Title

Particle physics implications and constraints on dark matter interpretations of the CDMS signal

Permalink
https://escholarship.org/uc/item/4qh758xx

Journal
Physical Review D, 90(1)

ISSN
2470-0010

Authors

Cotta, Randel C
Rajaraman, Arvind
Tait, Tim MP
et al.

Publication Date
2014-07-01

DOI
10.1103/physrevd.90.013020

Peer reviewed

UCI-HEP-TR-2013-10

Particle Physics Implications and Constraints on Dark Matter Interpretations of the CDMS Signal

Randel C. Cotta,[1] Arvind Rajaraman,[1] Tim M.P. Tait,[1] and Alexander M. Wijangco[1]
[1]*Department of Physics and Astronomy,*
University of California, Irvine, CA 92697, USA

(Dated: November 6, 2013)

Recently the CDMS collaboration has reported an excess of events in the signal region of a search for dark matter scattering with Silicon nuclei. Three events on an expected background of 0.4 have a significance of about 2σ, and it is premature to conclude that this is a signal of dark matter. Nonetheless, it is important to examine the space of particle theories capable of explaining this excess, to see what theories are capable of explaining it, and how one might exclude it or find corroborating evidence in other channels. We examine a simplified model containing a scalar mediator particle, and find regions consistent with the CDMS observations. Bounds from colliders put important restrictions on the theory, but viable points, including points leading to the observed thermal relic density, survive.

PACS numbers: 95.35.+d, 14.70.Bh

arXiv:1305.6609v2 [hep-ph] 5 Nov 2013

I. INTRODUCTION

Astronomical and cosmological probes of dark matter not only exist, but indicate that dark matter is five times as prevalent in the universe than the conventional forms of matter described by the Standard Model [1]. Despite this abundance however, knowledge of dark matter remains perplexingly incomplete. Principle among these unknowns are the mass of the dark matter (DM) particle and the nature of its interactions with the Standard Model (SM), both of which are unconstrained over many orders of magnitude.

A diversity of theoretical models has grown to accompany the diversity of allowed phenomenology [2]. Extremely light and weakly-coupled axions [3, 4] are a canonical scenario of DM with phenomenology that differs drastically from that of the more usually discussed WIMPs [5–10], though essentially arbitrary phenomenology can be obtained from hidden sector models [11–14], which may be designed to solve problems unrelated to dark matter (*e.g.*, generation of cosmic baryon number [15–17]).

Given this diversity, the experimental effort to measure such interactions has become increasingly creative. In addition to the traditional three-pronged experimental program consisting of direct detection, which seeks to measure DM-nucleon scattering, colliders searches for DM production and indirect detection searches for the energetic products of DM annihilation in astroparticle experiments, are studies of even more diverse effects, *e.g.*, observed and simulated shapes of DM halos [18], the detailed nature of the CMB [19–21] and primordial element abundances [22] and cooling of astrophysical objects [23].

Recently, the CDMS collaboration has made the interesting observation of an excess of 3 events over an expected background of 0.4 events, that can be interpreted as a signal detection with $\sim 2\sigma$ significance. Such a result is clearly inconclusive on its own and should be subjected to the utmost scrutiny, especially as the favored mass $m_{DM} \simeq 8.6\,\mathrm{GeV}$ coincides with the sensitivity threshold of the experiment. Despite these considerations, the result is very interesting in light of similar anomalous results, such as from CoGeNT [24], and in the favored-region's proximity to the predictions of some well-motivated theoretical models [25].

Describing a light DM particle with such (relatively) large interactions with the SM and that wouldn't have already been seen elsewhere is a phenomenological challenge. There exist several "portals" (in effective operator language: SM-singlet operators built only out of SM fields) by which such DM may easily communicate with the SM, each of which may naturally suggest vector, scalar or fermionic mediators and have been studied in some detail in the context of light DM [25–30]. In this work we will consider a generic model of Dirac fermionic DM interacting with the Standard Model via a relatively light scalar mediator particle. For such a model to avoid being ruled out from the outset we consider our mediator to be coupled to SM fermions in minimal-flavor-violating (MFV [31]) fashion, suggesting a natural connection between the physics that generates our DM and messenger to the physics of the Higgs sector and electroweak symmetry breaking. We will describe regions of parameter space for which our model obtains scattering in the range of the CDMS result, where the annihilations in our model are sufficient for equalling the cosmological DM relic density and regions that are already ruled out by collider and low-energy experiments.

The rest of this paper is divided into four sections. In Section II we describe and discuss our simplified model framework, in Section III we describe our model's DM phenomenology, in Section IV we describe collider and low-energy bounds that can be placed on the parameter space of our model and in Section V we present a concluding discussion.

II. SIMPLIFIED MODEL FRAMEWORK

We work in the framework of a simplified model consisting of the Standard Model supplemented by a Dirac DM particle χ and a CP-even scalar messenger ϕ. Since the CDMS signal is suggestive of a WIMP whose mass is well below $M_Z/2$, we restrict ourselves to considering dark matter which is an electroweak singlet in order to avoid large contributions to the invisible width of the Z boson [32]. Fitting the CDMS signal region will imply $\mathcal{O}(0.1-1)$ coupling between ϕ and $\bar{\chi}\chi$, suggesting that ϕ should also be an electroweak singlet. The mass of the χ is fixed by the CDMS signal to $m_\chi \simeq 8.5$ GeV. In the discussion below, we fix the dark matter mass to this value and comment where appropriate as to how our results would change for different masses.

In order to evade very strong bounds from flavor-violating observables, we invoke minimal flavor violation [31] with regard to the ϕ coupling to quarks,

$$\mathcal{L}_{int} = g_\chi \phi \bar{\chi}\chi + \sum_i g_d \lambda_i^d \phi \bar{d}_i d_i + \sum_i g_u \lambda_i^u \phi \bar{u}_i u_i \tag{1}$$

where λ_i^d and λ_i^u are the down-type and up-type Yukawa interactions. In addition to the masses m_χ and m_ϕ, the model is specified by the dimensionless couplings to dark matter g_χ, to down-type quarks (scaled by the appropriate Yukawa interaction) g_d, and similarly defined coupling to up-type quarks g_u. In what follows we will work primarily in the 3-dimensional space (m_ϕ, g_χ, g_d). We consider two distinct cases for g_u:

- $g_u \sim 1.8\ g_d$, leading to iso-spin preserving (IP) elastic scattering in direct detection experiments; or
- $g_u \sim -1.015\ g_d$, leading to isospin-violating (IV) scattering with $f_n/f_p \sim -0.7$, designed to maximally weaken the sensitivity of Xenon-based searches [33].

It is worth noting that even for $g_u \sim\ g_d$, the elastic scattering cross section will be similar for protons and neutrons, owing to the relatively small contribution of the up and down quarks because of their small Yukawa interactions. One could also write down (and put bounds on) a coupling between ϕ and leptons, but such an interaction is largely orthogonal to a discussion of the CDMS signal. Where relevant, we will comment on the bounds on such a coupling below.

There are also potentially renormalizable interactions between ϕ and the Standard Model Higgs doublet, H. In general, the details of the scalar potential are not very important for the phenomena of interest here, and we leave a detailed analysis for future work. However, it is worth noting that mixing between ϕ and the Higgs boson allows for ϕ to be produced via typical Higgs production modes, including ϕZ at LEP II. For masses less than about 110 GeV, null results of Higgs searches at LEP generically imply that the mixing is no larger than $\mathcal{O}(10\%)$ [34], although there are windows of mass where bounds are weaker, and might even be interpreted as not very significant hints for a positive signal [35].

