Searching for Dark Matter with $\bar{t}t$ Resonance

Yoav Afik$^{a,1}$, Eitan Gozani$^{b,1}$

$^1$Department of Physics, Technion: Israel Institute of Technology
Haifa, Israel

Abstract Many models consisting of dark matter assume the dark matter and the standard model particles are mediated by a spin-0 particle. At the LHC, one can use those models for dark matter searches. One of the possible approaches for the search of those models is to consider the decay of the spin-0 particle to a pair of $\bar{t}t$, modifying the pattern of the top quark pair invariant mass spectrum. This kind of search suggest good sensitivity in a different parameter space comparing to the more traditional searches. We examine this type of sensitivity and put limits on two benchmark models consisting of dark matter. It was found that when the mediator mass ($m_{Y_0}$) and the dark matter mass ($m_\chi$) have values of $m_{Y_0} \sim 2 \cdot m_\chi$, mediator masses in the range of [400, 600] GeV are excluded. Using those results, we obtain a comparison to direct detection experiments and gain sensitivity for new regions, not covered by other searches.

1 Introduction

Astrophysical observations support the existence of nonbaryonic component of the universe: Dark Matter (DM) [1–4]. DM particles have to be stable, massive, and do not participate in the strong and electro-magnetic interactions. There are many searches for DM candidates at the Large Hadron Collider (LHC) experiment that use different approaches to model the signal for DM. One of the most popular candidates is a Weakly Interacting Massive Particle (WIMP) [5]. At the LHC, one can search for DM particles ($\chi$) produced in $pp$ collisions.

Searches for DM using the models with DM and spin-0 mediators as a signal were already presented by ATLAS [6–11] and CMS [12–16] collaborations, with up to $36/fb^{-1}$ of integrated luminosity, with centre of mass energy $\sqrt{s} = 13$ TeV. Those searches focus on production of DM in association with a pair of top or bottoms quarks. In all of those searches, the mediator decays into a pair of DM particles, leaving a signature of high missing transverse momentum in the detector.

A complementary search for these models can be achieved if the mediator decays to a pair of top quarks, leaving a more complex signature in the detector. Those searches are challenging since strong interference with the SM $\bar{t}t$ production is expected [17], leading to a pick-dip shape in the spectrum of the $\bar{t}t$ invariant mass [18, 19]. Good sensitivity is expected in the parameter space where the mediator is heavier than twice the mass of the top quark. Representative Feynman diagrams for leading-order production of a $\bar{t}t$ pair by a spin-0 mediator ($Y_0$) and by the SM are presented at Figure 1.

There have been a few analyses targeting searches for heavy particles decaying to a pair of top quarks [20–22], creating a Breit-Wigner resonance in the $m_{\bar{t}t}$ spectrum. However, for most of those analyses, spin-0 particles were not taken into account. The recent search published in a similar context, considering interference with the SM for $\bar{t}t$ production, was done by the ATLAS collaboration [23] using data of $pp$ collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV and integrated luminosity of $20.3/fb^{-1}$. This analysis used Two-Higgs-Doublet model for the interpretation of the results, using the spin-0 particle mass of 500 – 750 GeV. Here, we show how the search for $\bar{t}t$ resonance originating from spin-0 particles is important for models consisting of
DM and covering parameter space that is not covered by the more traditional searches, especially in a signature with a mediator that decays into a pair of DM particles.

This paper is organized as follows: in section 2 we discuss the theoretical framework for models with spin-0 mediators that couples to DM and top quarks; in section 3 we discuss two selected benchmark models; in section 4 we present the results; finally, we present our conclusions at section 5.

2 Theoretical Framework

In many models consisting of new spin-0 particles, the couplings with the SM fermions are being set as proportional to the SM Yukawa terms, by using the Minimal Flavor Violation assumption [29]. This leads to a motivation for a search in association with heavy flavor quarks. There are many types of these models assuming interactions between DM particles and spin-0 CP-odd or CP-even mediators, see for example [24, 27, 28].

