

# Dark Matter Working Group recommendation for Two Higgs Doublet Model (draft title)

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**Abstract.** Draft abstract.

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## 1 Model kinematics and mapping to existing models

The signature and kinematic distributions of the 2HDM+a model at colliders are driven by the values assigned to the parameters described in the previous chapter. The model parameters can affect the total signal cross-section, the kinematic distributions, or both. In order to obtain a representative grid of benchmark points for collider searches and reduce this multi-dimensional parameter space, we scan ranges of the possible values of

these parameters and observe the impact on the kinematic distributions for representative collider searches.

In this chapter, we will outline the existing experimental searches that can be used to search for this model, and present the distributions of the kinematic variables for each of the searches as a function of the free parameters of the model. We note that in the following we have chosen to fix the DM coupling  $y_\chi$  to unity, and  $\lambda_{P1} = \lambda_{P2} = \lambda_P = 3$  as explained in ??.

## 1.1 Description of experimental searches

### 1.1.1 Signatures including a Higgs boson

Events with a 125 GeV Higgs boson, recently discovered with ATLAS and CMS [1, 2], and  $E_T^{\text{miss}}$  can indicate the production of Dark Matter candidates that recoil against the Higgs boson [3, 4]. The initial-state radiation (ISR) production of a Higgs boson is suppressed by the small Yukawa couplings of the Higgs boson to light quarks. Thus  $h + E_T^{\text{miss}}$  searches such as [5, 6] directly probe potential new interactions of the Higgs and Dark Matter, as predicted by the 2HDM+a model [7, 8] due to the  $a - A - h$  vertex.

**$h(bb) + E_T^{\text{miss}}$  signature** For the case where the Higgs boson decays into two  $b$ -quarks, such as studied in [5], the signal kinematics are studied at parton level. This allows a straightforward comparison to the model-independent results in [5], as described in [subsection 3.1](#), and fast iteration over different model scenarios.

### 1.1.2 Signatures including a Z boson

Events with a Z boson and  $E_T^{\text{miss}}$  may signal the presence of invisible particles recoiling against the Z boson [9, 10]. LHC searches (e.g. [11, 12] for the most recent ones) have focused on invisible decays of the SM-like Higgs bosons or on topologies where the Z boson is produced as ISR from a quark. The ISR-based topologies generically favor radiation of a gluon or photon rather than a massive gauge boson, thus limiting the discovery sensitivity of a Z-based approach compared to monojet and mono-photon searches. In contrast, the model studied in this document generates the mono-Z signature dominantly via the all-bosonic H-a-Z vertex, which can lead to enhancements in the mono-Z sensitivity compared to jet and photon signatures.

**Mono-Z (leptonic) signature** Three consecutive stages of event selection are considered in the case the Z decays leptonically:

- Inclusive: Lepton  $p_T$  and  $\eta$  requirements corresponding to the typical experimental trigger acceptance are applied.
- Preselection: A dilepton candidate with an invariant mass in a window around the Z mass is required, and a minimum transverse momentum of the  $\chi\bar{\chi}$  system is required.
- Final selection: Requirements on the main discriminating variables used in the relevant analyses are added: The angular separation in the transverse plane between

the  $\chi\bar{\chi}$  and  $l^+ l^-$  systems  $\Delta\Phi(l, E_T^{\text{miss}})$ , the relative transverse momentum difference between them  $|p_{T,l} - E_T^{\text{miss}}|/p_{T,l}$  and the angular separation between the leptons  $\Delta R(l)$ . Additionally, the  $E_T^{\text{miss}}$  requirement is tightened.

The exact event selection criteria are listed in the appendix, in ???. The results in this and in the following section are at particle level.

**Mono-Z (hadronic) signature** The hadronic signature in  $Z + E_T^{\text{miss}}$  events ( $Z \rightarrow q\bar{q}$  decays in association with large missing transverse momentum) is complementary to the leptonic signature. Hadronic decays are more frequent than leptonic decays, but suffer from larger backgrounds. For these reasons, the  $Z$  (hadronic) +  $E_T^{\text{miss}}$  search is favored if the model include higher mass scalar and pseudoscalar bosons.

The event selection in this case changes depending on the production transverse momentum of the  $Z$ -boson, as in the case of the exchange of a high-mass CP-even  $H$  boson. If the  $Z$ -boson is boosted, then its hadronic decay products could be merged into a single jet, and the  $Z$  to QCD background discrimination can be improved by exploiting the presence of substructure within a single, large-radius jet (denoted by  $J$ ). The *boosted* search is performed in addition to the *resolved* search, where the  $Z$  decay products are reconstructed as two separate small-radius jets (denoted by  $j$ ).

For mono- $Z(\rightarrow q\bar{q})$  events intermediated by the exchange of a high-mass CP-even  $H$  boson, the  $Z$ -boson will be produced with a large transverse momentum and the hadronic decay products of such  $Z$ -boson could be merged into a single jet. Such “boosted” event topology is investigated by exploiting the reconstruction technique with a large-radius jet (denoted by  $J$ ), in addition to more conventional “resolved” event topology where the  $Z$  decay products are reconstructed as two separate small-radius jets (denoted by  $j$ ). The jet reconstruction and the following analysis are all performed at particle level after showering and hadronization implemented in Pythia 8.212 described above.

Two consecutive stages of event selection are considered for the boosted and resolved event topologies:

- Inclusive: minimal kinematic requirements are applied to a pair of small-radius jets (a single large-radius jet) for the resolved (boosted) event topology. These selection criteria are applied separately, i.e, not sequentially.
- Final selection: selection criteria are applied to the a number of variables. The invariant mass of the pair of small-radius jets or the single large-radius jet is required to be within a window around the  $Z$  mass. In addition, selection is applied to the azimuthal angular difference between the  $\chi\bar{\chi}$  and the hadronic  $Z$ -boson system,  $\Delta\Phi(jj \text{ or } J, E_T^{\text{miss}})$ , and the magnitude of  $E_T^{\text{miss}}$ . These final selection cuts are applied sequentially to mimic a realistic analysis; in this study the boosted selection cuts are applied first and then the resolved selection cuts are applied to those events that fail the boosted ones.

The exact event selection criteria are listed in the appendix, in ???. The results in this and in the following section are at particle level.

### 1.1.3 Signatures including heavy flavor quarks

Heavy flavor final state can have sizable contributions to the production of the CP-even and CP-odd scalar mass eigenstates, due to the Yukawa structure of the couplings in the SM sector.

## 1.2 Kinematic distributions justifying the choice of parameter scan

### 1.2.1 Masses of the $A$ , $H$ , and $a$ bosons ( $M_A$ , $M_H$ , and $M_a$ )

The masses of the mediators  $M_A$ ,  $M_H$ , and  $M_a$  of the pseudoscalars  $A$  and  $a$  and the scalar  $H$ , which are the mediators of the resonant mono- $h$  and mono- $Z$  processes, affect the shape of the  $E_T^{\text{miss}}$  distribution of these processes. In the mono- $Z$  and mono- $H$  channels, the resonant production occurs through the  $2 \rightarrow 1 \rightarrow 2$  processes  $gg \rightarrow A \rightarrow ah$  and  $gg \rightarrow H \rightarrow aZ$ , respectively, with the light pseudoscalar decaying invisibly as  $a \rightarrow \chi\chi$ . In this case, the  $A/H \rightarrow ah$  process produces a resonance in the invariant mass distribution of the final state system with a width determined by the widths of  $a$ ,  $A/H$ , and of the SM bosons. This results in a peak in the transverse momentum distribution of the DM system, reconstructed as  $E_T^{\text{miss}}$  in the detector.

The location of this Jacobian peak can be calculated analytically starting from the masses of the particles involved in the decay [7]:

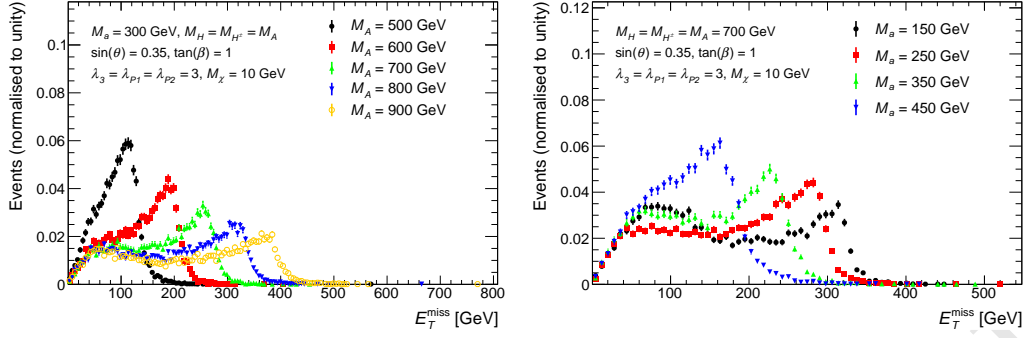
$$E_T^{\text{miss}, \text{max}} \approx \frac{\sqrt{\left(M_{A/H}^2 - M_a^2 - M_{h/Z}^2\right)^2 - 4M_a^2 M_{h/Z}^2}}{2M_{A/H}}. \quad (1.1)$$

Thus, increasing  $M_A$  results in a Jacobian peak at higher  $E_T^{\text{miss}}$ , as shown in Figure 1a, Figure 2 and Figure 3. Conversely, models with higher  $M_a$  have a Jacobian peak at lower  $E_T^{\text{miss}}$ , as indicated in Figure 1b and Figure 4. For  $M_{A/H} \approx M_a + m_{Z/h}$ , both the  $a$  and  $Z/h$  bosons are produced approximately at rest, leading to an event population with overall low boost. These qualitative trends are consistent with the distributions of the other main selection variables as shown in the appendix (??).

A potentially large fraction of the mono- $h$  signal events is also produced in non-resonant  $2 \rightarrow 3$  processes  $gg \rightarrow h\chi\chi$ , as in ??, leading to a broader distribution of the invariant mass of the decay products. Consequently, this results in a broader and softer  $E_T^{\text{miss}}$  distribution that is distinct from the Jacobian peak discussed above, and contributes to the off-peak features of Figure 1b and Figure 1a.

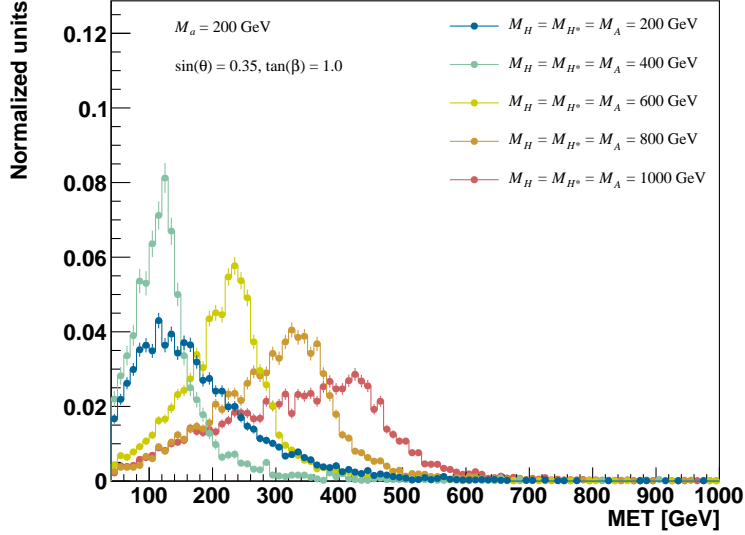
The masses  $M_a$  and  $M_A$  influence the kinematics in the  $t\bar{t} + E_T^{\text{miss}}$  signature as well. As shown in Figure 5, the  $E_T^{\text{miss}}$ , and leading and trailing top quark  $p_T$  distributions broaden with increasing  $M_a$ . Similarly, for values of  $M_A < M_a$ , as  $M_A$  increases, the kinematic distributions mentioned above also broaden, as shown in Figure 6.

Since the shape of the  $E_T^{\text{miss}}$  distribution affects the design of experimental searches, and to a large extent their sensitivity, *it is desirable to scan the  $M_A$  and  $M_a$  parameter space.*



(a)  $E_T^{\text{miss}}$  distribution for points with different  $M_A$  and fixed  $M_a = 300$  GeV. (b)  $E_T^{\text{miss}}$  distribution for points with different  $M_a$  and fixed  $M_A = 700$  GeV.

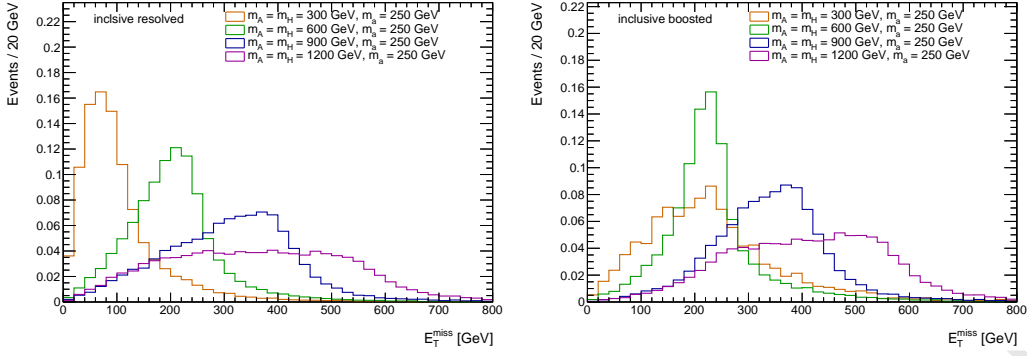
**Figure 1:** Parton-level  $E_T^{\text{miss}}$  distribution of mono-Higgs events for different  $M_a$  and  $M_A$ , with  $M_H = M_{H^\pm} = M_A$ ,  $\sin \theta = 0.35, \tan \beta = 1, M_\chi = 10$  GeV and  $\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3$



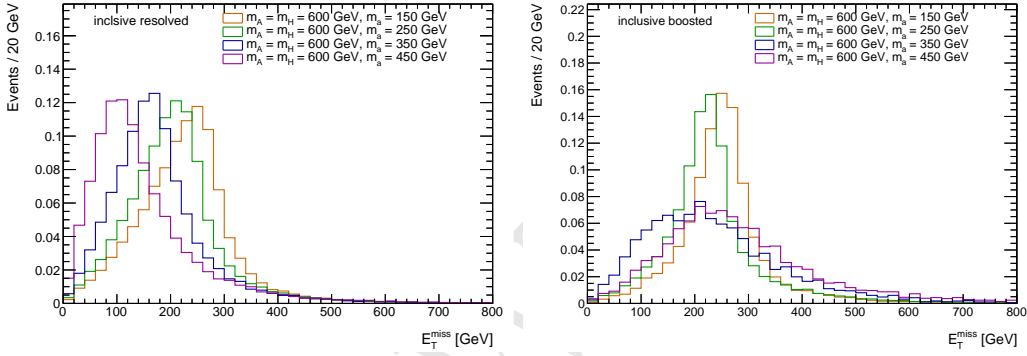
**Figure 2:** The  $E_T^{\text{miss}}$  distribution in signatures including a Z boson after preselection in the leptonic channel, with varying  $M_H$  values for fixed  $M_a = 200$  GeV and  $M_A = M_{H^\pm} = M_H$ .

In designing a search for evidence of this particular model, it may be useful to consider not only the  $E_T^{\text{miss}}$ , but also the transverse mass  $M_T$ <sup>1</sup> variable. The distributions of both variables after final selection are shown in Figure 7 for the  $Z + E_T^{\text{miss}}$  searches. Both distributions show Jacobian peak structures due to dominant effect of the diagram with resonant H exchange. In the case of  $M_a < M_H$ , the peak structure is more defined in the  $M_T$  distribution than in the  $E_T^{\text{miss}}$ , thus helping to distinguish a possible signal from background. Where the resonant diagram does not contribute, i.e. for  $M_a \approx M_H$  or

<sup>1</sup>The massless definition is used here:  $M_T = \sqrt{2E_T^{\text{miss}} p_{T,Z} (1 - \cos(\Delta\phi))}$



**Figure 3:**  $E_T^{\text{miss}}$  distributions in the resolved (left) and boosted (right) hadronic Z search, after applying the inclusive selection. The signal masses are chosen to be  $M_H = 300, 600, 900$  and  $1200$  GeV with the fixed  $M_a = 250$  GeV and  $M_A = M_{H^\pm} = M_H$ .

