}_n^{\text{SI}}$  as a function of  $\chi_1$  mass for rescaling factor  $r_\rho = r_\Omega$  and the same  $\theta$  values as in Figure 1, compared to upper limits from CDMS [109] and Xenon100 [110]. (b) The corresponding spin-dependent cross-section  $\tilde{\sigma}_n^{\text{SD}}$ , compared to upper limits from KIMS [111], CDMS [112], and Xenon10 [113]. Plots from [10].

the  $Z'$  resonance region,  $2M_\chi \sim M_{Z'}$ . This is depicted for a couple of  $M_{Z'}$  examples in Figure 3, where  $g_X$  is the  $U(1)'$  coupling constant. Thus this model provides a stable fourth-generation neutrino that can be a good DM candidate. Although the  $Z'$  boson is leptophobic with respect to the leptons of the first 3 generations, its couplings to the quarks

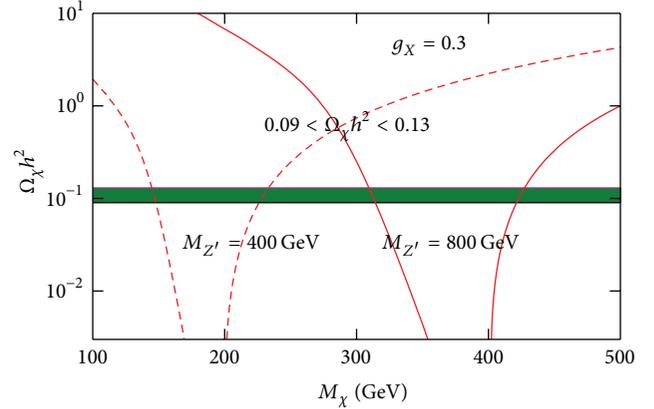


FIGURE 3: Relic density of stable fourth-generation neutrino  $\chi$  as a function of its mass for  $M_{Z'} = 400$  GeV (dashed) and 800 GeV (solid) with a coupling constant  $g_X = 0.3$ . The green band represents the observed DM density. Plot from [11].

and fourth-generation charged lepton may allow it to be detectable at colliders.

**2.2. Scenario 2: A Stable Heavy Quark.** Another possibility is that all members of the fourth generation carry some new, unbroken  $U(1)$  charge. This can be realized, for example, in grand unified theories with the unification group  $E_6$ . In this case, the new heavy quarks can only decay through GUT-scale operators to the lightest member of the fourth generation, typically the neutrino. The lightest of these quasi-stable quarks can easily have a lifetime longer than that of the universe [12–14].

If the heavy quarks receive a baryon asymmetry leaving a predominance of up-type antiquarks  $\bar{U}$ , during the cooling of the universe, these antiquarks will mainly form antibaryons  $\bar{U}\bar{U}\bar{U}$  (due to strong chromo-Coulomb forces) with charge  $-2$ . Immediately after nucleosynthesis, these negatively charged baryons will bind to  ${}^4\text{He}$  nuclei to form  $\bar{U}\bar{U}\bar{U}{}^4\text{He}$ , also called “O-helium” or OHe. The resulting OHe atoms act as DM for the remainder of the lifetime of the universe. Due to their short-range nuclear interactions, this DM behaves as slightly “warm” in structure formation.

O-helium has some special implications. One is in nucleosynthesis, where the  $\bar{U}$  baryons can act as catalysts for the generation of  ${}^7\text{Li}$  in the merging of a  ${}^3\text{H}$  and a  ${}^4\text{He}$  nucleus, as well as for the production of heavier nuclei. Furthermore, the Earth is opaque to O-Helium, which would be slowed down in the Earth’s crust and, through gravitational interactions, sink down to the Earth’s core. Some of the O-helium would be destroyed in reactions, with  $\bar{U}$  baryons forming bound states with other nuclei. Such anomalous  $Z-2$  isotopes could in principle be detected, although the prevalence should be below present experimental limits.

In underground direct detection experiments, the O-helium would be very difficult to detect since it is slowed down by the passage through matter and would release a minimal energy transfer of order  $10^{-4}$  eV. Therefore, direct

production of  $U\bar{U}$  pairs in colliders would be the main way to detect this scenario, see further Section 3.2.

**2.3. Scenario 3: Mediator Heavy Quarks.** A notable property of DM inferred from observations is the so-called “WIMP miracle”, that is, that the observed DM abundance can be explained by a new particle with weak-scale mass ( $\mathcal{O}(100)\text{GeV}$ ) and weak-scale interaction cross-section. This observation was taken up in WIMPlless models [15–19], where the DM resides in a hidden sector, which receives mass through the same mechanism as the SM sector (such as gauge-mediated supersymmetry breaking) in such a way that the ratio of the mass scale to gauge structure constant is the same as in the SM. This hidden-sector DM will then automatically have a relic density of the correct order of magnitude, independently of the DM mass. The stability of the DM particles is naturally explained by their carrying some unbroken  $U(1)$  gauge quantum number or a  $Z_2$  symmetry, forbidding decays into lighter SM particles. The precise cosmology of the model depends on whether the DM experiences long-range interactions through an unbroken  $U(1)$  symmetry (“self-interacting dark matter”, see [26–28]) or not.

This hidden sector DM can either interact with the SM only through the high-energy supersymmetry breaking mechanism, in which case discovery in direct or indirect detection experiments would be impossible, or through some mediator particles, carrying both hidden-sector and visible-sector quantum numbers. A tantalizing possibility is that the DM is a real scalar particle  $X$  that couples to the SM sector through heavy chiral quarks (or, to be precise, mirror quarks, since their chirality is opposite to that of the SM quarks) through Yukawa terms

$$V = \lambda_i^q X \bar{Q}_L^i q_{Li} + \lambda_i^u X \bar{T}_R^i u_{Ri} + \lambda_i^d X \bar{B}_R^i d_{Ri}. \quad (3)$$

In order to avoid any flavor constraints, we assume the usual Yukawa hierarchy for coupling to the SM generations, giving dominant coupling of the new quarks to 3rd-generation SM quarks. The original motivation for these model choices [29] was that in this scenario, with a DM mass in the range 1–10 GeV,  $\lambda \sim 1$ , and  $m_Q \sim 400$  GeV, the model could explain the anomalies reported by the DAMA [30] and CoGeNT [31] experiments, while staying marginally consistent with the stringent constraints from other DM detection experiments, see Figure 4.

However, the general scenario, with DM which couples to the SM through heavy (chiral or vector-like) quarks that are charged under a new symmetry and decay to the DM and 3rd-generation quarks, is recovered in many models. Examples include “asymmetric dark matter” models [32], little Higgs models with unbroken  $T$ -parity [33], and extra-dimensional models [34, 35]. These models have identical collider signatures, and they can all be explored at the LHC [36, 37], as detailed in Section 3.3.