For a spin-0 particle decays into a pair of Dirac fermions, which can be either DM particles (χχ) or SM fermions (ff), the calculation of the mediator width at tree level behaves as the following:

$$\Gamma(\phi/a \rightarrow \chi\chi) = (g_{\text{med}-\chi\chi})^2 \frac{m_{\phi/a}}{8\pi} \left(1 - \frac{4 \cdot m_{\chi}^2}{m_{\phi/a}^2}\right)^{n/2}$$ (1)

$$\Gamma(\phi/a \rightarrow ff) = (g_{\text{med}-ff})^2 \frac{\gamma_f \cdot m_{\phi/a}}{16\pi} \left(1 - \frac{4 \cdot m_f^2}{m_{\phi/a}^2}\right)^{n/2}$$ (2)

Where n = 3 for a scalar (φ) and n = 1 for a pseudo-scalar (a). Here, χ is a DM particle, f is a SM fermion, m_{\phi/a} is the mass of the scalar / pseudo-scalar, m_\chi is the DM mass, m_f and y_f are the corresponding mass and Yukawa term for the SM fermion, respectively. The parameters g_{\text{med}-\chi\chi} and g_{\text{med}-ff} are model dependent couplings. In general, equations 1-2 can be applied to other types of DM particles, however we keep it as a benchmark assumption. In principle, interactions between the dark sector and the SM gauge bosons do exist in part of those models, and are taken into account when analyzing the results.

The calculation of the mediator width from equations 1-2 presents an interesting behavior: In the case the mediator is heavy enough to decay into a pair of top quarks (i.e. ff = tt), the partial decay width of (φ/a → χχ) is significantly smaller. This is especially true in the case of high m_\chi, since the partial decay width of (φ → χχ) becomes even more suppressed. Therefore, the tt resonance search along the search for ττ + χχ are complementary: the former gain better sensitivity for low DM masses, while the latter has better sensitivity for high DM masses. The Branching Ratio of this kind of spin-0 decay into a pair of top quarks is presented in Figure 2, assuming couplings only for DM and top quarks, and setting g_{\text{med}-\chi\chi} = g_{\text{med}-ff} = 1. The behavior discussed above is well observed in those figures.

3 Benchmark Models

In order to emphasize how the behavior described in section 2 affects the sensitivity for models consisting of spin-0 and DM particles, we select two suitable benchmark models.

3.1 Benchmark 1: Simplified Models

The first model we consider is a simplified model with a spin-0 mediator couples to both to the SM fermions and to a new dark sector [24–26]. We will consider two choices: in the first one the interaction with the SM is mediated by a real scalar, and in the second we consider only a new pseudo-scalar (assuming that the associated scalar is decoupled from the low-energy spectrum). The dark sector, in general, can contain more than a single particle. We assume the dark sector contain only one DM particle which is a Dirac
fermion, keeping in mind this assumption effects mostly on the width of the mediator, so the results can be easily converted to more complicated cases. This model assumes Yukawa-like couplings between the dark sector mediator and the SM fermions. The Lagrangians for the scalar ($\mathcal{L}_\phi$) and pseudo-scalar ($\mathcal{L}_a$) are [24]:

$$\mathcal{L}^{\text{int}}_\phi = -g_\phi \phi \bar{f} f - \sum_{\text{fermions}} g_f \frac{y_f \sqrt{2}}{\Lambda} \phi \overline{\gamma^\mu} \gamma_\mu f$$

(3)

$$\mathcal{L}^{\text{int}}_a = -ig_a \overline{a} \gamma^\mu f \phi - \sum_{\text{fermions}} ig_f \frac{y_f \sqrt{2}}{\Lambda} \phi \overline{\gamma^\mu} f$$

(4)

Here, $\phi$ and $a$ are scalar and pseudo-scalar fields (respectively) connect the SM with the dark sector, $\chi$ is the DM particle, $g_\phi$ is the DM-mediated coupling, $g_f$ is the flavour-universal SM-mediator coupling and $y_f$ are the SM Yukawa couplings for fermions.

