Dark matter production in association with a single top-quark at the LHC in a two-Higgs-doublet model with a pseudoscalar mediator

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Abstract

The sensitivity of the LHC experiments to the associated production of dark matter with a single top is studied in the framework of an extension of the standard model featuring two Higgs doublets and an additional pseudoscalar mediator. It is found that the experimental sensitivity is dominated by the on-shell production of a charged Higgs boson, when this assumes a mass below 1 TeV. Dedicated selections considering one and two lepton final states are developed to assess the coverage in parameter space for this signature at a centre-of-mass energy of 14 TeV assuming an integrated luminosity of 300 fb\textsuperscript{-1}. For a pseudoscalar mediator \( a \) with mass 150 GeV and maximally mixed with the pseudoscalar of the two Higgs doublets, values of \( \tan\beta \) up to 3 and down to 15 can be excluded at 95% CL, if the \( H^\pm \) mass is in the range 300 GeV-1 TeV. This novel signature complements the parameter space coverage of the mono-Higgs, mono-\( Z \) and \( t\bar{t}+E_T^{\text{miss}} \) signatures considered in previous publications for this model.

Keywords: ATLAS, LHC, dark matter, missing energy, pseudoscalar mediators, top quark.

1. Introduction

The nature of the dark matter (DM) is one of the key open questions of contemporary physics, and its experimental investigation is the subject of a worldwide effort based on several different and complementary experimental techniques.

The search for particle DM produced at accelerators is an essential part of this program, and it is vigorously pursued at the CERN LHC, a proton-proton (\( pp \)) collider currently operating at a center-of-mass energy of 13 TeV. Since the DM particles are weakly interacting they would escape the detector unseen when produced in \( pp \) collisions at the LHC. The minimal experimental signature of DM production at a hadron collider thus consists in events with a visible final-state object \( X \) recoiling against missing transverse energy \( E_T^{\text{miss}} \) associated with the undetected DM. Based on the LHC data collected between 2009 and 2016, the ATLAS and CMS collaborations have analysed a variety of such signatures involving jets of hadrons, photons, electroweak (EW) gauge bosons, top and bottom quarks as well as the Higgs boson in the final state [1–13]. Given the absence of a signal, upper limits on the production cross sections have been obtained. The corresponding \( E_T^{\text{miss}} \) searches have been interpreted in the context of three different classes of theories: ultraviolet (UV) complete theories, simplified models (see the reviews [14–16] for a complete list of references), and effective field theories [17–22]. In particular, simplified models have become quite popular recently. They allow the study of the different possible signatures for DM production at the LHC focusing on the final state kinematics, and thanks to their very limited set of parameters, they provide a very effective mapping of the phenomenological space accessible to experimentation. While handy and in many cases useful, in general simplified models need to be employed with care. In some instances they might be too “simplified” to allow for an adequate investigation of the experimental potential of DM searches, as they sometimes neglect unique signatures which may arise from a more complete description of the interactions of DM with the standard model (SM). In addition, it might happen that specific research channels become explicitly sensitive to the UV completion. Glaring examples are given by violation of unitarity and gauge invariance, which points to the need for more complex extensions of the SM [23–28].

Focusing on the cases where the interaction with DM is mediated by a scalar or a pseudoscalar particle [29–34], a natural extension of the spin-0 simplified models is achieved by considering the mixing of the mediator with the Higgs boson. The experimental constraints on the Higgs boson couplings [35], however already severely constrain such a possibility. One way to relax the constraints from Higgs physics is to add to the SM a second Higgs doublet (2HDM), [36–40]. In this case the mediator that couples to DM can obtain its couplings to SM fermions from mixing with the second Higgs doublet.

In the case of a 2HDM and a pseudoscalar mediator that couples to Dirac DM (2HDM+\( \alpha \)), a detailed phenomenological analysis of the resulting \( E_T^{\text{miss}} \) signatures at the LHC has been performed in [39]. The conclusion drawn in that article is that the mono-Higgs and mono-\( Z \) signatures provide a very good and complementary coverage of the parameter space of the model, with a minor but relevant role for the associated production of DM and a top-anti-top pair (DM\( \bar{t}\bar{t} \)). However...
the DM$t$ signature, as discussed in [29, 31–33, 41–43], gives through the study of the kinematics of the top-anti-top pair, access to CP properties of the mediator and is therefore of great phenomenological interest in case of the future observation of a non-SM $E_\text{T}^{miss}$ signal.

A complementary signature with heavy quarks in the final state is the associated production of a single top quark with DM (DM$t$). This signature has typically lower cross-section than DM$t$, and has received little attention in the literature. A recent study [44] based on a simplified model with a singlet scalar or pseudoscalar mediator shows that the consideration of this process increases the coverage of existing analyses targeting the DM$t$ process. Given the promising result, it is worthwhile to extend the investigation of [44] in two directions. On the one hand it is necessary to check whether the DM$t$ signature is still promising in a more complete model that is not plagued by unitarity issues, as discussed above. We choose the 2HDM$+a$ model of [39] as a benchmark model for this purpose. On the other hand, the possible interest of the signature for future searches at the LHC can only be properly assessed if a dedicated experimental analysis is developed, fully exploiting the final state topology of the signal in order to suppress the SM backgrounds.