**2.4. Scenario 4: SM4 with Minimal Dark Matter.** If the fourth-generation fermions are all unstable, it will be necessary to invoke extra particles in order to account for the observed DM relic density. The simplest possibility along this line is

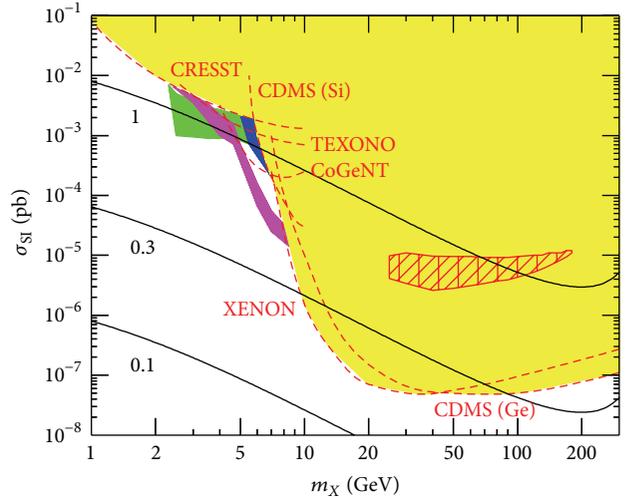


FIGURE 4: Direct detection cross-section limits for spin-independent  $X$ -nucleon scattering as a function of DM mass  $m_X$ . The solid curves are the predictions for WIMPlless DM with mediator mass  $m_Q = 400$  GeV and the Yukawa couplings  $\lambda_b$  indicated. The light yellow shaded region is excluded by the experimental results indicated. The dark blue, medium green, medium-dark magenta, and cross-hatched regions are the DAMA-favored regions under different assumptions, see [29] for details. Figure from [29].

the SM4+D, which is the SM with four sequential generations slightly expanded with the addition of a real scalar field  $D$  acting as the WIMP candidate [20]. The stability of  $D$ , sometimes dubbed darkon, is ensured by requiring it to be a singlet under the SM gauge group and introducing a discrete  $Z_2$  symmetry, under which  $D$  is odd, while the SM particles are even. The renormalizable Lagrangian of the darkon has the form

$$\mathcal{L}_D = \frac{1}{2} \partial^\mu D \partial_\mu D - \frac{1}{4} \lambda_D D^4 - \frac{1}{2} m_0^2 D^2 - \lambda D^2 H^\dagger H, \quad (4)$$

where  $\lambda_D$ ,  $m_0$ , and  $\lambda$  are free parameters and  $H$  is the Higgs doublet containing the physical Higgs field  $h$ . This Lagrangian is the same as that in the three-generation case, the SM3+D, which has been much studied in the literature [38–56], but the presence of the fourth generation gives rise to potentially detectable processes which are absent or suppressed in the SM3+D case, as will be discussed later. Clearly the DM sector of SM4+D has a small number of free parameters, only two of which are relevant here: the Higgs-darkon coupling  $\lambda$  and the darkon mass  $m_D = (m_0^2 + \lambda v_H^2)^{1/2}$ , where  $v_H$  is the Higgs VEV.

Since the  $\lambda$  term in (4) leads to the darkon relic density,  $\lambda$  can be extracted from the observed DM density once the darkon and Higgs masses,  $m_D$  and  $m_h$ , are specified. With  $\lambda$  determined, one can then predict the cross-section  $\sigma_{el}$  of a darkon elastically scattering off a nucleon. Based on the calculations of [20, 56] with the fourth-generation fermion masses adopted therein, we display in Figure 5 the results for  $2.5 \text{ GeV} \leq m_D \leq 400 \text{ GeV}$  and some illustrative values of  $m_h$ . The band widths in Figure 5(a) corresponds to the 90%-CL range of the observed DM density  $\Omega_{\text{DM}}$  [57], whereas those

in Figure 5(b) reflect mainly the substantial uncertainty of the Higgs-nucleon coupling [56].

Also shown in Figure 5(b) are data on the spin-independent cross-section of WIMP-nucleon interactions from the leading direct-detection experiments. Evidently the potential WIMP signals measured by DAMA, CoGeNT, and CRESST-II are at odds with the upper bounds reported by CDMS, XENON10, and XENON100. Since the null results of the latter for WIMP masses  $\leq 15$  GeV have been seriously disputed in the literature [58–62], pending a general consensus on this puzzle we will here regard it as an open question and consequently assume that the range 2.5–15 GeV is still viable. (In the SM4+D, most of the  $m_D \leq 2.5$  GeV region is disallowed by restrictions from the data on a number of kaon and  $B$ -meson rare decays with missing energy [20].) It is then interesting to observe that the  $\sigma_{\text{el}}$  predictions in Figure 5(b) overlap well with the signal cross-sections suggested by CoGeNT and CRESST-II for this mass range. Thus darkon masses from 15 to  $\sim 80$  GeV are ruled out by the direct search limits, as the black-dotted portions of the curves in Figure 5(b) indicate. In contrast, most of the  $m_D \geq 80$  GeV region is not yet subject to the existing direct-search bounds, but will be within reach of future searches such as XENONIT. Before moving on, we remark that there is a fresh update on the XENON100 limit [63], which roughly amounts to lowering the XENON100 curve in Figure 5(b) by up to almost a factor of four.

### 3. Collider Phenomenology

Detecting stable weakly-interacting neutral particles at a hadron collider is extremely difficult. Typically, the only prompt production mechanisms are through off-shell  $Z$  bosons, on- or off-shell Higgs bosons, or through new heavy gauge bosons ( $Z'$ ). These all have quite low production cross-sections, and the signal, which in all cases consists of missing transverse energy,  $E_T$ , recoiling against hadron jets (or possibly other recoils such as photons or weak bosons) all suffer from very large SM backgrounds, including  $W^\pm$  and  $Z \rightarrow \nu\bar{\nu}$  plus jets, top pair production, and QCD multijet production with missing energy due to mismeasurement and/or heavy flavor decays. (See however [64] for a model-independent study using effective 4-fermion operators comparing the reach for Majorana fermion DM detection at the Tevatron and the LHC to direct detection experiments, where collider experiments are found to increase the detection reach significantly for several operator types, in particular for very low mass DM. Their study might be directly relevant for scenario 1, and, indirectly, for scenario 4.)

The only hope for distinguishing and identifying the production of DM is therefore usually through the decay of heavier particles, which are either more readily produced or have more easily distinguishable decay modes, such as high-momentum isolated leptons and/or jets. With a significant mass difference between the decaying particle and its decay products (including the DM), the amount of missing  $E_T$  can also be increased without requiring recoil against high- $p_T$  initial state radiation (jets or photons).

