Searches for Top-associated Dark Matter Production at the LHC

Dominic Stafford[1*], on behalf of the ATLAS and CMS collaborations

1 Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

* dominic.william.stafford@cern.ch

The 17th International Workshop on
Top Quark Physics (TOP2024)
Saint-Malo, France, 22-27 September 2024
doi:10.21468/SciPostPhysProc.?

Abstract

Recent searches for dark matter (DM) produced in association with top quarks from the ATLAS and CMS experiments using data collected between 2015 and 2018 are presented. These comprise searches from both experiments for DM in association with a single top quark; an improved ATLAS search for DM in single lepton $t\bar{t}$ final states; an ATLAS search for stop squarks decaying to a top quark, a charm quark and neutralinos; and a CMS search for DM produced in association with a pair of top quarks or a single top. These analyses feature novel machine learning and advanced background estimation techniques. No statistically significant excess is observed in any of these searches.

Received Date
Accepted Date
Published Date

1 Introduction

Astronomical and cosmological observations (for example from the bullet cluster [1]) suggest that approximately 80% of matter in the universe is formed of dark matter (DM) not described Standard Model of particle physics (SM). One of the simplest models which predicts this density is the "thermal freeze-out” model [2], which predicts, for a DM-SM interaction via a single s-channel mediator with order 1 couplings, the mediator would have a mass between roughly 100 GeV and 1 TeV. This is around the electroweak scale, and so many DM models also relate to other new physics at this scale, for instance Higgs sector extensions. In these models DM is often produced in association with top quarks, the heaviest particles in the SM. These proceedings cover searches by the ATLAS [3] and CMS [4] experiments for top quarks produced in association with DM, which can be inferred from the negative vector sum of the transverse momenta of all visible particles, referred to as "missing transverse momentum", p_T^{miss}.

2 Mono-top searches

Some dark matter models include flavour-changing neutral current (FCNC) mediators, which can give a distinctive signature of a single boosted top quark recoiling against p_T^{miss}, as shown in figure 1. Previous studies have found the channel in which the top quark decays hadronically and can be reconstructed as a single large radius jet is most sensitive to this signal.

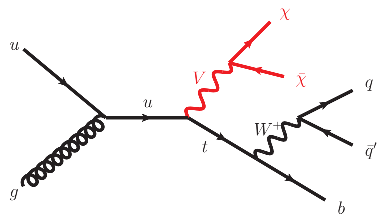


Figure 1: Production of DM in association with a single top quark via emission of a FCNC mediator. Source: [5]

The main challenge for these analyses is that the SM backgrounds are not always well modelled in Monte Carlo Simulation, and hence require data-driven background estimation techniques. Until this year, the most sensitive searches from ATLAS [6] and CMS [7] with data collected in 2016 excluded mediator masses up to about 1.8 TeV. In the past year both experiments have published searches using the full Run 2 dataset (data collected at 13 TeV between 2015 and 2018) [5,8], which are presented here.

2.1 Search strategies

Both searches select events with high p_T^{miss} (> 250 GeV for ATLAS, > 350 GeV for CMS), a single large-radius jet clustered with the anti-kT algorithm (radius 1.0 and $p_T > 350$ GeV for ATLAS and radius 1.5 and $p_T > 250$ GeV for CMS), and veto events with isolated leptons. Deep Neural Networks (DNNs) are used to select large-radius jets coming from top quarks. The CMS search fits on the p_T^{miss} distribution in the top-pass and -fail categories, whilst ATLAS fit on the score of a boosted decision tree (BDT) trained on the full event kinematics in 0- and 1- b-tagged small radius jet categories. These distributions are shown in figure 2.