The aim of this article is therefore to develop an experimental search strategy at the LHC for the DM$t$ signature, and to explore the parameter space of the chosen model that can be covered with the full LHC Run 3 statistics of 300 fb$^{-1}$ taken at a centre-of-mass energy of 14 TeV.

2. The 2HDM$+a$ model

The extension to the SM proposed in [39] includes a scalar sector with two Higgs doublets (see for example [45, 46]), where the parameters relevant for phenomenology are $\alpha$, the mixing angle of the two doublets and $\tan\beta$, the ratio of the vacuum expectation values (VEVs) of the two doublets. The angles $\alpha$ and $\beta$ are chosen according to the well-motivated alignment/decoupling limit of the 2HDM where $\alpha = \beta - \pi/2$. In this case $\sin(\beta - \alpha) = 1$ meaning that the field $h$ has SM-like EW gauge boson couplings. It can therefore be identified with the boson of mass $m(h) \approx 125$ GeV discovered at the LHC [47, 48].

Dark matter is coupled to the SM by mixing a SU(2) singlet CP-odd mediator $P$ with the CP-odd Higgs that arises from the 2HDM potential. The relevant interactions terms read

$$V_P = \frac{1}{2}m_P^2P^2 + P\left(ib_PH_1^+H_2 + \text{h.c.}\right) + P^2\left(\lambda_{P1}H_1^2 + \lambda_{P2}H_2^2\right),$$

where $m_P$ and $b_P$ are parameters with dimensions of mass. The quartic portal interactions with couplings $\lambda_{P1}$ and $\lambda_{P2}$ do not affect the phenomenology studied in this paper, and $\lambda_{P1}$ and $\lambda_{P2}$ are thus set to zero hereafter. The portal coupling $b_P$ appearing in (1) mixes the two neutral CP-odd weak eigenstates $h$ and $H$, while in the CP-odd sector the states will be denoted by $A$ and $a$, where $a$ denotes the mixing of the CP-odd scalar from the 2HDM and of the CP-odd mediator with weights $\sin\theta$ and $\cos\theta$, respectively. The scalar spectrum also contains two charged mass eigenstates $H^\pm$ of identical mass.

The Yukawa sector is built by respecting the so-called natural flavour conservation hypothesis, requiring that not more than one of the Higgs doublets couples to fermions of a given charge [49, 50]. In the following we consider a 2HDM Yukawa assignment of type II yielding a coupling of the top quark (bottom quark and $\tau$ lepton) proportional to $-\cot\beta (\tan\beta)$ respectively.

The DM is taken to be a Dirac fermion $\chi$ and is coupled to the pseudoscalar mediator $P$ through the interaction term

$$L_\chi = -i\gamma_5 P\gamma_5 \gamma_5 \chi. \quad (2)$$

The DM coupling strength $\gamma_5$ and the DM mass $m_\chi$ are further free parameters and are fixed as $\gamma_5 = 1$ and $m_\chi = 1$ GeV throughout our work. The choice of the value of $m_\chi$ has no impact on the phenomenology addressed in this study as long as the decays $A,a \rightarrow \chi\chi$ are kinematically open.

To avoid constraints from EW precision measurements, we furthermore assume that $m(H) = m(A) = m(H^+)$. Together with the restrictions specified above, this leaves a four-dimensional
parameter space including \( \tan \beta, \sin \theta, m(H^+) \) and \( m(a) \) for the phenomenological exploration in this paper.

3. The DM\(_\tau\) signal

Like single top production within the SM, the DM\(_\tau\) signature in the model (1) receives three different types of contributions at leading order (LO) in QCD. These are \( t\) channel production, \( s\) channel production and associated production together with a \( W\) boson \( (tW)\). The relative impact of the three production modes has been discussed in detail in [44] for the case of simplified spin-0 DM models. DM\(_\tau\) production in the \( s\) channel is, compared to the other channels, characterised by a very small cross-section, and we therefore neglect its contribution in our analysis. The \( t\)-channel process \( pp \rightarrow t j \chi \chi\) receives the dominant contributions from the two diagrams shown in Figure 1.

One has (a) the SM single top \( t\)-channel diagram with radiation of the mediator from the top \((a\text{-strahlung})\), and (b) the \( r\)-channel fusion of a charged Higgs and a \( W\) into the mediator \( a\). The two diagrams interfere destructively, and the amount of interference decreases with increasing \( H^+\) mass. As a result the \( t\)-channel production cross-section in our model (1) is, for equivalent values of the mediator mass and couplings, always smaller than the corresponding prediction in the spin-0 DM simplified model. The observed destructive interference ensures perturbative unitarity of the process \( pp \rightarrow t j \chi \chi\) in the 2HDM++ model.