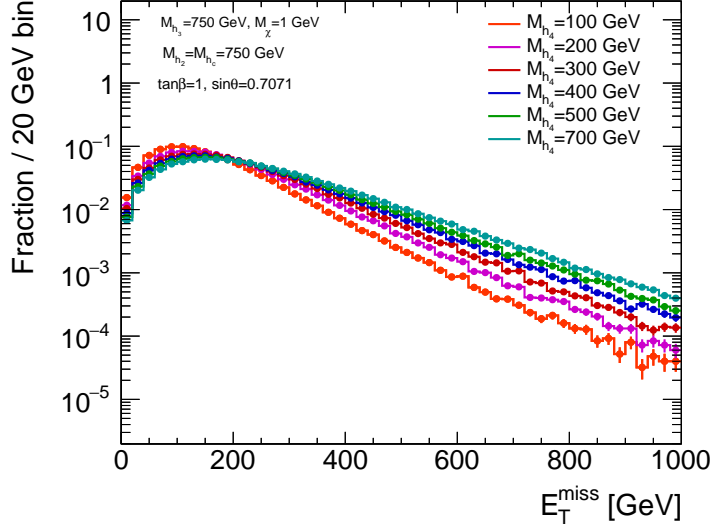


**Figure 4:**  $E_T^{\text{miss}}$  distributions in the resolved (left) and boosted (right) hadronic Z search, after applying the inclusive selection. The signal masses are chosen to be  $M_a = 150, 250, 350$  and  $450$  GeV with the fixed  $M_H = 600$  GeV ( $= M_A = M_{H^\pm}$ ).

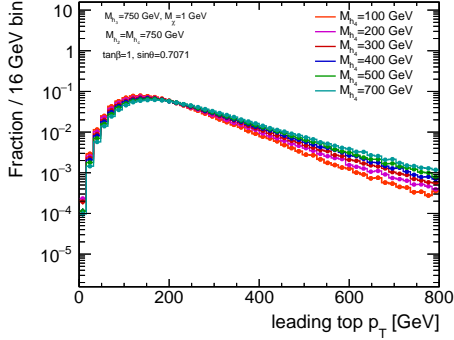
$M_a > M_H$ , the  $M_T$  distribution does not show a significantly different structure from the  $E_T^{\text{miss}}$  distribution and will not provide an improved sensitivity.

For mono- $h$ , the **mass of the heavy neutral scalar Higgs boson  $H$**  has an indirect effect on the rate and kinematics of the signal. This is caused by the dependence of the coupling strength of the  $a - A - h$  vertex, and thus decay width of the pseudoscalar  $A$ , on  $M_H$  [7]. Therefore, a change of  $M_H$  can strongly affect the relative contribution of resonant versus non-resonant signal processes, as illustrated in Figure 8. For mono- $Z$ , there is no corresponding effect of  $M_A$  on the resonant and non-resonant signal yields, since the  $a - H - h$  vertex has a simpler structure with no  $M_A$  dependence.

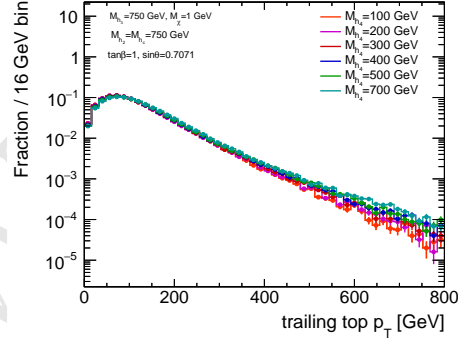
The choice  $M_H = M_A$  results in a detectable total cross section and a dominant contribution of the resonant mono- $h$  signal process for many signal points. This choice allows us to test diverse  $E_T^{\text{miss}}$  distributions and results in about equal contributions to the sensitivity through the  $Z + E_T^{\text{miss}}$  and  $h + E_T^{\text{miss}}$  signatures, highlighting their complementarity. For this reason *the choice  $M_H = M_A$  is adopted* for all scans.



(a)  $E_T^{\text{miss}}$



(b) Leading top quark  $p_T$



(c) Trailing top quark  $p_T$

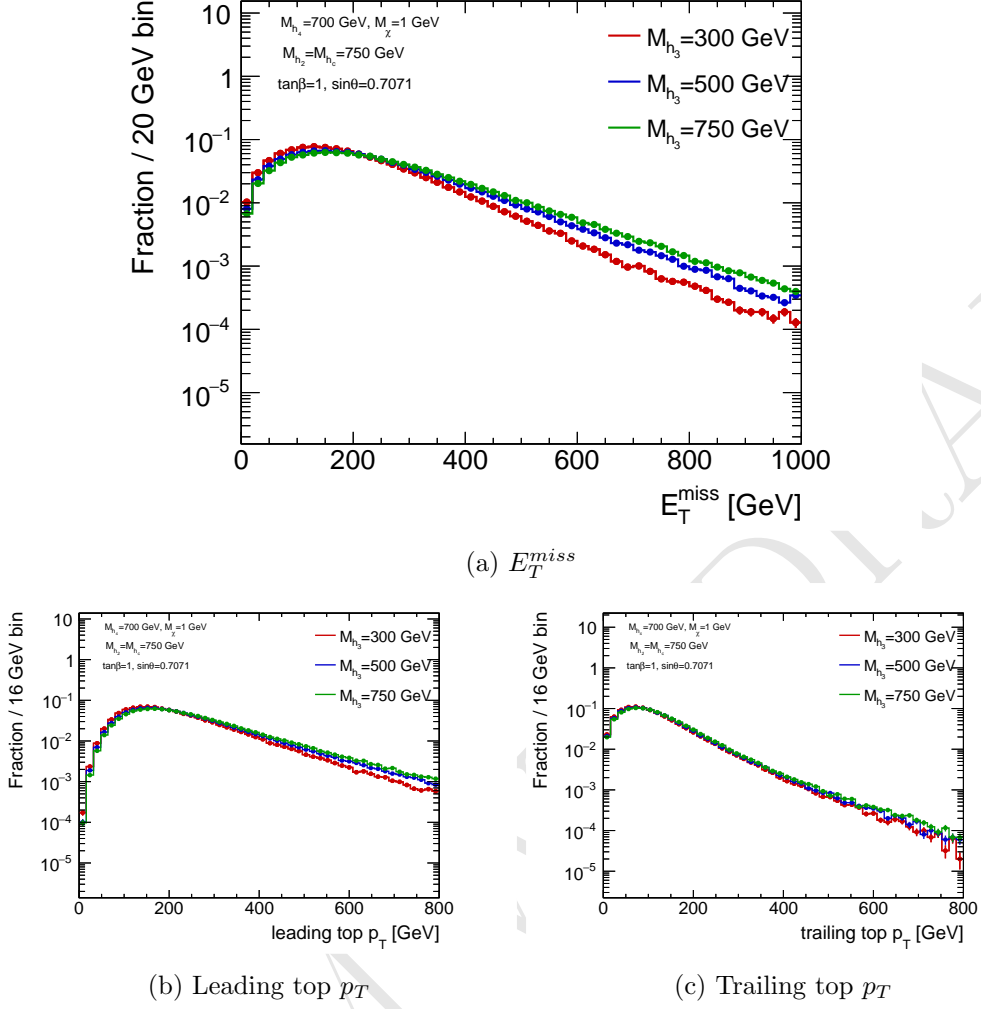
**Figure 5:** The  $E_T^{\text{miss}}$ , leading and trailing top  $p_T$  distributions for inclusive  $t\bar{t} + \chi\bar{\chi}$  production for various values of  $M_A$ , with  $M_A = 750$  GeV,  $M_H = M_{H^\pm} = 750$  GeV,  $\tan\beta = 1$ , and  $\sin\theta = 0.7071$ .

The mass of the neutral scalar  $H^\pm$  does not affect the model kinematics, as shown in Appendix ???. Models with  $M_{H^\pm} \neq M_H$  are moreover strongly constrained by electroweak precision measurements of the  $\rho$  parameter [7]. Therefore, for simplicity, the *neutral scalar  $H^\pm$  is assumed to be mass-degenerate to  $H$ .*

### 1.2.2 Mixing angle between the two pseudoscalars $A$ and $a$ ( $\sin\theta$ )

The sine of the mixing angle between the two pseudoscalars  $A$  and  $a$ ,  $\sin\theta$ , affects not only the cross section, but also the shape of the  $E_T^{\text{miss}}$  distribution in searches including a Higgs boson, as shown in Figure 12a. For the resonant diagram  $gg \rightarrow A \rightarrow ah \rightarrow \chi\bar{\chi}h$ , the product of cross section times branching ratios  $\mathcal{B}(A \rightarrow ah)\mathcal{B}(a \rightarrow \chi\bar{\chi})$  scales with  $\sin^2\theta \cos^6\theta$ , while for the diagram  $gg \rightarrow a \rightarrow A^*h \rightarrow \chi\bar{\chi}h$ , the product of cross section



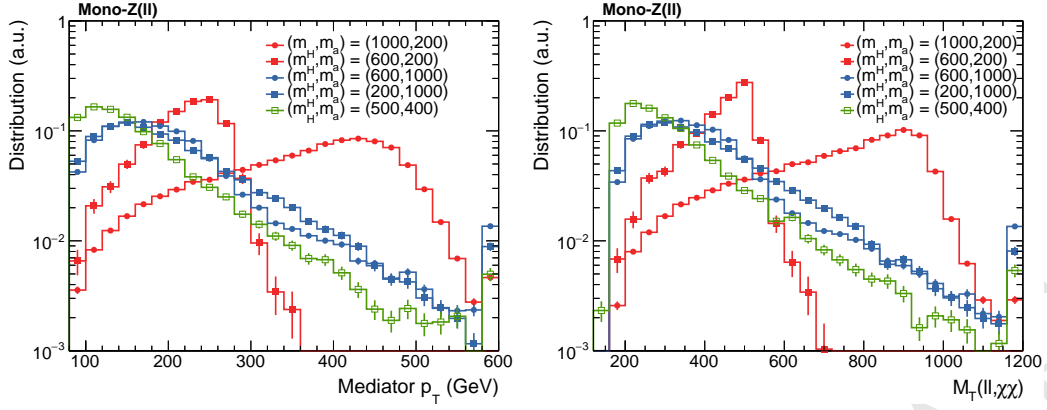


**Figure 6:** The  $E_T^{miss}$ , leading and trailing top  $p_T$  distributions for inclusive  $t\bar{t} + \chi\bar{\chi}$  production for various values of  $M_A$ , with  $M_a = 700$  GeV,  $M_H = M_{H^\pm} = 750$  GeV,  $\tan\beta = 1$ , and  $\sin\theta = 0.7071$ , before any analysis selection.

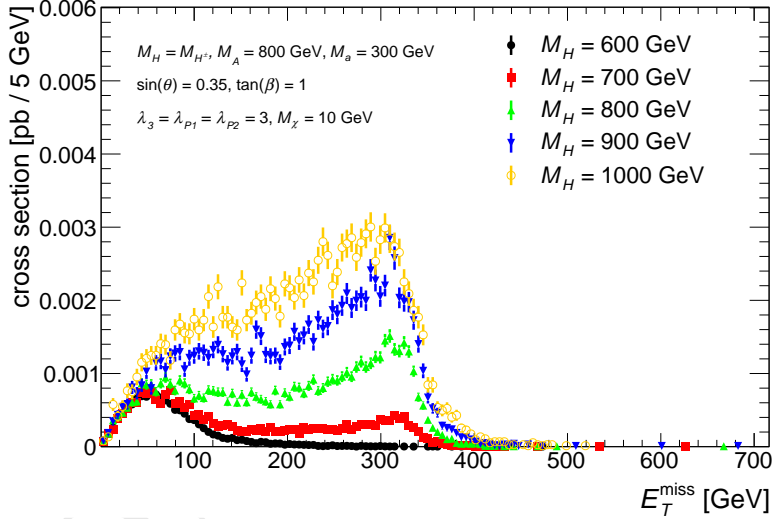
times branching ratios  $\mathcal{B}(a \rightarrow Ah)\mathcal{B}(A \rightarrow \chi\bar{\chi})$  scales with  $\sin^6\theta \cos^2\theta$ . This is shown in Appendix ???. Therefore, at small  $\sin\theta$ , the resonant diagram  $A \rightarrow ah$  is the dominant production mode and the  $E_T^{miss}$  distribution has a Jacobian peak following Equation 1.1; while at large  $\sin\theta$ , the  $a \rightarrow A^*h$  diagram starts to dominate and produces a second peak at a lower  $E_T^{miss}$  value.

Scans of the  $\sin\theta$  parameter show they have minimal effect on the kinematic distributions for searches with a Z boson (Figure 12b).

In the  $t\bar{t} + E_T^{miss}$  signature, the  $A$  ( $h_3$  in the figure) and  $a$  ( $h_4$  in the figure) mass peaks are quite narrow for values where  $\sin\theta$  approaches 1, and  $a \rightarrow \chi\bar{\chi}$  is the dominant  $\chi\bar{\chi}$  production mode, as shown in Figure 10. However, no significant kinematic dependence on  $\sin\theta$  is observed in the  $E_T^{miss}$  and top quark  $p_T$  as shown in Figure 11 before any analysis



**Figure 7:**  $E_T^{\text{miss}}$  and  $M_T$  distributions after the full selection of  $Z(\text{lep}) + E_T^{\text{miss}}$  search. Both distributions show a peaked structure around  $M_H$  in the  $M_H > M_a$  regime, reflecting the resonant production of  $H$  with a subsequent decay  $H \rightarrow aZ$ .



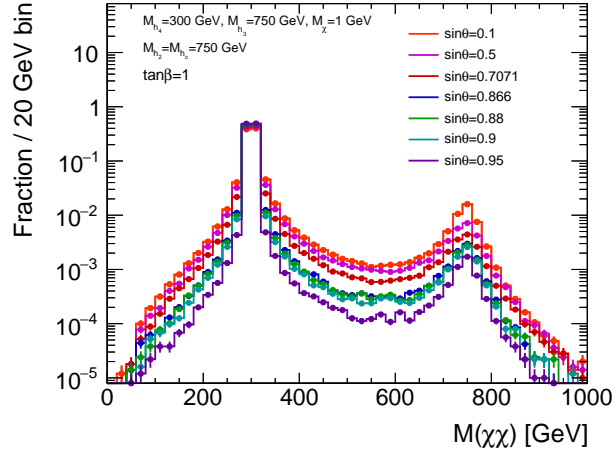
**Figure 8:** The  $E_T^{\text{miss}}$  distribution, accounting for the production cross section, of  $h(bb) + E_T^{\text{miss}}$  signal events for five representative choices of  $M_H = M_{H^\pm}$ .