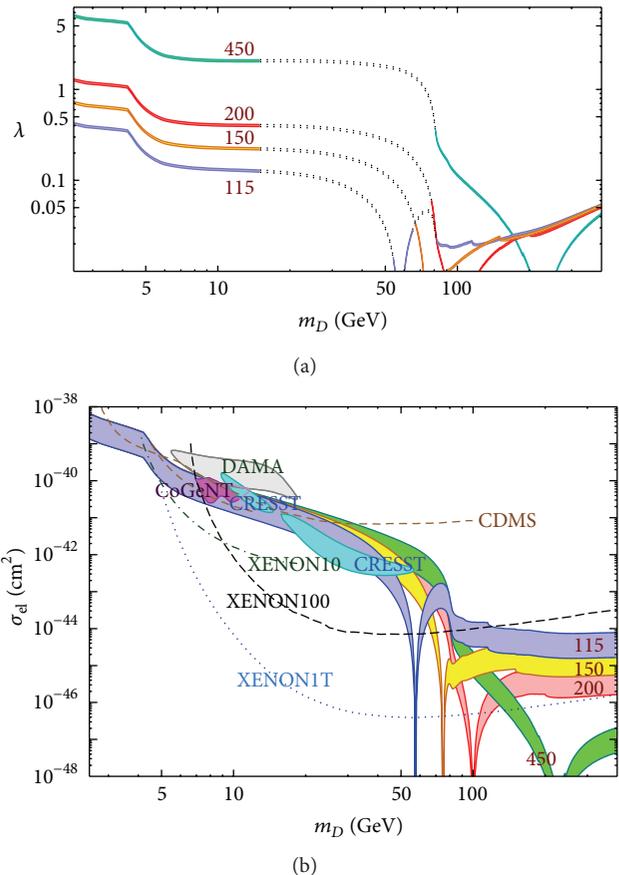


FIGURE 5: (a) Darkon-Higgs coupling  $\lambda$  as a function of darkon mass  $m_D$  for Higgs mass values  $m_h = 115, 150, 200, 450$  GeV in SM4+D. (b) The corresponding darkon-nucleon cross-section  $\sigma_{\text{el}}$ , compared to 90%-CL upper limits from CDMS (brown long-dashed curves) [114, 115], XENON10 (green dot-dashed curve) [116], and XENON100 (black short-dashed curve) [110], as well as a (gray) patch compatible with the DAMA modulation signal at the  $5\sigma$  level [117], the 90%-CL (magenta) signal region suggested by CoGeNT [31], and two  $2\sigma$ -confidence (cyan) areas representing the CRESST-II result [118]. Also plotted is the projected sensitivity of XENONIT (blue dotted curve) [119]. The black-dotted parts of the curves in (a) are ruled out by the direct search limits in (b) as discussed in the text.

This type of signatures are by necessity model-dependent, and therefore help distinguish the type of DM scenario. In the following, we will survey the expected collider signatures of the four scenarios of DM and heavy chiral fermions. We leave the comparison and discussion about the possibility to distinguish the scenarios for the concluding section.

**3.1. Scenario 1: A Stable Heavy Neutrino.** In scenarios with a stable fourth-generation neutrino, the viable collider signatures depend on the details of the model. In the models discussed in Section 2.1, the fourth-generation neutrino is stabilized by a new  $U(1)$  symmetry which is broken at or above the TeV scale. Furthermore, the fourth-generation neutrino has both Majorana and Dirac mass terms, generating mixing between the left- and right-handed neutrinos, with

possibly both mass eigenstates light enough to be within reach of the LHC.

The first model discussed in Section 2.1 (see [10]) has a mass matrix

$$M_{\nu_4} \sim \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \quad (5)$$

in the basis of  $(\nu_{4L}, (\nu_{4R})^c)^T$ . This means that the lightest neutrino state  $N_1 = \chi_1$  is predominantly left-handed, with a sizable coupling to the SM Z boson.

In [21], the collider phenomenology of a corresponding scenario was analyzed, where the fourth-generation Majorana neutrino states  $N_1$  and  $N_2 = \chi_2$  have comparable masses, and  $N_2$  decays as  $N_2 \rightarrow Z^{(*)}N_1$ , where  $Z^{(*)}$  indicates an on- or off-shell SM Z boson. Parts of the  $N_1$  and  $N_2$  mass plane can in this case be excluded already by existing squark searches at LEP 2. The squark signal considered in the LEP search was  $e^+e^- \rightarrow \bar{q}q \rightarrow q\bar{q} + \chi_0\chi_0$ , and the search excluded squark masses up to the kinematic limit of LEP 2. The corresponding signal of jets plus missing energy would be generated also by fourth-generation neutrino pair production,  $e^+e^- \rightarrow Z \rightarrow N_i N_j$ , with at least one of  $N_i$  and  $N_j$  being the heavier neutrino. The resulting exclusion region is given in Figure 6(a).

Turning to the LHC, the cross-section for  $N_1$  pair production is far too small to give a distinguishable missing  $E_T$  signal at the LHC, but there is an interesting possibility:

$$pp \rightarrow N_2 N_2 \rightarrow N_1 Z^{(*)} N_1 Z^{(*)} \rightarrow \ell\ell\ell\ell N_1 N_1, \quad (6)$$

where  $Z^{(*)}$  indicates on- or off-shell Z bosons. The  $pp \rightarrow N_2 N_2$  production mechanism is assumed to be through an s-channel SM Z boson. The resulting signal is four isolated leptons and missing transverse energy. While this signal is suppressed by the branching ratio into four leptons and the efficiency for detecting four isolated leptons, on the other hand, it is practically background free. In Figure 6(b), cross-section limits in the  $(m_{N_1}, m_{N_2})$  plane is shown for  $30 \text{ fb}^{-1}$  integrated luminosity at the LHC.

In the second model (that of [11]), the inclusion of the scalar triplet with a nonvanishing VEV renders the lighter fourth-generation neutrino predominantly right-handed. In this case, the coupling of the lighter neutrino to the Z boson vanishes, which allows the neutrino, on one hand, to have sufficient relic density to make up virtually all the DM and, on the other hand, to escape the DM direct detection bounds. In the model studied in [11], the mixing between the heavier and lighter fourth-generation neutrinos is furthermore strongly suppressed. As is shown in Figure 3, however, an acceptable relic density requires the mass of the associated  $Z'$  to be close to twice the mass of  $N_1 = \chi$ .

This  $Z'$  couples to a  $B - 4L_4$  current, and therefore has a coupling to SM quarks, but not to leptons of the first three generations. The standard dilepton decay channel is therefore closed. Possible detection channels could instead be either diquark (or  $t\bar{t}$ ) decay, or decay of the  $Z'$  to fourth-generation charged leptons  $e_4^+ e_4^-$ . As seen in Figure 7, the present  $Z'$  searches in the dijet channel at the LHC do not yet constrain this model.