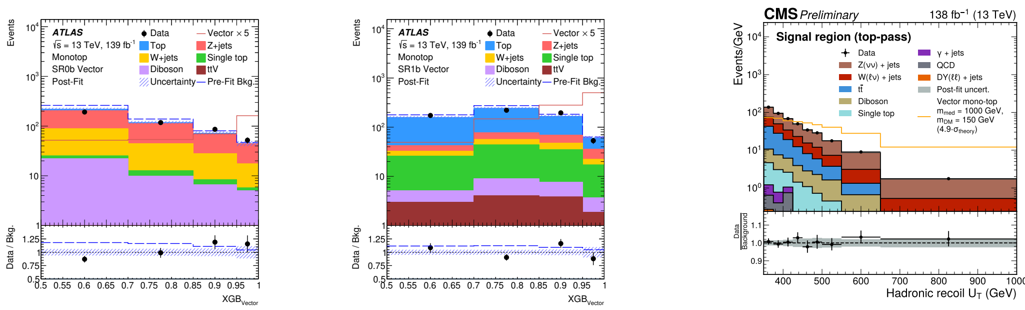
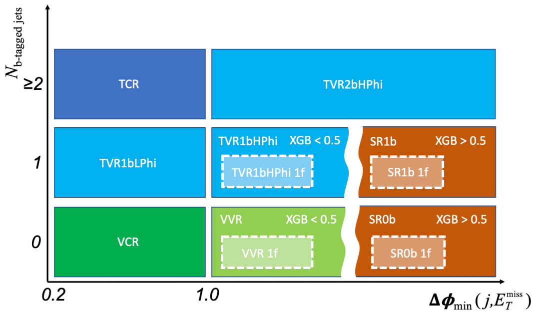
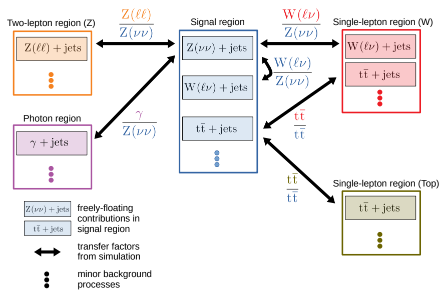


Figure 2: Signal regions for the ATLAS [5] 0b (left) and 1b (centre) categories, and for the CMS [8] signal-enriched top-pass category (right)

The different fitting strategies are largely due to different background estimation methods. The major backgrounds are vector boson + jet production (particularly $Z \to \nu\bar{\nu}$ +jet) and single lepton $t\bar{t}$ decays, where the lepton is not identified. ATLAS estimate the total rate of these backgrounds in control regions (CRs) using a selection on the angle between the large-radius jet and p_T^{miss} and the number of b-tags, with validation regions to ensure good modelling of these backgrounds (figure 3a). CMS estimate the rate differentially in bins of p_T^{miss} via transfer factors from regions selecting leptons to target these processes (figure 3b).



(a) The control, validation and signal regions for the ATLAS analysis. Source: [5]



(b) The signal and control regions and transfer factors in the CMS analysis. Source: [8]

2.2 Results

Neither search observed a significant excess, so both analyses set lower limits on possible combinations of DM mass, mediator mass and couplings. These are shown in figure 4. These are not directly comparable, but one can see that the for a coupling to DM of 0.25 and a DM mass of 1 GeV, the ATLAS analysis is expected to exclude mediator masses up to 80 GeV higher than the CMS search, and in the observed results the difference is even larger due to the downward fluctuation of the CMS observed limits. However for higher mediator masses CMS is able to exclude more of the region close to the kinematic limit of $2m_{\text{DM}} = m_{\text{med}}$, where the mediator starts to go off-shell, likely due to the larger jet radius used by CMS giving access to less boosted topologies.

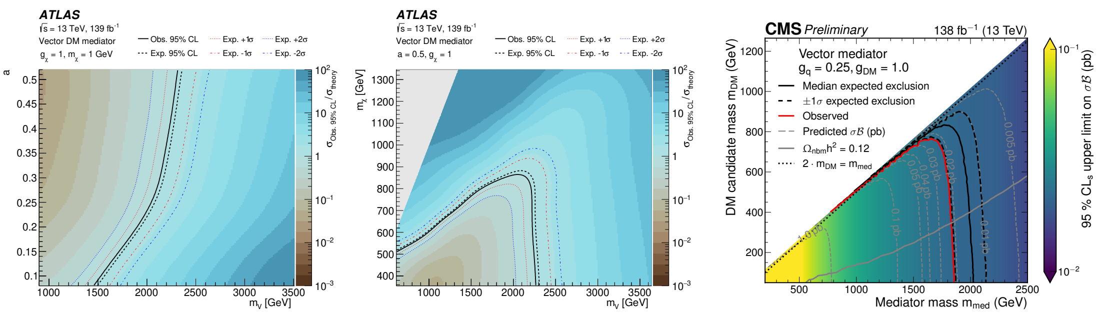
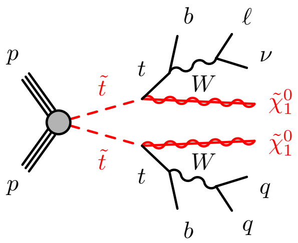