**Figure 9:**  $E_T^{\text{miss}}$  distribution in  $h(bb) + E_T^{\text{miss}}$  and  $Z + E_T^{\text{miss}}$  events for different  $M_H$

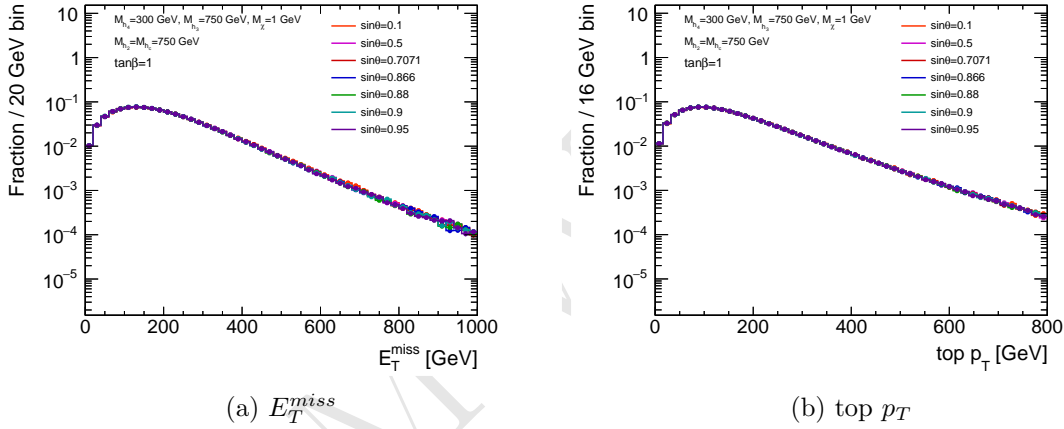
cuts are applied.

### 1.2.3 Ratio of the doublet vacuum expectation values ( $\tan \beta$ )

For mono- $h$  signals, the shape of the  $E_T^{\text{miss}}$  distribution also has a non-trivial dependence on  $\tan \beta$ , as can be seen in Figure 13. As discussed in the sensitivity study later, at small  $\tan \beta$ , the Yukawa coupling to top quark is large and the signal production mode is dominated by the non-resonant 3-body process  $gg \rightarrow h\chi\bar{\chi}$ , which gives a broad and soft  $E_T^{\text{miss}}$  spectrum. As  $\tan \beta$  increases,  $\Gamma_A$  decreases. With a more narrow  $A$ , the relative contribution of resonant  $A$  decays increases, and the Jacobian peak grows more pronounced,



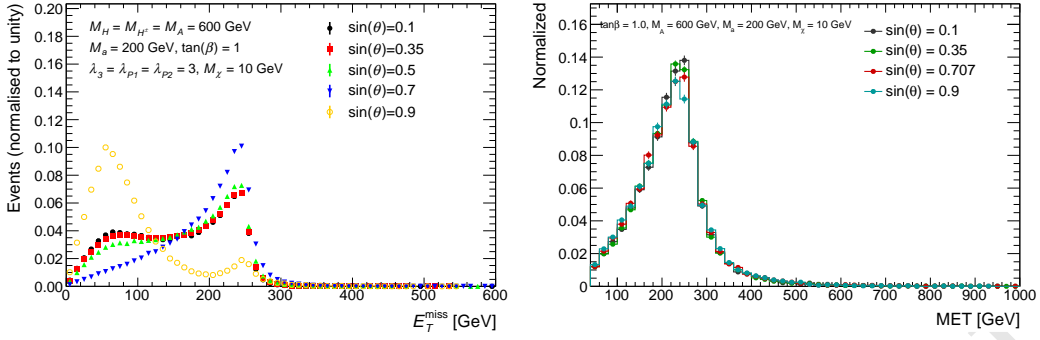
**Figure 10:** The mass distribution of the  $\chi\bar{\chi}$  system for various values of  $\sin\theta$ , with  $M_a = 300$  GeV,  $M_A = 750$  GeV,  $M_H = M_{H^\pm} = 750$  GeV, and  $\tan\beta = 1$ .



**Figure 11:** The  $E_T^{miss}$  and top  $p_T$  distribution for inclusive  $t\bar{t} + \chi\bar{\chi}$  production for various values of  $\sin\theta$ , with  $M_a = 300$  GeV,  $M_A = 750$  GeV,  $M_H = M_{H^\pm} = 750$  GeV, and  $\tan\beta = 1$ .

eventually dominating the  $E_T^{miss}$  spectrum. When the on-shell  $A \rightarrow ah$  decay is kinematically forbidden, i.e. when  $M_A < M_a + M_h$ , the shapes of  $E_T^{miss}$  distributions become similar and the dependence on  $\tan\beta$  almost disappears. For small values of  $\tan\beta$  there is a slight softening and broadening of the  $E_T^{miss}$  distribution caused by the increased contribution from non-resonant  $Z + a$  production in  $Z + E_T^{miss}$  searches.

In the  $t\bar{t} + E_T^{miss}$  signature, and in the limit of small  $\tan\beta$  values, the couplings of  $A$  ( $h_3$  in the figure) and  $a$  ( $h_4$  in the figure) to down-type quarks are heavily suppressed regardless of the Yukawa assignment. At LO,  $t\bar{t} + \chi\bar{\chi}$  associated production is mediated through either CP-odd weak eigenstate,  $A$  or  $a$ , though it is shown in Figure 15 that  $a \rightarrow \chi\bar{\chi}$  is the dominant production mode. Although the relative mediator contribution is dependent on  $\tan\beta$ , observables such as  $E_T^{miss}$  and top quark  $p_T$  only have a moderate



(a)  $E_T^{\text{miss}}$  distribution for five representative models with different  $\sin \theta$  and fixed scans of  $\sin \theta$  for fixed  $M_A = M_H = M_{H^\pm} = 600$  GeV,  $M_a = 600$  GeV and  $M_\chi = 200$  GeV. (b)  $E_T^{\text{miss}}$  distribution after preselection for fixed  $M_A = M_H = M_{H^\pm} = 600$  GeV,  $M_a = 600$  GeV and  $M_\chi = 200$  GeV.

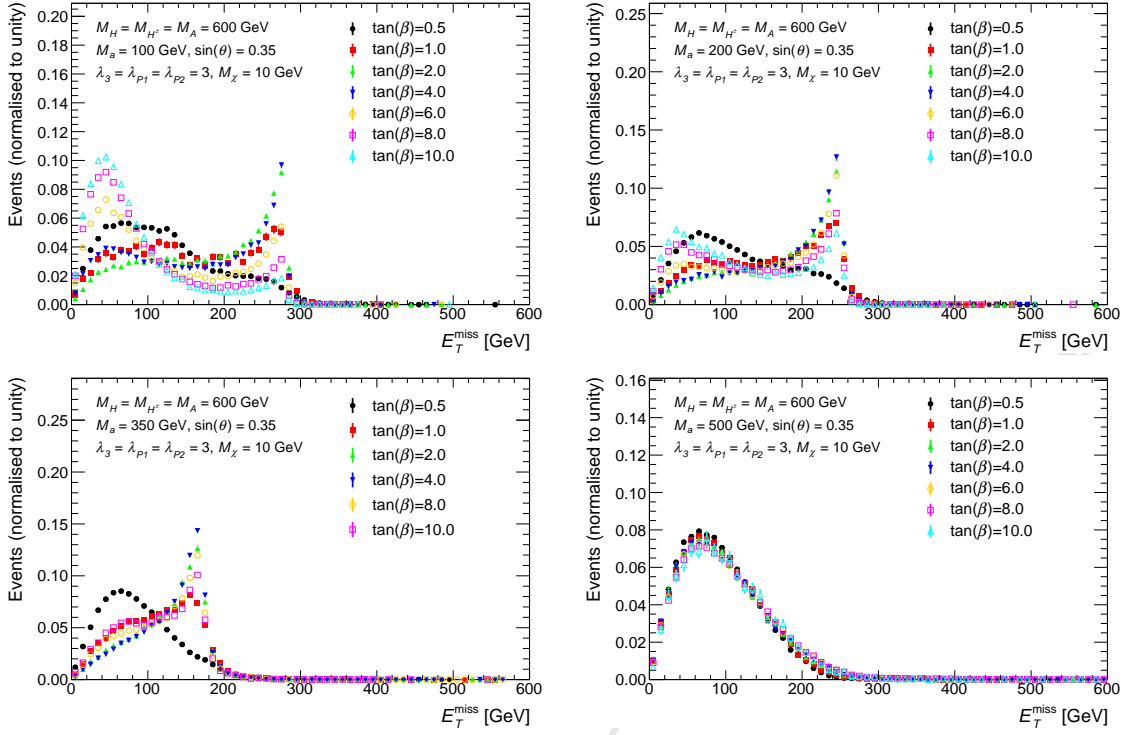
**Figure 12:**  $E_T^{\text{miss}}$  distributions in  $h(bb) + E_T^{\text{miss}}$  and  $Z(\text{lep}) + E_T^{\text{miss}}$  events for different  $\sin \theta$ . In both cases,  $\tan \beta = 1$  and  $M_\chi = 10$  GeV.

kinematic dependence on  $\tan \beta$  as demonstrated in Figure 16 before any analysis cuts. Other variables, such as the transverse mass  $M_T$ , are more affected by the contribution of the high mass mediator, as shown in Figure 16 after kinematic cuts.

The production cross-section for  $a, h, H$  and  $A$  are driven by top-quark loops in the gluon-fusion channel [13], as shown e.g. [as shown in the Feynman diagram], and enhanced for small values of  $\tan \beta$ . For this reason, and to highlight the complementarity of the  $H + E_T^{\text{miss}}$  and  $Z + E_T^{\text{miss}}$  signatures, the main focus of the parameter scans should be on the small  $\tan \beta$  region. *Setting  $\tan \beta$  to unity* leads to a sufficiently large on-shell contribution even at low masses. This in turn increases the number of events at higher  $E_T^{\text{miss}}$ , so that the  $H + E_T^{\text{miss}}$  search can have a comparable sensitivity to the  $Z + E_T^{\text{miss}}$  search even though it requires higher  $E_T^{\text{miss}}$ . Moreover, since the cross-section times branching ratio for the  $b\bar{b} + E_T^{\text{miss}}$  signature is enhanced at high values of  $\tan \beta$  (see Eq. 3.2 and 3.3 in Ref. [7]) *it is desirable to perform a coarse scan in  $\tan \beta$  as well.*

It is interesting to note however that the relative total width for the heavy scalar  $H$  becomes unphysically large at high  $\tan \beta$  when all scalars have the same mass, due to the very large  $H \rightarrow aa$  rate. This can be cured by tuning the mass of the heavy scalar so that the coupling between the heavy scalar and the light pseudoscalar  $g_{Haa}$  becomes small for this scan only, therefore suppressing the  $H \rightarrow aa$  rate that drives the width. An example of the heavy scalar width as a function of  $\tan \beta$ , with  $M_H = M_A = 600$  GeV,  $M_{H^\pm} = 664$  GeV,  $\sin \theta = 0.35$ ,  $M_\chi = 10$  GeV and  $g_{\text{DM}} = 1$  is shown in Fig. 17.

Even though this choice of parameters for this scan introduces a specific tuning and therefore model-dependence, it can be justified by noting that the trilinear scalar couplings are very sensitive to changes in the model's masses and couplings, and this in turn changes the decay partner of the heavy scalar and of the Higgs partners. Furthermore, the Higgs width does not influence the  $b\bar{b} + E_T^{\text{miss}}$  signal directly. Nevertheless, if this tuning is not performed, particular care has to be taken at high  $\tan \beta$  values to obtain reasonable



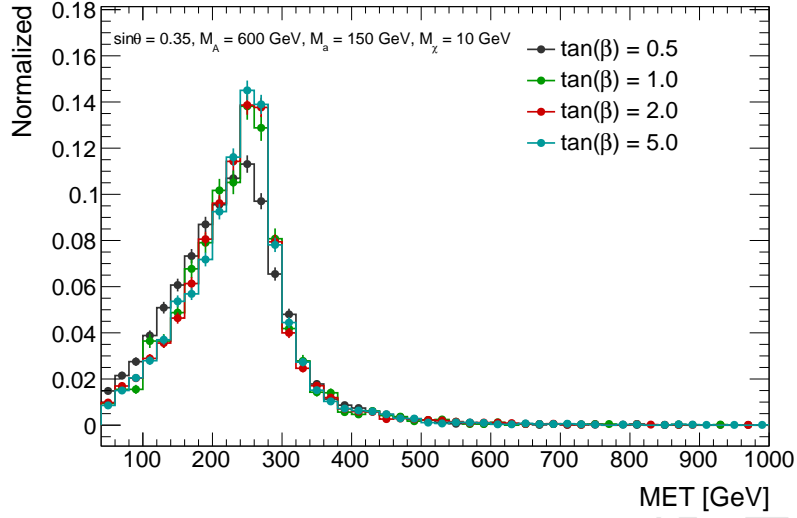
**Figure 13:** Missing transverse momentum distribution of  $h \rightarrow bb + E_T^{\text{miss}}$  signal events at parton level with different  $\tan\beta$  and fixed  $M_A = M_H = M_{H^\pm} = 600$  GeV,  $M_\chi = 10$  GeV,  $\sin\theta = 0.35$ , and  $\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3$ . The values of  $M_a$  are set to 100, 200, 350, and 500 GeV, respectively. The shapes of the  $E_T^{\text{miss}}$  distributions for different  $\tan\beta$  are similar when  $M_A < M_h + M_a$ . Note, in these figures, both the contributions of  $gg$  and  $b\bar{b}$  initiated processes are included and a combined histogram is produced according to their corresponding cross sections.

results outside the narrow-width approximation, both for the generation of the signal and for the interpretation of the results.

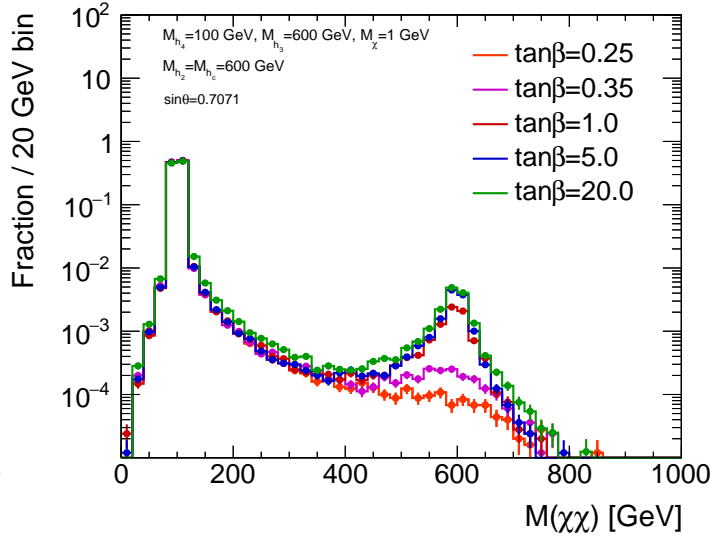
#### 1.2.4 Mass of DM fermion ( $M_\chi$ )

The mass of the DM fermion  $M_\chi$  can change the total cross section and shape of the  $E_T^{\text{miss}}$  distribution, depending on the mass hierarchy of the  $A, a, h, \chi$  particles. This is demonstrated in Figure 19. Provided on-shell decays  $a \rightarrow \chi\chi$  are possible, i.e.,  $M_\chi < M_a/2$ , the exact value of  $M_\chi$  has no effect on either kinematics or the total cross section. The only exception is the case  $M_a/2 > M_\chi > \frac{1}{2}(M_a - M_h)$ . In this  $M_\chi$  range, the non-resonant process  $a \rightarrow hA^*(\chi\chi)$  is kinematically inaccessible. This reduces the overall cross section relative to the  $M_\chi \leq \frac{1}{2}(M_a - M_h)$  case, and slightly changes the soft part of the total  $E_T^{\text{miss}}$  spectrum. However, since the contribution of the  $a \rightarrow hA^*(\chi\chi)$  process is minor in any case, the differences are negligible.

