

WIMPS – how to hunt them and how to save them

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The non-observation of new physics at the LHC and in direct detection experiments puts significant pressure on the idea that dark matter consists of weakly-interacting massive particles (WIMPs) produced from thermal freeze-out. In light of these results I will discuss ways to extend the WIMP idea by introducing new mediators and/or additional states in the dark sector. Doing so affects the phenomenology of WIMP models in important ways, leading to additional constraints but also offering new ways to avoid thermal overproduction of dark matter. I will discuss how to constrain such models with the LHC and whether thermal dark matter can still be viable.

1 Introduction

Out of the many different approaches for explaining the observed abundance of dark matter (DM) in the Universe, the most widely studied paradigm is thermal freeze-out.¹ This idea is based on the assumption that DM particles were in thermal equilibrium with Standard Model (SM) states at high temperatures in the early Universe and then decoupled as the temperature dropped below the rest mass of the DM particles and their number density became exponentially suppressed. What makes this idea so appealing from the theoretical perspective is that a new stable particle with weak interactions and a mass around the electroweak scale is predicted to obtain roughly the correct relic abundance from thermal freeze-out. For this reason DM particles from thermal freeze-out are often referred to as Weakly Interacting Massive Particles (WIMPs).

But the WIMP idea is also appealing from the experimental perspective, because it makes a number of important predictions. First of all, the requirement of thermal equilibrium implies that DM must have some sizeable interaction with SM particles, meaning that it should be possible in principle to observe interactions of DM particles with ordinary matter. A number of strategies to search for such interactions have been devised and can be categorized in three different classes: indirect detection experiments trying to observe DM annihilation, direct detection experiments searching for DM scattering and collider searches for DM production. Crucially, it turns out that WIMPs cannot be arbitrarily heavy, because perturbative unitarity requires their mass to be below approximately 100 TeV.² It should therefore be possible to comprehensively probe the WIMP paradigm.

The search for WIMPs has so far however been without success. Most recently, a number of direct detection experiments, such as LUX³ and PandaX⁴ have published results from their most recent data sets without observing any significant excess over expected backgrounds. Similarly, the LHC has now performed a large number analyses at a centre-of-mass energy of 13 TeV, without finding evidence for the production of DM particles.⁵ These results raise the question whether the WIMP idea is beginning to be disfavoured, i.e. whether experimental data now excludes the bulk of the WIMP parameter space.

In this short talk I will try to answer this question by considering a number of different WIMP models. I will first review some of the simplest WIMP models and their experimental status and then discuss possible ways to extend these models. The central conclusion will be that extensions of the simplest models typically do not only open up new parameter space (to save WIMPs) but also lead to interesting new experimental signatures that can be used to devise new search strategies (to hunt WIMPs).

2 The status of simple WIMP models

We begin by reviewing different simple WIMP models. One can classify these models by the spin of the DM particle (which can be 0, $\frac{1}{2}$ or 1), the mediator of the DM interaction (which can be the SM Z boson or the SM Brout-Englert-Higgs (BEH) boson) and, in the case of fermionic DM, the parity and CP properties of the interaction.^{6,7} In each case one can then compare the coupling strength required for a successful prediction of the DM relic abundance from thermal freeze-out to current experimental bounds. For the case of DM particles interacting via Z boson exchange (the prototypical WIMP), the conclusion is essentially that direct detection constraints are so strong that these models have already been ruled out for a long time. The notable exception is the case of fermionic DM with axial couplings, where direct detection constraints are weakened. For example, a Majorana fermion (e.g. a supersymmetric higgsino) with mass around 1 TeV is still perfectly consistent with all experimental results.

It is important to note that these constraints rely on tree-level Z boson exchange. It is still perfectly possible for DM to be part of a multiplet of $SU(2)_L$ provided there is no direct coupling to Z bosons. A number of possible realizations of this so-called minimal DM⁸ have been considered in the literature. For the most promising candidate, a quintuplet with zero hypercharge, the only free parameter of the model is the mass of the DM particle, which is fixed to around 10 TeV from the requirement to reproduce the observed relic abundance. While direct detection experiments are not very sensitive to such a DM particle, strong indirect detection constraints arise from searches for gamma rays due to a significant Sommerfeld enhancement of the annihilation rate in the Galactic Centre.