If $g_\phi \sim g_\chi$ and $m_{\phi/\chi} > 2m_\chi$, the decay of the mediator to DM is expected to dominate, unless the mediator is heavy enough for the top channel to open. This is true because the Yukawa couplings to light fermions are significantly small comparing to the Yukawa term of the top. The minimal viable value of $\Gamma_\phi/\alpha$ can be calculated from the other parameters. The mediator width can have larger values than the minimal one if additional dark sector particles are present. In our interpretation, however, we assume only one type of DM particle. For simplicity, the couplings $g_\chi$ and $g_\phi$ were set to be equal to each other: $g = g_\chi = g_\phi$. This leaves us with only three free parameters: $m_{\chi}, m_{\phi/\chi}, g$.

The DMS1MP [30–32] models have been used with MadGraph [33] in order to model the signal.

3.2 Benchmark 2: 2HDM+Z$^\prime$

The second model we consider is a type-II two-Higgs-doublet model with an additional U(1) gauge symmetry. This model, introduced in [27], is an extension to the familiar type-II 2HDM model [34], and introduces an extra spin-1 mass eigenstate which is denoted as Z$^\prime$. The pseudo-scalar ($A_0$) is the only one couples to a pair of DM particles, therefore this particle is identified as the mediator between the SM particles and the dark sector. The decoupling limit [35] is assumed. This model has 6 parameters, which is set as following: The mass of the light scalar, $m_\phi = 125$ GeV, as the measured value at the LHC; the mass of the heavier scalar and charged scalar $m_{H^+} = m_{H^0} = 300$ GeV; the mass of the pseudo-scalar, $m_{a_0} = 400$ GeV; the mass of Z$^\prime$, $m_{Z^\prime} = 3$ TeV; and the coupling of the new spin-1 boson, $g_{Z^\prime} = 1$. The mass $m_{Z^\prime}$ was chosen to be high which makes it effectively decoupled. Therefore, the results are valid also for other values of $m_{Z^\prime}$, as long as it is heavy enough to avoid decays of $A_0$ into Z$^\prime$ with another Higgs boson. In the chosen parameter space the effect of $g_{Z^\prime}$ was found to be negligible as well, therefore the value chosen for this parameter was set in an arbitrary way. The ratio between vacuum expectation values of the two Higgs doublets, $\tan(\beta)$, and the mass of the DM particle, $m_\chi$, are free parameters.

In the selected parameter space the masses of the CP-even bosons are set to be lower than the $t\bar{t}$ decay threshold, and the mass of the CP-odd boson is higher than this threshold. Therefore, the dominant process for $t\bar{t}$ resonant production is via the pseudo-scalar mediator: $A_0 \to t\bar{t}$.

4 Results

Limits on spin-0 mediator models were already set at 95% Confidence Level (CL) at [17], using the latest ATLAS $t\bar{t}$-resonance search with an available data [21]. Limits were also put on spin-0 mediators at [23]. In both of the cases interference effects with the SM were considered, and the signal was generated at Next to Leading Order (NLO) and Next to Next to Leading Order (NNLO) in QCD corrections, respectively. For those limits, however, no interaction with DM particles was taken into account, as we do in this section. The results of the former was found to be more efficient for mediator mass which is lower than 500 GeV, while the latter is more sensitive for mediator masses which is higher than 500 GeV. This is expected since the corresponding ATLAS analysis used spin-0 particle masses which are higher than 500 GeV.