If the DM particle mass is exactly on threshold, i.e.,  $M_\chi = M_a/2$ , the total cross section is resonantly enhanced. This resonant threshold enhancement drops rapidly towards

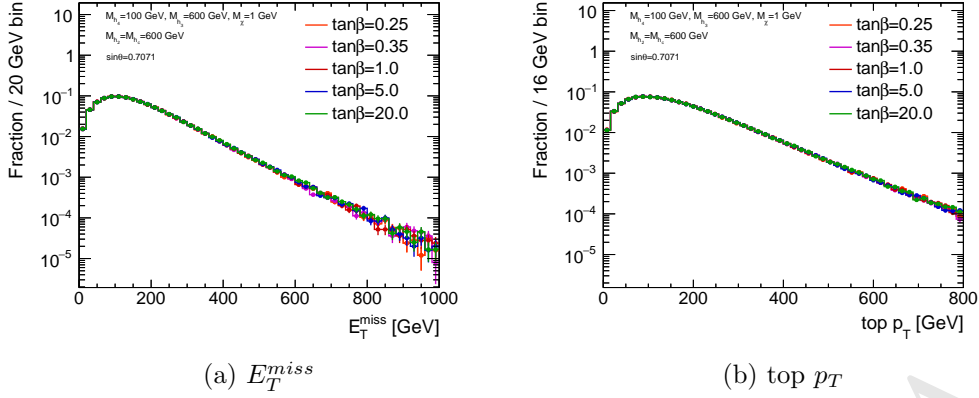


**Figure 14:**  $E_T^{\text{miss}}$  distribution after preselection for scans of  $\tan \beta$  for fixed  $M_A = 600$  GeV and  $M_a = 150$  GeV. This parameter has little impact on the kinematic distributions, except for small values of  $\tan \beta$  where there is a slight softening and broadening of the  $E_T^{\text{miss}}$  distribution caused by the increased contribution from the top box feynman diagram.

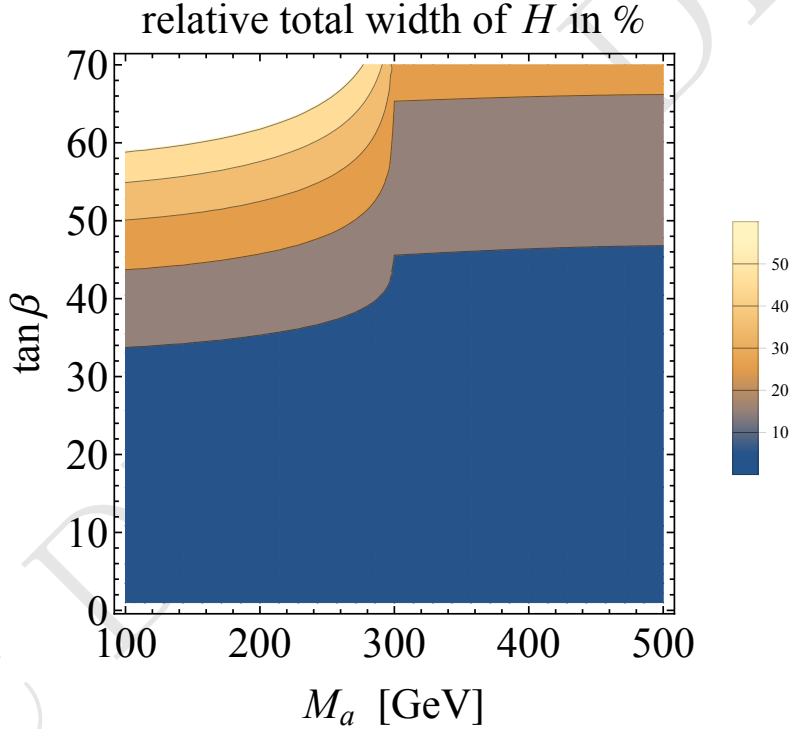


**Figure 15:** The mass distribution of the  $\chi\bar{\chi}$  system for various values of  $\tan \beta$ , with  $M_a = 100$  GeV,  $M_A = 600$  GeV,  $M_H = M_{H^\pm} = 600$  GeV, and  $\sin \theta = 0.7071$ .

both higher and lower  $M_\chi$ . Furthermore, the shape of the  $E_T^{\text{miss}}$  distribution at threshold, where amplitudes involving  $a \rightarrow \chi\chi$  decays make up a larger fraction of the signal, differs significantly from the one below threshold. Below threshold ( $M_\chi > M_a/2$ ), the total cross section quickly drops by several orders of magnitude. In this regime, the shape of the  $E_T^{\text{miss}}$  distribution changes with  $M_\chi$  continuously.

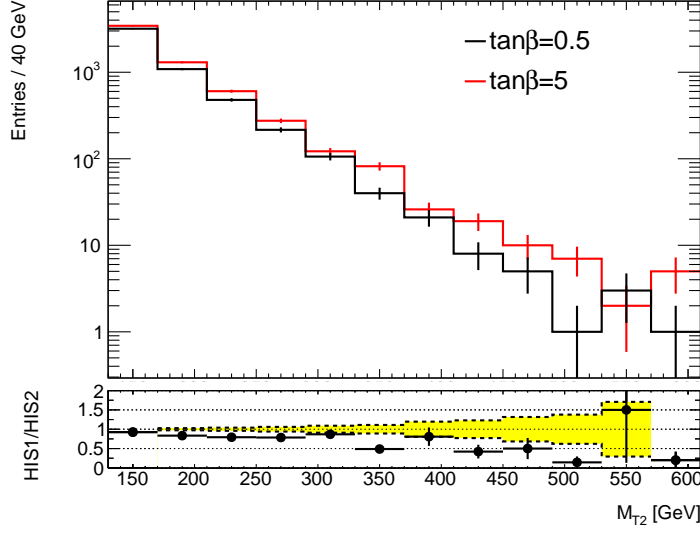


**Figure 16:** The  $E_T^{\text{miss}}$  and top  $p_T$  distribution for inclusive  $t\bar{t} + \chi\bar{\chi}$  production for various values of  $\tan\beta$ , with  $M_a = 100$  GeV,  $M_A = 600$  GeV,  $M_H = M_{H^\pm} = 600$  GeV, and  $\sin\theta = 0.7071$ .

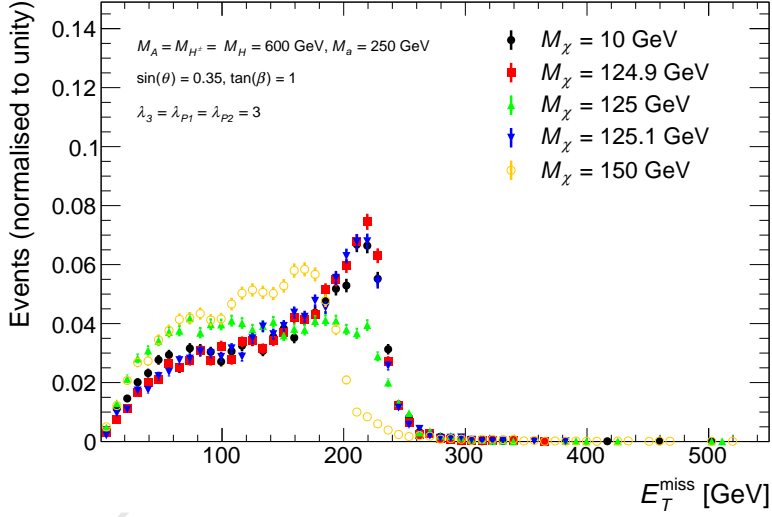


**Figure 17:** The width of the heavy scalar as a function of  $\tan\beta$ , with  $M_H = M_A = 600$  GeV,  $M_{H^\pm} = 664$  GeV,  $\sin\theta = 0.35$ ,  $M_\chi = 10$  GeV and  $g_{\text{DM}} = 1$ .

Similar effects are seen in Figure 20. In the  $M_\chi < \frac{M_a}{2}$  region,  $M_\chi$  has no effect on event yield or  $E_T^{\text{miss}}$  distribution, at  $M_\chi = \frac{M_a}{2}$  a resonant enhancement to the cross section occurs, and in the off-shell region where  $M_\chi > \frac{M_a}{2}$  cross section steeply drops. The  $E_T^{\text{miss}}$  shape remains the same up to, and even slightly above,  $M_\chi = \frac{M_a}{2}$ , but further off shell the  $E_T^{\text{miss}}$  distribution becomes increasingly disperse. For  $M_\chi = 200$  GeV, DM can still



**Figure 18:** The  $M_T$  distribution in the  $t\bar{t} + E_T^{\text{miss}}$  signature for different values of  $\tan\beta$ , after all selection cuts.

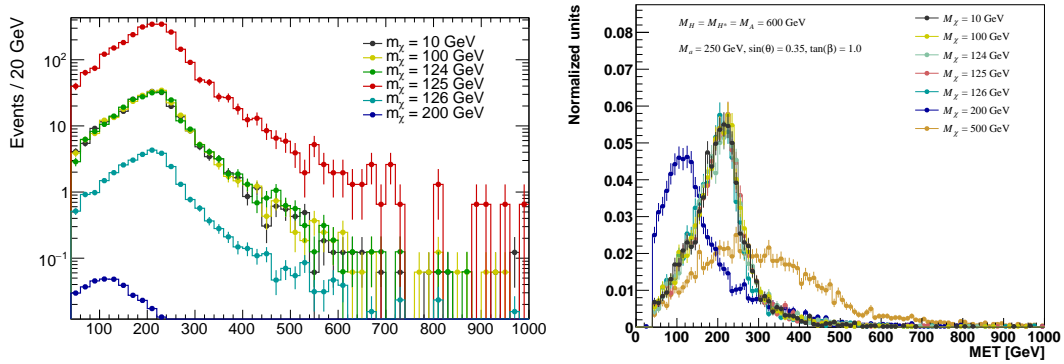


**Figure 19:** Missing transverse momentum distribution of  $h(bb) + E_T^{\text{miss}}$  signal events at parton level for five representative models with different  $M_\chi$  and fixed  $M_A = M_H = M_{H^\pm} = 600$  GeV  $M_a = 250$  GeV,  $\sin\theta = 0.35$ ,  $\tan\beta = 1$  and  $\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3$ . The shape of the  $E_T^{\text{miss}}$  distribution does not change for  $M_\chi < M_a/2$ , then changes significantly for  $M_\chi \geq M_a/2$ .

decay on-shell through the  $A$ . For  $M_\chi = 500$  GeV both pseudoscalars are off-shell leading to an event yield too low to fit on the figure on the left and a  $E_T^{\text{miss}}$  distribution without structure.

A value of  $M_\chi=10$  is chosen as the baseline for the following studies, as it produces a





**Figure 20:**  $E_T^{\text{miss}}$  distributions following preselection in the  $Z(\text{lep}) + E_T^{\text{miss}}$  search are shown (left) scaled to  $40 \text{ fb}^{-1}$  and (right) normalized to unity for different values of  $M_\chi$  with fixed  $M_A = 600 \text{ GeV}$  and  $M_a = 250 \text{ GeV}$ .

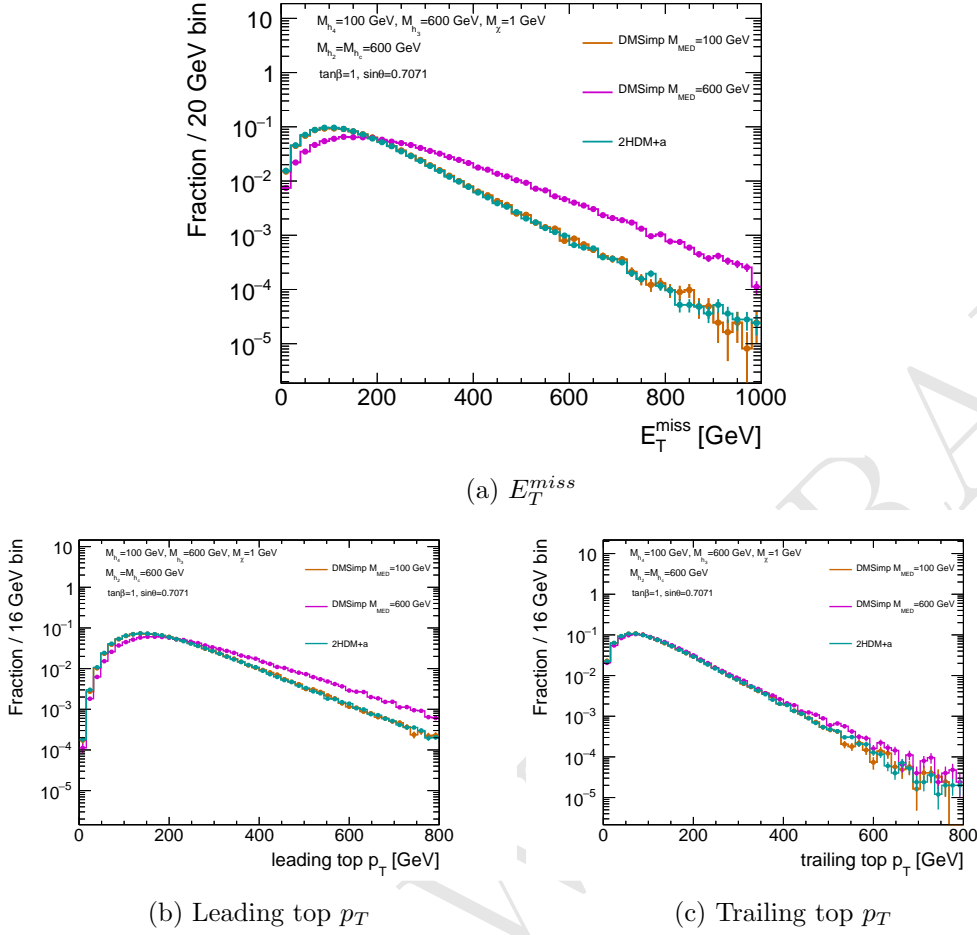
cross-section that is sufficiently large for this model to be detected with Run-2 LHC data and highlights the resonant features of the  $E_T^{\text{miss}}$  spectrum.

### 1.3 Comparison with existing pseudoscalar models and recasting of $\text{HF} + E_T^{\text{miss}}$ search results

To date, simplified models of DM [14, 15] that add a single scalar or pseudoscalar mediator and the DM particle to the SM are used as benchmarks for the Run II CMS and ATLAS  $\text{HF} + E_T^{\text{miss}}$  searches. These are called **DMsimp** models in the following. The kinematics and cross-section of the pseudoscalar **DMsimp** models can map directly onto those of the 2HDM+a model, when accounting for the contributions from the light and heavy pseudoscalar mediators.

The comparison of some of the relevant kinematic distributions between the pseudoscalar simplified model and the 2HDM+a model using two different values of  $M_a$ , is shown in Figure 21. In these figures, the parameters used are:  $M_A = 600 \text{ GeV}$ ,  $M_H = M_{H^\pm} = 600 \text{ GeV}$ ,  $\sin \theta = 0.7071$ ,  $\tan \beta = 1$ , while  $M_a$  is either 100 or 600 GeV. The distributions for the two models agree when the mediator mass in the **DMsimp** model is set to  $M_a$  and the contribution from  $A$  decays is smaller since  $A$  is more massive than  $a$ .

