On the complementarity of Dark Matter Searches at Resonance

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We consider models of dark matter where the couplings between the standard model and the dark sector fall at resonance due to kinematics and direct detection experiments become insensitive. To be specific, we consider a simple model of 100 GeV - TeV scale dark matter coupled to the standard model via a vector boson. We explore whether it will be possible to exclude such regions of the parameter space using future observations of dijet rates at the LHC and CTA and AMS observations of the Galactic Centre.

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I. INTRODUCTION

One of the most compelling classes of dark matter are the thermal relics (including WIMPs) where self annihilation cross sections set by new physics at the electroweak scale give rise to a density comparable to that observed in the Universe today. There are many experimental searches in progress looking for this kind of dark matter. Collider searches (such as the LHC and its predecessor the Tevatron) hope to produce heavy dark matter particles directly in a laboratory setting and to test the interactions of heavier short lived particles to look for signals of new mediators to the dark sector. There are also direct detection experiments, such as LUX [1], looking for the interaction of astrophysical dark matter with baryons in detectors. Finally there are also indirect searches for dark matter such as Fermi [2] and CTA [3] which search for the standard model products associated with the self-annihilation of dark matter in space.

Each of these different methods for searching for dark matter adds complementary information which is very important in finding out if a given dark matter model is excluded by experimentation or not. One classic example is that of a fermionic dark matter particle which interacts with the rest of the standard model via an additional boson which has not yet been discovered, for example a new vector boson (see next section). The relic abundance of the dark matter particle is set by the rate at which it annihilates with itself in the early Universe, which depends upon both gauge couplings and kinematics. If the masses of the new particles just happen to be such that the dark matter has close to half the mass of the gauge boson then the annihilation will be resonant and the couplings can step in and give discriminating power.

The resonance will however increase the probability of the dark matter particle annihilating with itself, so we increase the sensitivity of gamma ray experiments such as CTA and Fermi for detecting a signal from this candidate.

In this letter we explore the complementarity of various experimental results on a simplified dark matter model, specifically to explore our ability to rule out or detect the model at resonance. First in section II the model is introduced, then in section III the various experimental constraints on dark matter are considered separately in the case where we keep the mediator mass fixed in order to understand qualitatively the way different constraints apply. Afterwards in section IV the different constraints are combined both for the case where we have a single mediator mass and when we allow it to vary. Finally we will discuss the results.

II. THE THEORETICAL SETUP

A. Lagrangian

We consider an extension to the standard model where a Dirac fermion dark matter candidate $\chi$ couples to the Standard Model through a new massive vector boson $A'$ (with a field strength $F'$). This additional vector boson couples to each of the quarks in a flavour blind way - the modification to the Lagrangian is given in equation 1 (this Lagrangian has been previously studied elsewhere [5–9]).

$$\Delta \mathcal{L} = - \frac{1}{4} F_\mu' F'^\mu + \frac{1}{2} m_A' A'_\mu A'^\mu + \bar{\chi} (\gamma^\mu \partial_\mu - m_\chi) \chi + A'_\mu \bar{\chi} \gamma^\mu (g_\chi V - g_\chi A' \gamma^5) \chi$$

$$+ A'_\mu \tilde{\gamma}^\mu (g_\ell V - g_\ell A' \gamma^5) \ell$$  \hspace{0.5cm} (1)