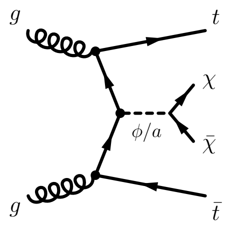
Figure 4: Left, the ATLAS limits on the mass of the mediator, m_V, and the coupling to the SM, a, for DM mass, $m_\chi = 1$ GeV; centre, the ATLAS limits on m_V and m_χ for $a = 0.5$ (source: [5]). Right, the CMS limits on mediator mass, m_{med}, and DM mass, m_{DM}, for a coupling to the SM of 0.25 (source: [8]). All have a DM coupling of 1.0

3 Dark Matter in $t\bar{t}$ Final States

Another important signature for LHC DM searches is the production of DM in association with a $t\bar{t}$ pair. The two most common models for this are stop quark pair production in supersymmetry, where the stops decay to a top quark and a neutralino, which is the DM candiate (figure 5a), and spin-0 (scalar and pseudoscalar) mediators, which have a Yukawa coupling and can be produced in association with $t\bar{t}$ and decay to a pair of DM particles (figure 5b) — these models tend to have less boosted topologies than stop pair production.



(a) Production of a pair of stop squarks decaying to top quarks and neutralinos. Source: [9]



(b) Production of DM in association with $t\bar{t}$ via a spin-0 mediator. Source: [9]

Both ATLAS and CMS have already performed searches for both of these models using the full run 2 datasets [10, 11]. However there was still room for sensitivity improvements in this dataset, and so both collaborations have released new results featuring novel analysis strategies in the past year. CMS also performed a measurement of the dineutrino kinematics of SM dileptonic $t\bar{t}$ production [12], which can be a major background for these kinds of searches, and was presented in [13].

3.1 Searches in single-lepton $t\bar{t}$ final states

The first result is a re-analysis of the single lepton $t\bar{t} + p_T^{\text{miss}}$ channel by ATLAS, targeting both stop squark pair production and simplified $t\bar{t}$+DM models [9]. This included numerous improvements, including a new resolved top tagger, and dedicated neural networks targeting each signal.

No significant excess was observed, and limits were set on both models (figure 6). The previous search for stop squark pair production used a large number of categories, which targeted both the compressed and boosted regions, and hence the new result only achieves the same level of sensitivity for the compressed region and slightly less for very boosted topologies. However the more general strategy, and the combination of resolved and boosted top tags, provides a significant improvement in sensitivity for the intermediate mass-gap scenario, where the old category-based analysis was particularly insensitive. For the simplified $t\bar{t}$+DM model the analysis shows a significant improvement compared to the previous result due to the dedicated neural network and resolved top taggers. This result was also combined with existing results in the 0 and 2 lepton channels, dramatically improving the sensitivity of the combination as this channel overtakes the dilepton channel to become the most sensitive.

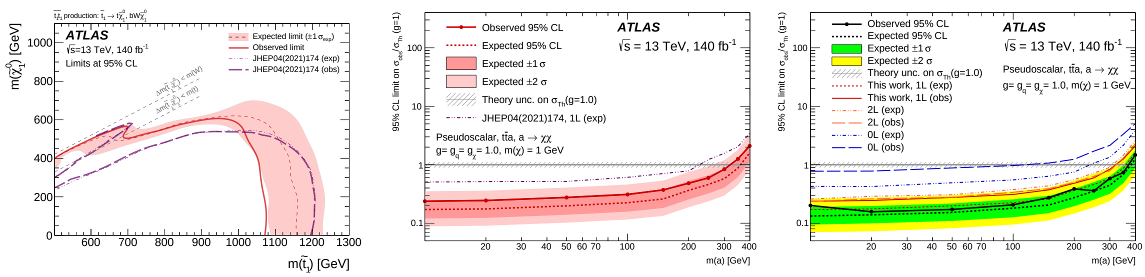


Figure 6: Comparisons of latest ATLAS 1l results [9] (red lines) with the previous result published in [14] (purple lines) for stop quark pair production (left) and $t\bar{t}$+DM production via pseudoscalar mediator (center), and, right the combination of pseudoscalar $t\bar{t}$+DM limits with existing results in the 0 and 2 lepton channels.