The **DMsimp** model has only one mediator particle. Figure 22 shows that the 2HDM+a model can be represented as the sum of two contributions, one from the light pseudoscalar and the other one from the heavy pseudoscalar. This is because the  $\text{HF} + E_T^{\text{miss}}$  signatures are dominantly produced in diagrams involving the invisible decays of the two CP-odd scalars. The 2HDM+a model is equivalent to the single pseudoscalar simplified model **DMsimp** when  $A$  is much heavier than  $a$ , and therefore the former does not contribute to the considered final state. However, when the two mediators are closer in mass, the  $pp \rightarrow ttA$  contribution becomes more relevant. This can be seen in Figure 23, where the two models are compared assuming  $m(A) = 750 \text{ GeV}$  and two different values for  $m(a)$ . An excellent agreement is observed between **DMsimp** and 2HDM+a at parton-level variables sensitive to the helicity structure of the interaction between top and the mediator[16], if



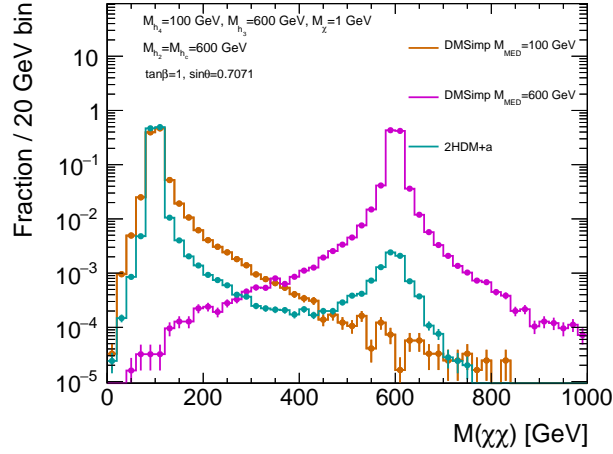
**Figure 21:** The  $E_T^{miss}$ , leading and trailing top  $p_T$  distributions for inclusive  $t\bar{t} + \chi\bar{\chi}$  production for different values of  $M_a$ , with  $M_A = M_H = M_{H^\pm} = 600$  GeV,  $\tan\beta = 1$ ,  $M_\chi = 1$  GeV and  $\sin\theta = 0.7071$ , compared to the **DMSimp** pseudoscalar model.

the invariant mass of the two DM particles in the 2HDM is smaller than 200(300) GeV for  $m(a) = 150(300)$  GeV respectively. This gives confidence that, once the contribution from  $A$  production is identified and separated, it is possible to fully map the  $2HDM + a$  kinematics to the existing **DMSimp** model.

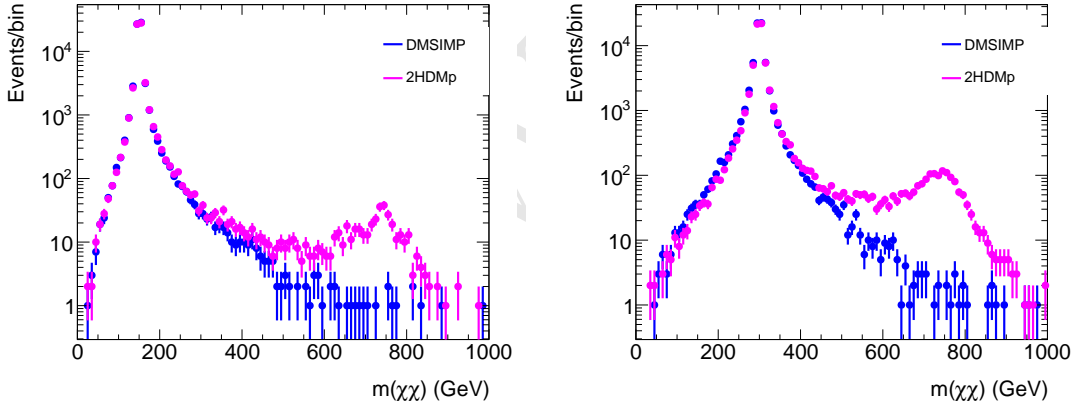
The mapping that can be used to reinterpret existing searches that use the **DMSimp** model is achieved by taking, for each set of the parameters, the average of the selection acceptances for  $m(A)$  and  $M(A)$  obtained from the **DMSimp** model, weighted by the respective cross-section for  $A$  ( $\sigma_A$ ) and  $a$  ( $\sigma_a$ ) production:

$$Acc_{2HDM}(m(A), M(a)) = \frac{\sigma_a \times Acc_{DMSimp}(m(a)) + \sigma_A \times Acc_{DMSimp}(m(A))}{\sigma_a + \sigma_A} \quad (1.2)$$

The acceptance in this case is obtained as a parton-level implementation of the two-lepton analysis described in [arXiv:1710.11412]. The acceptance estimated in this way is

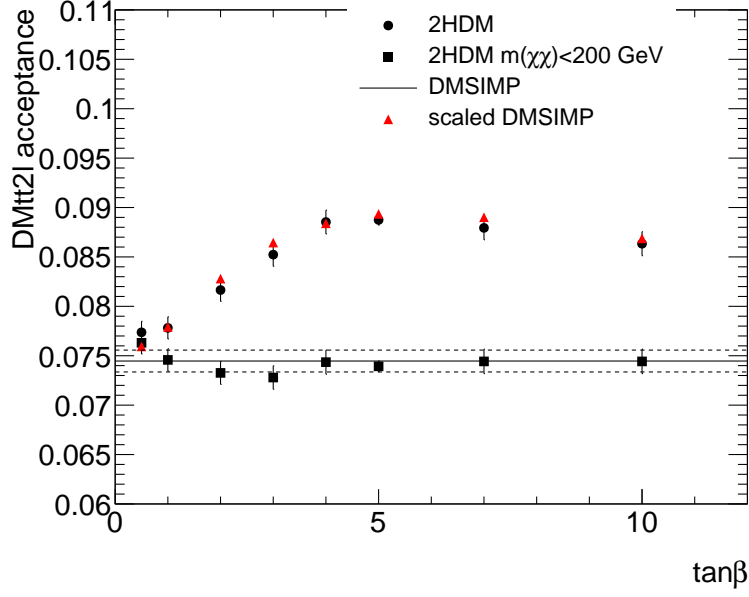


**Figure 22:** The mass distribution of the  $\chi\bar{\chi}$  system for DMSimp pseudoscalar models with  $M_a = 100$  GeV and  $M_a = 600$  GeV, compared with 2HDM+a with  $M_a = 100$  GeV,  $M_A = 600$  GeV,  $M_H = M_{H^\pm} = 600$  GeV,  $\sin\theta = 0.7071$  and  $\tan\beta = 1$ . TODO: needs different markers.



**Figure 23:** Comparison of  $m(\chi\chi)$ , the invariant mass of the two DM particles for the DMSimp (blue) and the 2HDMp model (magenta) with  $m(A) = M_{med} = 750$  GeV. The plot on the left uses  $M_a = 150$  GeV, while the plot on the right uses  $M_a = 300$  GeV.

shown as red triangles in Figure 24, and an excellent agreement can be seen with the acceptances evaluated directly on the 2HDM samples. Further validation was performed also on the acceptances calculated as a function of  $\sin\theta$  and  $\tan\beta$ . Finally, the formula was successfully tested also with  $|M_A - M_a| \sim 50$  GeV, where interference between the production of the two bosons is possible.



**Figure 24:** Acceptance of the two-lepton analysis as a function of  $\tan\beta$  for the  $2HDMp$  model (round markers), for the  $2HDMp$  model considering only events with  $m(\chi\chi) < 200$  GeV (square markers), and for the  $DMSIMP$  model (full line) for a mediator mass of 150 GeV. The two dashed lines indicate the statistical error of the  $DMSIMP$ . The value of  $m(A)$  is fixed at 600 GeV, and  $\sin\theta = 0.35$ . The acceptance calculated from the  $DMSIMP$  acceptance rescaled following the prescription in Equation 1.2 (red triangles) is also shown.

## 2 Parameter grid

The studies in the previous section show that varying most of the model parameters lead to non-trivial modifications of the for the  $H+E_T^{\text{miss}}$  and  $Z+E_T^{\text{miss}}$  searches. We decide to investigate the model parameter space through two-dimensional and one-dimensional scans of five parameters: the light pseudoscalar mass ( $M_a$ ), the heavy pseudoscalar mass ( $M_A$ ) that we set equal to the mass of the heavy and charged Higgs bosons ( $M_A = M_H = M_{H^\pm}$ ), the mixing angle  $\sin\theta$ , the ratio of VEVs of the Higgs doublets  $\tan\beta$  and the dark matter particle mass  $M_\chi$ . The benchmark model points that have been agreed within the DMWG and are suggested here do not provide an exhaustive scan the entire parameter space of this model, but highlights many of the features that are unique of this model and showcases the complementarity of the various signatures.

**Scan in the  $M_a, M_A = M_H = M_{H^\pm}$  plane** The main parameter grid proposed to investigate this model with LHC data spans combinations of the light pseudoscalar mass ( $M_a$ ) and the heavy pseudoscalar mass ( $M_A$ ) plane, fixing  $M_A = M_H = M_{H^\pm}$ . The mixing angle  $\sin\theta$  is fixed to 0.35 (leading to asymmetric mixing between the pseudoscalars), to evade precision constraints.  $\tan\beta$  is fixed to unity to obtain a mixture of resonant and non-resonant processes for the  $H+E_T^{\text{miss}}$  and  $Z+E_T^{\text{miss}}$  searches. The DM particle mass is

fixed to 10 GeV, to obtain cross-sections that are sufficiently large to be probed by Run-2 LHC searches. The spacing of the grid in  $M_a$  and  $M_A$  is left to the individual searches. The parameters  $\sin\theta$ ,  $\tan\beta$  and  $M_\chi$  are scanned separately.

**Scan in the  $M_a, \tan\beta$  plane** A two-dimensional scan in the  $M_a, \tan\beta$  plane, fixing  $M_A = M_H = M_{H^\pm} = 600$  GeV, is used to emphasize the complementarity of the  $H+E_T^{\text{miss}}$  and  $Z+E_T^{\text{miss}}$  searches with the heavy flavor +  $E_T^{\text{miss}}$  searches. The scan in  $M_a$  includes masses between 10 and 350 GeV, while the  $\tan\beta$  scan includes  $\tan\beta = 50, 45, 40, 35, 30, 25, 20, 15, 10, 5$ , where the high- $\tan\beta$  points are of primary interest for the heavy flavor searches.

**Scans in  $\sin\theta$**  Two one-dimensional scans in  $\sin\theta$  are also suggested for further comparison of the  $H/Z+E_T^{\text{miss}}$  and  $b\bar{b}+E_T^{\text{miss}}$  analyses, as the latter is more sensitive at higher values of  $\sin\theta$ . In the first scan, resonant processes dominate with  $M_A = M_H = M_{H^\pm} = 600$  GeV and  $M_a = 200$  GeV, while in the second scan  $M_A = M_H = M_{H^\pm} = 1000$  GeV and  $M_a = 350$  GeV. For both scans,  $\tan\beta$  and the DM mass are fixed to  $\tan\beta=1$  and  $M_\chi = 10$  GeV. [TODO: add statement about precision constraints?]

**Scan in  $M_\chi$**  A one-dimensional scan in  $M_\chi$  spanning from 1 GeV to 500 GeV, with fixed  $M_A = M_H = 600$  and  $M_a = 250$  GeV, is also suggested to connect this model to a standard cosmological history. Even though the model points with where the DM particle has a mass above 100 GeV are not within immediate reach of Run-2 searches, the measured relic density is satisfied by this model at values of DM mass around 100 GeV, as shown in [section 4](#).

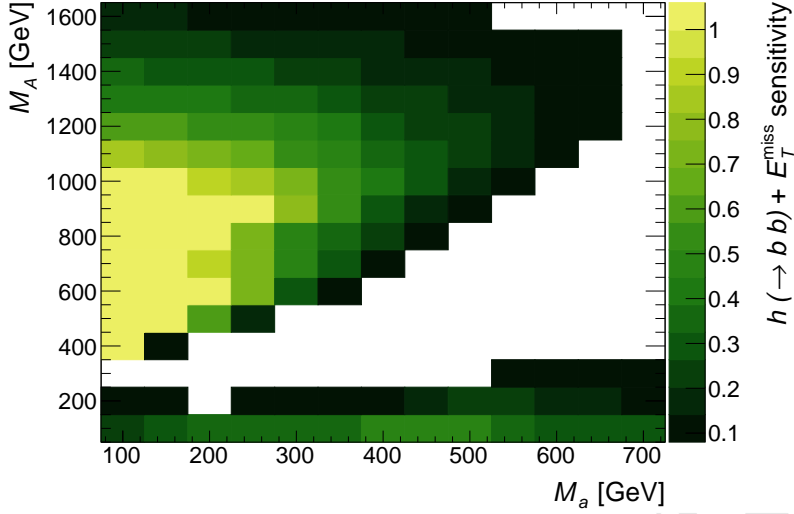
### 3 Sensitivity studies

In the first part of this section we present the sensitivity estimates for two of the main signatures that are sensitive to the model, the Higgs+ $E_T^{\text{miss}}$  and the  $Z+E_T^{\text{miss}}$  signatures, in the parameter scans chosen for comparison. These estimates are based on generator-level reinterpretation of existing results with  $36 \text{ fb}^{-1}$  of LHC data at a center-of-mass energy of 13 TeV. These results contain different amounts of public information. In the case of the Higgs+ $E_T^{\text{miss}}$  from [5], model-independent limits are used for the reinterpretation, while for the  $Z+E_T^{\text{miss}}$  signature an estimate of the sensitivity is obtained using generator-level information from signal and background simulations.

The second part of this section briefly outlines additional signatures that are also sensitive to this model. Firstly we briefly discuss the jet +  $E_T^{\text{miss}}$  signatures and the heavy flavor +  $E_T^{\text{miss}}$  signatures, which do not yet have sensitivity with the  $36 \text{ fb}^{-1}$  dataset for most of the scans. Then we enumerate other signatures that can be sensitive to this model, emphasizing those that are not yet fully covered by experimental searches.

#### 3.1 Studies of the $h(bb) + E_T^{\text{miss}}$ signature

The sensitivity estimates of the ATLAS and CMS  $h(bb) + E_T^{\text{miss}}$  searches to the 2HDM+a scenarios are based on limits on the minimally model-dependent anomalous production of 125 GeV Higgs bosons in association with  $E_T^{\text{miss}}$  in [5]. As these limits are set in terms



**Figure 25:** Sum over all  $E_T^{\text{miss}}$ -bins of the estimated sensitivity to  $H \rightarrow b\bar{b} + E_T^{\text{miss}}$  events as a function of  $(M_A, M_a)$ . The sensitivity, defined as the sum of Equation 3.1 over the  $E_T^{\text{miss}}$  bins, is based on the limits with reduced model dependence from Ref. [5]. The remaining parameters take the values  $M_H = M_{H^\pm} = M_A$ ,  $\sin \theta = 0.35$ ,  $\tan \beta = 1$ ,  $M_\chi = 10$  GeV and  $\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3$ . Bins with no content have a negligible sensitivity.

of the observed production cross-section of non-SM events with large  $E_T^{\text{miss}}$  and a Higgs boson, they can be compared directly to the cross-sections obtained from the 2HDM+a model after folding the detection efficiency  $\varepsilon$  times the kinematic acceptance  $\mathcal{A}$  of the event selection. This approach reduces the need for computing resources to simulate further event generation steps and detector response. The variable of interest for the sensitivity study of the  $h(bb) + E_T^{\text{miss}}$  searches is the ratio between the parton-level cross-section  $\sigma_i^{\text{parton}, h+\text{DM}}$  times the  $H \rightarrow b\bar{b}$  branching ratio  $\mathcal{B}^{\text{SM}, h \rightarrow b\bar{b}}$  predicted by the SM for the 125 GeV Higgs boson, multiplied by the acceptance  $\mathcal{A}$  and detector efficiency  $\varepsilon$ , and the upper observed cross-section of the anomalous production of Higgs bosons in association with  $E_T^{\text{miss}}$  ( $\sigma_i^{\text{obs}, h(bb)+E_T^{\text{miss}}}$ ):

$$\mathcal{S}_i \equiv \frac{\sigma_i^{\text{parton}, h+\text{DM}} \times \mathcal{B}^{\text{SM}, h \rightarrow b\bar{b}} \times (\mathcal{A} \times \varepsilon)_i}{\sigma_i^{\text{obs}, h(bb)+E_T^{\text{miss}}}}, \quad (3.1)$$

where is the  $H \rightarrow b\bar{b}$  branching ratio predicted by the SM for the 125 GeV Higgs boson. This quantity is summed over the  $i$   $E_T^{\text{miss}}$  bins of the search, since the model will populate more than one  $E_T^{\text{miss}}$  bin at a time. A particular point in the space is excluded by the current search if  $\mathcal{S}_i \geq 1$ .