In the case of the \( tW\) production channel it turns out that also two diagrams provide the dominant contributions to the DM\(_\tau\) cross-section. The relevant graphs are shown in Figure 2. The \( a\text{-strahlung}\) diagram, also present in the simplified spin-0 DM model, is displayed on the left-hand side, while the right diagram represents the associated production of a \( H^+\) and a \( t\) quark. Like in the case of \( t\)-channel production the two diagrams interfere destructively to ensure unitarity. When the decay \( H^+ \rightarrow W^+a\) is possible, the \( H^+\) is produced on-shell, and the cross-section of \( pp \rightarrow tW \chi \chi\), assuming \( H^+\) masses of a few hundred GeV, is around one order of magnitude larger than the one for the same process in the simplified model. Moreover the production and cascade decay of a resonance yields kinematic signatures which can be exploited to separate the signal from the SM background. The dependence of the production cross-section on \( \tan \beta\) for both the \( t\)-channel and \( tW\) processes is shown in the two panels of Figure 3. Both panel employ \( \sin \theta = 1/\sqrt{2}\) and \( m(a) = 150\) GeV, while \( m(H) = m(A) = m(H^+) = 500\) GeV and 1 TeV is used in the left and right plot, respectively. The cross-section for the production of the on-shell production of \( H^+\) to the \( tW\) final state is also shown as a dashed line. The calculation is performed at LO in QCD in the 5-flavour scheme, and the Yukawa couplings of both \( t\) and \( b\) quarks are included in the calculation.

From the shown results, one observes that the \( tW\) contribution to the DM\(_\tau\) cross-section always dominates over the \( t\)-channel, and that this dominance is more pronounced for lower values of \( m(H^+)\). This feature is easy to understand by noting that the \( tW\) channel itself receives the dominant contribution from resonant \( H^+\) production for charged Higgs masses of a few hundred GeV, while for \( m(H^+) = 1\) TeV resonant \( H^+\) production amounts to only around 50% of the \( tW\) cross-section.

For all processes a rapid decrease with increasing \( \tan \beta\) is observed, with a minimum at \( \tan \beta \approx 5\), followed by a slower increase towards high \( \tan \beta\) values. The resonant \( H^+\) production has a broad maximum for \( \tan \beta\) in the range of \([20, 30]\). This \( \tan \beta\) dependence is the result of the interplay of four factors: the production cross-section for \( H^+\) production in \( gb\) fusion is proportional to \( m(t) \cot^2 \beta + m(b)^2 \tan^2 \beta + \text{const.}\); the cross-section for diagrams where the \( a\) is radiated off a top quark is proportional to \( \cot^2 \beta\); the branching ratio (BR) for \( H^+ \rightarrow W^+a\) acquires a \( \tan \beta\) dependence from the competition with the decay \( H^+ \rightarrow t\beta\); finally, the BR for \( a \rightarrow \chi \chi\) decreases at high \( \tan \beta\) since the partial decay width \( a \rightarrow bb\) grows as \( \tan^2 \beta\).

Since both the widths for \( H^+ \rightarrow W^+a\) and \( a \rightarrow \chi \chi\) are proportional to \( \sin \theta\), the cross-section for DM\(_\tau\) grows monotonically with \( \sin \theta\). For the following studies we fix the value of the mixing angle \( \theta\) such that \( \sin \theta = 1/\sqrt{2}\), corresponding to maximal mixing in the pseudoscalar sector.

4. MC simulations

In this section we provide a brief description of the MC simulations used to generate both the DM signal and the SM backgrounds and explain how muons, electrons, photons, jets and missing transverse energy, \( E_T^{\text{miss}}\), are built in our detector simulation. Throughout our analysis we will consider \( pp\) collisions at \( \sqrt{s} = 14\) TeV.

4.1. Signal generation

The signal samples used in this paper are generated at LO using the 2HDM++ UFO model [51] implementation provided in [39]. The DM\(_\tau\) events are generated with MadGraph5_aMC@NLO [52], employing NNPDF3.0 parton distribution functions (PDFs) [53]. The final-state top quarks and \( W\) bosons are decayed with MadSpin [54] and the events are showered with PYTHIA 8.2 [55] and a 5-flavour scheme is assumed. We consider a grid in the \((m(H^+), \tan \beta)\) plane with seven different values of the \( H^+\) mass, varying from 300 GeV to 1 TeV and nine values of \( \tan \beta\) between 0.5 and 50. The mass of the pseudoscalar mediator \( m(a)\) is set to 150 GeV for this grid. An additional scan of the pseudoscalar mediator \( m(a)\) between 50 GeV and 375 GeV is performed, taking \( m(H^+\) = 500 GeV and \( \tan \beta = 1\), in order to assess the dependence of the results on the \( m(a)\) assumption. In both grid scans, the heavy scalar and pseudoscalar masses are always set to the same value \( m(H) = m(A) = m(H^+\).