While we remain agnostic as to the origin of the simplified model framework, it is worth noting that one can imagine a simple UV-completion of the scalar sector based on a two Higgs doublet model augmented by a gauge singlet scalar. The two Higgs doublets provide sufficient freedom in the Yukawa couplings so as to realize g_u and g_d in the desired ranges, with the (mostly singlet) ϕ inheriting the couplings through modest mixing with a combination of the physical CP even Higgs bosons. Perhaps the most studied model containing these ingredients is the NMSSM [36, 37]. It has been pointed out that one can find limits in the NMSSM parameter space that attain large scattering cross-sections with a low DM mass [38–40] although there may be some tension with other constraints as, in supersymmetric models like these, large cross-sections tend to come hand-in-hand with sizable couplings to $W^{\pm}/Z^0$ [41]. Variations of supersymmetric models consisting of the MSSM plus a singlet super-field can realize suitable cross sections [42–44]. For an example of a non-supersymmetric UV completion see [45].

III. DM OBSERVABLES

In this section we focus on finding regions of our parameter space that are attractive from a DM standpoint: light DM with large elastic scattering cross-sections. Although we are particularly interested in scattering, we also calculate relic density and discuss current annihilation cross-sections for our χ to give a sense of the cosmological history necessary in such a scenario. We consider messenger masses in a wide range, $1\,\text{GeV} \lesssim m_\phi \lesssim 100\,\text{GeV}$, anticipating (as is confirmed below) that mediator masses above $\sim 100\,\text{GeV}$ will be non-trivially constrained by collider monojet searches[1]. We use *MicrOMEGAs v2.4* [47] for all elastic scattering and annihilation cross section calculations.

For our direct detection calculation we use a local DM density $\rho_0 = 0.3\,\text{GeV/cm}^3$ and nuclear form factors:

$$\begin{aligned} f_u^p &= 0.023, \qquad & f_d^p &= 0.033, \qquad & f_s^p &= 0.05, \\ f_u^n &= 0.018, \qquad & f_d^n &= 0.042, \qquad & f_s^n &= 0.05. \end{aligned}$$

Appropriate values for the strange-flavored scalar form factors are hotly-debated at current [48–55], the choice $f_s^N \approx 0.05$ is on the low side of proposed values, making it a conservative choice for our purposes. The uncertainty coming from the strange quark is anyway not critical for our purposes: we consider a wide range of elastic scattering cross-sections[2],

$$10^{-6}\text{pb} \lesssim \sigma_{\text{SI,N}} \lesssim 3 * 10^{-4}\text{pb}, \tag{2}$$

as interesting for our purposes. The scattering cross section depends on the couplings only through the product, $g_\chi g_d$.

We calculate the thermal relic density of our χ assuming that the only relevant processes at freezeout are those in our simplified model. As always, this is a fairly heavy-handed assumption and may or may not be relevant in any particular completion of our model. Despite this, our thermal relic calculation remains useful for denoting regions of parameter space where extra theoretical structure[3] may be necessary to increase or decrease the relic density with respect to our minimal scenario and where our model saturates the *Planck* collaboration's measurement [1], $\Omega_{CDM}h^2 \approx 0.1146$, on its own. Annihilations proceed through t-channel $\chi\bar{\chi} \to \phi\phi$ (when kinematically available) and through s-channel $\chi\bar{\chi} \to f\bar{f}$, the former depending on the couplings only as g_χ^2 and the latter as $g_\chi g_d$. Both of

---

[1] For mediator masses heavier than typical LHC center-of-mass energies the limit should be essentially the same as the stringent EFT bounds derived in [46]

[2] This range corresponds to the lower-most and upper-most values on the 2σ ellipse of the result [56].

[3] *e.g.*, non-thermal evolution or dark sector states that participate in the thermal calculation

these processes are actually p-wave processes at leading order (suppressed by $v^2 \sim 10^{-6}$) so current annihilations from our simplified model are predicted to be much below the canonical $\langle \sigma v \rangle \sim 3 * 10^{-26}\mathrm{cm}^3/\mathrm{s}$. Similarly low rates are calculated in the resonant region $2m_\chi \approx m_\phi$, although *Planck*-level relic densities are achieved for much lower coupling values. If our model were to also include a pseudo-scalar state, a, then there would be available s-wave processes giving current annihilations close to the canonical value[4]. Such pseudo-scalars are not hard to come by theoretically (*e.g.*, in approximately SUSY-preserving multiplets) and would have no effect on scattering rates (momentum suppressed) but potentially sizable effects on the other observables, such as collider production.

In Figure 1 we map out the combinations of g_χ and m_ϕ for which scattering cross sections are within the range Eqn. 2 and for which the relic density matches the *Planck* value for both IP and IV cases and for several values of g_d. The features of the relic density band are easy to understand: there is a sharp upturn where the $\chi\chi \to \phi\phi$ channel becomes phase space suppressed ($m_\phi \approx m_\chi$) and a sharp downturn in the resonant annihilation region ($m_\phi \approx 2m_\chi$). Annihilation cross-sections (not shown) are $\langle \sigma v \rangle \lesssim 3 * 10^{-30}\mathrm{cm}^3/\mathrm{s}$ on the *Planck* band. In the IV case, scattering cross-sections are reduced by destructive interference and we observe a shift of the favored region for scattering toward larger coupling values. We observe regions where both large scattering cross-sections and $\Omega_\chi \approx \Omega_{CDM}$ can be obtained simultaneously, for essentially any choice of g_d. While this happens both for very light mediators ($m_\phi < 10\,\mathrm{GeV}$) and for very heavy mediators ($m_\phi > 20\,\mathrm{GeV}$), we expect these regions to be in danger either from Υ-decay data or from collider searches. In contrast, regions of overlap in the $m_\Upsilon < m_\phi < 2m_\chi$ range are particularly hard to constrain.

---

[4] As may be desired given the current (inconclusive, but interesting) hints of $\sim$ 10 GeV DM particles annihilating to b's or τ's conributing to the γ-ray spectrum at the Galactic Center [57, 58].

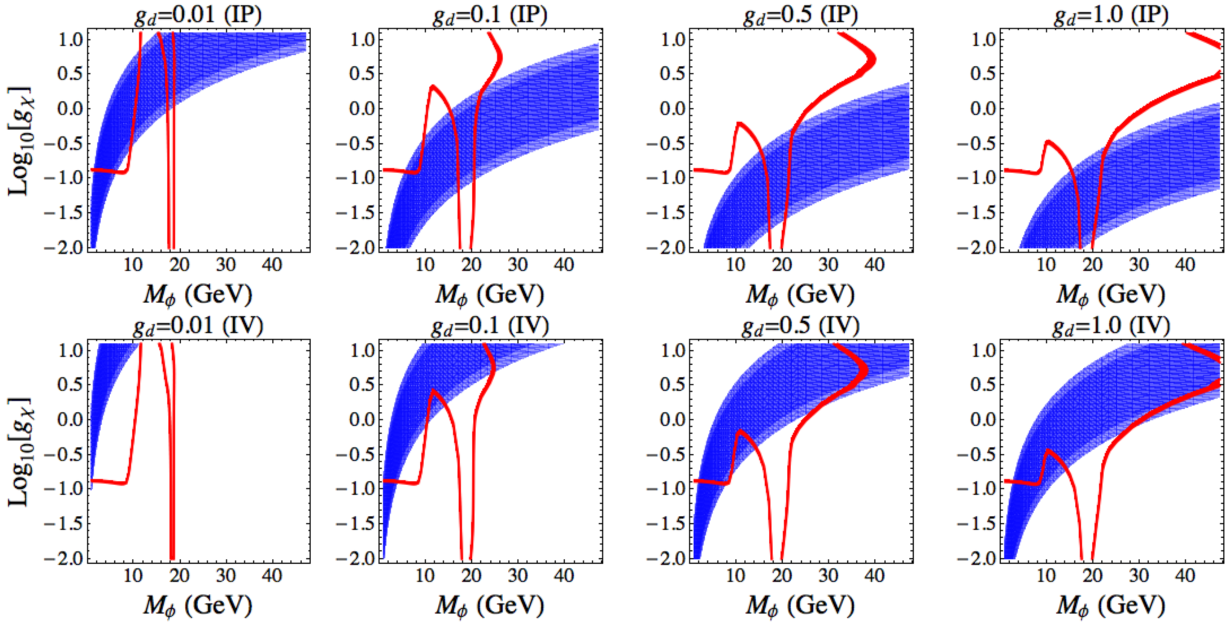


FIG. 1: Spin-Independent Scattering and Relic Density. The blue band denotes SI scattering cross-sections within the range Eqn. 2 (darker and lighter regions describing the extent of 1σ and 2σ ellipses in the result [56], respectively). The red band shows where our χ's relic density is $\Omega_\chi \approx \Omega_{CDM}$. In the upper panels g_u and g_d are related such that $f_n = f_p$ (IP), while in the lower panels $f_n/f_p = -0.7$ (IV).