For the case of BEH boson exchange (and neglecting CP-violating couplings) the situation becomes more interesting. While there is considerable tension for fermionic DM, there is viable parameter space for both spin-0 and spin-1 DM with a mass above the TeV scale. A particularly attractive case is the one where DM is a real scalar singlet, coupled to the SM via the so-called Higgs portal. This fully renormalizable three-parameter model offers arguably the simplest realization of the WIMP idea. A large number of studies of this model have been performed, most recently by the GAMBIT collaboration.⁹ The conclusion is that this simple model is still perfectly viable and can account for all of the DM provided the singlet mass is sufficiently large. Intriguingly, for singlet masses between 700 GeV and 2 TeV the contribution of the scalar singlet to the scalar potential stabilizes the electroweak vacuum, leading to a model that is viable all the way up to the Planck scale.¹⁰ Xenon1T will be decisive in probing this parameter space, demonstrating once again how experimental searches are closing in on the simplest WIMP models.

3 New mediators

The mounting experimental tension on the simplest WIMP models may lead one to conclude that it is time to abandon the WIMP idea and focus on alternative DM candidates, such as axions or sterile neutrinos. However, it is important to keep in mind that the thermal freeze-out paradigm is very general and does in particular not require the DM particle to participate in the SM weak interactions. Indeed, it is not necessary for the DM particle to couple directly to *any* SM particle, provided that there is a new mediating particle that is responsible for communicating the interactions of DM. Clearly, postulating the existence of such a new mediator will open up new parameter space, but it will also give rise to additional experimental constraints. A new mediator coupling to SM fermions, for example, may appear as a resonance at the LHC and is therefore constrained by searches for dijet and dilepton resonances.^{11,12}

The interesting question is therefore whether viable parameter space for thermal freeze-out remains when combining the results from DM searches with the direct constraints on new mediators. Compared to the relatively small number of simple WIMP models discussed above, the list of possible models of DM interacting via a new mediator is significantly longer, making it challenging to comprehensively discuss all possibilities. Nevertheless, we can significantly reduce the number of interesting cases by focussing on models that are more likely to be phenomenologically viable. First of all, one would like to avoid the strong constraints on spin-independent scattering from direct detection experiments, which can for example be achieved by focussing on Majorana fermions and spin-1 mediators. Secondly, strong constraints on the leptonic couplings of the new mediator compel one to focus on mediators coupling dominantly to quarks. A number of further possibilities (e.g. spin-1 mediators with purely axial couplings) are disfavoured by the requirement that the model respect the full gauge symmetry of the SM before electroweak symmetry breaking.¹³

An interesting example for a model that satisfies all of these criteria is the one where the new mediator corresponds to the gauge boson of a new $U(1)'$ gauge group, under which only quarks and DM are charged (with effective couplings g_χ and g_q , respectively). This gauge group is spontaneously broken by the vacuum expectation value of a SM singlet S , which thereby generates the mass of the Z' boson and the DM particle χ . After the spontaneous symmetry breaking, the physical component s of the new Higgs field can have a mixing angle θ with the SM BEH boson and thereby obtain couplings also to SM fermions. The model therefore contains two possible dark mediators: the Z' boson and the dark Higgs s . The relevant terms in the interaction Lagrangian are given by:

$$\mathcal{L}_\chi \supset -\frac{g_\chi}{2}\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu - \frac{y_\chi}{2\sqrt{2}}\bar{\chi}\chi s, \quad (1)$$

$$\mathcal{L}_q \supset -\sum_q \left(g_q \bar{q}\gamma^\mu q Z'_\mu + \sin\theta \frac{m_q}{v} \bar{q}q s \right), \quad (2)$$

where the two DM couplings are related via the underlying gauge symmetry via

$$\frac{y_\chi}{m_\chi} = 2\sqrt{2} \frac{g_\chi}{m_{Z'}}. \quad (3)$$

The model is fully described by six parameters (three masses and three couplings), out of which one can be eliminated by requiring the model to reproduce the observed DM relic abundance. For example, for given masses m_χ , $m_{Z'}$ and m_s one can eliminate the coupling g_χ and then scan over the remaining two couplings g_q and $\sin\theta$ to determine whether any combination of couplings can be consistent with all experimental constraints. An example for such a scan¹⁴ is shown in Figure 1. This plot shows the viable regions of parameter space as a function of $m_{Z'}$ and m_s for fixed $m_\chi = 100$ GeV. For the parameter points shaded in red it is impossible to find any combination of couplings that is consistent with the relic density

requirement as well as with all experimental constraints, whereas in the white regions at least one coupling combination can be found that is compatible with all requirements.