The experimental resolution on the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$, was calculated to be 8% at both of the analyses. Since the width of the mediator has a strong effect on the shape of the pure signal and interference distributions, an upper limit $\frac{\Gamma_{t\bar{t}}}{m_{t\bar{t}}} < 8\%$ was set, where $\Gamma_{t\bar{t}}$ is total decay width of the mediator. In the case that the mediator decays into a pair of DM particles, $\frac{\Gamma_{t\bar{t}}}{m_{t\bar{t}}} < 40\%$ was used to keep the narrow width approximation valid. Results with higher total widths were discarded.

4.1 Benchmark 1: Simplified Models

Figure 3 presents upper limits at 95% CL on the coupling $g$. The figure presents the lowest coupling excluded for the model. Both scalar and pseudo-scalar mediator cases are considered. The best limits obtained from [10] searching for $t\bar{t} + \chi \gamma$ processes are presented as well for comparison. The exclusion contour is more stringent for the $t\bar{t}$ resonance searches when $m_{\phi/\alpha} > 400$ GeV, especially when the DM mass is high. The limits obtained from the $t\bar{t}$ resonance are stronger for the scalar case since the width calculation (see equations 1, 2) allows higher values for the pseudo-scalar case with similar parameters, leading to higher total widths which we discard.
contour corresponds to the lowest value of the coupling \( g \) plane for the scalar (upper) and pseudo-scalar (bottom) scenarios. The \( A \) they do not provide any constraint in the considered parameter space. 

4.2 Benchmark 2: 2HDM+

Figure 4 presents exclusion contour at 95% CL in the plane of \((m_\phi, m_\chi)\) for the scalar (upper) and pseudo-scalar (bottom) scenarios. The contour corresponds to the excluded values of the model. All of the other parameters of the model are fixed and mentioned in the figure. Results from both \( t\bar{t} \) resonance only are presented, since the \( t\bar{t} + \chi\bar{\chi} \) signature do not exclude any part of the presented parameter space. 

![Fig. 3 Exclusion contour for DM simplified models in the \((m_0, m_\chi)\) plane for the scalar (upper) and pseudo-scalar (bottom) scenarios.](image)

![Fig. 4 Exclusion contour for 2HDM+Z' model in the \((m_\chi, \tan\beta)\) plane. The contour corresponds to the excluded values of the model.](image)

use the prescription described at [36], setting limits on DM-nucleon interaction.

4.3 Comparison to Direct Detection Experiments

Results from LHC analyses with DM simplified models can be compared to direct detection experiments, for both spin-independent and spin-dependent cases. For this purpose, we use the prescription described at [36], setting limits on DM-nucleon interaction.

4.3.1 Spin-Independent

For scalar simplified models, we set an upper limit on the DM-nucleon cross section \((\sigma_{SI})\) as follows [36]:

\[
\sigma_{SI} \simeq 6.9 \cdot 10^{-43} \cdot cm^2 \cdot (gv \cdot g_\chi)^2 \left( \frac{125 GeV}{m_\phi} \right)^4 \left( \frac{\mu_\chi}{1 GeV} \right)^2
\]

Where we introduce the nucleon mass, \( m_n \approx 0.939 \) GeV, and the reduced DM-nucleon mass, \( m_n \cdot m_\chi/(m_n + m_\chi) \). In the results presented at 4.1, we find that scalar masses in the range of \( m_\phi \in [400, 600] \) GeV are excluded, with the lowest couplings in the range of \( g \in [1.1 - 2.0] \) and \( m_\chi \geq 160 \) GeV. In order to use the prescription above the couplings should be fixed, therefore we choose \( g_\chi = g_v = 1.5 \). The results obtained in this paper are presented along with direct detection experiments [37–41] and with the contour calculated at [10] at Figure 5. There are two caveats for this comparison, however: first, the results we state are at 95% CL, while the results of the other experiments are at 90% CL; second, one has to keep in mind that the comparison is model dependent.