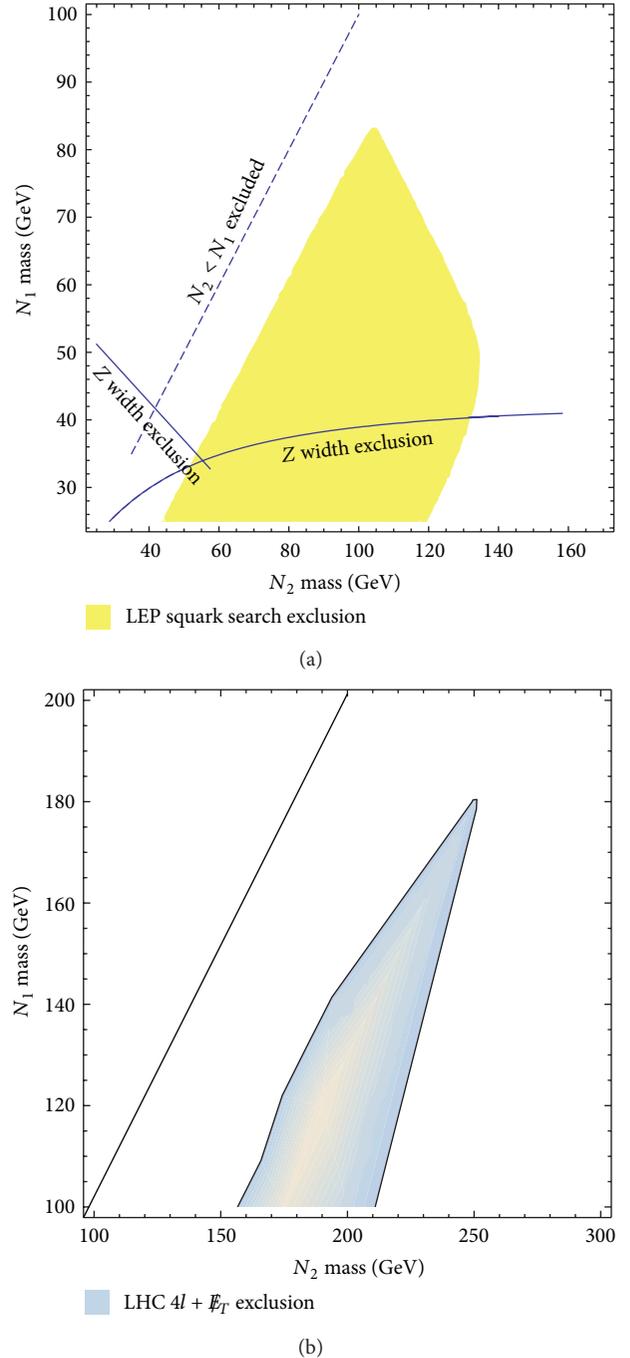


FIGURE 6: Exclusion limits in the  $(N_2, N_1)$  mass plane at 95% confidence limits. (a) Likely exclusion limit from the LEP 2 squark search and Z-pole constraints. (b) Exclusion region for an LHC  $4l + \cancel{E}_T$  search, for  $30 \text{ fb}^{-1}$  integrated luminosity. Figures from [21].

**3.2. Scenario 2: A Stable Heavy Quark.** In the model of composite DM consisting of baryons  $\bar{U}\bar{U}\bar{U}$  of a stable heavy chiral antiquark  $\bar{U}$  combining with Helium nuclei to form O-helium, what would be produced at a hadron collider is  $U\bar{U}$  pairs. The production cross-section for these pairs is identical to that of regular fourth-generation quarks, and the

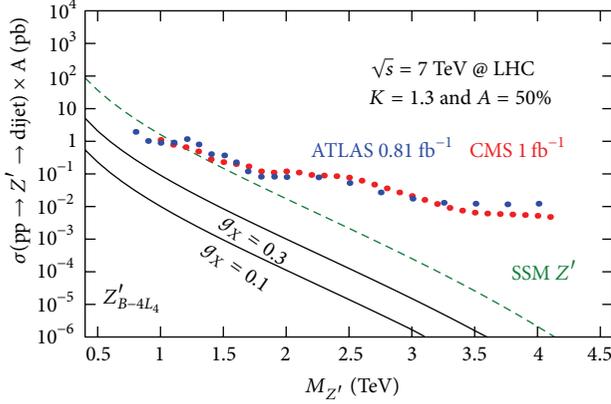


FIGURE 7: The constraints on  $Z'$  in the dijet search from CMS (red dots) with integrated luminosity of  $1 \text{ fb}^{-1}$  and from ATLAS (blue dots) with integrated luminosity of  $0.81 \text{ fb}^{-1}$ . The predicted events at LHC through the  $Z'$  boson of the  $U(1)_{B-4L_4}$  with a range of coupling constant (for instance,  $g_X = 0.3$ ) lie below the current reach of the CMS and ATLAS data. Also plotted is the predicted signal from the sequential  $Z'$  model (green dashes), for comparison. See [11] for references and details. Figure from [11].

difference in phenomenology comes solely from the fact that they do not decay, but instead hadronize with light quarks and antiquarks into  $U$ -baryons and -mesons and then traverse the detector [65]. The phenomenology of these  $U$ -baryons and -mesons is identical to that of  $R$ -hadrons [66, 67], in particular hadrons formed with a stable top squark  $\tilde{t}^{(*)}$  and SM light quarks. The interactions of such heavy hadrons with matter has been thoroughly investigated using GEANT [68]. Note that the  $1/2$  difference in spin between stop-hadrons and  $U$ -hadrons has no impact on the collider phenomenology, which is completely determined by the interaction of the light quarks with the matter of the detector. In this sense, the only function of the spectator heavy constituent is to give mass and momentum to the heavy hadrons.

While the heavy quarks immediately after production hadronize mainly into heavy mesons  $U\bar{d}/U\bar{u}$  and  $\bar{U}d$  and  $\bar{U}u$ , while traversing the detector they frequently interact with the nuclear matter. It is kinematically advantageous for a  $U\bar{q}$  meson to exchange baryon number in the collision, emitting a pion. Therefore, nearly 100% of the  $U\bar{q}$  mesons transform during their passage through the detector into charge-1  $Uud$  baryons, which is the lightest baryonic state. This means that in a significant fraction of the events, the  $U$  hadron changes charge from the neutral  $U\bar{u}$  to the positive  $Uud$  (see Figure 8).  $\bar{U}$  mesons on the other hand cannot form antibaryons through interactions with the detector material. They can however still change charge (between  $-1$  and  $0$ ) through exchange of  $u$  and  $d$  quarks.

This gives rise to interesting signals of a slow-moving positively charged particle (the  $Uud$  baryon) seen in the muon detector, often with no corresponding track in the inner tracker, together with either

- (i) a negatively charged  $\bar{U}d$  inner track with minimal energy deposit in the calorimeters and possibly no

corresponding negative track in the muon chamber (due to  $d \rightarrow u$  exchange in the calorimeter), or

- (ii) a negatively charged track in the muon chambers but no corresponding track in the inner tracker, or
- (iii) simply missing transverse momentum and no additional tracks on the opposite side of the detector.

Some experimental searches have been done for stable heavy hadrons in particular as well as heavy stable charged particles in general, both at the Tevatron and the LHC [69–72]. If in the future a signal would be seen, it would be necessary to experimentally cover a significant range of charge exchange combinations to fully determine the properties of the heavy stable particle and distinguish different scenarios.

**3.3. Scenario 3: Mediator Heavy Quarks.** In this scenario, scalar DM particles  $X$  couple to the SM sector through heavy quarks carrying both SM and dark quantum numbers (due to either a continuous or a discrete symmetry). In order to avoid flavor constraints, these exotic heavy quarks are assumed to couple preferentially to 3rd-generation quarks. The new quarks can then be pair produced at hadron colliders through standard QCD interactions, and then decay to DM and 3rd-generation quarks. The production of new quarks with up-type quantum numbers ( $T'$  quarks), decaying to scalar DM particles and (possibly off-shell) SM top quarks, was studied in [36], while the production of decays of heavy down-type quarks ( $B'$ ), decaying to DM and  $b$  quarks, was studied in [37].