Without specifying the new Beyond the Standard Model (BSM) physics theory the direct mass for $A'$ is not gauge invariant but we assume the mass arises due to new physics at higher energies. The mediator mass is
fixed for the first part of this analysis to \( m_{A'} = 3 \) TeV in order to study in detail the behaviour of couplings around the resonance more clearly. We choose 3 TeV as it will be an energy range where dijet information is likely to improve significantly. The couplings are allowed to vary between \( 0 < g_{A'V} < 3 \) to maintain perturbativity while we consider dark matter masses in the range \( 0 < m_\chi < 2.5 \) TeV. The decay width of \( A' \) is given by

\[
\Gamma_{A'} = \frac{g_{A'q}\alpha_{A'}m_{A'}}{12\pi} \left[ 1 - \frac{4m_\chi^2}{m_{A'}^2} \left( 1 + \frac{2m_q^2}{m_{A'}^2} \right) \right] + \sum_q N_q g_{A'q} m_{A'} \left[ 1 - \frac{4m_q^2}{m_{A'}^2} \left( 1 + \frac{2m_q^2}{m_{A'}^2} \right) \right]
\]

Where we respect \( \Gamma_{A'} < 0.15m_{A'} \) in order to allow all the points to be studied in the context of CMS’s Narrow dijet searches discussed in section III B. This constraint places a limit on \( g_{A'q} \) while leaving \( g_{A'\chi} \) unaffected as the terms in equation[4] which are related to \( g_{A'\chi} \) come with an extra factor of the number of colours and flavours of quarks that the mediator can decay to, so small increases to \( g_{A'q} \) increase \( \Gamma_{A'} \) more rapidly. The majority of the couplings which give \( \Gamma_{A'} > 0.15m_{A'} \) have a coupling to the SM quarks which would lead to a direct detection cross section (discussed in section III A) which is already excluded by experimental searches.

**B. Relic Density**

The density of dark matter observed today assuming the normal \( \Lambda \)CDM cosmology is set by observations from the Planck experiment[10] which when combined with WMAP[11] observations give (where \( h \) is the dimensionless Hubble’s constant),

\[
\Omega_{DM} h^2 = 0.1198 \pm 0.0026
\]

While the relic density could be provided by a combination of particles, here \( \chi \) is treated as the only stable BSM particle so it must provide the full relic density within \( 2\sigma \) of the Planck value. We assume that \( \chi \) is in thermal equilibrium with the rest of the plasma at early times and that the relic density is given by the co-moving density of particles after freeze-out of the equilibrium.

We use micrOMEGAs[2] to calculate the relic density for the model considered here using the full integral formulation to avoid potential pitfalls in velocity expansion methods which could become more significant in resonance regions[12]. The cross section involved in the annihilation which determines abundance at the point of thermal freeze-out can be written:-

\[
\sigma(s) = \frac{4g_{A'V}^2g_{A\chi}^2s}{3\pi(s - m_{A'}^2)^2 + m_{A'}^2\Gamma_{A'}} \sum_q \frac{\beta_q}{\beta_\chi} \left[ \frac{2m_\chi^2}{s} + \frac{2m_q^2}{s} + \frac{16m_\chi^2m_q^2}{s^2} \right]
\]

where \( s \) is the centre of mass energy and the parameters \( \beta_q \) and \( \beta_\chi \) are given by

\[
\beta_i = \sqrt{1 - \frac{4m_i^2}{s}}
\]

Most of the energy of the annihilating dark matter particles is in their rest mass at freeze-out, so \( s \approx 4m_\chi^2 \). Because of this, around \( 2m_\chi \approx m_{A'} \) the product of the couplings goes towards zero. This is due to the cross section rapidly increasing as the annihilation approaches the resonant production of the mediating \( A' \), so to keep with the range for the relic density \( g_{A'V}^2g_{A\chi}^2 \) has to become correspondingly smaller.

**III. SEPARATE EXPERIMENTAL CONSTRAINTS**

**A. Direct Detection**

Recently liquid xenon detectors have given the best constraints on dark matter nucleon interactions using a combination of scintillation and ionization to help further discriminate between background and signal events by providing greater identification of nuclear recoil events.