4.2. Background generation

In order to describe the \( t + E_T^{\text{miss}}\) backgrounds accurately, SM processes involving at least one lepton coming from the decay of vector bosons are generated. Backgrounds either with fake electrons from jet misidentification or with real non-isolated leptons from the decay of heavy flavours are not considered in our analysis, as a reliable estimate of these backgrounds would require a simulation of detector effects beyond the scope of this
work. Based on ATLAS experimental results [10], we estimate these backgrounds not to exceed around 15% for the selections considered in this paper. The backgrounds from t\bar{t} [56], tW [57], WW, WZ and ZZ production [58, 59] were all generated at next-to-leading order (NLO) with POWHEG BOX [60]. The jets + Z and jets + W samples are generated at LO with MadGraph5_aMC@NLO and considering up to four jets for the matrix element calculation. MadGraph5_aMC@NLO is also used to simulate the t\bar{t}V backgrounds with V = W, Z at LO with a multiplicity of up to two jets, and the t\bar{t}Z and t\bar{t}W backgrounds at LO. The samples produced with POWHEG BOX are normalised to the NLO cross section given by the generator, except t\bar{t} which is normalised to the cross section obtained at next-to-next-to-leading order (NNLO) plus next-to-next-to-leading logarithmic accuracy [61, 62]. The jets + W/Z samples are normalised to the known NNLO cross sections [63, 64], and finally the NLO cross sections calculated with MadGraph5_aMC@NLO are used as normalisations for the t\bar{t}V samples.

4.3. Detector smearing

Muons, electrons, photons, jets and \( E_T^{\text{miss}} \) are constructed from the stable particles in the generator output. Jets are constructed by clustering the true momenta of all the particles interacting in the calorimeters, with the exception of muons. An anti-\( k_t \) algorithm [65] with a parameter \( R = 0.4 \) is used, as implemented in FastJet [66]. Jets originating from the hadronisation of bottom-quarks (b-jets) are experimentally tagged with high efficiency (b-tagged jets). The variable \( p_T^{\text{miss}} \) with magnitude \( E_T^{\text{miss}} \) is defined at truth level, i.e. before applying detector effects, as the negative of the vector sum of the \( p_T \) of all the invisible particles (neutrinos and DM particles in our case). The effect of the detector on the kinematic quantities utilised in the analysis is simulated by applying a Gaussian smearing to the momenta of the different reconstructed objects and reconstruction and tagging efficiency factors. The parametrisation of the smearing and the reconstruction and tagging efficiencies is tuned to mimic the performance of the ATLAS detector [67, 68] and is defined as a function of momentum and pseudorapidity of the objects. The discrimination of the signal from the background is greatly affected by the experimental smearing assumed for the \( E_T^{\text{miss}} \), which is the main handle to tame the large \( t\bar{t} \) background. To this aim, the transverse momenta of unsmeared electrons, muons and jets are subtracted from the truth \( E_T^{\text{miss}} \) and then replaced by the corresponding smeared quantities. The residual truth imbalance is then smeared as a function of the scalar sum of the transverse momenta of the particles not assigned to jets or electrons. The final selections and results are derived by analysing the simulated sample using the TDataFrame tool [69].

5. Kinematic properties of DMt and analysis strategy

The discussion of the DMt signal in Section 2 should have made clear that the t\bar{t}W channel is the dominant production mechanisms for all parameter choices in which the \( H^\pm \) can decay on-shell into the pseudoscalar mediator and a W boson. In order to search for this signal, we consider two different final states in our analysis, containing either one or two leptons. In both cases the leptons are produced in the decay of a W boson,
either prompt or in a cascade from the top-quark decay. Furthermore, the signal events contain one $b$-jet, which again stems from the top-quark decay. In the one-lepton final state, two additional jets are produced from the hadronic decay of one of the $W$ bosons. A significant amount of $E_{T}^{\text{miss}}$ associated to both the DM particles and the neutrinos from $W \rightarrow \ell\nu$ decays is also present in the events.

If the $W$ boson from $H^{\pm} \rightarrow aW^{\pm}$ decays leptonically into an electron or a muon, the resulting final state includes one lepton and three invisible particles, with two invisible particles upstream of the lepton, and one downstream. See Figure 4 for the corresponding decay chain. The kinematics of this decay topology is analysed in the appendix of Ref. [70]. The transverse mass $m_{T}^{\ell}$ built with the components transverse to the beam of the lepton momentum ($p_{T}^{\ell}$) and of the vector sum of the momenta of the invisible particles ($\vec{p}_{T}^{\text{miss}}$) has a distribution with an end-point which is a function of $m(H^{\pm})$, $m(W)$ and $m(a)$. This variable can be directly measured for the one-lepton final state when the lepton is produced in the $H^{\pm}$ decay. In the case of the two-lepton final state, the distribution of $m_{T2}$ for the $H^{\pm}$ decay enters the construction of the $m_{T2}$ variable [71, 72] built out of the two leptons and $\vec{p}_{T}^{\text{miss}}$, which has the same end-point. The two variables $m_{T}^{\ell}$ and $m_{T2}$ can therefore be exploited to strongly reduce the dominant SM backgrounds from single or double production of top quarks, in which case $E_{T}^{\text{miss}}$ is generated only from the neutrinos from $W$ decay and the distributions display an end-point at the $W$-boson masses. The discriminating power of the $m_{T}^{\ell}$ (left panel) and $m_{T2}$ (right panel) observables is illustrated in Figure 5, which shows the relevant distributions after all the one-lepton and two-lepton selection requirements, as described in the next section, have been applied.