Both studies used MadGraph/MadEvent 4 [73] interfaced to Pythia 6.4 [74] and PGS 4 [75] for the simulation of both signals and backgrounds, and investigate the exclusion and discovery potential, at the Tevatron and the LHC, for the  $(m_{Q'}, m_X)$  parameter plane. The authors optimized the exclusion and discovery reach for each parameter point, using different cut combinations for a number of different signatures.

For  $T'\bar{T}'$  production with  $T'\bar{T}' \rightarrow tX(\bar{t}X)$  decay [36], there are several channels corresponding to the different decays of the top and anti-top quarks: all-hadronic (when both the top and anti-top decay to quarks), semileptonic (when one of the top or anti-top decays to a charged lepton and a neutrino), and doubly leptonic (when both the top and anti-top decay to charged leptons). These channels have quite different background and signal efficiencies and were therefore studied separately. In both cases (as for all signals with large missing transverse energy), the dominant backgrounds are top pair production,  $W$  + jets production, and (for the all-hadronic case)  $Z \rightarrow \nu\bar{\nu}$  + jets production.

Contrary to what one might expect, the best limits (and best discovery reach) for  $T'\bar{T}'$  production are obtained, not from the semileptonic channel, but from the all-hadronic channel. The reason is that the main backgrounds, semileptonic  $t\bar{t}$  and  $W$  + jets, both have a lepton in the final state, while the all-hadronic  $t\bar{t}$  decay has no missing energy at parton level. Therefore, a large missing  $E_T$  cut, large cut on transverse hadronic energy  $H_T$ , and a lepton veto combine to efficiently suppress the backgrounds. Furthermore, the

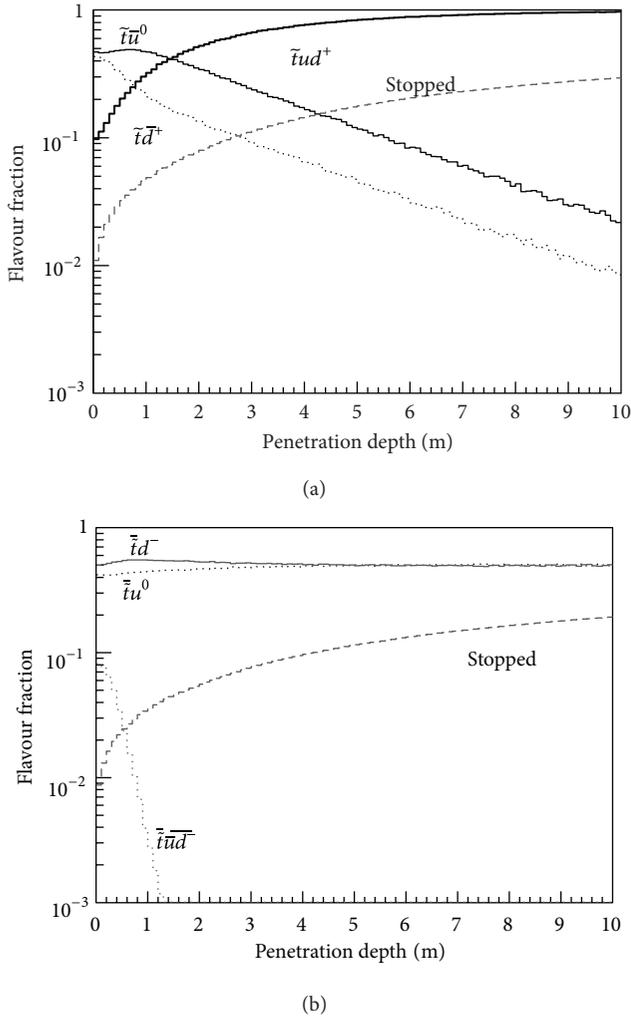


FIGURE 8: Flavor decomposition of heavy hadrons as a function of penetration depth in iron. The figures are for hadrons with stable scalar top and anti-top quarks, but the results are identical if  $\tilde{t}/\bar{\tilde{t}}$  is replaced by stable fourth-generation  $U/\bar{U}$  quarks. For the figure, a stop mass of 300 GeV was used. Figure from [68].

all-hadronic mode has larger branching ratio, and does not suffer from the relatively low efficiencies in detecting an isolated lepton. The additional  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  background is not large enough to considerably modify this picture. In order to optimize the exclusion and discovery reach, the cuts on missing  $E_T$ ,  $H_T$ , and number of jets were chosen to maximize the signal significance point-by-point in the  $(m_{T'}, m_X)$  parameter space.

Something worth special mentioning in the  $T'\bar{T}'$  scenario is the case in which the mass of the  $T'$  is very close to  $m_t + m_X$ . In this case, the momentum of the  $X$  particle from the  $T'$  decay and the  $\bar{T}'$  decay tend to be back-to-back, since the  $X$  particle is produced nearly at rest in the  $T'$  and  $\bar{T}'$  rest frames. Therefore, the amount of missing energy is reduced in this region, leading to a considerably worse exclusion reach. However, once  $m_{T'} < m_t + m_X$ , the decay is effectively a

3-body decay  $T' \rightarrow W^+ b X$ , and the phase space for the  $X$  particle again opens up. This effect is clearly seen in the exclusion regions for  $T'\bar{T}'$  production at a 10 TeV LHC run, see Figure 9.

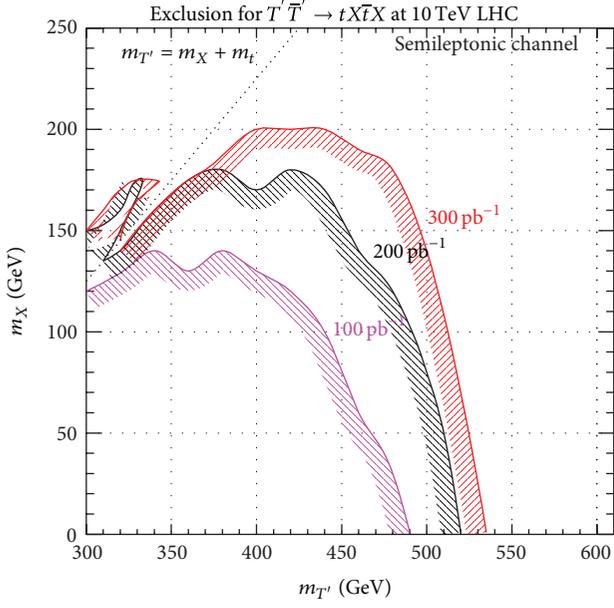
The expected exclusion reach for  $300 \text{ pb}^{-1}$  at a 10 TeV LHC run was found to extend beyond 600 GeV  $T'$  mass for  $m_X < 100$  GeV, with a maximum reach in  $m_X$  at around 220 GeV (for  $m_{T'}$  between 430 and 520 GeV), and the maximum  $3\sigma$  evidence reach going up to  $m_{T'}$  at 480 GeV for  $m_X < 80$  GeV. These numbers roughly correspond to the exclusion and evidence reaches at  $1 \text{ fb}^{-1}$  at the 7 TeV LHC run.