Here the pure vectorial case \( (g_{A'\chi} = g_{A\chi} = 0) \) is investigated such that the spin independent direct detection experiments provide the strictest limits of which LUX[11] is the most recent and has the greatest exclusion for the dark matter mass range of interest (the exclusion is shown in figure 1). Alternatively the axial coupling
FIG. 2: Dijet limits and expected exclusions from a 14 TeV LHC with 300 fb$^{-1}$ as the ratio of the dijet resonance cross section and the CMS dijet search limit as a function of $m_\chi$. The vertical structure in the density of points at $m_\chi = 1400$ GeV and 1600 GeV is a numerical artefact of the search strategy.

could be investigated to find the impact of spin dependent searches on such models [13–15] as well as monojet searches [8]. For the low energies of the dark matter nucleon interaction with respect to the chosen mediator mass, resonance effects can be ignored. Even taking into account the projected future sensitivity of direct detection experiments (such as LUX-ZEPPLEIN [16]) these effects can produce thermal dark matter which would be unseen in direct detection.

B. Narrow Dijet Resonance

This model naturally leads to changes in the rate of dijet production at the LHC since there are $q\bar{q} \rightarrow A \rightarrow q\bar{q}$ processes, which would be produced resonantly. The use of dijets to constrain dark matter and the complementarity of such approaches with other search methods has been studied for a variety of models [17–21]. Though a signal alone would not be a clear sign of dark matter, it could be used as a cross check for models which avoid the LUX constraint. Current CMS dijet limits [22] (ATLAS has also searched for signals in this channel [23]) do constrain some of the parameter space. The cross sections for this model were calculated using calcHEP [24] with the trigger cuts for the jets applied to the outgoing quarks ($p_T > 30$ GeV and $|\eta| < 2.5$). As mentioned earlier, to be able to use the dijet limit we have restricted the decay width of our mediator to $\Gamma_A < 0.15 m_A$. While the t-channel exchanges are allowed their contributions are minimal compared to the s-channel on the resonance. To extend the effectiveness of this search channel, we estimate the limits after the 14 TeV run of the LHC producing 300 fb$^{-1}$ of data assuming no changes to the analysis and a similar signal to background ratio. This means the major increase would be from the increase in luminosity, so the cross section is scaled as the ratio of the square roots of the luminosity. Figure 2 shows the effectiveness of the dijet searches in excluding parameters which would not be seen by LUX. This plot also shows an asymmetry around the resonance - a mediator produced on shell can decay into a dark matter pair as $2 m_\chi < m_A$, which gives another decay channel for the mediator and thus reduces the branching ratio to dijets. The dijet limit is therefore stronger on the left of the resonance.

Looking at the effect this has on the allowed couplings (figure 3) it is clear that the dijet searches can put a strict constraint on $g_{qV}$ but have no direct effect on $g_{\chi V}$. This arises from the the major diagram in this model being proportional to $g_{qV}^2$ unlike both the relic density and direct detection diagrams which scale as $g_{\chi V}^2 g_{qV}^2$. Points with high $g_{\chi V}$ are favoured as the relic density fixes a value for the product of the couplings for a given set of masses, and LUX only constrains this product.

While mono-jet and $E_T$ searches are the favoured dark matter detection channel for collider searches (and have been studied in depth for this simplified model elsewhere [6–8]) they typically set a constraint on the product $g_{qV}^2 g_{\chi V}^2$. For the parameters which satisfy the dijet width constraints and evade detection by LUX the values of $g_{qV}^2 g_{\chi V}^2$ would produce a mono-jet signature at least 2 orders of magnitude below the current discovery bound from the most recent CMS results [25].
C. Indirect Detection

Finally we look at the implications of the indirect limits that can be obtained from the self annihilation of dark matter in regions of high density. The detectors are set up to observe the distribution of high energy photons, positrons and anti-protons from these proposed dense regions.

For gamma rays, the future Cherenkov Telescope Array (CTA) will be a promising experiment \cite{26–28} and many studies into the use of the CTA in dark matter detection have already been carried out \cite{3, 29–36}.