The events surviving the $m_{T}^{\ell}$ requirement for the one-lepton selection are dominated by $t\bar{t}$ events that decay into two leptons, but one of the two leptons is not identified in the detector. The variable $m_{T2}$ [73, 74] was developed to tame this background and is therefore employed in the one-lepton analysis.

Secondary backgrounds like the production of single or double vector bosons are efficiently suppressed by requiring QCD jet production in the event. The angular correlation between the jets and $E_{T}^{\text{miss}}$ has a good discrimination power, both for the 1-lepton and the 2-lepton case, as for leptonic decays of the $H^{\pm}$ all jets in the event are produced in the decay of the accompanying top quark, while $E_{T}^{\text{miss}}$ is dominantly aligned with the $H^{\pm}$, implying that $E_{T}^{\text{miss}}$ is mostly isolated from jets.

5.1. One-lepton analysis

Events with exactly one isolated lepton ($e$ or $\mu$) with $p_{T} > 25$ GeV, at least three jets ($p_{T} > [50, 20]$ GeV, $|\eta| < 2.5$) and $E_{T}^{\text{miss}} > 250$ GeV are selected for this topology. All reconstructed jets with $p_{T}^{j} > 25$ GeV within $|\eta| < 2.5$ have to satisfy $|\Delta \phi_{\text{min}}| > 1.1$, where $\Delta \phi_{\text{min}}$ is defined to be the angle between $\vec{p}_{T}^{j}$ and $\vec{p}_{T}^{\text{miss}}$ for the jet closest to $E_{T}^{\text{miss}}$ in the azimuthal plane. At least one jet is required to be $b$-tagged. All dominant backgrounds except for single top production are characterised by two hard $b$-jets produced in the decay of a top quark. In order to suppress these backgrounds, event with a second $b$-tagged jet with $p_{T} > 50$ GeV are rejected. The semi-leptonic and dileptonic $t\bar{t}$ backgrounds are strongly suppressed by requiring $m_{T}^{\ell} > 300$ GeV and $m_{T2} > 200$ GeV, respectively.

Further requirements on the invariant mass of the lepton and the leading $b$-tagged jet ($m(b1, \ell) > 160$ GeV) and on the invariant mass of the leading light jet and the leading $b$-tagged jet ($m(b1, j1) < 150$ GeV) are placed to further suppress the residual background compatible with the presence of a semileptonic top decay in the event. As it can be seen in Figure 6, these requirements select the signal topology where the $H^{\pm}$ decays leptonically, which was found to have kinematic features that made it easier to discriminate from the backgrounds. The signal events where the $H^{\pm}$ decays hadronically are kinematically more similar to the SM backgrounds, due to the smearing of $E_{T}^{\text{miss}}$ associated to neutrinos in top decays. In this case a dedicated strategy would be needed to successfully distinguish between signal and background. The same applies to the production via $t$-channel diagrams, which is also rejected by the requirements of the analysis. The definition of a dedicated signal region targeting the hadronic $H^{\pm}$ decay is expected to increase significantly the sensitivity of the analysis. We leave the definition of such region to the experimental collaborations.

5.2. Two-lepton analysis

As a first step, events with two leptons and at least one $b$-tagged jet are selected. The events are required to contain exactly two isolated oppositely charged leptons (electrons, muons or one of each flavour) with $p_{T}^{\ell} > 25$ GeV, $p_{T}^{\ell} > 20$ GeV, $|\eta| < 2.5$ and an invariant mass that satisfies $m_{\ell\ell} > 20$ GeV. If the charged signal leptons are of the same flavour the additional requirement $m_{T2} \in [71, 111]$ GeV is imposed to veto events where the charged lepton pair arises from a $Z \rightarrow \ell^{+}\ell^{-}$ decay. Furthermore, each event is required to contain at least one $b$-tagged jet with $p_{T} > 40$ GeV. All reconstructed jets with $p_{T}^{j} > 25$ GeV within $|\eta| < 2.5$ have to satisfy $|\Delta \phi_{\text{min}}| > 1.5$. The variable $\Delta \phi_{\text{boost}}$, the azimuthal angular distance between

\[ m_{T}^{\ell} = M_T(\beta_T, p_{T}^{\text{miss}})^2 = 2 \beta_T |p_{T}^{\text{miss}}|(1 - \cos \Delta \phi_{\text{boost}})\]
The dominant b ant mass of at least one lepton with the leading of the leptons must satisfy the requirement \( |\Delta \phi_{\text{boos}}| < 1 \). The reducible backgrounds are suppressed by requiring that the invariant mass of at least one lepton with the leading b-jet is smaller than 150 GeV, and thence compatible with the decay of a top quark. The dominant \( t\bar{t} \) backgrounds have a second b-tagged jet, with \( p_T \) typically in excess of 50 GeV, whereas the signal has only one top decay. The requirement that the scalar sum of the transverse momenta of all the jets observed in the event be lower than 150 GeV suppresses events with two real top quarks. The final cut, following [43] is based on the following linear combination of \( E_T^\text{miss} \) and \( m_{\text{T2}} \):

\[
C_{\text{em}} \equiv m_{\text{T2}} + 0.2 \cdot E_T^\text{miss}.
\]

The requirement that this variable be larger than 180 GeV, together with the cut \( m_{\text{T2}} > 100 \) GeV reduces the background from \( t\bar{t} \) production well below the irreducible \( t\bar{t}Z \) background. This is shown in the right panel of Figure 5.