IV. COLLIDER & LOW-ENERGY CONSTRAINTS

A. Mono-Objects

Intuition garnered from DM effective theory analyses over the last few years suggests that collider searches may have the final say on the viability of this scenario [46, 59–68]. Such searches typically look for DM direct production by studying single objects (monojets, monophotons, etc.) recoiling off of a missing transverse momentum vector and, unlike direct detection experiments, remain sensitive to arbitrarily small DM masses. The caveat to these searches is the efficacy of the EFT description, which can give either an overly-conservative or an overly-optimistic sense of the collider reach in light-mediator scenarios. For our mediators, with the DM mass fixed at $m_\chi = 8.5\,\text{GeV}$, there are roughly three regimes for collider production: *(i)* the mediator is very heavy compared to typical machine center-of-mass energies, *(ii)* the mediator is light compared to collider center of mass energies but heavier than $2m_\chi$ and *(iii)* the mediator is lighter than $2m_\chi$. Scenario *(i)* is the regime where the EFTs should give basically the right answer, in scenario *(ii)* the mediator can be produced on-shell so we would expect the EFT bounds to be conservative relative to the exact bounds and in scenario *(iii)* the mediator can never be put on-shell, the production cross-section is a rapidly falling function of the mono-object's p_T and the EFT bounds would suggest much tighter constraints than what one would actually get in the full calculation. Of course these regimes bleed into each other a bit, here we seek to describe this behavior. For studies involving light vector mediators, see Refs. [69–72].

Here we focus on LHC monojet searches, which we expect to provide the tightest constraints in this class of experiments. Monojet bounds from the Tevatron were checked (*c.f.*, [62]) as well and they are not competitive with those coming from the LHC[5]. We mimic cuts from the ATLAS analysis [73] and use the typical *MadGraph*(v5)-*Pythia*(v6)-*PGS*(v4) chain [74–76] (hereafter *MPP*) with default ATLAS detector card to simulate signal and background rates. Monojet bounds are presented in Figure 2. The features of these curves can be easily understood: The cross-section is highly suppressed and nearly constant in the $m_\phi < 2m_\chi$ regime where the mediator cannot be put on-shell. The kink occurs at $m_\phi = 2m_\chi$ whereafter the monojet bounds become more and more constraining until the eventual fall off above typical center-of-mass energies. We know that our couplings must increase with the mediator mass in order to have scattering cross-sections in the range Eqn. 2, here we see that our model will actually run into monojet constraints before reaching its ultimate perturbativity bound at $g_\chi g_d \sim 4\pi$. Interestingly however, Figure 2 shows that the monojet reach is much less than that from the heavy-flavor $t\bar{t}+$MET search for all m_ϕ, this is what we will describe next.

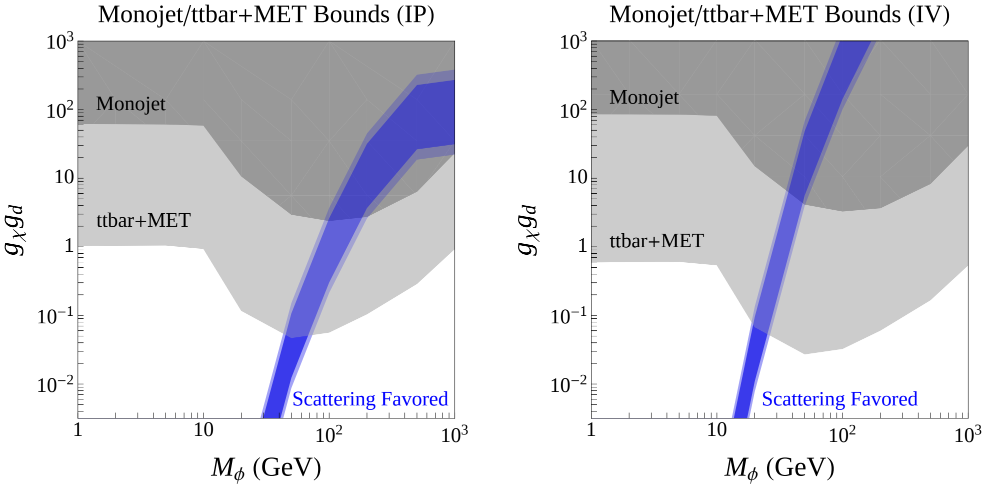


FIG. 2: Monojet and $t\bar{t}+$MET bounds on our model in the $g_\chi g_d$ vs. m_ϕ plane (IP left panel, IV right panel). The blue bands gives scattering cross-sections in the desired range, as in Fig. 1, while the gray regions are excluded by the ATLAS monojet search [73] and the ATLAS $t\bar{t}+$MET search [77] (both at 95% confidence) as noted in the figure. The limits in this plot were generated with fixed $g_d = 1$.

B. Heavy-Flavor Searches

While the MFV structure of our messenger's couplings keep direct collider production of ϕ's highly-suppressed, the large couplings to top and bottom quarks suggest large rates for ϕ's radiated off of the final states in heavy flavor (HF) production. Since our ϕ's may

---

[5] Monophoton bounds from LEP are irrelevant unless our mediator were to have large couplings to the electron, which seems unlikely in our construction.

be made to decay either dominantly to missing transverse energy (for $g_\chi \gg g_d$) or to $b\bar{b}$ (for $g_d \gg g_\chi$), heavy flavor searches both with and without associated MET may be applicable. HF searches with MET are typical of the suite of SUSY searches for third-generation squarks (*e.g.*, [77]), while HF searches without MET are not nearly as common. An example of the latter is the search for signals of Higgs production in the $t\bar{t}H \to t\bar{t}b\bar{b}$ channel (in practice, the $t\bar{t}$+b-jet channel [78, 79]). Here we investigate bounds on our model's parameter space that can be derived from these two searches. Another recent work that considered heavy-flavored final states and dark matter is [80]

The ATLAS analysis [77], uses 13 fb^{-1} of 8 TeV data to place very stringent constraints, $\mathcal{O}$(1fb), on $t\bar{t}$ + MET from BSM sources. Here we use the full *MPP* analysis chain to simulate the SM background to this search and to get a sense of the acceptance profile for tagging the two tops in our signal. To calculate the signal rate we assume that the acceptance (more precisely, the part of which comes from top-tagging) for signal events is essentially the same as that for the SM background. This allows us to do an initial calculation of the signal at parton level, before applying the more involved m_{T2} cut to accurately reproduce the MET acceptance (the quantity that is really sensitive to the kinematics of our signal events) in reasonable computational time. The particular MET and p_T cuts that we used were those of the "110 SR" signal region defined in [77]. The resulting excluded region is described in Figure 2 and is seen to be stronger for all m_ϕ than that from the monojet search. Our model's mediator mass is bounded to be $m_\phi \lesssim 45\,\text{GeV}$ (IP) or $m_\phi \lesssim 20\,\text{GeV}$ (IV), in both cases far smaller than the model's ultimate perturbativity bound $g_\chi g_d \lesssim 4\pi$.