The expected sensitivity of  $h(bb) + E_T^{\text{miss}}$  searches to the 2HDM+a model in the  $(M_a, M_A)$  plane is shown in Figure 25. The sensitivity decreases with increasing  $M_A = M_H = M_{H^\pm}$  for  $M_A \geq 1$  TeV because the fraction of resonant signal events drops. This drop is caused by increasingly large  $\Gamma_A$ , which allows for an increasing fraction of non-resonant signal events, driven by events with very off-shell  $A$ . Near the mass diagonal

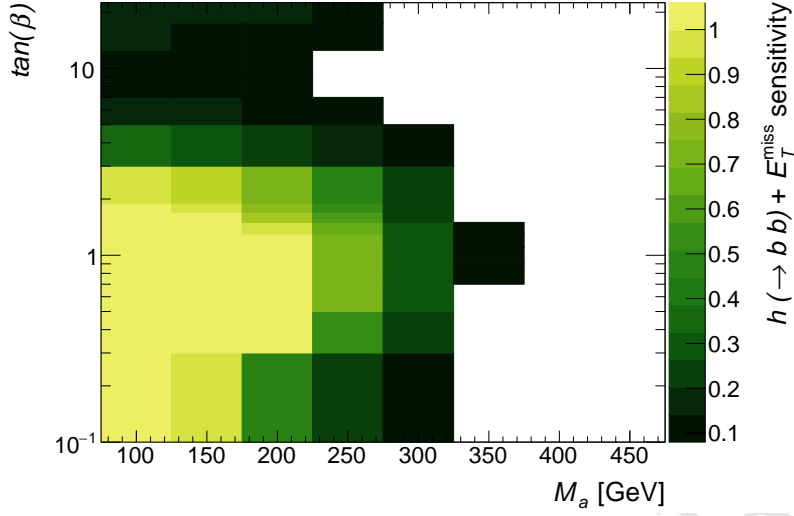
$M_a = M_A$ , there is little to no sensitivity. This is because the Jacobian peak moves to low  $E_T^{\text{miss}}$  for a small mass splitting  $|M_A - M_a|$  (as shown in Equation 1.1, Figure 1a, and Figure 1b). Moreover, the coupling  $g_{Aah}$  is small when all Higgs bosons are nearly degenerate in mass, cf. Equation 4.12 in Ref. [7], resulting in a small total cross section and therefore a further decrease in sensitivity. The sensitivity above the mass diagonal,  $M_A > M_a$ , is larger than below the mass diagonal. Two parameter choices cause this asymmetry:

1. The choice of  $M_A = M_H = M_{H^\pm}$  forces the neutral and charged  $CP$ -even scalars to have lower masses below the diagonal and higher masses above the diagonal, leading to configurations with a lower fraction of resonant signal events. One can use Figure 8 to exemplify this behaviour. Considering the symmetry between the two pseudoscalars, when the neutral and charged scalars  $M_H = M_{H^\pm}$  are lighter than one of the two pseudoscalars (marked as  $A$  in the figure, but effectively representing  $a$  in the case of this scan because of the symmetry), one can see that non-resonant configurations are preferred. This also yields a reduced total cross-section.
2. The choice of  $\sin \theta = 0.35 \neq 1/\sqrt{2}$  means that the mixing between the pseudoscalars  $A$  and  $a$  is asymmetric.  $A$  couples more strongly to SM particles than  $a$ , while the opposite happens to the DM fermion  $\chi$ . The situation below the diagonal corresponds to the case of  $\sin \theta = \sqrt{1 - 0.35^2} \approx 0.938$  and  $M_A > M_a$ . As it can be seen in Figure 12a, this  $\sin \theta$  configuration yields a higher fraction of non-resonant signal events with low  $E_T^{\text{miss}}$ , and correspondingly a lower sensitivity is found, as also seen in Figure 27.

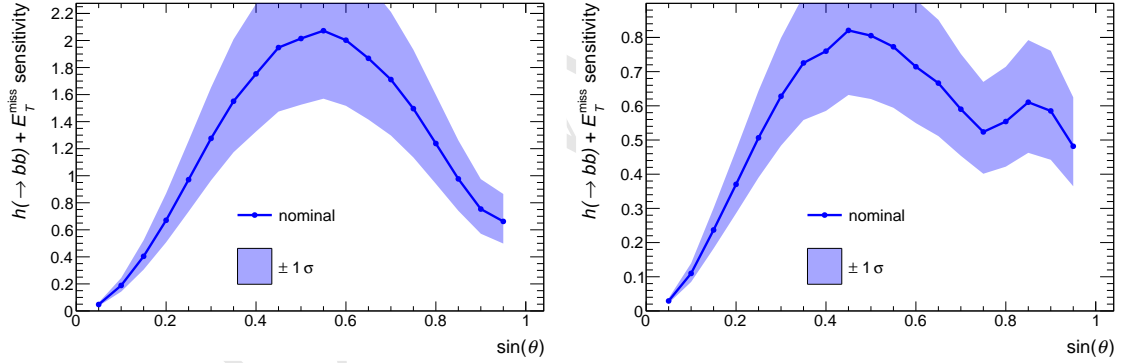
The scan of the sensitivity in the  $(M_a, \tan \beta)$  plane is shown in Figure 26. At very low  $\tan \beta$ , the Yukawa coupling to top quarks is large, and most of the signal events come from non-resonant processes, as can be seen from Figure 13. The non-resonant processes are characterised by soft  $E_T^{\text{miss}}$ , which lowers the kinematic acceptance and reduces the sensitivity of the search. For higher  $\tan \beta$ , the fraction of resonant events increases due to the reduced top Yukawa coupling, resulting in an increase of sensitivity. However, reducing the top Yukawa coupling also reduces the total production cross section. Above  $\tan \beta \approx 1.2$ , the sensitivity loss due to reduced cross section outpaces the sensitivity gain due the resonant signal. At very high  $\tan \beta$  ( $\geq 10$ ), this trend is reversed again because the  $\tan \beta$  enhancement<sup>2</sup> of the coupling to  $b$ -quarks compensates for the small  $b$ -quark mass. At this point  $bb$  initiated processes start to dominate the production cross section and drive the increase in sensitivity.

The sensitivity as a function of  $\sin \theta$  is shown in Figure 27. The sensitivity vanishes at  $\sin \theta = 0$  and  $\sin \theta = 1$ , since those values correspond to no mixing between  $A$  and  $a$ , and thus no connection between the SM and the dark sector. For its intermediate values, the  $\sin \theta$  parameter influences the couplings of the pseudoscalars to DM as well as to SM fermions, as well as the coupling strength of the trilinear scalar vertices such as  $g_{Aah}$  [7]. Increasing these couplings increases the total cross section, but it can also increase  $\Gamma_A$  and

<sup>2</sup>The 2HDM+a scenario assumes a Yukawa sector of type II.



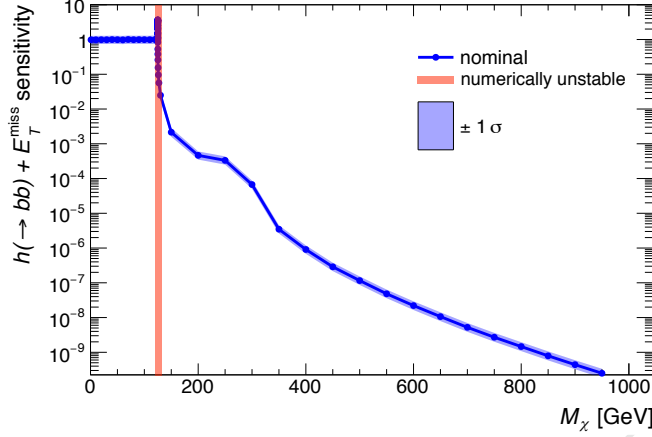
**Figure 26:** Sum over all  $E_T^{\text{miss}}$ -bins of the estimated signal sensitivity to  $h \rightarrow bb + E_T^{\text{miss}}$  events as a function of  $(M_a, \tan \beta)$ . The sensitivity, defined as the sum of Equation 3.1 over the  $E_T^{\text{miss}}$  bins, is based on the limits with reduced model dependence from Ref. [5]. The remaining parameters take the values  $M_H = M_{H^\pm} = M_A = 600$  GeV,  $\sin \theta = 0.35$ ,  $M_\chi = 10$  GeV and  $\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3$ . Bins with no content have a negligible sensitivity.



**Figure 27:** Sum over all  $E_T^{\text{miss}}$ -bins of the estimated signal sensitivity to  $h \rightarrow bb + E_T^{\text{miss}}$  events as a function of the pseudoscalar mixing parameter  $\sin \theta$ , for  $M_a = 200$  GeV and  $M_H = M_{H^\pm} = M_A = 600$  GeV (left) as well as  $M_a = 350$  GeV and  $M_H = M_{H^\pm} = M_A = 1000$  GeV (right). The remaining parameters take the values  $M_\chi = 10$  GeV,  $\tan \beta = 1$ , and  $\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3$ . The sensitivity, defined as the sum of Equation 3.1 over the  $E_T^{\text{miss}}$  bins, as well as the uncertainty on the sensitivity (shaded blue) are based on the limits with reduced model dependence from Ref. [5] and the uncertainties described therein. Bins with no content have a negligible sensitivity.

thereby decrease the resonant fraction of signal events and the overall search sensitivity. For this reason, the dependence of the sensitivity on  $\sin \theta$  depends on the interplay of the couplings. As a consequence, the sensitivity curve as a function of  $\sin \theta$  has more than one





**Figure 28:** Sum over all  $E_T^{\text{miss}}$ -bins of the estimated signal sensitivity to  $h \rightarrow bb + E_T^{\text{miss}}$  events as a function of the DM mass  $M_\chi$ . The sensitivity, defined as the sum of Equation 3.1 over the  $E_T^{\text{miss}}$  bins, as well as the uncertainty on the sensitivity (shaded blue) are based on the limits with reduced model dependence from Ref. [5] and the uncertainties described therein. The remaining parameters take the values  $M_a = 250$  GeV,  $M_H = M_{H^\pm} = M_A = 600$  GeV,  $\sin \theta = 0.35$ ,  $\tan \beta = 1$ , and  $\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3$ . The sensitivity is constant below  $M_\chi < M_a/2$ , and rapidly drops for  $M_\chi > M_a/2$ . The sensitivity is resonantly enhanced for  $M_\chi = M_a/2$ .

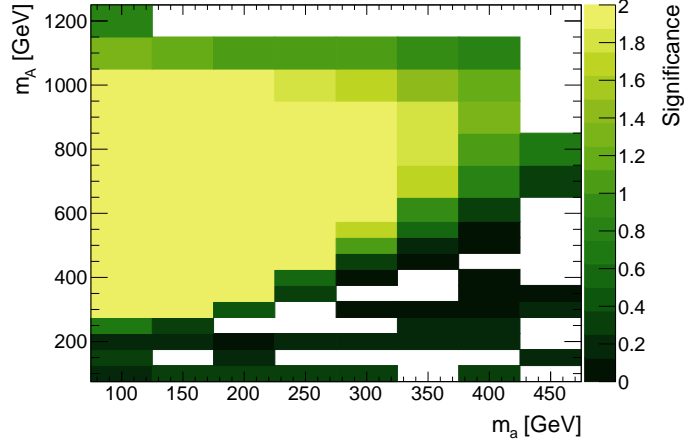
local maximum, as shown the right panel of Figure 27.

The sensitivity to models with varying  $M_\chi$  is shown in Figure 28. Below the threshold of  $M_\chi < M_a/2$ , the sensitivity is constant since the  $E_T^{\text{miss}}$  distribution and the total signal cross section remain unchanged. The region at threshold  $M_\chi = M_a/2 \pm 5\text{ GeV}$  (shaded in red in Figure 28) is numerically unstable and should be avoided. Above threshold, the sensitivity drops rapidly because  $M_\chi > M_a/2$  requires an off-shell  $a^* \rightarrow \chi\chi$  decay, which is strongly suppressed by the typically narrow width of  $a$ . The width of  $a$  is substantially reduced once  $a \rightarrow \chi\chi$  is kinematically inaccessible, as  $\Gamma_{a \rightarrow \chi\chi}$  is a large contribution to the total width of  $a$  for  $M_\chi \leq M_a/2$  [7]. There is a slight increase in sensitivity for  $M_\chi \approx M_A/2$  when the  $A \rightarrow \chi\chi$  decay hits its kinematic threshold, yet the absolute sensitivity remains negligible.

### 3.2 Studies of the $Z + E_T^{\text{miss}}$ signature

In the absence of generic limits on anomalous production of  $Z + E_T^{\text{miss}}$  events, the expected sensitivity of the  $Z + E_T^{\text{miss}}$  searches to this model is approximated comparing the number of generator-level signal events to the respective background estimates.

For the leptonic channel, the published background estimates corresponding to  $36\text{ fb}^{-1}$  of 13 TeV data [11] are used, and a reconstruction efficiency of 75% is assumed for signal events. The same selection cuts applied to data in [11] are applied to signal. Signal and



**Figure 29:** Expected significances for the  $Z+E_T^{\text{miss}}$  leptonic signature in the  $(M_a, M_A)$  plane. Bins with no content have a negligible sensitivity.

background are binned in the same published  $E_T^{\text{miss}}$  bins, and a conservative background systematic uncertainty of 20% is assumed for  $E_T^{\text{miss}} < 120$  GeV and 10% for  $E_T^{\text{miss}} > 120$  GeV.

For the hadronic channel,  $Z \rightarrow \nu\nu$  events in association with jets are simulated using Sherpa 2.2.1 [17] and the matrix elements are calculated up to 2 partons at next-to-leading order and up to 4 partons at leading order. Signal and background are scaled to  $40 \text{ fb}^{-1}$  of 13 TeV data. The  $Z(\rightarrow \nu\nu)+\text{jets}$  events are analyzed at particle level with the same criteria used for the signal. The number of  $Z \rightarrow \nu\nu$  events after applying the cuts is increased by a factor 2 to conservatively account for the contribution from other backgrounds. This factor is based on the ATLAS dark matter search in the mono- $Z$  hadronic signature using  $3.2 \text{ fb}^{-1}$  of 13 TeV data ??.

Following the Asimov approximation, the significance for individual bins is calculated as a Poisson ratio of likelihoods modified to incorporate systematic uncertainties on the background [18]:

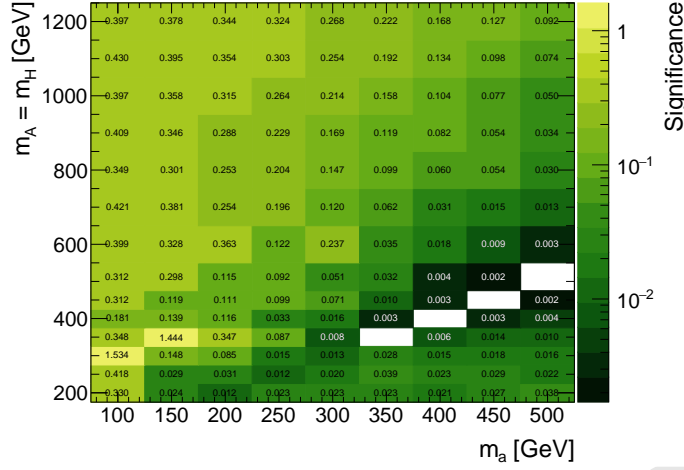
$$Z'_{bin} = \sqrt{2 \cdot \left( (s+b) \ln \left[ \frac{(s+b)(b+\sigma_b^2)}{b^2 + (s+b)\sigma_b^2} \right] - \frac{b^2}{\sigma_b^2} \ln \left[ 1 + \frac{\sigma_b^2 s}{b(b+\sigma_b^2)} \right] \right)} \quad (3.2)$$

This metric has the advantage that it accounts for background systematics and is still valid for  $s \gg b$ . Similarly to the  $h(bb) + E_T^{\text{miss}}$  case, the total significance is defined as the per bin significances summed in quadrature. The ATLAS and CMS experiments are expected to be sensitive to regions with significances greater than 2.