4.3.2 Spin-Dependent

For the pseudo-scalar scenario, a velocity suppression term in the non-relativistic limit creates large difference by several orders of magnitude in favor of LHC results [10, 36], and therefore it is not presented. However, this actually makes the motivation to use \( t\bar{t} \) resonance interpretation for DM models even stronger: it covers regions with higher DM masses, for which both \( t\bar{t} + \chi\bar{\chi} \) and direct detection searches are insensitive to.
3. Jungman, Gerard and Kamionkowski, Marc and Griest, Kim, "Supersymmetric dark matter", Phys. Rept. 267, 195-373 (1996).
4. Binney, J. and Tremaine, S., Errata in Binney and Tremaine, 'Galactic Dynamics'", arXiv:astro-ph/9304010 [astro-ph].
5. Steigman, Gary and Turner, Michael S., "Cosmological Constraints on the Properties of Weakly Interacting Massive Particles", Nucl. Phys. B 253, 375 (1985).
6. ATLAS Collaboration, "Search for a Scalar Partner of the Top Quark in the Jets+$$E_\text{T}^{\text{miss}}$$ Final State at $$\sqrt{s} = 13$$ TeV with the ATLAS detector", ATLAS-CONF-2016-077 (2016).
7. ATLAS Collaboration, "Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in $$\sqrt{s} = 13$$ TeV $$pp$$ collisions with the ATLAS detector", ATLAS-CONF-2016-050 (2016).
8. ATLAS Collaboration, "Search for direct top squark pair production and dark matter production in final states with two leptons in $$\sqrt{s} = 13$$ TeV $$pp$$ collisions using 13.3 fb$$^{-1}$$ of ATLAS data", ATLAS-CONF-2016-076 (2016).
9. ATLAS Collaboration, "Search for Dark Matter production associated with bottom quarks in 13.3 fb$$^{-1}$$ of $$pp$$ collisions at $$\sqrt{s} = 13$$ TeV with the ATLAS detector at the LHC", ATLAS-CONF-2016-086 (2016).
10. Aaboud, Morad and others, "Search for dark matter produced in association with bottom or top quarks in $$\sqrt{s} = 13$$ TeV $$pp$$ collisions with the ATLAS detector", Eur. Phys. J. C (2018) 78: 18.
11. ATLAS Collaboration, "Constraints on mediator-based dark matter models using $$\sqrt{s} = 13$$ TeV $$pp$$ collisions at the LHC with the ATLAS detector", ATLAS-CONF-2018-051 (2018).
12. Sirunyan, Albert M and others [CMS Collaboration], "Search for dark matter produced in association with heavy-flavor quarks in proton-proton collisions at sqrt(s)=13 TeV", Eur. Phys. J. C (2017) 77: 845.
13. CMS Collaboration, "Search for dark matter in association with a top quark pair at sqrt(s)=13 TeV", CMS-PAS-EXO-16-005 (2016).
14. CMS Collaboration, "Search for dark matter in association with a top quark pair at $$\sqrt{s} = 13$$ TeV in the dilepton channel", CMS-PAS-EXO-16-028 (2016).
15. CMS Collaboration, "Search for Dark Matter produced in association with bottom quarks", CMS-PAS-B2G-15-007 (2016).
16. CMS Collaboration, "Search for dark matter particles produced in association with a top quark pair at $$\sqrt{s} = 13$$ TeV", CMS-EXO-16-049 (2018).
17. Hespel, B. and Maltoni, F. and Vryonidou, E., "Signal background interference effects in heavy scalar production and decay to a top-anti-top pair", J. High Energ. Phys. (2016) 2016: 16.
18. Dicus, D. and Stange, A. and Willenbrock, S., "Higgs decay to top quarks at hadron colliders", Phys. Lett. (1994) B333: 126-131.
19. Frederix, Rikkert and Maltoni, Fabio, "Top pair invariant mass distribution: A Window on new physics", J. High Energ. Phys. (2009) 01: 047.

20. CMS Collaboration, "Search for Anomalous $t\bar{t}$ Production in the Highly-Boosted All-Hadronic Final State", J. High Energ. Phys. (2012) 2012: 29.