We make the following three observations from Figure 1 (and similar plots for different values of m_χ):

1. Heavy mediators are generally disfavoured. There is no allowed parameter space if both the Z' and the dark Higgs are significantly heavier than the DM particle.
2. Allowed parameter space is found if either $m_\chi = m_{Z'}/2$ or $m_\chi = m_s/2$, such that DM annihilations are resonantly enhanced and much smaller values of g_χ (and hence y_χ) are sufficient to obtain large annihilation cross sections.
3. Experimental constraints are significantly relaxed if either $m_{Z'} < m_\chi$ or $m_s < m_\chi$.

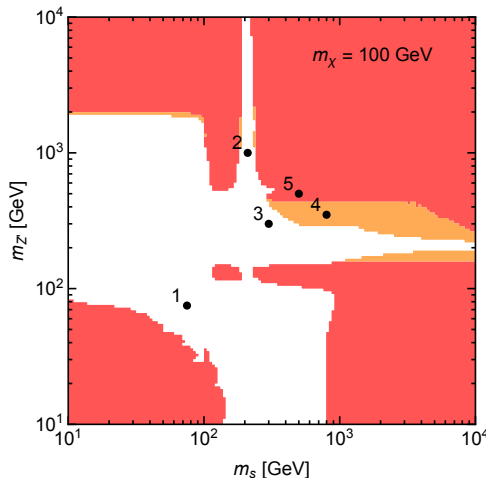


Figure 1 – Global scan for $m_\chi = 100$ GeV to determine those values of the two SM–mediator couplings that give the weakest constraints. The red shaded region is excluded for all possible combinations, while in the white region all constraints can be evaded. In the orange shaded region it is not possible to exclude large values of g_q , corresponding to large mediator width.

The final observation can be understood as follows. If one of the mediators is lighter than the DM particle, a new final state for DM annihilation opens up, namely either $\chi\chi \rightarrow Z'Z'$ or $\chi\chi \rightarrow ss$. Since the cross section for these processes is independent of g_q and θ , it is easily possible to reproduce the observed relic abundance while evading experimental constraints (as long as the couplings are large enough that the mediator decays eventually). Clearly, such a set-up deviates quite significantly from the simplicity of the original WIMP idea and likely warrants a different name such as *secluded DM*.¹⁵ Still, it serves as a useful illustration that thermal freeze-out can easily be viable in more complex dark sectors.

4 Experimental signatures of complex dark sectors

Let us finally focus on the question whether it is possible to probe models of DM interacting with a new light mediator experimentally. For concreteness, we consider the case in which the light mediator is the scalar singlet s discussed above. To be experimentally viable, this singlet must have a tiny but non-zero mixing with the SM Higgs boson, so that it can decay into SM fermions without violating experimental bounds on Higgs invisible decays. Due to the smallness of this mixing angle, it is virtually impossible to produce the new light scalar at colliders, and constraints from DM searches are equally suppressed. Nevertheless, couplings within the dark sector must be large in order for the dark Higgs field to generate the masses of the other dark sector particles. This means that, if any dark sector state can be produced at colliders (for

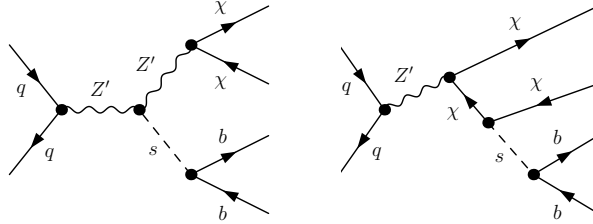


Figure 2 – Processes leading to a mono-dark-Higgs signal at the LHC.

example via the interactions of an additional Z' boson), it has a high probability of radiating off a scalar singlet (so-called dark-Higgs-strahlung). This is illustrated in Figure 2, which shows possible diagrams contributing to the process $pp \rightarrow \chi\chi s$.