3.2 A charming Alternative: Stop squarks decaying to top and charm quarks

In more exotic supersymmetric models, stop quarks may decay to other flavours of quark in addition to the top, such as the charm quark. A new search [15] targets the case in which one stop squark decays to a neutralino and a (hadronically decaying) top quark, and the other to a charm quark. This uses boosted and resolved top taggers similar to [9], and a dedicated tagger for jets from charm quarks. Selections are applied on numerous kinematic variables to suppress common backgrounds, and a fit is performed in numerous signal categories targeting the boosted, intermediate and compressed topologies. Control regions are used to estimate the rates of major backgrounds, (single top, Z and W boson and $t\bar{t}$ production). The distribution in the boosted and intermediate SRs, and limits for this analysis are shown in figure 7 — there is a 2 σ excess in the boosted signal regions (SRA and SRB).

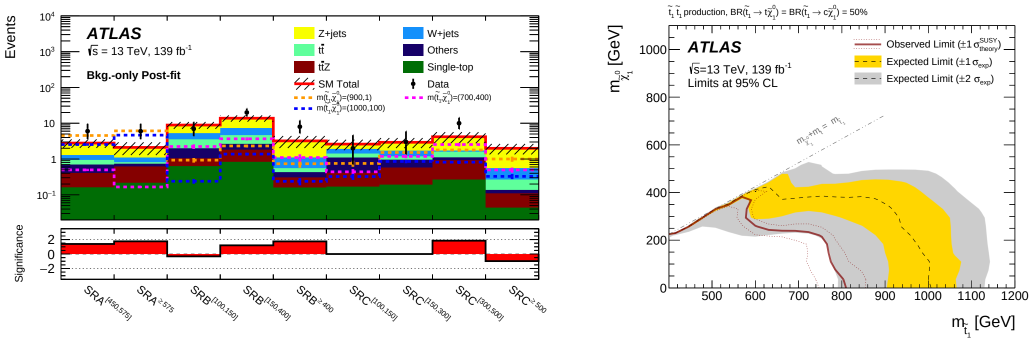


Figure 7: Left: Post-fit agreement with ATLAS data in the boosted and intermediate SRs for flavour violating stop quark production. Right: ATLAS limits on this model. Source: [15]

3.3 Putting it all together: Dark matter produced in association with a single top quark or top quark pair

The simplified models which predict $t\bar{t}$+DM signatures also give rise to single top + DM (t+DM) diagrams, as shown in figure 8. The cross sections for these processes are lower than for $t\bar{t}$+DM production, but they decrease more slowly as a function of mediator mass, so can provide significant sensitivity to higher mediator masses [17]. CMS has recently released an analysis [16] targeting both t+DM and $t\bar{t}$+DM across all top quark decay modes. This analysis requires fewer jets than analyses only targeting $t\bar{t}$+DM, and the number of b-tagged jets is used to categorise SRs targeting t+DM (1 b jet) and $t\bar{t}$+DM (2 b jets). Additionally, in the 0 and 1 lepton channels the t+DM region includes a forward jet category to enhance sensitivity to t-channel single top + DM production.