For  $B'\bar{B}'$  production with decay to  $b/\bar{b} + X$  [37], there is only one search channel,  $b$ -tagged jet(s) associated with large missing transverse energy. Also here, the cuts were optimized point by point in the  $(m_{B'}, m_X)$  parameter plane by choosing between a number of cuts on the hardest jet, missing  $E_T$ , and summed hadronic and missing transverse momentum  $M_{\text{eff}}$ . The 7 TeV LHC exclusion limits are shown in Figure 10. The larger mass difference between the produced  $B'$  and the decay products translate larger missing  $E_T$  and a significantly better reach in  $m_X$  compared to  $T'$  production, while the reach in  $m_{B'}$  is comparable to that for  $m_{T'}$  for a corresponding integrated luminosity.

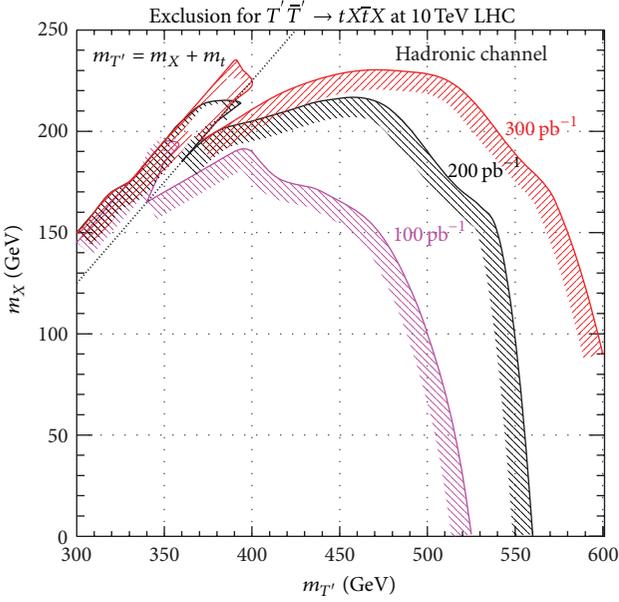
After the publication of [36], searches for the corresponding  $T'\bar{T}'$  signal have been done with the Tevatron CDF detector [76, 77] and the ATLAS detector at the LHC [78].

**3.4. Scenario 4: SM4 with Minimal Dark Matter.** The existence of the fourth-generation quarks can offer potentially important means to probe the DM sector of the SM4+D which are lacking or unavailable in the SM3+D. In the SM3 the flavor-changing neutral current (FCNC) top-quark decay  $t \rightarrow ch$  is known to have a tiny branching ratio, between  $10^{-15}$  and  $10^{-13}$  [79–84], but in the SM4 the new quarks can induce an enhancement factor of several orders of magnitude [85, 86]. In the SM4+D the related decay with a darkon pair in the final state,  $t \rightarrow ch^* \rightarrow cDD$ , if kinematically allowed, can be similarly enhanced and therefore may be detectable at the LHC. The analogous processes involving the fourth-generation quarks,  $t' \rightarrow (c, t)h^* \rightarrow (c, t)DD$  and  $b' \rightarrow (s, b)h^* \rightarrow (s, b)DD$ , may also be observable. These decays could, in principle, probe darkon masses all the way up to half the mass difference between the initial and final quarks,  $(m_Q - m_q)/2$ , hence covering potentially broader  $m_D$  ranges than those covered by some of the DM direct searches in the future.

Some numerical results for these FCNC processes involving the darkon have been obtained in [20]. With  $2m_D < m_h = 115$  GeV and fourth-generation quark masses of order 500 GeV, assuming that the mode  $h \rightarrow DD$  dominates the Higgs width leads to the branching ratio  $\mathcal{B}(t \rightarrow cDD) \leq 1.0 \times 10^{-8}$  [20]. Since estimates suggest that  $\mathcal{B}(t \rightarrow ch)$  needs to be at least several times  $10^{-5}$  in order to be detectable [83, 84], then  $t \rightarrow cDD$  may be unfeasible to measure. In contrast, its  $t'$  and  $b'$  counterparts are more promising, yielding  $\mathcal{B}(t' \rightarrow cDD) \leq 8.2 \times 10^{-5}$ ,  $\mathcal{B}(t' \rightarrow tDD) \leq 1.4 \times 10^{-3}$ ,  $\mathcal{B}(b' \rightarrow sDD) \leq 3.1 \times 10^{-4}$ , and  $\mathcal{B}(b' \rightarrow$



(a)



(b)

FIGURE 9: 95% CL exclusion contours for a 10 TeV LHC run in the semileptonic (a) and the all-hadronic (b) search channels, for integrated luminosities of 100, 200, and 300  $\text{fb}^{-1}$  (roughly comparable to 0.3, 0.6 and 1  $\text{fb}^{-1}$  at the 7 TeV LHC). Figure from [36].

$bDD) \leq 3.3 \times 10^{-3}$  [20]. Since  $t' \rightarrow qh$  and  $b' \rightarrow qh$  decays with branching ratios between  $10^{-4}$  and  $10^{-2}$  are expected to be within LHC reach [85, 86], we may expect that these  $t' \rightarrow qDD$  and  $b' \rightarrow qDD$  decays would also be detectable at the LHC despite their final states involving missing energy. Once they are seen, comparing the data with those from DM direct searches could provide further consistency tests for the darkon model.

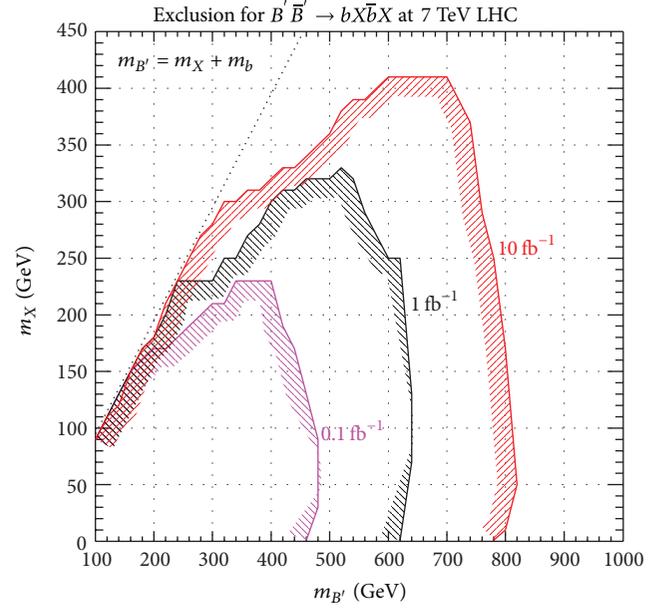


FIGURE 10: 95% CL exclusion reach in the  $(m_{B'}, m_X)$  plane for integrated luminosities of 0.1, 1, and 10  $\text{fb}^{-1}$  at 7 TeV LHC. Figure from [37].