It turns out that for large Z' masses the rate of dark Higgs bosons emitted with large transverse momentum from an intermediate or final state can become comparable to the rate of QCD radiation from the initial state, which is commonly used to search for DM production at the LHC. Moreover, since the dark Higgs will decay dominantly into b -quarks (for $10 \text{ GeV} \leq m_s \leq 150 \text{ GeV}$), we then end up with a very characteristic signal: a fat jet containing two b -jets with an invariant mass m_J close to the singlet mass, produced in association with large amounts of missing transverse momentum.¹⁶ In other words, we expect large production cross sections for a final state that can much more easily be distinguished from background processes than generic QCD radiation.

The experimental search for this new class of events is conceptually very similar to existing searches for SM BEH bosons produced in association with DM (so-called mono-Higgs searches). The only difference of a *mono-dark-Higgs* search is simply to consider general invariant masses of the fat jet. Adopting the event selection from a recent ATLAS analysis¹⁷, we find that the dominant background for $m_s < m_h$ stems from $V + b\bar{b}$, in agreement with the background estimates published by the ATLAS collaboration. As expected, however, the shape of the m_J -distribution is very different for signal and background. This makes it possible to achieve a sensitivity that significantly surpasses the the one of conventional mono-jet searches. This is illustrated¹⁶ in Figure 3, which shows the expected sensitivity of a mono-dark-Higgs search using 40 fb^{-1} in the conventional parameter plane of Z' mass versus DM mass for $m_s = 50 \text{ GeV}$ and fixed couplings. The conclusion is that mono-dark-Higgs searches are a highly promising way to probe models with an additional light Higgs boson in the dark sector up to Z' masses of several TeV and thereby explore dark sectors that would otherwise evade detection.

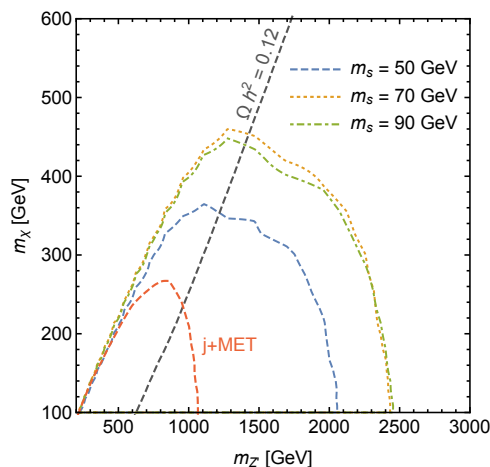


Figure 3 – Expected sensitivity of a mono-dark-Higgs search with an integrated luminosity of 40 fb^{-1} for different values of m_s . For comparison, we show the expected sensitivity of a conventional mono-jet search and the parameter combinations for which the observed relic abundance is reproduced.

5 Conclusions

Thermal freeze-out and in particular the WIMP idea have dominated DM model building for the past decades and have shaped the experimental search programme. While it is true that the non-observation of new physics at the LHC and null results in direct DM searches put significant pressure on this paradigm, it is important to note that some of the simplest WIMP models such as scalar singlets interacting via the Higgs portal are still viable. Nevertheless, it is certainly timely to question whether the idea of thermal freeze-out is beginning to be disfavoured and whether more emphasis should be placed on alternative approaches.

A useful way to address this question is to extend the simplest WIMP models by new mediators, which open up large new parameter space but also predict many new signatures, such as dijet resonances. Considering for example the case of new mediators from a broken $U(1)'$ gauge group, we find significant experimental pressure on heavy mediators. If on the other hand the dark sector has additional structure, for example because the additional singlet in the dark sector is light, thermal freeze-out remains perfectly viable. Intriguingly, such models of secluded WIMPs can be probed experimentally, for example with LHC searches for boosted fat jets in association with missing transverse energy. Implementing such new search strategies will help to make the best use of the increasing sensitivity of direct detection experiments and LHC searches in order to probe a wide range of viable realizations of the thermal freeze-out paradigm.

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