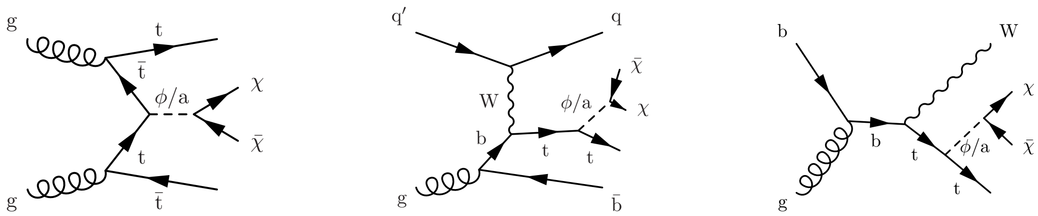


Figure 8: Diagrams for production of DM in association with a top quark pair or a single top quark: left, $t\bar{t}$+DM production; centre, t-channel t+DM production, and right, tW+DM production. Source: [16]

The different lepton channels face different challenges, and hence use different analysis strategies. The 0 and 1 lepton channels generally have high statistics but challenging backgrounds to model, and therefore cut on a series of kinematic variable and fit on p_T^{miss}, with numerous control regions linked to the SR in the final fit on a per-bin basis, allowing fine-grained estimation of the backgrounds. A categorisation on a variable called "topness", designed to suppress contributions from dileptonic $t\bar{t}$ where one lepton is not reconstructed, was used in the 1 lepton channel. p_T^{miss} is less sensitive in the 2 lepton channel, since the main background is dileptonic SM $t\bar{t}$ events containing two neutrinos, and so a simpler selection was used and the final fit was performed on the output of a NN. Some example SR distributions are shown in figure 9, and the limits on pseudoscalar mediator masses are shown in figure 10. An excess of approximately 2 σ significance is observed — since all signals peak at high p_T^{miss} (or NN score) this excess is consistent with all mediator masses considered, but is highest for mediators around 200 GeV.

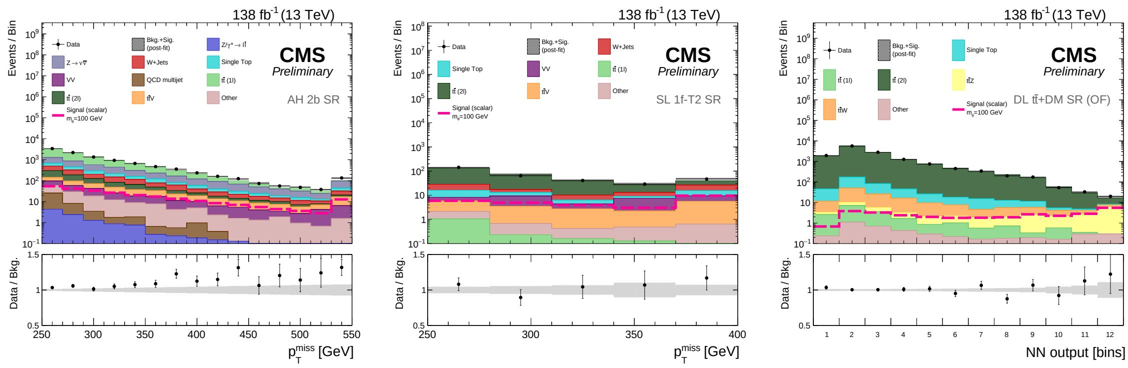


Figure 9: Example SRs for the combined CMS t+DM and $t\bar{t}$+DM search. Left, the 0 lepton, $\geq$ 2 b jet SR; centre, the 1 lepton, 1 b jet, $\geq$ 1 forward jet, high topness SR; right, the 2 lepton different flavour, $\geq$ 2 b jet SR. Source: [16]

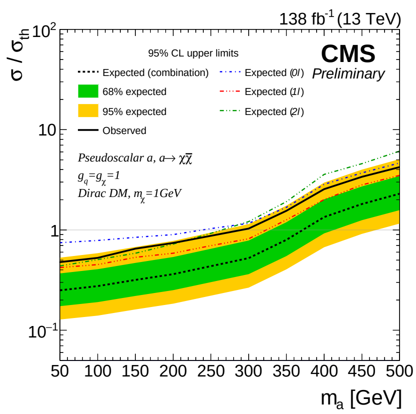


Figure 10: CMS limits on the combined cross section of t+DM and $t\bar{t}$+DM as a function of pseudoscalar mediator mass. Source: [16]

4 Conclusion

Many models predict that dark matter could be produced in association with top quarks at the LHC. Several results have been published in the past year which search for these models and have been presented here. These analyses aim to maximise the potential of the Run 2 LHC dataset, using machine learning to improve signal extraction, and advanced data-driven background estimation techniques to confront the challenging phase space. Many of these analyses are dominated by the statistical uncertainties and the signal cross sections highly dependent on collision energy, so there remains a lot of phase space to be explored in Run 3 and beyond.