In the $t\bar{t}b$ channel it is more difficult to obtain an accurate bound in our parameter space. The most relevant[6] analysis in this regard is the ATLAS measurement [79] of the ratio of $t\bar{t}b$ and $t\bar{t}j$ (where b denotes a b-tagged jet and j denotes all jets) in 4.7 fb^{-1} of 7 TeV data. The result is not easy to interpret as a bound in the present context, as the measured ratio $t\bar{t}b/t\bar{t}j$ is found to be in excess of the SM expectation at the 1.4σ level. Rather than trying to interpret this as evidence for new physics, we simply suppose that the measurement is roughly consistent with the SM (including a 125 GeV Higgs) prediction and require that our model not contribute to $t\bar{t}b$ at a level greater than that from the Higgs. We calculate both the $t\bar{t}\phi$ and $t\bar{t}H$ cross-sections using *MPP* with the "nominal" sample selection cuts described in [79] to determine the "excluded" regions for which the $t\bar{t}\phi$ cross-section is greater than the $t\bar{t}H$ cross-section. The result is described in Figure 3, where the excluded region is compared to the preferred regions for scattering with two choices for g_χ, $g_\chi = 0.01$ and $g_\chi = 1$ (as the $t\bar{t}\phi$ cross-section depends only on g_d).

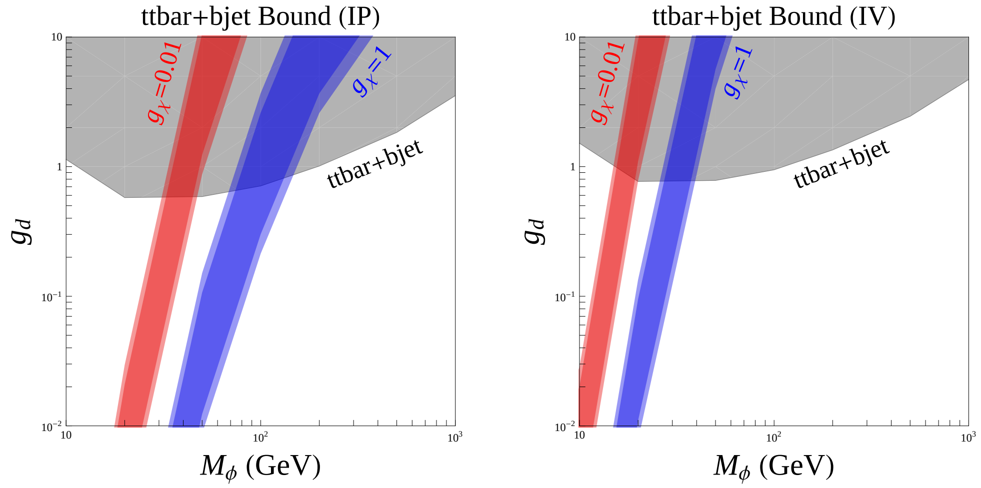
C. B-Factory Constraints

For mediators with $m_\phi \lesssim m_\Upsilon \approx 10\,\text{GeV}$ one must consider the possible signatures of our model in $\Upsilon(nS)$ decay processes. Since our DM has $2m_\chi > m_\Upsilon$ we do not expect signatures in Υ decays with invisible products (although these would become relevant for $m_\chi \lesssim 5\,\text{GeV}$), instead we consider radiative Υ decays, $\Upsilon(nS) \to \gamma\phi \to \gamma X$ where[7] X is some visible system recoiling off of a monochromatic γ. We consider two *BaBar* collaboration

---

[6] The analysis [78] uses a similar data sample but is too focused on the SM Higgs to be useful in bounding our model.

[7] Of course, "ϕ" here refers to our mediator, not the light unflavored meson.


ttbar+bjet Bound (IP)

ttbar+bjet Bound (IV)

FIG. 3: Heavy Flavor bounds on our model in the $t\bar{t}b$ channel (IP left panel, IV right panel). As this search depends only on the coupling g_d we display, in red and blue bands, the favored regions for scattering with $g_\chi = 0.01$ and $g_\chi = 1$, respectively. The gray region denotes parameter space for which the $t\bar{t}\phi$ production cross-section is greater than that for $t\bar{t}H$ production of the SM Higgs (our rough criterion for exclusion given the result [78]).

analyses: [81], a search for photon resonances in $\Upsilon(3S) \to \gamma +$ hadrons and [82], a search for photon resonances in $\Upsilon(1S) \to \gamma + \tau^+\tau^-$. Both of these results provide a bound on g_d (independent of g_χ), the former considering only quark coupling while the latter requires the model-dependent assumption that $g_l = g_d$. We calculate the associated rates in our model space, following closely the work [83]. The resulting bounds are shown in Figure 4. The Υ data limits the g_d coupling to be generally $g_d \lesssim 0.1$ for models with $m_\phi \lesssim 10$ GeV, ruling out favored parts of parameter space where g_χ is small. There is a large dependence on the choice of IP or IV scattering, the latter being constrained much more tightly at a given scattering cross-section by the Υ data.

D. Exotic Higgs Decays

Given the necessarily small mixing between our messenger and the SM Higgs, we expect that the current constraint on the Higgs invisible width (about 40%, per [84]) is not tight enough to constrain our model. If our mediator is light, $m_\phi \ll m_H$, then, as in many NMSSM discussions, we may imagine producing a pair of boosted ϕ's and searching for pairs of boosted objects from their decays. While the rate of such events depends on the details of the UV physics that give rise to our simplified model, the resultant striking signature may be the first place in which such a model can be discovered.

An example of such an analysis is the "ditau-jet" search strategy, outlined in [85], wherein one tries to discern "jets" composed of a pair of boosted τ's (*e.g.*, coming from the ϕ decays) from generic QCD jets. In this work it was demonstrated that (with consideration of a jet's p_T/m_j ratio and application of jet-substructure techniques) one can tag ditau-jets with high-efficiency and low-mistag rates. It was argued that, for a light-scalar model with nearly exactly the same kinematics as ours, an appropriate series of cuts would yield effective

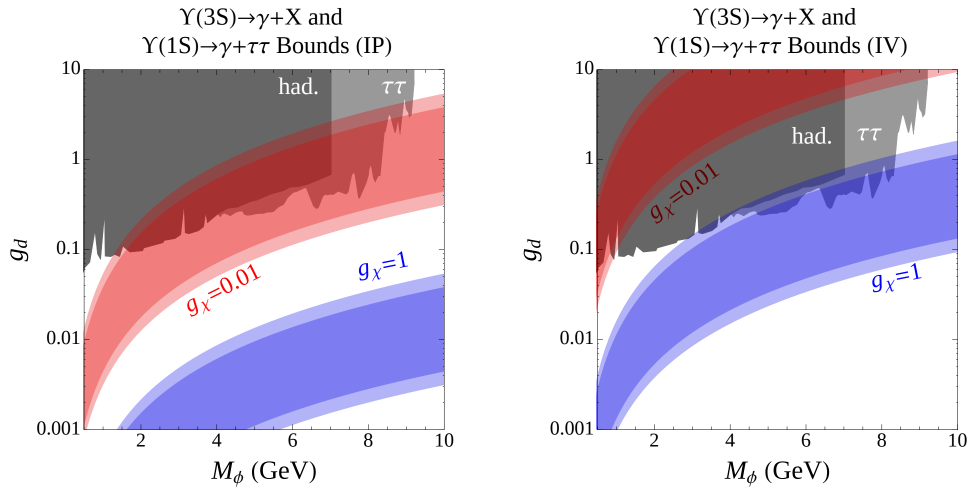


FIG. 4: Bounds from the radiative ϒ-decays to hadronic and di-tau final states. Gray regions are excluded by *BaBar* analyses [81] and [82] (as noted in the figure) at 90% confidence. The red and blue bands give direct detection favored regions for $g_\chi = 0.01$ and $g_\chi = 1$ as in Fig. 3. Favored regions are calculated for both IP (left) and IV (right) cases.