## 4. Implications for Higgs Searches

A Higgs boson which has couplings to a pair of dark matter particles can decay into the latter if kinematically allowed. Such a mode will enlarge the rate of its invisible decay, suppressing the Higgs production cross-section into other decay modes and hence its detectability. In this section, we discuss some more details about the effect of dark matter on the Higgs sector in two of the scenarios treated above. We also touch on the implication of the information gained from the recent discovery of a Higgs-like particle at the LHC.

**4.1. Stable Heavy Neutrino.** If the fourth-generation neutrinos are long-lived or stable and couple nonnegligibly to the Higgs, it may have a significant invisible decay channel into the neutrinos, depending on the Higgs mass [8, 87–89]. This can happen in the first model considered in Section 2.1 in which the stable fourth-generation neutrino  $\chi_1$  is a predominantly left-handed Majorana fermion and has a coupling to the Higgs roughly proportional to the  $\chi_1$  mass [10]. In contrast, the second model discussed in Section 2.1 contains a stable fourth-generation neutrino that is a predominantly right-handed Majorana fermion and has negligible couplings to the Higgs [11].

To illustrate how large this invisible mode can modify the Higgs branching ratios in the first model, we display in Figure 11 two examples from [8] for two sets of the masses of  $\chi_1$  and its heavier partner  $\chi_2$ , which are related to their mixing angle  $\theta$  by  $\tan^2 \theta = m_1/m_2$ . Evidently  $\mathcal{B}(h \rightarrow \chi_1 \chi_1)$  tends to be substantial and can approach unity, especially for  $m_h < 2m_W$  before the opening of the important  $h \rightarrow WW, ZZ$  channels. One can infer from the bottom plot and

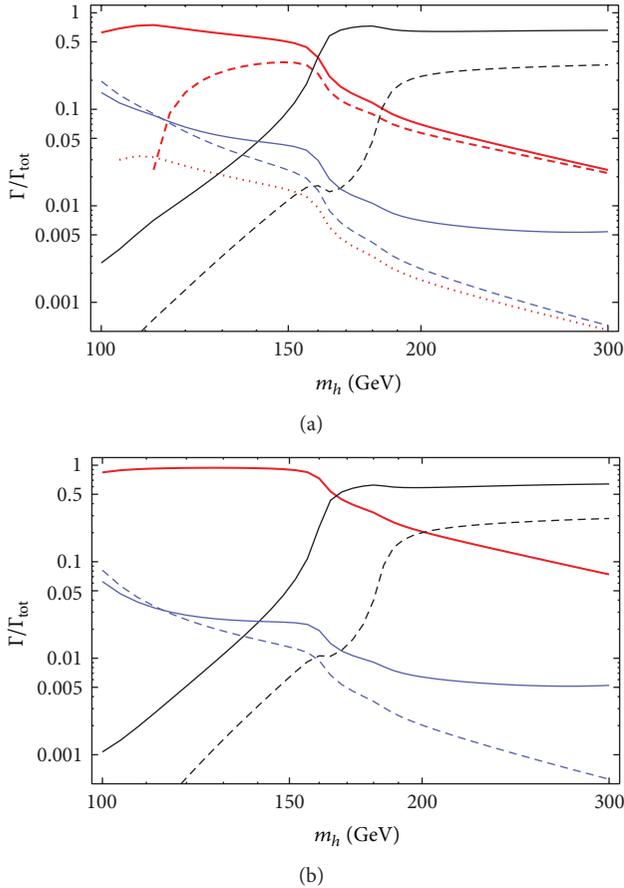


FIGURE 11: Branching ratios of the Higgs as a function of its mass in SM4 with stable fourth-generation neutrino  $\chi_1$  of mass  $m_1 = 45$  GeV and its heavier partner  $\chi_2$  of mass (a)  $m_2 = 55$  GeV and (b)  $m_2 \gg m_1$ . Red thick lines represent decays into  $\chi_1\chi_1$  (red solid),  $\chi_2\chi_2$  (dashed), and  $\chi_1\chi_2$  (dotted). Black lines represent decays into  $WW$  (solid) and  $ZZ$  (dashed). Blue lines represent decays into  $gg$  (solid) and  $b\bar{b}$  (dashed). Other decays have smaller branching ratios and are not shown. Plots from [8].

Figure 1 that for  $m_h \sim 120$  GeV and the viable range  $m_1 \sim 40$ – $50$  GeV the Higgs can be hidden from view. Since Figure 1 was based on assuming that the local density of  $\chi_1$  is proportional to its cosmic density and on limits from recent DM direct searches, we should note that a different assumption and more stringent data from future searches may yield a different conclusion.

It is worth remarking that for  $m_h < 2m_W$  the dominance of the decay into fourth-generation neutrinos will generally persist if there is another Higgs doublet in the scalar sector [90]. Yet the expanded parameter space in that case can accommodate the appearance of a Higgs with SM3-like characteristics.

**4.2. SM4 with Minimal Dark Matter.** In the SM4+D case, with all the fourth-generation fermions being unstable, the opening of the invisible channel  $h \rightarrow DD$  can drastically decrease the Higgs' visibility [20, 56]. Some examples of this

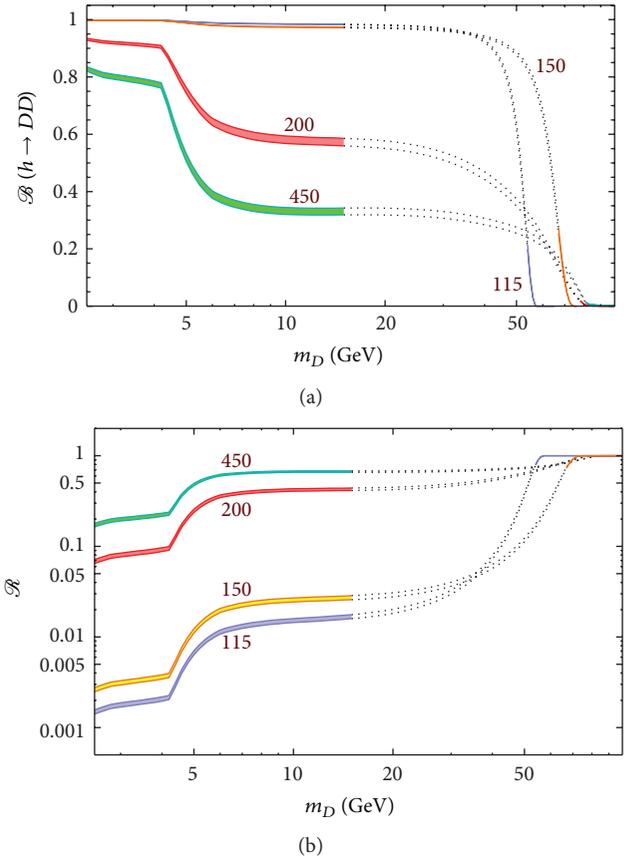


FIGURE 12: (a) Branching ratio of  $h \rightarrow DD$  as a function of  $m_D$  in SM4+D for  $m_h = 115, 150, 200, 450$  GeV. (b) The corresponding reduction factor  $\mathcal{R}$ . The black-dotted portions are disallowed by direct search limits. Plots from [56].

can be seen in Figure 12(a), drawn with the same values of Higgs-darkon coupling  $\lambda$  and their masses  $m_{D,h}$  as in Figure 5(a). Like the preceding scenario, the darkon effect is most striking for  $m_h < 2m_W$ .