### 6. Results

On the basis of the selection criteria defined in the previous section, we study the LHC sensitivity to the DMt signature for an integrated luminosity of 300 fb\(^{-1}\) at \( \sqrt{s} = 14 \) TeV.

The total background in the one-lepton selection is approximately 25 events. More than half of the background contribution is coming from \( t\bar{t} + V \) and \( tZ \) processes and the rest is due to the contribution of top pairs (dileptonic decays) and single top \( tW \) channel in an approximate ratio of 2 to 1. In the charged Higgs mass range from 500 GeV to 1 TeV the acceptance for signal events containing at least one lepton amounts to [0.5, 1]% ([0.2, 0.8]% for \( m(a) = 150 \) GeV and \( \tan \beta = 1 \)).

The total background in the two-lepton selection is approximately 10 events, dominantly composed of the \( t\bar{t} + V \) and \( tWZ \) background processes. For \( m(H^\pm) \) between 300 GeV to 700 GeV the acceptance for signal events containing at least two leptons is in the range [0.1, 0.7]% ([0.06, 0.5]% for \( m(a) = 150 \) GeV and \( \tan \beta = 1 \)).
A profiled likelihood ratio test statistic is used to evaluate the upper limit on the ratio of the signal yield to that predicted in the 2HDM+$\alpha$ model. The CLs method [75] is used to derive exclusion limits at 95% Confidence Level (CL). The statistical analysis has been performed by employing the RooStat toolkit [76]. The results are interpreted in terms of relevant parameters defining the model, namely $m(H^\pm)$, $m(\alpha)$ and $\tan\beta$. The masses of the other Higgs bosons, except for the SM one, are set to the mass of the charged Higgs.

![Graph showing upper limits on the ratio of the signal yield to that predicted in the 2HDM+α model](image)

Given the relatively large irreducible background surviving all the selections, the experimental sensitivity will be dominantly determined by the systematic uncertainty on the estimate of the SM backgrounds. Such uncertainty has two main sources: the uncertainties affecting the detector performance such as the energy scale for hadronic jets and the identification efficiency for leptons, and, in addition, the uncertainties plaguing the evaluation procedure for the background which typically includes a mix of theoretical uncertainties on the MC modelling of SM processes and uncertainties on the data-driven estimates of the main backgrounds. Depending on the process and on the kinematic selection, the total uncertainty can vary between a few percent and a few tens of percent. Since the present analysis does not select an extreme kinematic phase space for the dominant $t\bar{t}Z$ background, it should be possible to control the systematic uncertainties at the 10% to 30% level. In the following, we will assume a 20% uncertainty on the backgrounds and, furthermore, a 5% uncertainty on the signal, which accounts for the impact of scale and PDF variations on the signal modelling.

Since the one-lepton and two-lepton analyses select two orthogonal event samples, they can be statistically combined, in order to assess the potential gain in sensitivity deriving from such treatment. In the combination, both signal and background uncertainties are treated as correlated.

Figure 7a shows the exclusion limits obtained by the combination of the one-lepton and two-lepton selections described in the text. The limits are presented in (a) as a function of $\tan\beta$ for different $m(H^\pm)$ masses and $m(\alpha) = 150$ GeV, and in (b) as a function of $m(\alpha)$ for $m(H^\pm) = 500$ GeV and $\tan\beta = 1$. The reach assumes 300 fb$^{-1}$ of 14 TeV LHC data and a systematic uncertainty of 20% (5%) on the SM background (signal).

Figure 8: Regions in the ($m(H^\pm), \tan\beta$) plane which can be excluded at 95% CL through the one-lepton and two-lepton searches described in the text. The reach assumes 300 fb$^{-1}$ of 14 TeV LHC data and a systematic uncertainty of 20% (5%) on the SM background (signal).
Finally, Figure 8 shows the exclusion contour in the $(m(H^0), \tan \beta)$ plane for the separate one-lepton and two-lepton selections and their combination. The $z$-axis shows the ratio of the excluded and the theoretical cross-sections for the combined fit. Comparing the contours, the complementarity in reach between the one-lepton and the two-lepton selections is evident, resulting only in a small improvement when the two channels are combined.