signal and background cross-sections of $\sigma_s = 0.5$ fb and $\sigma_b = 0.12$ fb, and thus a $S/\sqrt{B} = 5$ discovery for $\mathcal{L} = 12$ fb^{-1} of 14 TeV LHC data. In our model, if we assume that down-type quarks *and* down-type leptons are both normalized with the parameter g_d, then $BR(\phi \to \tau\tau) \sim \mathcal{O}(10\%)$. Given this then, even assuming a scalar trilinear coupling $g_{h\phi\phi} = \sqrt{4\pi}$, our model would be far from detectable in such a search. If, however, the lepton couplings are normalized independently of g_d then, with g_l such that $BR(\phi \to \tau\tau) \sim \mathcal{O}(100\%)$, our model would also be observable in $\mathcal{L} = 12$ fb^{-1} of 14 TeV LHC data.

V. DISCUSSION

We have investigated diverse bounds on the parameter space of a simplified model of DM whose phenomenology could plausibly explain the low-mass and high-cross-section signal of DM scattering in the CDMS Silicon data. Our model is typical of some extensions of the SM Higgs sector that give light scalars coupling to SM fermions in an MFV pattern (*e.g.*, coupling like a Higgs). We have shown that such models can easily attain the necessary large scattering cross-sections for couplings of $\mathcal{O}(0.1 - 1)$, while also attaining the correct relic density, in many regions of this subspace. If such a model were to be supplemented with a pseudoscalar of similar mass to our messenger ϕ, essentially none of the above story would change qualitatively, except that one would have the kind of canonical s-wave annihilation rates that we may already be seeing in the Galactic Center.

We have discussed collider and low-energy B-factory bounds on our parameter space and the complementarity of these bounds. A round-up of these results is described in Figures 5-6, where all bounds are collected and plotted in the $g_\chi g_d$ vs. m_ϕ plane. Results are given for two different choices of $g_\chi = 1$ and $g_\chi = 0.1$. In Fig. 5 we find that, for large $g_\chi = 1$, the combination of $t\bar{t}+$ MET and $\Upsilon(nS)$ data require $g_d \lesssim 0.1$ except in the difficult region $m_{\Upsilon(3S)} < m_\phi < 2m_\chi$ where $g_d \lesssim 1$. For smaller $g_\chi = 0.1$ we see that the $t\bar{t}$+b-jet bound (depending only on g_d) supplants the $t\bar{t}$+MET bound (depending on $g_\chi g_d$) to require $g_d \lesssim 1$ for all m_ϕ. In Figure 6 we overlay the favored regions for scattering and relic density in our parameter space. We see that the isospin-violating case is more highly constrained than the isospin-preserving case, owing to the generally larger product $g_\chi g_d$ required to produce scattering signals at the CDMS level.

The fact that a light DM particle and scalar messenger coupling **so strongly** to SM fermions is even phenomenologically viable at this point is very interesting. It is completely plausible that a model like ours could be discovered first in direct detection experiments (as it may already have been!), especially for mediator masses in the difficult range $m_{\Upsilon(3S)} < m_\phi < 2m_\chi$. From what we have shown it is also plausible that such a discovery could be corroborated (or such a model ruled out) by LHC searches for anomalous heavy flavor final states, strongly motivating a more careful look at such signatures under more generic (*i.e.*, than SM Higgs or MSSM sparticle) expectations.

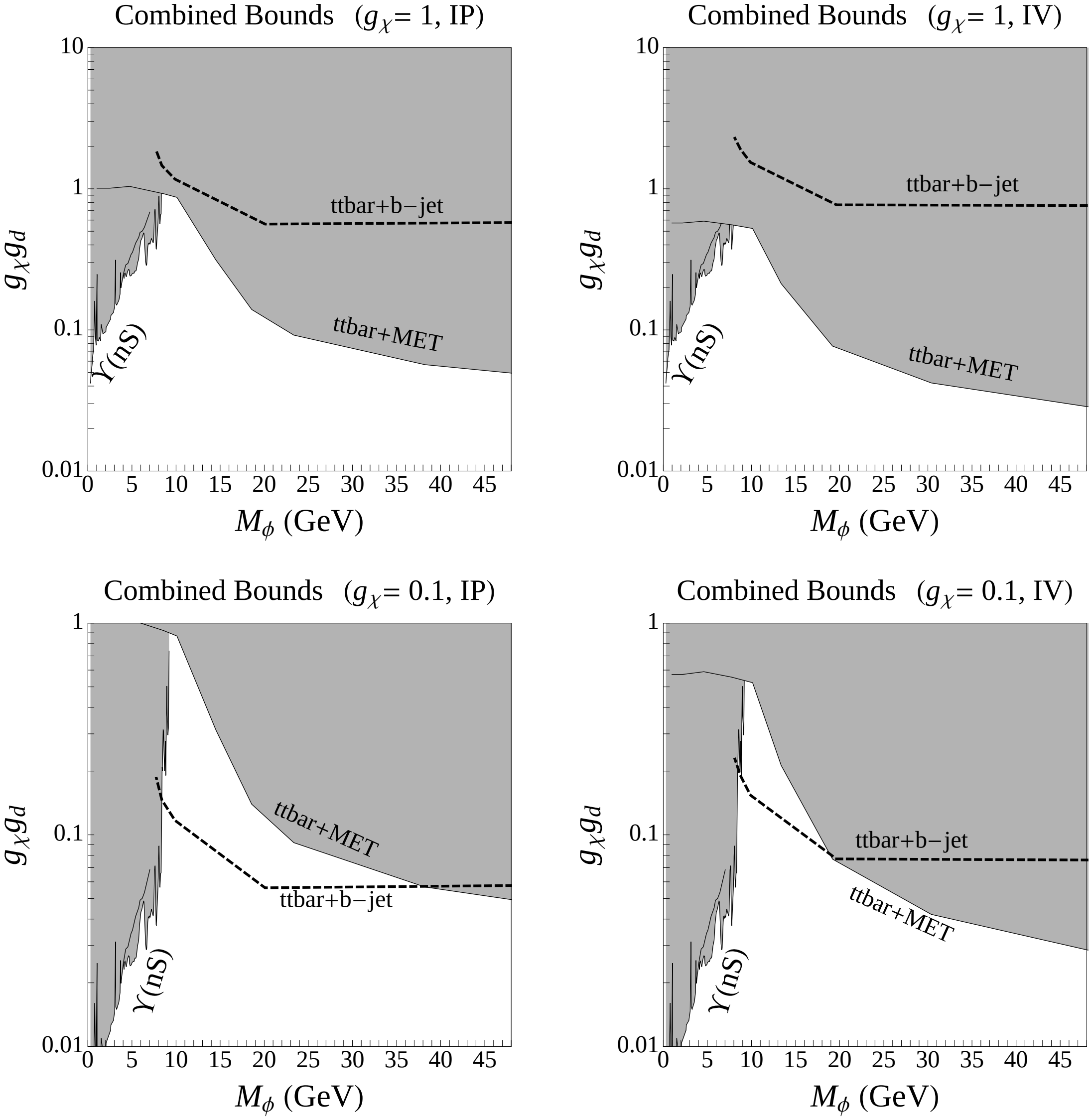
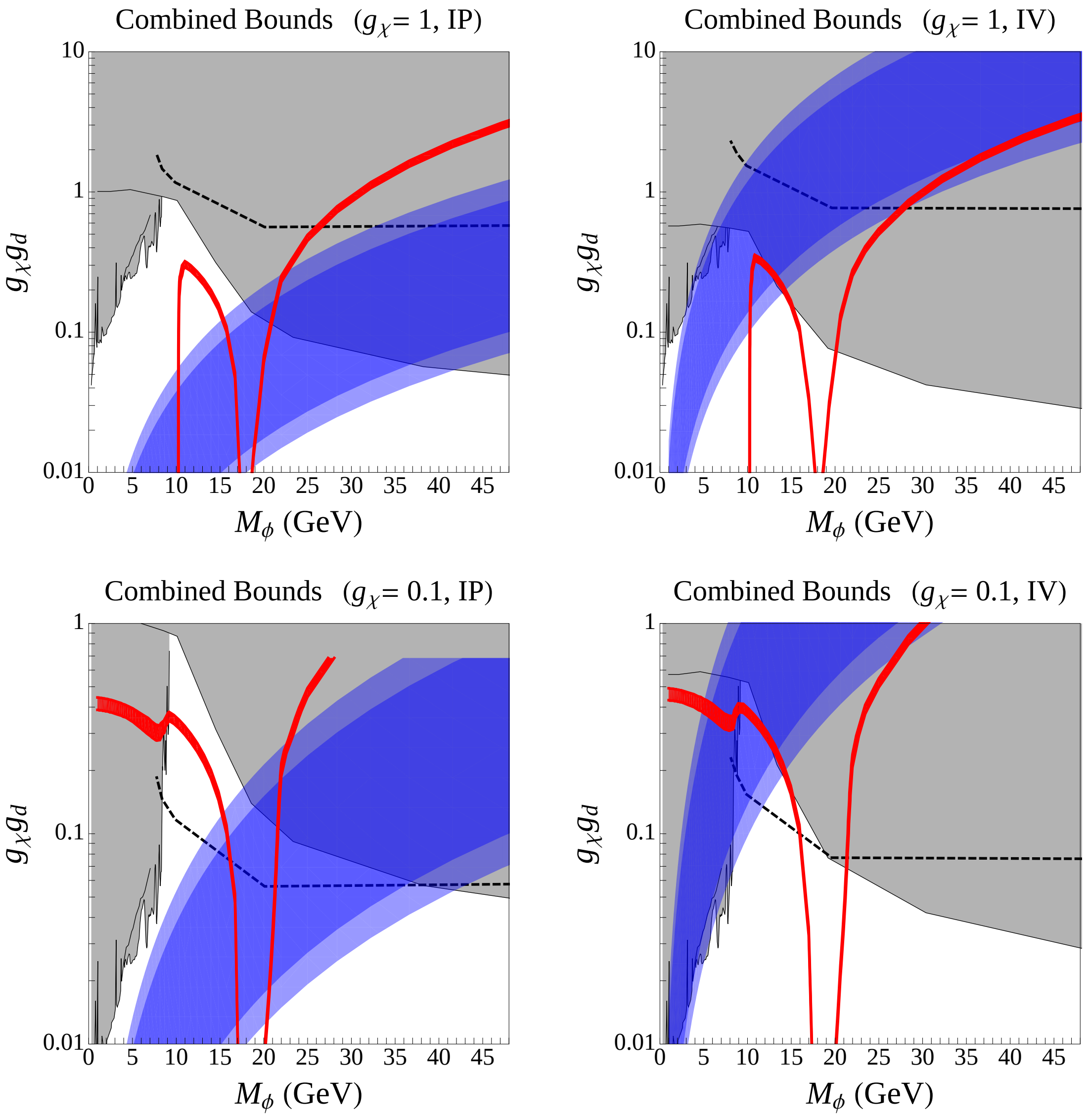