Acknowledgements

The author would like to thank the ATLAS and CMS collaborations for the opportunity to present these interesting results, as well as the organisers of the Top Workshop for a well-run conference with an excellent scientific programme.

Funding information The author acknowledges support from DESY (Hamburg, Germany), a member of the Helmholtz Association HGF.

References

[1] D. Clowe, M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones and D. Zaritsky, *A direct empirical proof of the existence of dark matter**, The Astrophysical Journal **648**(2), L109 (2006), doi:10.1086/508162.

[2] M. Srednicki, R. Watkins and K. A. Olive, *Calculations of relic densities in the early universe*, Nuclear Physics B **310**(3), 693 (1988), doi:https://doi.org/10.1016/0550-3213(88)90099-5.

[3] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3**, S08003 (2008), doi:10.1088/1748-0221/3/08/S08003.

[4] CMS Collaboration, *The CMS Experiment at the CERN LHC*, JINST **3**, S08004 (2008), doi:10.1088/1748-0221/3/08/S08004.

[5] ATLAS Collaboration, *Search for new particles in final states with a boosted top quark and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **05**, 263 (2024), doi:10.1007/JHEP05(2024)263, 2402.16561.

[6] ATLAS Collaboration, *Search for large missing transverse momentum in association with one top-quark in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **05**, 041 (2019), doi:10.1007/JHEP05(2019)041, 1812.09743.

[7] CMS Collaboration, *Search for dark matter in events with energetic, hadronically decaying top quarks and missing transverse momentum at $\sqrt{s} = 13$ TeV*, JHEP **06**, 027 (2018), doi:10.1007/JHEP06(2018)027, 1801.08427.

[8] CMS Collaboration, *Search for dark matter production in association with a single top quark*, CMS Physics Analysis Summary CMS-PAS-SUS-23-004 (2024).

[9] ATLAS Collaboration, *Search for new phenomena with top-quark pairs and large missing transverse momentum using 140 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **03**, 139 (2024), doi:10.1007/JHEP03(2024)139, 2401.13430.

[10] CMS Collaboration, *Combined searches for the production of supersymmetric top quark partners in proton–proton collisions at $\sqrt{s} = 13\,TeV$*, Eur. Phys. J. C **81**(11), 970 (2021), doi:10.1140/epjc/s10052-021-09721-5, 2107.10892.

[11] ATLAS Collaboration, *Constraints on spin-0 dark matter mediators and invisible Higgs decays using ATLAS 13 TeV pp collision data with two top quarks and missing transverse momentum in the final state*, Eur. Phys. J. C **83**(6), 503 (2023), doi:10.1140/epjc/s10052-023-11477-z, 2211.05426.

[12] CMS Collaboration, *Measurement of the dineutrino system kinematics in dileptonic top quark pair events in pp collisions at $\sqrt{s} = 13\,eV$*, CMS Physics Analysis Summary CMS-PAS-TOP-24-001 (2024).

[13] S. Consuegra Rodríguez, *Differential cross section measurements of top quark pair production for variables of the dineutrino system with the CMS experiment* (2024), 2412.14806.

[14] ATLAS Collaboration, *Search for new phenomena with top quark pairs in final states with one lepton, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **04**, 174 (2021), doi:10.1007/JHEP04(2021)174, 2012.03799.

[15] ATLAS Collaboration, *A search for top-squark pair production, in final states containing a top quark, a charm quark and missing transverse momentum, using the 139 fb^{-1} of pp collision data collected by the ATLAS detector*, JHEP **07**, 250 (2024), doi:10.1007/JHEP07(2024)250, 2402.12137.

[16] CMS Collaboration, *Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV*, CMS Physics Analysis Summary CMS-PAS-EXO-22-014 (2024).

[17] D. Pinna, A. Zucchetta, M. R. Buckley and F. Canelli, *Single top quarks and dark matter*, Phys. Rev. D **96**, 035031 (2017), doi:10.1103/PhysRevD.96.035031, 1701.05195.