Limits on the production of $H^+$ followed by the decay into either $\tau \nu$ [77, 78] or $tb$ [79–81] are available from the ATLAS and CMS collaborations. For the decay into $\tau \nu$ the limits are outside the range of parameters considered in this analysis. For the $tb$ decay we recast the limits given in [81] taking into account that the $H^+ \rightarrow tb$ BR is reduced because the partial decay width $H^+ \rightarrow aW^*$ is in general non-vanishing in our model (1). The results are shown as a blue dashed line in Figure 8, and they cover an area largely complementary to the results of the DM$\tau$ analysis.

7. Conclusions

In this article we have assessed the prospects of future LHC runs to probe spin-0 interactions between DM and top quarks via the $t+E^{\text{miss}}_T$ signature. We have focused on a model with two Higgs doublets and a pseudoscalar mediator. The rich structure of the Higgs sector in the 2HDM+$a$ model provides interesting final-state signatures dependent on the mass hierarchy of the different bosons. In particular, the $t+E^{\text{miss}}_T$ signature is dominated by on-shell production of the charged Higgs associated with a top-quark, if the decay channel $H^+ \rightarrow W^*a$ is kinematically accessible.

Two final states were considered, involving one and two leptons from the decay of the two $W$ bosons in the event. Analysis strategies were developed which take advantage of the topology of the leptonic $H^+$ decay to enhance the signal with respect to the SM backgrounds. It was shown that the one-lepton and two-lepton analyses have complementary sensitivity as a function of $m(H^0)$, with the former (latter) being more sensitive at higher (lower) masses.

For a mediator with mass $150$ GeV, and maximally mixed with the pseudoscalar $A$ of the two Higgs doublet model, values of $\tan E^{\text{miss}}_T$ up to 3 and down to 15 can be excluded at $95\%$ CL by the LHC with an integrated luminosity of $300$ fb$^{-1}$ at $\sqrt{s} = 14$ TeV, if the $H^+$ mass is in the range of $300$ GeV and 1 TeV. The $t+E^{\text{miss}}_T$ signature considered here for the first time therefore complements the parameter coverage of the mono-Higgs, mono-$Z$ and $t+E^{\text{miss}}_T$ searches that have been discussed in the context of the 2HDM+$a$ model in [39].

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[1] ATLAS Collaboration, Search for dark matter produced in association with a hadronically decaying vector boson in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B763 (2016) 251–268. arXiv:1608.02372, doi:10.1016/j.physletb.2016.10.042.

[2] CMS Collaboration, Search for dark matter produced with an energetic jet or a hadronically decaying $W$ or $Z$ boson at $\sqrt{s} = 13$ TeV, JHEP 07 (2017) 014. arXiv:1703.01651, doi:10.1007/JHEP07(2017)014.

[3] CMS Collaboration, Search for associated production of dark matter with a Higgs boson decaying to $bb$ or $\gamma\gamma$ at $\sqrt{s} = 13$ TeV, (2017). arXiv:1703.05236.

[4] ATLAS Collaboration, Search for dark matter at $\sqrt{s} = 13$ TeV in final states containing an energetic photon and large missing transverse momentum with the ATLAS detector, Eur. Phys. J. C77 (6) (2017) 393. arXiv:1704.03848, doi:10.1140/epjc/s10052-017-4965-8.

[5] CMS Collaboration, Search for dark matter produced in association with heavy-flavor quarks in proton-proton collisions at $\sqrt{s}$=13 TeV, (2017). arXiv:1706.02583.

[6] CMS Collaboration, Search for new physics in the monophoton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, (2017). arXiv:1706.03794.

[7] ATLAS Collaboration, Search for dark matter in association with a Higgs boson decaying to two photons at $\sqrt{s} = 13$ TeV with the ATLAS detector, (2017). arXiv:1706.03948.

[8] ATLAS Collaboration, Search for Dark Matter Produced in Association with a Higgs Boson Decaying to $b\bar{b}$ using 36 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector, Phys. Rev. Lett. 119 (18) (2017) 181804. arXiv:1707.01302, doi:10.1103/PhysRevLett.119.181804.

[9] ATLAS Collaboration, Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a $Z$ boson in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, (2017). arXiv:1708.09624.

[10] M. Aaboud, et al., Search for dark matter produced in association with bottom or top quarks in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, (2017). arXiv:1710.11412.

[11] CMS Collaboration, Search for top squarks and dark matter particles in opposite-charge dilepton final states at $\sqrt{s} = 13$ TeV, (2017). arXiv:1711.00752.

[12] ATLAS Collaboration, Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector, (2017). arXiv:1711.03301.

[13] ATLAS Collaboration, Search for top-squark pair production in final states with one lepton, jets, and missing transverse momentum using 36 fb$^{-1}$ of $\sqrt{s} = 13$ TeV $pp$ collision data with the ATLAS detector, (2017). arXiv:1711.11520.

[25] J. Abdallah, et al., Simplified Models for Dark Matter and Missing Energy Searches at the LHC (2014). arXiv:1409.2893.

[26] J. Abdallah, et al., Simplified Models for Dark Matter Searches at the LHC, Phys. Rev. 9-10 (2015) 8-23. arXiv:1506.03116, doi: 10.1016/j.dark.2015.08.001.