FIG. 5: Combined bounds in the $g_\chi g_d$ vs. m_ϕ plane. Bounds from $t\bar{t}$ + MET, $t\bar{t}$+b-jet and radiative Υ decays (in both hadronic and τ channels) are labelled accordingly. Monojet bounds are irrelevant, given the axes ranges plotted. We choose $g_\chi = 1$ ($g_\chi = 0.1$) in the upper (lower) panels to translate bounds that only depend on g_d onto this plane. Left and right panels correspond to IP and IV scenarios, respectively. We use a dashed line to remind the reader that the $t\bar{t}$+b-jet bound is particularly rough (as described in the text).

Acknowledgments

The authors would like to acknowledge helpful discussions with J. Shelton, J. Zupan, C. Wagner, and L. Tao. The research of R.C.C. and A.R. is supported by the National Science Foundation under grant PHY-0970173. The research of T.M.P.T. is supported in part by NSF grant PHY-0970171 and by the University of California, Irvine through a Chancellor's fellowship.



Combined Bounds (g_χ= 1, IP)

Combined Bounds (g_χ= 1, IV)

Combined Bounds (g_χ= 0.1, IP)

Combined Bounds (g_χ= 0.1, IV)

FIG. 6: As in Figure 5, but with the inclusion of direct detection and *Planck* favored bands in blue and red, respectively.

---

[1] **Planck Collaboration**, P. Ade *et. al.*, *Planck 2013 results. XVI. Cosmological parameters*, `arXiv:1303.5076`.

[2] J. L. Feng, *Dark Matter Candidates from Particle Physics and Methods of Detection*, *Ann.Rev.Astron.Astrophys.* **48** (2010) 495–545, [`arXiv:1003.0904`].

[3] J. E. Kim and G. Carosi, *Axions and the Strong CP Problem*, *Rev.Mod.Phys.* **82** (2010) 557–602, [`arXiv:0807.3125`].

[4] L. Rosenberg and K. van Bibber, *Searches for invisible axions*, *Phys.Rept.* **325** (2000) 1–39.

[5] G. Bertone, D. Hooper, and J. Silk, *Particle dark matter: Evidence, candidates and constraints*, *Phys.Rept.* **405** (2005) 279–390, [`hep-ph/0404175`].

[6] G. Jungman, M. Kamionkowski, and K. Griest, *Supersymmetric dark matter*, *Phys.Rept.*

267 (1996) 195–373, [`hep-ph/9506380`].

[7] D. Chung, L. Everett, G. Kane, S. King, J. D. Lykken, *et. al.*, *The Soft supersymmetry breaking Lagrangian: Theory and applications*, *Phys.Rept.* **407** (2005) 1–203, [`hep-ph/0312378`].

[8] G. Servant and T. M. Tait, *Is the lightest Kaluza-Klein particle a viable dark matter candidate?*, *Nucl.Phys.* **B650** (2003) 391–419, [`hep-ph/0206071`].

[9] H.-C. Cheng, J. L. Feng, and K. T. Matchev, *Kaluza-Klein dark matter*, *Phys.Rev.Lett.* **89** (2002) 211301, [`hep-ph/0207125`].

[10] D. Hooper and S. Profumo, *Dark matter and collider phenomenology of universal extra dimensions*, *Phys.Rept.* **453** (2007) 29–115, [`hep-ph/0701197`].

[11] M. Pospelov, A. Ritz, and M. B. Voloshin, *Secluded WIMP Dark Matter*, *Phys.Lett.* **B662** (2008) 53–61, [`arXiv:0711.4866`].

[12] M. Pospelov and A. Ritz, *Astrophysical Signatures of Secluded Dark Matter*, *Phys.Lett.* **B671** (2009) 391–397, [`arXiv:0810.1502`].

[13] J. L. Feng and J. Kumar, *The WIMPless Miracle: Dark-Matter Particles without Weak-Scale Masses or Weak Interactions*, *Phys.Rev.Lett.* **101** (2008) 231301, [`arXiv:0803.4196`].