21. ATLAS Collaboration, "A search for $t\bar{t}$ resonances using lepton-plus-jets events in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", J. High Energ. Phys. (2015) 2015: 148.

22. ATLAS Collaboration, "Search for heavy particles decaying into top-quark pairs using lepton-plus-jets events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", Eur. Phys. J. C (2018) 78: 565.

23. ATLAS Collaboration, "Search for Heavy Higgs Bosons $A/H$ Decaying to a Top Quark Pair in $pp$ Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector", Phys. Rev. Lett. 119, 191803.

24. Buckley, Matthew R. and Feld, David and Goncalves, Dorival, "Scalar Simplified Models for Dark Matter", Phys. Rev. D 91, 015017 (2015).

25. Haisch, Ulrich and Re, Emanuele, "Simplified dark matter top-quark interactions at the LHC", J. High Energ. Phys. (2015) 2015: 78.

26. Abercrombie, Daniel and others, "Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum", arXiv:1507.00966 [hep-ex].

27. Berlin, Asher and Lin, Tongyan and Wang, Lian-Tao, "Mono-Higgs Detection of Dark Matter at the LHC", J. High Energ. Phys. (2014) 2014: 78.

28. Bauer, Martin and Haisch, Ulrich and Kahlhoefer, Felix, "Simplified dark matter models with two Higgs doublets: I. Pseudoscalar mediators", J. High Energ. Phys. (2017) 2017: 138.

29. D’Ambrosio, G. and Giudice, G. F. and Isidori, G. and Strumia, A., "Minimal flavor violation: An Effective field theory approach", Nucl. Phys. B 645, 155-187 (2002).

30. Mattelaer, Olivier and Vryonidou, Eleni, "Dark matter production through loop-induced processes at the LHC: the s-channel mediator case", E. Eur. Phys. J. C (2015) 75: 436.

31. Backovic, Mihailo and Krämer, Michael and Maltoni, Fabio and Martini, Antony and Mawatari, Kentarou and Pellen, Mathieu, "Higher-order QCD predictions for dark matter production at the LHC in simplified models with s-channel mediators", Eur. Phys. J. C (2015) 75: 482.

32. Afik, Y. and Maltoni, F. and Mawatari, K. and Pani, P. and Polesello, G. and Rozen, Y. and Zaro, M., "DM+bb simulations with DMSimp: an update", arXiv:1811.08002 [hep-ex].

33. J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, "MadGraph 5 : Going Beyond", arXiv:1106.0522 [hep-ph].

34. Branco, G. C. and Ferreira, P. M. and Lavoura, L. and Rebelo, M. N. and Sher, Marc and Silva, Joao P., "Theory and phenomenology of two-Higgs-doublet models", Phys. Rept. (2012) 516: 1-102.

35. Gunion, John F. and Haber, Howard E., "The CP conserving two Higgs doublet model: The Approach to the decoupling limit", Phys. Rev. D 67, 075019.

36. Boveia, Antonio and Buchmueller, Oliver and Doglioni, Caterina and Hahn, Kristian and Haisch, Ulrich and Kahlhoefer, Felix and Mangano, Michelangelo and McCabe, Christopher and Tait, Tim M. P., "Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter", arXiv:1603.04156 [hep-ex].

37. Akerib, D. S. and others, "Results from a search for dark matter in the complete LUX exposure", Phys. Rev. Lett. 118, 021303.

38. Ren, Xiangxiang and others, "Constraining Dark Matter Models with a Light Mediator at the PandaX-II Experiment", Phys. Rev. Lett. 121, 021304.

39. Aprile, E. and others, "First Dark Matter Search Results from the XENON1T Experiment", Phys. Rev. Lett. 119, 181301.

40. Agnese, R. and others, "New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment", Phys. Rev. Lett. 116, 071301.

41. Petricca, F. and others, "First results on low-mass dark matter from the CRESST-III experiment", arXiv:1711.07692 [astro-ph.CO].