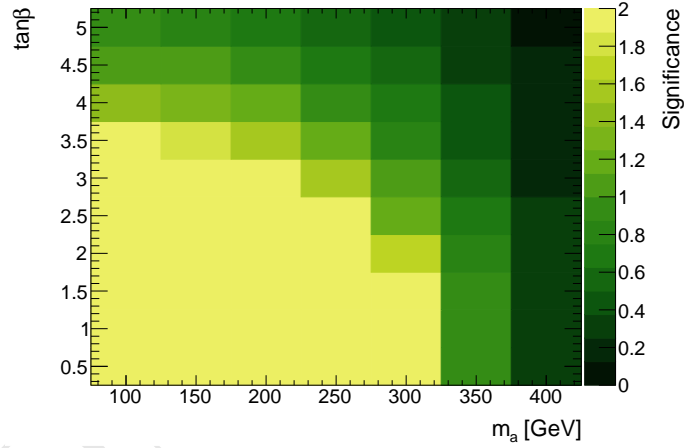
The expected sensitivity of  $Z+E_T^{\text{miss}}$  searches to the 2HDM+a model in the  $(M_a, M_A)$  plane is shown in Figure 31 for the leptonic case, and Figure 32 for the hadronic case.

The sensitivity for the  $Z+E_T^{\text{miss}}$  signatures in the  $(M_a, \tan \beta)$  plane is shown in Figure 31

The leptonic  $Z+E_T^{\text{miss}}$  search provides experimental coverage of this model for a broad part of the parameter space. The pseudoscalar mediator  $a$  can be probed up to mass values

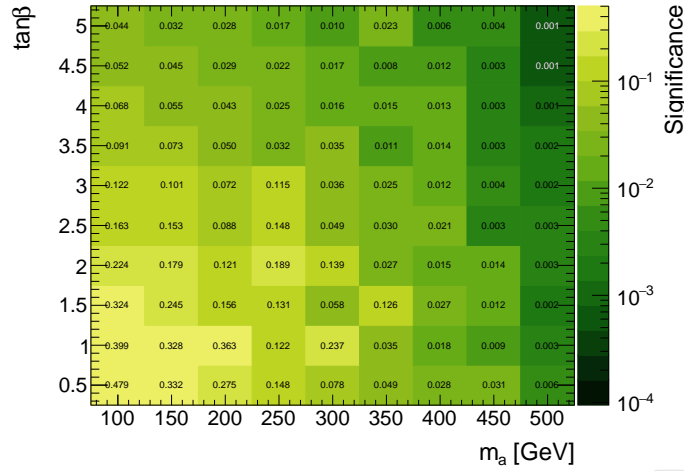


**Figure 30:** Expected significances for the  $Z+E_T^{\text{miss}}$  hadronic signature in the  $(M_a, M_A)$  plane, combining both boosted and resolved analyses. Bins with no content have a negligible sensitivity.



**Figure 31:** Expected significances for the  $Z+E_T^{\text{miss}}$  leptonic signature in the  $(M_a, \tan \beta)$  plane. Bins with no content have a negligible sensitivity.

of  $\approx 350$  GeV, depending on the choice of parameters. Leptonic  $Z+E_T^{\text{miss}}$  searches are mostly sensitive in the region of  $\tan \beta < 4$ . The hadronic  $Z+E_T^{\text{miss}}$  search covers a smaller parameter space with respect to the leptonic search, but it is nevertheless complementary.



**Figure 32:** Expected significances for the  $Z + E_T^{\text{miss}}$  hadronic signature in the  $(M_a, \tan \beta)$  plane, combining both boosted and resolved analyses. Bins with no content have a negligible sensitivity.

### 3.3 Other signatures

#### 3.3.1 Heavy flavor + $E_T^{\text{miss}}$ signatures

The choice of  $\sin \theta = 0.35$  and  $\tan \beta = 1$  means that the searches with heavy flavors are not sensitive to parameter scans other than the  $\tan \beta$  and  $\sin \theta$  scans. As discussed in [subsection 1.3](#), it is possible to recast the results of searches reinterpreted with the pseudoscalar model from [14], but this has not been done for this whitepaper.

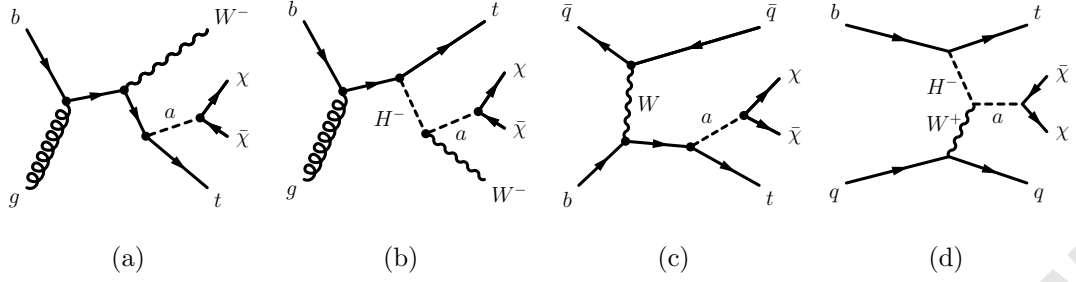
#### 3.3.2 Jet + $E_T^{\text{miss}}$ signature

The search for events with at least one jet and large missing transverse momentum in the final states can be also interpreted in the context of the 2HDM+a model. In this scenario the pseudoscalar mediator can be radiated from heavy quark loops providing such a signature. This channel is able to probe a phase space with low  $\tan \beta$  and high  $\sin \theta$  in which the cross-sections of this kind of processes are enhanced, as shown in Fig. 13 of [7]. The choice of  $\tan \beta = 1$  for the studies in this whitepaper highlights the complementarity between  $H + E_T^{\text{miss}}$  and  $Z + E_T^{\text{miss}}$  signatures; however the jet +  $E_T^{\text{miss}}$  signature is only sensitive to values of  $\tan(\beta)$  up to 0.5 and is not studied in detail in this whitepaper.

Since the models used for the interpretation of the jet +  $E_T^{\text{miss}}$  search in terms of scalar DM mediators are the same used for the HF +  $E_T^{\text{miss}}$  searches, it is possible to reinterpret the results of the search in terms of this model using the same rescaling strategy discussed in [subsection 1.3](#).

#### 3.3.3 $tW + E_T^{\text{miss}}$ signature

The sensitivity of the LHC experiments to the associated production of dark matter with a single top has been recently studied [19] in the framework of an extension of the standard model featuring two Higgs doublets and an additional pseudoscalar mediator. This study



**Figure 33:** Representative diagrams for  $tW$  and  $t$ -channel production of DM in association with a single top quark.

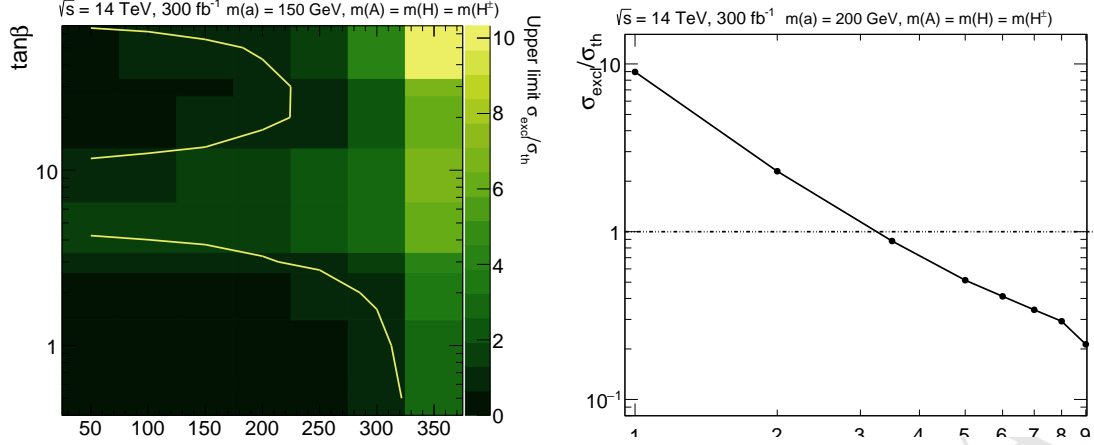
extends the work of previous literature [20], which demonstrated using a simplified model that the consideration of final states involving a single top quark and DM (DM $t$ ) increases the coverage of existing analyses targeting the DM $t\bar{t}$  process.

Like single top production within the SM, the DM $t$  signature in the model includes three different types of contributions at leading order (LO) in QCD:  $t$ -channel production,  $s$ -channel production and associated production together with a  $W$  boson ( $tW$ ) (Fig. 33). When the decay  $H^\pm \rightarrow W^\pm a$  is possible, the  $H^\pm$  is produced on-shell, and the cross-section of  $pp \rightarrow tW\chi\chi$ , assuming  $H^\pm$  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.

Ref. [19] analyzes detector-smeared generator-level signal and background samples using dedicated selections considering one and two lepton final states, in order to assess the coverage in parameter space for this signature at a centre-of-mass energy of 14 TeV assuming an integrated luminosity of  $300 \text{ fb}^{-1}$ . Figure 34 shows the reach of this signature for two of the parameter scans proposed in this whitepaper, in the  $(M_a, \tan\beta)$  plane assuming  $\sin\theta = 0.35$  and  $m(A) = m(H^\pm) = m(H) = 500 \text{ GeV}$ , and as a function of  $\tan\beta$  assuming  $\sin\theta = 0.35$ ,  $m(a) = 150 \text{ GeV}$  and  $m(A) = m(H^\pm) = m(H) = 500 \text{ GeV}$ . The sensitivity of this signature is comparable to the one of the Higgs +  $E_T^{\text{miss}}$  signature [7].

### 3.3.4 Signatures with $tth + E_T^{\text{miss}}$

As discussed in subsection 1.3, the production of the heavy mediator  $A$  contributes sizably to the  $t\bar{t} + E_T^{\text{miss}}$  production cross section in the  $2HDM + a$  model. This is also true for the heavy  $H$ . When the decay of these mediators into the lightest pseudoscalar  $a$  is allowed, this decay process dominates over the direct decay into  $\chi\chi$ . In analogy with what happens for the mono- $h$  signature discussed in [7], for certain region of parameter space the contribution of the processes  $pp \rightarrow t\bar{t}A \rightarrow t\bar{t}ah$  and  $pp \rightarrow t\bar{t}H \rightarrow t\bar{t}aZ$  become sizable. In the case of  $pp \rightarrow t\bar{t}A \rightarrow t\bar{t}ah$ , it can be inferred from Fig. 12(b) of Ref. [7] that for relatively small  $m(A)$  the  $pp \rightarrow t\bar{t}ah$  cross section can be up to 30% that of the  $pp \rightarrow t\bar{t}\chi\chi$  process. This encourages the study of the interplay of  $tth + E_T^{\text{miss}}$  searches with the traditional heavy flavor +  $E_T^{\text{miss}}$  searches.



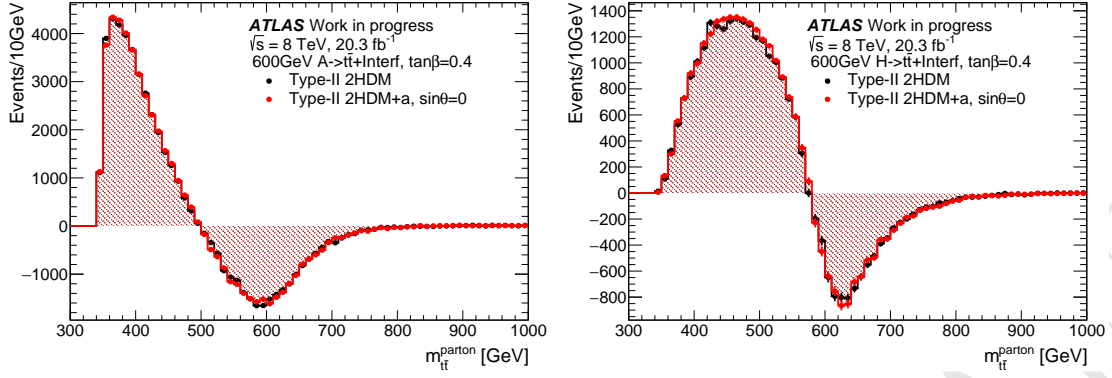
**Figure 34:** Sensitivity in terms of excluded/theoretical cross-section for the  $tW+E_T^{\text{miss}}$  signature in the  $(m(a), \tan\beta)$  plane, fixing  $m(a)$  to 150 GeV,  $\sin\theta = 0.35$  and  $m(A) = m(H^\pm) = m(H)$  (left). Sensitivity as a function of  $\tan\beta$ , assuming  $\sin\theta = 0.35$ ,  $m(a) = 150$  GeV and  $m(A) = m(H^\pm) = m(H) = 500$  GeV (right).

### 3.3.5 $\bar{t}t$ resonances

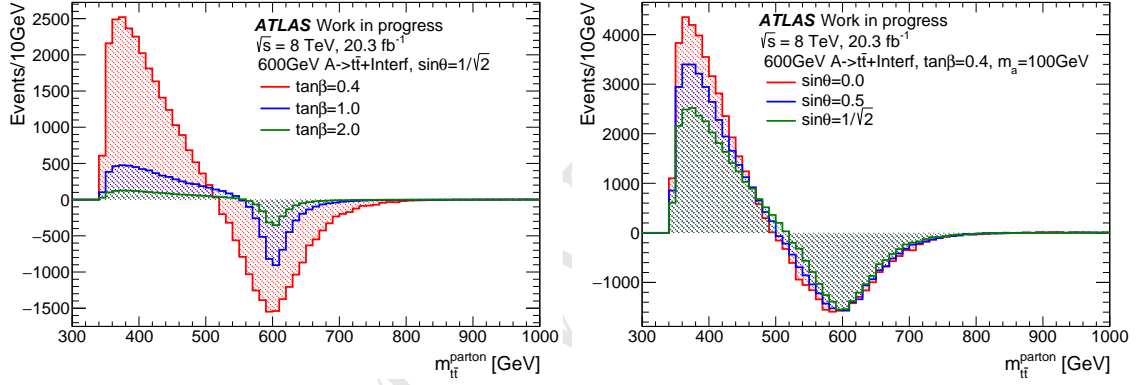
Heavy (pseudo)scalar bosons with  $M_{A/H} \geq 2M_t$  and  $\tan\beta \sim \mathcal{O}(1)$  will decay dominantly into top-quark pairs. Searches for features in the  $\bar{t}t$  invariant mass spectra are sensitive to this process. In this case, interference effects between the signal processes and the SM  $\bar{t}t$  production distort the signal shape from a single peak to a peak-dip structure [21].

The results of the first LHC search accounting for this feature in Ref. [22] can be reinterpreted in the context of the 2HDM+a, after modifying the MADGRAPH 5 model to feature this effect. Since interference between loop-induced and tree-level processes cannot currently be simulated, "Higgs\_Effective\_Couplings\_FormFactor" approach from Ref. [22] is adopted, replacing the loop production by an effective vertex. Using this approach, it can be verified that the 2HDM+a reduces to a minimal 2HDM when the pseudoscalar mediator  $a$  does not mix with the heavy pseudoscalar  $A$  ( $\sin\theta = 0$ ): Figure 35 shows the  $\bar{t}t$  invariant mass distribution in both cases, showing the peak-dip structure.