[14] J. L. Feng, H. Tu, and H.-B. Yu, *Thermal Relics in Hidden Sectors*, *JCAP* **0810** (2008) 043, [`arXiv:0808.2318`].

[15] D. E. Kaplan, M. A. Luty, and K. M. Zurek, *Asymmetric Dark Matter*, *Phys.Rev.* **D79** (2009) 115016, [`arXiv:0901.4117`].

[16] A. Falkowski, J. T. Ruderman, and T. Volansky, *Asymmetric Dark Matter from Leptogenesis*, *JHEP* **1105** (2011) 106, [`arXiv:1101.4936`].

[17] H. Davoudiasl and R. N. Mohapatra, *On Relating the Genesis of Cosmic Baryons and Dark Matter*, *New J.Phys.* **14** (2012) 095011, [`arXiv:1203.1247`].

[18] T. Lin, H.-B. Yu, and K. M. Zurek, *On Symmetric and Asymmetric Light Dark Matter*, *Phys.Rev.* **D85** (2012) 063503, [`arXiv:1111.0293`].

[19] S. Galli, F. Iocco, G. Bertone, and A. Melchiorri, *Updated CMB constraints on Dark Matter annihilation cross-sections*, *Phys.Rev.* **D84** (2011) 027302, [`arXiv:1106.1528`].

[20] G. Hutsi, J. Chluba, A. Hektor, and M. Raidal, *WMAP7 and future CMB constraints on annihilating dark matter: implications on GeV-scale WIMPs*, *Astron.Astrophys.* **535** (2011) A26, [`arXiv:1103.2766`].

[21] D. P. Finkbeiner, S. Galli, T. Lin, and T. R. Slatyer, *Searching for Dark Matter in the CMB: A Compact Parameterization of Energy Injection from New Physics*, *Phys.Rev.* **D85** (2012) 043522, [`arXiv:1109.6322`].

[22] R. H. Cyburt, B. D. Fields, K. A. Olive, and E. Skillman, *New BBN limits on physics beyond the standard model from He-4*, *Astropart.Phys.* **23** (2005) 313–323, [`astro-ph/0408033`].

[23] G. G. Raffelt, *Particle physics from stars*, *Ann.Rev.Nucl.Part.Sci.* **49** (1999) 163–216, [`hep-ph/9903472`].

[24] **CoGeNT collaboration**, C. Aalseth *et. al.*, *Results from a Search for Light-Mass Dark Matter with a P-type Point Contact Germanium Detector*, *Phys.Rev.Lett.* **106** (2011) 131301, [`arXiv:1002.4703`].

[25] A. L. Fitzpatrick, D. Hooper, and K. M. Zurek, *Implications of CoGeNT and DAMA for Light WIMP Dark Matter*, *Phys.Rev.* **D81** (2010) 115005, [`arXiv:1003.0014`].

[26] D. Hooper, N. Weiner, and W. Xue, *Dark Forces and Light Dark Matter*, *Phys.Rev.* **D86** (2012) 056009, [`arXiv:1206.2929`].

[27] S. Andreas, C. Arina, T. Hambye, F.-S. Ling, and M. H. Tytgat, *A light scalar WIMP*

through the Higgs portal and CoGeNT, *Phys.Rev.* **D82** (2010) 043522, [`arXiv:1003.2595`].

[28] A. Falkowski, J. Juknevich, and J. Shelton, *Dark Matter Through the Neutrino Portal*, `arXiv:0908.1790`.

[29] N. Okada and O. Seto, *Isospin violating dark matter being asymmetric*, `arXiv:1304.6791`.

[30] K.-Y. Choi and O. Seto, *Light Dirac right-handed sneutrino dark matter*, `arXiv:1305.4322`.

[31] G. D'Ambrosio, G. Giudice, G. Isidori, and A. Strumia, *Minimal flavor violation: An Effective field theory approach*, *Nucl.Phys.* **B645** (2002) 155–187, [`hep-ph/0207036`].

[32] **Particle Data Group**, J. Beringer *et. al.*, *Review of Particle Physics (RPP)*, *Phys.Rev.* **D86** (2012) 010001.

[33] J. L. Feng, J. Kumar, D. Marfatia, and D. Sanford, *Isospin-Violating Dark Matter*, *Phys.Lett.* **B703** (2011) 124–127, [`arXiv:1102.4331`].

[34] **LEP Higgs Working Group for Higgs boson searches, OPAL Collaboration, ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration**, *Search for the standard model Higgs boson at LEP*, `hep-ex/0107029`.

[35] R. Dermisek and J. F. Gunion, *The NMSSM Solution to the Fine-Tuning Problem, Precision Electroweak Constraints and the Largest LEP Higgs Event Excess*, *Phys.Rev.* **D76** (2007) 095006, [`arXiv:0705.4387`].

[36] U. Ellwanger, C. Hugonie, and A. M. Teixeira, *The Next-to-Minimal Supersymmetric Standard Model*, *Phys.Rept.* **496** (2010) 1–77, [`arXiv:0910.1785`].

[37] C. Balazs, M. S. Carena, A. Freitas, and C. Wagner, *Phenomenology of the nMSSM from colliders to cosmology*, *JHEP* **0706** (2007) 066, [`arXiv:0705.0431`].

[38] P. Draper, T. Liu, C. E. Wagner, L.-T. Wang, and H. Zhang, *Dark Light Higgs*, *Phys.Rev.Lett.* **106** (2011) 121805, [`arXiv:1009.3963`].

[39] M. Carena, N. R. Shah, and C. E. Wagner, *Light Dark Matter and the Electroweak Phase Transition in the NMSSM*, *Phys.Rev.* **D85** (2012) 036003, [`arXiv:1110.4378`].

[40] J.-J. Cao, K.-i. Hikasa, W. Wang, J. M. Yang, K.-i. Hikasa, *et. al.*, *Light dark matter in NMSSM and implication on Higgs phenomenology*, *Phys.Lett.* **B703** (2011) 292–297, [`arXiv:1104.1754`].

[41] D. Das and U. Ellwanger, *Light dark matter in the NMSSM: upper bounds on direct detection cross sections*, *JHEP* **1009** (2010) 085, [`arXiv:1007.1151`].

[42] D. Hooper and T. M. Tait, *Neutralinos in an extension of the minimal supersymmetric standard model as the source of the PAMELA positron excess*, *Phys.Rev.* **D80** (2009) 055028, [`arXiv:0906.0362`].

[43] A. V. Belikov, J. F. Gunion, D. Hooper, and T. M. Tait, *CoGeNT, DAMA, and Light Neutralino Dark Matter*, *Phys.Lett.* **B705** (2011) 82–86, [`arXiv:1009.0549`].

[44] M. R. Buckley, D. Hooper, and T. M. Tait, *Particle Physics Implications for CoGeNT, DAMA, and Fermi*, *Phys.Lett.* **B702** (2011) 216–219, [`arXiv:1011.1499`].

[45] X.-G. He and J. Tandean, *Low-Mass Dark-Matter Hint from CDMS II, Higgs Boson at LHC, and Darkon Models*, `arXiv:1304.6058`.

[46] A. Rajaraman, W. Shepherd, T. M. Tait, and A. M. Wijangco, *LHC Bounds on Interactions of Dark Matter*, *Phys.Rev.* **D84** (2011) 095013, [`arXiv:1108.1196`].

[47] G. Belanger, F. Boudjema, P. Brun, A. Pukhov, S. Rosier-Lees, *et. al.*, *Indirect search for dark matter with micrOMEGAs2.4*, *Comput.Phys.Commun.* **182** (2011) 842–856, [`arXiv:1004.1092`].

[48] J. R. Ellis, K. A. Olive, and C. Savage, *Hadronic Uncertainties in the Elastic Scattering of Supersymmetric Dark Matter*, *Phys.Rev.* **D77** (2008) 065026, [`arXiv:0801.3656`].