We also look at constraints from the AMS experiment on the production of anti-protons which can offer a useful constraint for a specific kinematic region \cite{37, 38}. We use micrOMEGAs to first calculate the self annihilation cross section for $\chi \bar{\chi} \rightarrow \Sigma q \bar{q}$ in the galactic centre and compared it to the proposed CTA \cite{36} and AMS limits \cite{38}.

Figure 4 shows that the proposed limits exclude all points with $2m_\chi > m_{A'}$ as in the zero velocity expansion of the self annihilation cross section the momentum is mainly from the mass of the annihilating particles. Conversely for $2m_\chi < m_{A'}$ a virtual mediator is produced. There remain a section of points which evade all these bounds, due to the ability for the couplings to become extremely small near the s-channel resonance.

IV. COMBINED EXPERIMENTAL CONSTRAINTS

A. Fixed $m_{A'}$

From the last section it can be seen that a large volume of the possible parameter space can be excluded and that future experiments will explore quite varied kinematic and coupling regimes. Figures 5 and 6 shows the region that could be excluded by future experiments when we combine these constraints. In the mass-direct detection cross section plot (figure 5) there is a region localised on the right hand side of the resonance curve of points that would not be seen by 14 TeV dijet searches but are excluded by CTA. This is due to the fact that in this
FIG. 7: Plotting the results for a range of different $m_{A'}$ values, brown points are cut by either LZ, Narrow dijet resonances, CTA or AMS. Round green points evade detection by all these methods.

part of parameter space the decay of the mediator into $\chi \bar{\chi}$ is kinematically unfavourable in the galactic centre. So at these setups will decay preferentially into standard model particles even for very small $g_{qV}$, including points with $g_{qV}$ too low to produce an observable dijet resonance signal.

The dijets would clearly be effective for setting an upper limit on the coupling to the standard model. The points which would not be excluded by these searches all lie in regions of parameter space where either both couplings are small or the coupling to dark matter is large which pushes down the quark coupling but finding a method to cut purely the dark matter coupling is extremely difficult.

B. Varied $m_{A'}$

In this section we allow $m_{A'}$ to vary so as to see where the dark matter particles lie which cannot be excluded by any experiment.

Figures 7 and 8 shows how the various experiments will restrict the parameter space for a range of $m_{A'}$ around the resonance in the thermal relic density, the $m_\chi$ is allowed to vary from 0 to 3 TeV with $m_{A'}$ being $2m_\chi$. Even for the lower mass dark matter the points which would not be excluded by LUX for this model still produce a monojet signature below the current experimental constraint.

V. CONCLUSIONS

There are many exciting new experimental programs which will shed light on the nature of dark matter over the next few years. In this work we have looked at the difficult situation where the dark matter mass is around half of the mediator mass. In this situation, the resonant enhancement means that the correct relic abundance can be achieved with small couplings making direct detection difficult.

We have tried to use other techniques to rule out such models such as narrow dijet resonances and indirect detection and while these techniques do rule out many of the models which pass LUX, we still find that there are parameter values that give good dark matter candidates. We also find that most of the models which can be ruled out using indirect detection are also ruled out by LZ.

There also exists a region of parameter space which would avoid direct detection where $m_\chi > m_{A'}$ so that in the early universe $\chi \bar{\chi}$ could annihilate into 2 $A'$ particles, but this requires a high $g_{qV}$ leading to points which have vanishingly low $g_{qV}$ so the constraints studied in this paper add no further cuts to that parameter space.

From these results it is clear that a combined analysis of a model with comparisons to dedicated Dark Matter searches and effects of the given model can be used to greatly constrain the parameter space. While some of these searches cannot be used as a discovery claim as signal is seen (such as dijets) as many other models or affects could be responsible, they can be useful for cutting parts of the parameter space which would be acceptable if only the dedicated searches were taken into account. The use of the simplified model enables one to see clearly the dependence of different constraints on different model parameter values. Hopefully this can inform possible constraints on more complete models.
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