[27] D. Abercrombie, et al., Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum (2015). arXiv:1507.00966.

[28] M. Beltran, D. Hooper, E. W. Kolb, Z. A. C. Krusberg, T. M. P. Tait, Maverick dark matter at colliders, JHEP 09 (2010) 037. arXiv:1002.4137, doi:10.1007/JHEP09(2010)037.

[29] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait, H.-B. Yu, Constraints on Light Majorana dark Matter from Colliders, Phys. Rev. D82 (2010) 116010. arXiv:1008.1783, doi:10.1103/PhysRevD.82.116010.
[64] R. Gavin, Y. Li, F. Petriello, S. Quackenbush, W Physics at the LHC with FEWZ 2.1, Comput. Phys. Commun. 184 (2013) 208–214. arXiv: 1201.5896, doi:10.1016/j.cpc.2012.09.005.

[65] M. Cacciari, G. P. Salam, G. Soyez, The Anti-k(t) jet clustering algorithm, JHEP 04 (2008) 063. arXiv:0802.1189, doi:10.1088/1126-6708/2008/04/063.

[66] M. Cacciari, G. P. Salam, G. Soyez, FastJet User Manual, Eur. Phys. J. C72 (2012) 1896. arXiv:1111.6097, doi:10.1140/epjc/s10052-012-1896-2.

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

[68] ATLAS Collaboration, Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics, (2009). arXiv:0901.0512.

[69] E. Guiraud, A. Naumann, D. Piparo, TDataFrame: functional chains for ROOT data analyses (Jan. 2017). doi:10.5281/zenodo.260230. URL https://doi.org/10.5281/zenodo.260230.

[70] G. Polesello, D. R. Tovey, Supersymmetric particle mass measurement with the boost-corrected contransverse mass, JHEP 03 (2010) 030. arXiv:0910.0174, doi:10.1007/JHEP03(2010)030.

[71] C. G. Lester, D. J. Summers, Measuring masses of semi invisibly decaying particles pair produced at hadron colliders, Phys. Lett. B463 (1999) 99–103. arXiv:hep-ph/9906349, doi:10.1016/S0370-2693(99)00945-4.

[72] A. Barr, C. Lester, P. Stephens, m(T2): The Truth behind the glamour, J. Phys. G29 (2003) 2343–2363. arXiv:hep-ph/0304226, doi:10.1088/0954-3899/29/10/304.

[73] P. Konar, K. Kong, K. T. Matchev, M. Park, Dark Matter Particle Spectroscopy at the LHC: Generalizing M(T2) to Asymmetric Event Topologies, JHEP 04 (2010) 086. arXiv:0911.4126, doi:10.1007/JHEP04(2010)086.

[74] C. G. Lester, B. Nachman, Bisection-based asymmetric M\textsubscript{T2} computation: a higher precision calculator than existing symmetric methods, JHEP 03 (2015) 100. arXiv:1411.4312, doi:10.1007/JHEP03(2015)100.

[75] A. L. Read, Presentation of search results: The CL(s) technique, J. Phys. G28 (2002) 2693–2704, [11(2002)]. doi:10.1088/0954-3899/28/10/313.

[76] L. Moneta, K. Belasco, K. S. Cranmer, S. Kreiss, A. Lazzaro, D. Piparo, P. Konar, K. Kong, K. T. Matchev, M. Park, Dark Matter Particle Spectroscopy at the LHC: Generalizing M(T2) to Asymmetric Event Topologies, JHEP 04 (2010) 086. arXiv:0911.4126, doi:10.1007/JHEP04(2010)086.

[77] ATLAS Collaboration, Search for charged Higgs bosons produced in association with a top quark and decaying via H\textsuperscript{±} → τν using pp collision data recorded at \(\sqrt{s} = 13\) TeV by the ATLAS detector, Phys. Lett. B759 (2016) 555–574. arXiv:1603.09203, doi:10.1016/j.physletb.2016.06.017.

[78] CMS Collaboration, Search for charged Higgs bosons with the H\textsuperscript{±} → τν decay channel in the fully hadronic final state at \(\sqrt{s} = 13\) TeV, CMS-PAS-HIG-16-031, Geneva (2016). URL https://cds.cern.ch/record/2228865.

[79] CMS Collaboration, Search for charged Higgs bosons in the H\textsuperscript{±} → τb decay channel in pp collisions at \(\sqrt{s} = 8\) TeV using the ATLAS detector, JHEP 03 (2016) 127. arXiv:1512.03704, doi:10.1007/JHEP03(2016)127.

[80] CMS Collaboration, Search for a charged Higgs boson in pp collisions at \(\sqrt{s} = 8\) TeV, JHEP 11 (2015) 018. arXiv:1508.07774, doi:10.1007/JHEP11(2015)018.

[81] ATLAS Collaboration, Search for charged Higgs bosons in the H\textsuperscript{±} → τb decay channel in pp collisions at \(\sqrt{s} = 13\) TeV using the ATLAS detector, ATLAS-CONF-2016-089, Geneva (Aug 2016). URL https://cds.cern.ch/record/2206809.