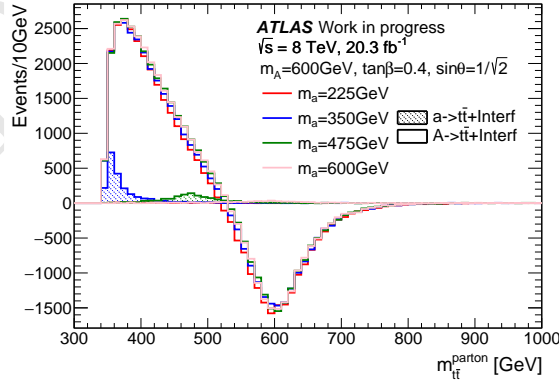
While a full study of the sensitivity of this search is not shown in this whitepaper, examples of how its reach changes as a function of the parameters of the 2HDM+a, the  $M_{\bar{t}t}$  signal distribution are presented in Fig 36. Larger values of  $\tan\beta$  or  $\sin\theta$  are expected to yield lower sensitivities to  $A \rightarrow \bar{t}t$  significantly while  $M_a$  almost only affects the contribution from  $a \rightarrow \bar{t}t$ , which becomes sizeable if  $M_a$  is close to  $2M_t$ .



**Figure 35:**  $M_{t\bar{t}}$  distribution of the heavy (pseudo)scalar boson decaying into  $t\bar{t}$  with  $M_A = M_H = 600\text{GeV}$ ,  $\tan\beta = 0.4$ ,  $\sin\theta = 1/\sqrt{2}$  and  $M_a = 100\text{GeV}$  in comparison with the one from the generic 2HDM.



(a)  $\tan\beta$  dependency with fixed  $\sin\theta = 1/\sqrt{2}$  and  $M_a = 100\text{GeV}$  (b)  $\sin\theta$  dependency with fixed  $\tan\beta = 0.4$  and  $M_a = 100\text{GeV}$



(c)  $M_a$  dependency with fixed  $\tan\beta = 0.4$  and  $\sin\theta = 1/\sqrt{2}$

**Figure 36:** Signal  $M_{t\bar{t}}$  distribution as a function of various model parameters. The value of  $M_a$  is fixed at  $600\text{GeV}$ .

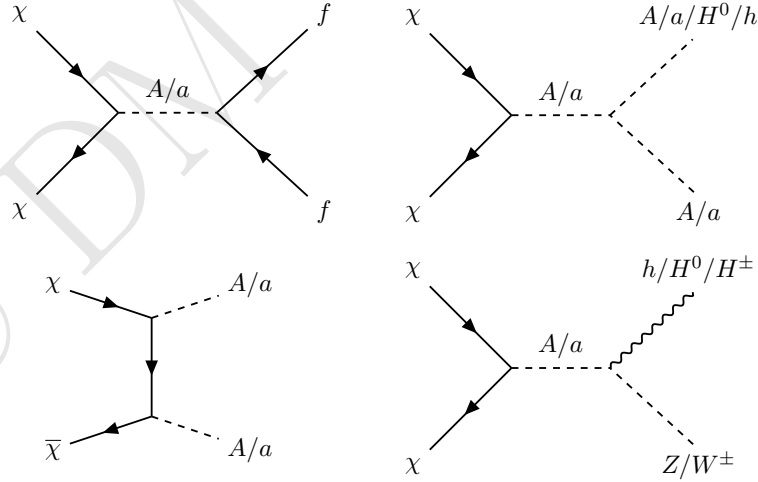
## 4 Connection with cosmology

In this section, we check the consistency of the 2HDM+a model as a function of the parameters chosen for the scans with the measured DM relic density, according to the standard thermal relic "freeze-out" scenario. This exercise requires the following assumptions, already described in Ref. [23]:

- The DM annihilation cross section receives only contributions from the interactions of the simplified model, while possible additional degrees of freedom and couplings not included in the model are irrelevant.
- The DM number density in the Universe today is entirely determined by the DM annihilation cross section predicted by the 2HDM+a. In particular, no additional mechanisms exist that enhance or deplete the relic density.

It is important to realize that if one or both of these assumptions are violated there is no strict correlation between the relic density and the strength of mono-X signals. For instance, if DM is overproduced, the relic density can be reduced if the DM has large annihilation cross sections to new hidden sector states. These states might however not be directly accessible at LHC energies. Conversely, the correct DM relic density can still be obtained if the DM is underproduced. For instance, if the hidden sector carries a particle-antiparticle asymmetry (similar to the baryon asymmetry) then this necessarily leads to a larger relic density compared to the conventional freeze-out picture.

### 4.1 Technical setup



**Figure 37:** Annihilation diagrams taken into account in the relic density calculation.

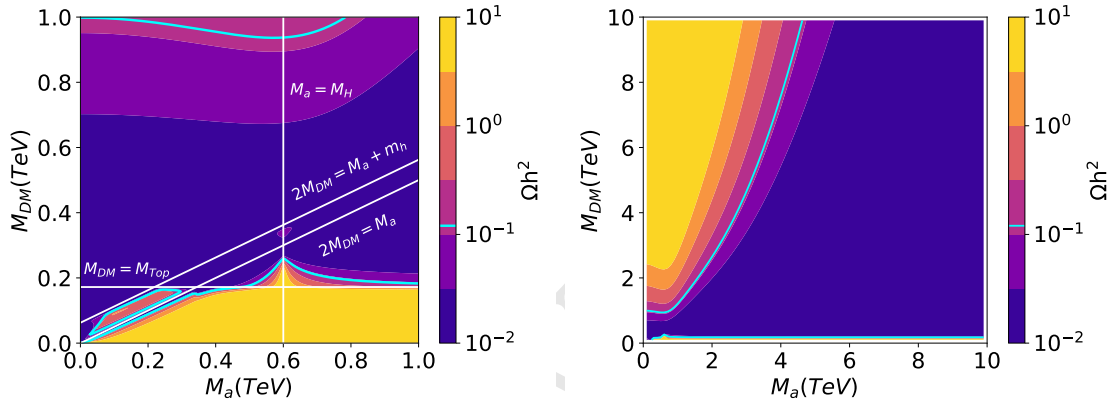
The MADDM [24, 25] plugin for MG5\_aMC@NLO is used to calculate the present-day relic density for this model. All tree-level annihilation processes are taken into account, and the Yukawa couplings of all fermions are taken to be non-zero. The Feynman diagrams



of annihilation processes taken into account in this calculation are shown in [Figure 37](#). Generally, the annihilation proceeds via single or double s-channel exchange of the pseudoscalars  $a$  and  $A$ , with subsequent decays. Since MADDM uses only tree-level diagrams, contributions from off-shell pseudoscalars can only be taken into account for the case of single s-channel mediation with direct decay of the pseudoscalars to SM fermions. If the pseudoscalars instead decays to other bosons or if the annihilation proceeds through double s-channel diagrams, the outgoing bosons are taken to be on-shell and their decays are not simulated.

Following [section 2](#), we use the parameter choices  $\sin(\theta) = 0.35$ ,  $m_h = 125\text{GeV}$ ,  $g_\chi = 1$ ,  $\lambda_i = 3$  for all scans in this section.

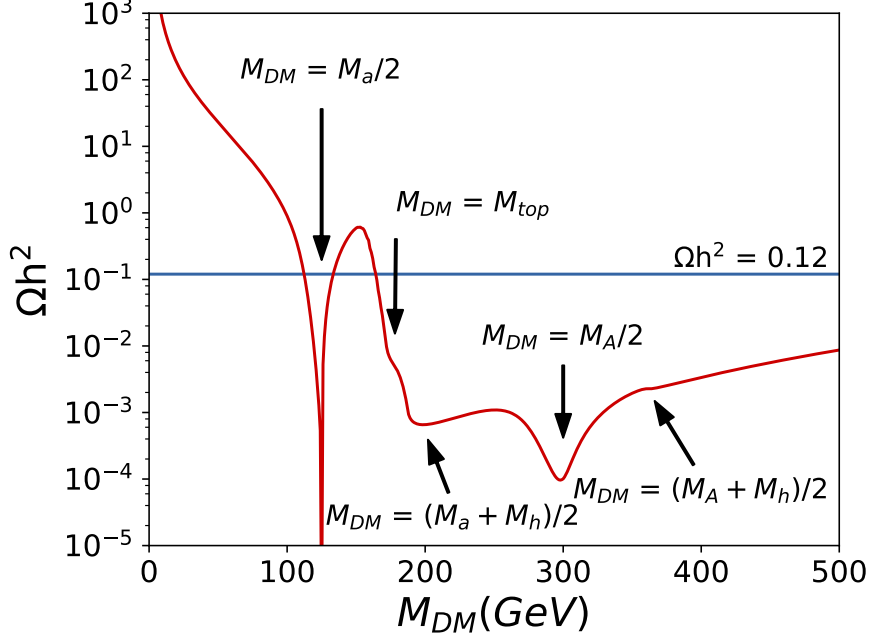
## 4.2 Results



**Figure 38:** Predicted relic density for a two-dimensional scan of  $M_\chi$  and  $M_a$ . The other parameters of the model remain fixed with  $m_H = m_A = m_{H^\pm} = 600\text{ GeV}$  and  $\tan\beta = 1$ , as well as the default choices described in the text. The color scale indicates the relic density, the cyan solid line shows the observed value of  $\Omega h^2 = 0.12$ . The color scale is truncated at its ends, i.e. values larger than the maximum or smaller than the minimum are shown in the same color as the maximum/minimum. While the left focuses on the mass region relevant to collider searches, the right panel shows the development of the relic density for a larger mass region.

The relic density is shown for in the  $M_a$ - $M_\chi$  plane in [Figure 38](#). For small values of  $M_\chi$  below the mass of the top quark, DM is mostly overabundant. In this regime, annihilation to quarks is suppressed by the small Yukawa couplings of the light fermions. The observed relic density can only be achieved for  $M_\chi \approx M_a/2$ , where annihilation is resonantly enhanced, or for  $M_\chi \approx (M_a + M_h)/2$ , close to the threshold for the  $\chi\chi \rightarrow ha$  process. Above the top threshold, annihilation into fermions becomes very efficient and DM is underabundant. As  $M_\chi$  increases further, annihilation via single s-channel diagrams is increasingly suppressed and the relic density rises again. The observed density is produced by this model for  $M_\chi \approx 1\text{TeV}$  at low  $M_a$ . [The following sentence is being checked with Andreas Albert - would remove] For values of  $M_a$  beyond the LHC reach of a few

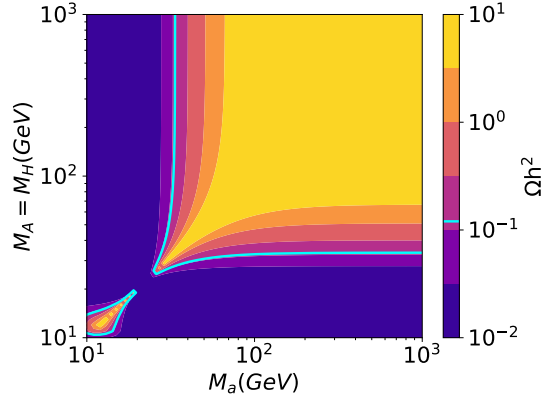
TeV, the allowed parameter region at the top threshold  $M_\chi \approx m_{\text{top}}$  remains independent of the value of  $M_a$ , indicating that a DM candidate that is mass degenerate with the top quark cannot be excluded by LHC searches alone.



**Figure 39:** Relic density for a one-dimensional scan of  $M_\chi$ . The other parameters of the model remain fixed with  $m_H = m_A = m_{H^\pm} = 600$  GeV,  $M_a = 250$  GeV and  $\tan \beta = 1$ , as well as the default choices described in the text. Various kinematic thresholds and regions of resonant enhancement are visible. Consistency with the observed value of  $\Omega h^2 = 0.12$  is mainly controlled by the resonant enhancement of  $\chi\chi \rightarrow a$ , as well as the onset of  $\chi\chi \rightarrow t\bar{t}$ .

The dependence of the relic density on the choice of  $M_\chi$  is further explored by performing a one-dimensional scan as a function of the DM mass fixing  $M_H = M_A = m_{H^\pm} = 600$  GeV,  $M_a = 250$  GeV, and shown in Figure 39. The relic density confirms structures corresponding to the previously discussed regions of resonant enhancement and to the kinematic boundaries. Overall, the behavior is dominated by the low- $M_\chi$  suppression of the annihilation cross-section, the resonant enhancement at  $M_\chi = M_a/2$  and the kinematic top thresholds. Other effects, such as the resonant enhancement of  $\chi\chi \rightarrow A$  annihilation are present, but only have small effects.

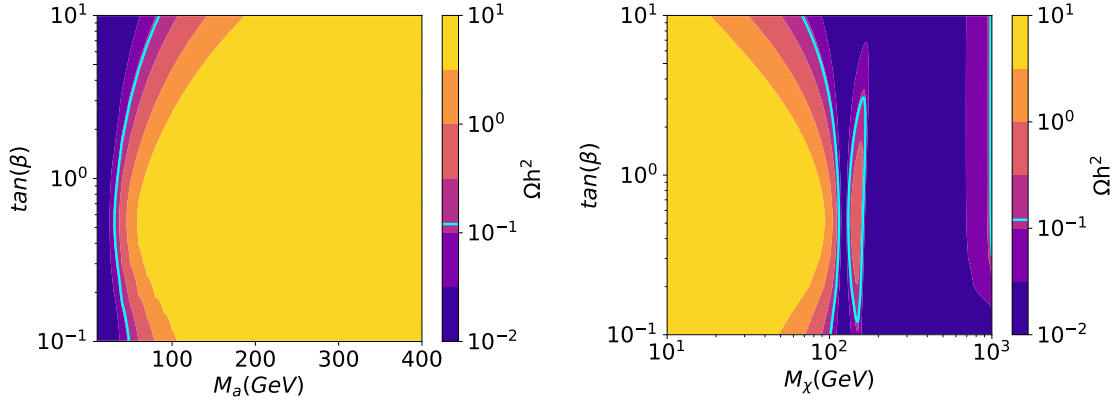
The relic density values for the  $M_a$ - $M_A$ / $M_H$  scan described in section 2 is shown in Figure 40. For the model parameters chosen in this whitepaper, the regions where the model generates a relic density compatible with the measured value are located at relatively small values of  $M_a < 30$  GeV or  $M_A = M_H < 30$  GeV, which are already excluded by invisible Higgs searches (see section 4.7 of Ref. [7]). The cosmological production of DM is largely driven by the choice of  $M_\chi$ . As shown in subsection 1.2.4, the model kinematics is largely insensitive to this choice if  $M_\chi < 2M_a$ . Future experimental results that are



**Figure 40:** Predicted relic density for a two-dimensional scan of  $M_a$  and  $M_A = M_H = M_{H^\pm}$ . The other parameters of the model remain fixed with  $M_\chi = 10$  GeV,  $\tan\beta = 1$ ,  $M_H = M_A = m_{H^\pm}$ . The color coding is identical to Fig. 38.

sensitive to DM masses around 100 GeV which can yield the measured relic density can still be interpreted by rescaling samples generated according to this parameter scan.

The  $\tan\beta$ -dependent scans, as a function of  $M_a$  and  $M_\chi$ , are shown in Fig. 41. The choice of  $\tan\beta$  acts as an overall modifier of the annihilation cross-section and thus the relic density, and the effect is largely independent of the choice of  $M_a$  and  $M_\chi$ . For a choice of  $\tan\beta \approx 0.6$ , the relic density becomes maximal and steadily decreases for larger and smaller values of  $\tan\beta$ . In the  $M_\chi$  dependent scan, where  $M_a$  is fixed to 250 GeV, the reduction of the relic density at low ( $\approx 0.1$ ) and high ( $\approx 3$ ) values of  $\tan\beta$  leads to the disappearance of the overabundant island around  $M_\chi \approx M_a/2$ .



**Figure 41:** Predicted relic density for a two-dimensional scan of  $\tan\beta$  and  $M_a$  (left),  $M_\chi$  (right). In the case of the  $M_\chi$  ( $M_a$ ) dependent scan,  $M_a = 250$  GeV ( $M_\chi = 10$  GeV) is used. The other parameters of the model remain fixed with  $m_H = m_A = m_{H^\pm} = 600$  GeV, as well as the default choices described in the text. The color coding is identical to Fig. 38.

## 5 Conclusions

# Appendix

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