Since the darkon has no gauge interactions and no mixing with the Higgs, in the SM4+D the rates of Higgs decays into visible particles are essentially the same as in the SM4 alone. Therefore their branching ratios in the SM4+D are all subject to the same reduction factor [55, 56]  $\mathcal{R} = \Gamma_h^{\text{SM4}} / (\Gamma_h^{\text{SM4}} + \Gamma(h \rightarrow DD))$ , where  $\Gamma_h^{\text{SM4}}$  is the Higgs width in the SM4 without the darkon. In Figure 12(b) we graph  $\mathcal{R}$  for the same  $m_{D,h}$  choices as in Figure 12(a). These graphs show that the visible branching ratios can be suppressed by up to 3 orders of magnitude. For  $m_h < 2m_W$ , although the SM4 with fourth-generation quark masses of hundreds of GeV predicts Higgs production cross-sections amplified by up to 9 times due to the enlarged  $gg \rightarrow h$  coupling [91], the enhancement would not sufficiently ameliorate the effect of the reduction factor  $\mathcal{R}$  in the SM4+D with  $m_D \leq 15$  GeV, causing the Higgs' to be highly invisible. On the other hand, for  $m_D \sim m_h/2$  the Higgs is mostly visible and for  $m_D > m_h/2$  its decay pattern is no different from that in the SM4.

**4.3. Impact of Higgs-Like Boson Discovery.** The recent observation at the LHC [92, 93] of a new resonance at  $\sim 125$ – $126$  GeV, with cross-sections and branching ratios consistent with those of the SM3 Higgs boson, supported by the latest findings from Higgs searches at the Tevatron [94], has spelled major trouble for the simplest version of the SM with four generations [95–98]. In particular, the large rate of  $H \rightarrow \gamma\gamma$  is difficult to accommodate in the SM4 with a minimal Higgs sector. However, the data acquired so far still offer room for the possibility that the discovered particle is some non-standard boson [99–101]. In the presence of a chiral fourth-generation, specifically, it turns out that one could expand the minimal SM4 with the appropriate extra particles in order to reproduce the current data well. This can be achieved, for instance, by adding another Higgs doublet [90, 102–108]. Such extended four-generation models may also include DM candidates, with phenomenology identical to the scenarios described in the previous sections. These scenarios are therefore still viable in general, once an extended Higgs sector is considered.

## 5. Summary and Discussion

In this paper, we have discussed some representative scenarios for dark matter in association with a fourth generation of chiral matter. In the first two scenarios, the DM is due to particles within the fourth generation itself (the fourth-generation neutrino and the up-type fourth-generation quark, respectively). This is a minimal solution in the sense that the motivation for the fourth-generation particles can be taken to be DM itself. However, some additional physics is needed to stabilize the DM candidate, typically a new  $U(1)$  symmetry with its associated gauge boson  $Z'$ .

Whereas the detection of direct generation of a stable heavy neutrino at the LHC might be very challenging, one discovery route might be through the decay of the  $Z'$  boson and possibly also through the production of heavier fourth-generation charged leptons which decay to the stable neutrino. A parallel detection route, if the stable neutrino has a significant left-handed component, is direct detection. In this case, if the fourth-generation neutrino has a nonnegligible contribution to the DM in our galactic halo, detection should be within reach for the next generation of experiments.

In the case of a stable heavy quark, direct detection of the DM particles is nearly impossible due to the large cross-section of the  $\bar{U}\bar{U}\bar{U}$ -Helium composites with terrestrial matter, slowing down the DM particles far below the necessary momentum transfer. However, if the mass of the stable quark is within reach for the LHC, the collider signature would be quite spectacular—massive, slow, highly ionizing particles which change charge as they pass through the detector.

In the third scenario, the DM resides in a hidden sector, and the role of the fourth-generation quarks is to act as mediators between the hidden sector and the visible sector. The quarks are therefore charged under both the hidden-sector and visible-sector gauge groups, and therefore must decay to SM quarks and DM. Comparing to sequential fourth-generation scenarios, due to the new conserved quantum

number of these exotic quarks, we do not have any of the regular CKM-inspired decays such as  $t' \rightarrow bW^+$ ,  $b' \rightarrow tW^-$ , and so forth. We focused on the situation where the new quarks couple predominantly to the third generation. The signatures for this scenario are quite similar to those of supersymmetric stop and sbottom production with decay to the lightest neutralino and SM quarks, but the production cross-section is an order of magnitude larger for the same mass, and there are no additional leptonic signatures from new charged electroweak states such as charginos and sleptons (apart from possible decays  $B' \rightarrow T'W^-$  or  $T' \rightarrow B'W^+$  if the mass difference between  $T'$  and  $B'$  is larger than the  $W$  mass).

Lastly, the fourth scenario is that of a sequential fourth generation with the addition of a neutral real scalar singlet, the darkon, coupling only to the SM Higgs field. In this scenario, the decays and other properties of the fourth-generation fermions are unchanged, and the only possibility to produce the darkon is through an (on- or off-shell) Higgs particle. This would therefore (together with scenario 1 of a stable fourth-generation neutrino) be the most difficult scenario to discover (or exclude) at the LHC. However, due to the small number of parameters of the model, most of the parameter space of this scenario can be tested at future direct detection experiments.

The recent discovery of a new resonance compatible with the SM3 Higgs boson seems difficult to accommodate within a fourth-generation scenario with a minimal Higgs sector. Nevertheless, present experimental as well as theoretical uncertainties still allow chiral fourth-generation models beyond the simplest versions, with or without DM, to survive. The viability of such extended models will likely be determined by measurements in the near future.

Finally, it is interesting to note the wide span of collider signatures associated with the scenarios treated in this paper, making them excellent benchmarks for LHC studies. Such benchmark studies, if presented in a model-independent way, can easily be reinterpreted to encompass also other models involving DM and new heavy states.

## Acknowledgments

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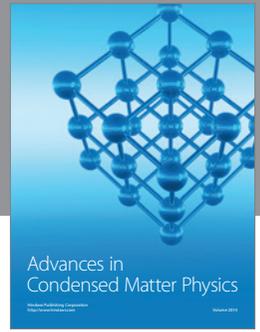
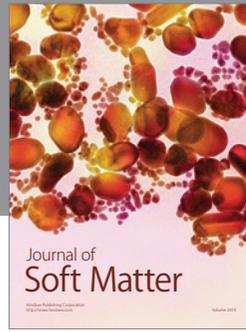
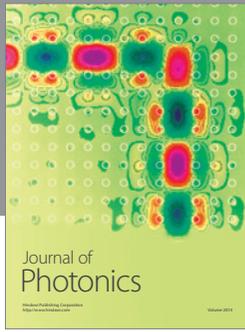
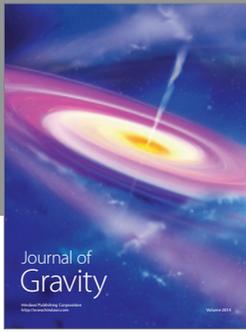
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