[49] J. Gasser, H. Leutwyler, and M. Sainio, *Form-factor of the sigma term*, *Phys.Lett.* **B253** (1991) 260–264.

[50] V. Bernard, N. Kaiser, and U. G. Meissner, *Critical analysis of baryon masses and sigma terms in heavy baryon chiral perturbation theory*, *Z.Phys.* **C60** (1993) 111–120, [`hep-ph/9303311`].

[51] M. Pavan, I. Strakovsky, R. Workman, and R. Arndt, *The Pion nucleon Sigma term is definitely large: Results from a G.W.U. analysis of pi nucleon scattering data*, *PiN Newslett.* **16** (2002) 110–115, [`hep-ph/0111066`].

[52] R. Young and A. Thomas, *Octet baryon masses and sigma terms from an SU(3) chiral extrapolation*, *Phys.Rev.* **D81** (2010) 014503, [`arXiv:0901.3310`].

[53] A. W. Thomas, P. E. Shanahan, and R. D. Young, *Strange quarks and lattice QCD*, *Few Body Syst.* **54** (2013) 123–128, [`arXiv:1111.0114`].

[54] P. Junnarkar and A. Walker-Loud, *The Scalar Strange Content of the Nucleon from Lattice QCD*, `arXiv:1301.1114`.

[55] J. Alarcon, L. Geng, J. M. Camalich, and J. Oller, *On the strangeness content of the nucleon*, `arXiv:1209.2870`.

[56] **CDMS Collaboration**, R. Agnese *et. al.*, *Dark Matter Search Results Using the Silicon Detectors of CDMS II*, *Phys.Rev.Lett.* (2013) [`arXiv:1304.4279`].

[57] K. N. Abazajian and M. Kaplinghat, *Detection of a Gamma-Ray Source in the Galactic Center Consistent with Extended Emission from Dark Matter Annihilation and Concentrated Astrophysical Emission*, *Phys.Rev.* **D86** (2012) 083511, [`arXiv:1207.6047`].

[58] D. Hooper and T. Linden, *On The Origin Of The Gamma Rays From The Galactic Center*, *Phys.Rev.* **D84** (2011) 123005, [`arXiv:1110.0006`].

[59] M. Beltran, D. Hooper, E. W. Kolb, Z. A. Krusberg, and T. M. Tait, *Maverick dark matter at colliders*, *JHEP* **1009** (2010) 037, [`arXiv:1002.4137`].

[60] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. Tait, *et. al.*, *Constraints on Light Majorana dark Matter from Colliders*, *Phys.Lett.* **B695** (2011) 185–188, [`arXiv:1005.1286`].

[61] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. Tait, *et. al.*, *Constraints on Dark Matter from Colliders*, *Phys.Rev.* **D82** (2010) 116010, [`arXiv:1008.1783`].

[62] Y. Bai, P. J. Fox, and R. Harnik, *The Tevatron at the Frontier of Dark Matter Direct Detection*, *JHEP* **1012** (2010) 048, [`arXiv:1005.3797`].

[63] P. J. Fox, R. Harnik, J. Kopp, and Y. Tsai, *LEP Shines Light on Dark Matter*, *Phys.Rev.* **D84** (2011) 014028, [`arXiv:1103.0240`].

[64] P. J. Fox, R. Harnik, J. Kopp, and Y. Tsai, *Missing Energy Signatures of Dark Matter at the LHC*, *Phys.Rev.* **D85** (2012) 056011, [`arXiv:1109.4398`].

[65] Y. Bai and T. M. Tait, *Searches with Mono-Leptons*, `arXiv:1208.4361`.

[66] R. Cotta, J. Hewett, M. Le, and T. Rizzo, *Bounds on Dark Matter Interactions with Electroweak Gauge Bosons*, `arXiv:1210.0525`.

[67] L. M. Carpenter, A. Nelson, C. Shimmin, T. M. Tait, and D. Whiteson, *Collider searches for dark matter in events with a Z boson and missing energy*, `arXiv:1212.3352`.

[68] N. F. Bell, J. B. Dent, A. J. Galea, T. D. Jacques, L. M. Krauss, *et. al.*, *Searching for Dark Matter at the LHC with a Mono-Z*, *Phys.Rev.* **D86** (2012) 096011, [`arXiv:1209.0231`].

[69] H. An, X. Ji, and L.-T. Wang, *Light Dark Matter and Z' Dark Force at Colliders*, *JHEP* **1207** (2012) 182, [`arXiv:1202.2894`].

[70] M. T. Frandsen, F. Kahlhoefer, A. Preston, S. Sarkar, and K. Schmidt-Hoberg, *LHC and Tevatron Bounds on the Dark Matter Direct Detection Cross-Section for Vector Mediators*,

JHEP **1207** (2012) 123, [`arXiv:1204.3839`].

[71] H. An, R. Huo, and L.-T. Wang, *Searching for Low Mass Dark Portal at the LHC*, `arXiv:1212.2221`.

[72] I. M. Shoemaker and L. Vecchi, *Unitarity and Monojet Bounds on Models for DAMA, CoGeNT, and CRESST-II*, *Phys.Rev.* **D86** (2012) 015023, [`arXiv:1112.5457`].

[73] **ATLAS Collaboration**, G. Aad *et. al.*, *Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector*, *JHEP* **1304** (2013) 075, [`arXiv:1210.4491`].

[74] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : Going Beyond*, *JHEP* **1106** (2011) 128, [`arXiv:1106.0522`].

[75] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **0605** (2006) 026, [`hep-ph/0603175`].

[76] J. Conway *et. al.*, "PGS 4, Pretty Good Simulation of High-Energy Collisions ." `http://www.physics.ucdavis.edu/~conway/research/software/pgs/pgs4-general.htm`, 2013.

[77] *Search for a supersymmetric top-quark partner in final states with two leptons in sqrt(s) = 8 tev pp collisions using 13 ifb of atlas data*, Tech. Rep. ATLAS-CONF-2012-167, CERN, Geneva, Dec, 2012.

[78] *Search for the standard model higgs boson produced in association with top quarks in proton-proton collisions at s = 7 tev using the atlas detector*, Tech. Rep. ATLAS-CONF-2012-135, CERN, Geneva, Sep, 2012.

[79] **ATLAS collaboration**, G. Aad *et. al.*, *A study of heavy flavor quarks produced in association with top quark pairs at $\sqrt{s} = 7$ TeV using the ATLAS detector*, `arXiv:1304.6386`.

[80] T. Lin, E. W. Kolb, and L.-T. Wang, *Probing dark matter couplings to top and bottom at the LHC*, `arXiv:1303.6638`.

[81] **BaBar Collaboration**, J. Lees *et. al.*, *Search for hadronic decays of a light Higgs boson in the radiative decay $\Upsilon \to \gamma A^0$*, *Phys.Rev.Lett.* **107** (2011) 221803, [`arXiv:1108.3549`].

[82] **BaBar Collaboration**, J. Lees *et. al.*, *Search for a Low-Mass Scalar Higgs Boson Decaying to a Tau Pair in Single-Photon Decays of Upsilon(1S)*, `arXiv:1210.5669`.

[83] G. K. Yeghiyan, *Upsilon Decays into Light Scalar Dark Matter*, *Phys.Rev.* **D80** (2009) 115019, [`arXiv:0909.4919`].

[84] Y. Bai, P. Draper, and J. Shelton, *Measuring the Invisible Higgs Width at the 7 and 8 TeV LHC*, *JHEP* **1207** (2012) 192, [`arXiv:1112.4496`].

[85] C. Englert, T. S. Roy, and M. Spannowsky, *Ditau jets in Higgs searches*, *Phys.Rev.* **D84** (2011) 075026, [`arXiv:1106.4545`].