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# Benchmarking the Inert Doublet Model for $e^+e^-$ colliders

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**ABSTRACT:** We present benchmarks for the Inert Doublet Model, a Two Higgs Doublet Model with a dark matter candidate. They are consistent with current constraints on direct detection, including the most recent bounds from the XENON1T experiment and relic density of dark matter, as well as with known collider and low-energy limits. We focus on parameter choices that promise detectable signals at lepton colliders via pair-production of  $H^+H^-$  and  $HA$ . For these we choose a large variety of benchmark points with different kinematic features, leading to distinctly different final states in order to cover the large variety of collider signatures that can result from the model.

**KEYWORDS:** Beyond Standard Model, Higgs Physics

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## 1 Introduction

The results from the ATLAS and CMS collaborations from Run I and ongoing Run II are in good agreement with the predictions of the Standard Model (SM) [1, 2]. Although the discovered Higgs particle appears to be consistent with the expectations for a SM Higgs boson, both the experimental uncertainties and theoretical speculations still leave room for new physics. In particular the scalar sector can provide intriguing scenarios in this respect which should be further scrutinized.

Although experimental collider data is in good agreement with predictions of the Standard Model alone, a number of non-collider observations can only be described in models containing additional (new physics) constituents. A prime example for this is dark matter (DM). Within the standard model of cosmology, the Planck mission data [3] implies that nearly 85% of the total matter content in the universe is dark. However, so far only the gravitational interactions of these hypothetical particles have been detected, and a fundamental nature of DM remains largely unknown. Since the Standard Model of elementary particles does not contain a viable DM candidate, any evidence of DM in the direct detection or indirect detection experiments or production at colliders would be a signal of new physics, the discovery of which is arguably one of the most important goals in the field.

An intriguing extension of the SM scalar sector is the Inert Doublet Model (IDM) which features a dark matter candidate [4–6]. In this two Higgs doublet model a discrete  $Z_2$

symmetry (called  $D$ -symmetry) is imposed, with the following transformation properties:

$$\phi_S \rightarrow \phi_S, \quad \phi_D \rightarrow -\phi_D, \quad \text{SM} \rightarrow \text{SM}, \quad (1.1)$$

where the  $\phi_S$  doublet plays the same role as the corresponding doublet in the SM, providing the SM-like Higgs particle. This doublet is even under the  $D$ -symmetry, while the second doublet, the inert (or dark)  $\phi_D$ , is  $D$ -odd and contains four scalars, two charged and two neutral ones, labelled  $H^\pm$  and  $H, A$ , respectively. The above symmetry renders the additional  $\text{SU}(2)_L$  doublet  $\phi_D$  inert, i.e. prevents its couplings to the SM matter sector, thereby providing a dark matter candidate. In the rest of this work, we consider cases where  $H$  serves as the dark matter candidate of the model.

The IDM was first discussed in [4] and later in [5, 6]. The model was further studied in [7–11], followed with further analyses of the IDM at colliders [11–31].

We here present a set of the IDM benchmarks proposed for detailed studies at the future  $e^+e^-$  colliders ILC and CLIC. They have been selected from updates of the scan presented in [23, 30] and represent distinct features for two prominent production processes at linear colliders,  $e^+e^- \rightarrow H^+H^-$  and  $e^+e^- \rightarrow AH$ . Our benchmarks are designed to cover all interesting parameter space, featuring different mass splittings between  $H$  and other dark particles, leading to distinct collider signatures.

The outline of this paper is as follows. We start with a short description of the IDM in section 2, followed with a discussion of theoretical constraints and current experimental limits in section 3. In section 4 we define benchmark points that pass all constraints and discuss their applications to further studies at the first stage of linear colliders running at 250, 380 and 500 GeV center-of-mass energies. Benchmarks suitable for testing at high energy stages of 1, 1.5 and 3 TeV linear colliders are presented in section 5. We also comment on the impact of future XENON-nT measurements and prospects of testing the IDM at the LHC in section 6.

## 2 The IDM

The scalar sector of the IDM consists of two  $\text{SU}(2)_L$  doublets of complex scalar fields,  $\phi_S$  and  $\phi_D$ , with the  $D$ -symmetric potential:

$$V = -\frac{1}{2} \left[ m_{11}^2 (\phi_S^\dagger \phi_S) + m_{22}^2 (\phi_D^\dagger \phi_D) \right] + \frac{\lambda_1}{2} (\phi_S^\dagger \phi_S)^2 + \frac{\lambda_2}{2} (\phi_D^\dagger \phi_D)^2 \\ + \lambda_3 (\phi_S^\dagger \phi_S) (\phi_D^\dagger \phi_D) + \lambda_4 (\phi_S^\dagger \phi_D) (\phi_D^\dagger \phi_S) + \frac{\lambda_5}{2} \left[ (\phi_S^\dagger \phi_D)^2 + (\phi_D^\dagger \phi_S)^2 \right]. \quad (2.1)$$

Exact  $D$ -symmetry implies that only  $\phi_S$  can acquire a nonzero vacuum expectation value ( $v$ ). As a result the scalar fields in  $\phi_D$  do not mix with the SM-like field from  $\phi_S$ , and the lightest particle of the dark sector is stable. The dark sector contains four new particles:  $H$ ,  $A$  and  $H^\pm$ . We here choose  $H$  to denote the dark matter candidate. A priori, any of the new scalars can function as a dark matter candidate. However, we neglect the choice of a charged dark matter candidate, as these are strongly constrained [32]. As inert scalars do not couple to fermions, it is not possible to assign a definite CP-property to them.

Therefore, choosing  $A$  instead of  $H$  to be the lightest particle changes only the meaning of  $\lambda_5$ , with rephasing of  $\lambda_5 \rightarrow -\lambda_5$ , but not the overall phenomenology of the model, cf. appendix A in [23].

After electroweak symmetry breaking, the model contains seven free parameters. Agreement with the Higgs boson discovery and electroweak precision observables fixes the SM-like Higgs mass  $M_h$  and  $v$ , and we are left with five free parameters, which we take as

$$M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345}, \quad (2.2)$$

where the  $\lambda$ 's refer to couplings within the dark sector and to the SM-like Higgs respectively. In the following, we will use the abbreviation  $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$ .

### 3 Experimental and theoretical constraints

In this work, we make use of the tool chain used in [23], and explicitly follow the scan procedure described therein; however, we update several constraints as discussed below. Explicit benchmark points (BPs) for the IDM, taking all constraints viable at that time into account, have been presented in [23, 33], which focus on processes at the LHC; some of these were already investigated in a linear collider context in [24]. Ref. [30] shows how the available parameter space for certain scenarios is further limited by more recent constraints.

As the experimental constraints have evolved significantly since that time, we decided to define the new set of benchmark points, fulfilling the updated constraints and focused on the detailed analysis of  $e^+e^-$  collider sensitivity. Unless stated otherwise, all considered BPs fulfil the latest experimental limits; following [23] (see also the discussion in [34]), we do not require the IDM to provide 100% of the dark matter relic density. Below we briefly summarize the imposed constraints, emphasizing on updates with respect to [23], and describe the set-up to find good BPs and discuss the obtained limits.

#### 3.1 Theoretical and experimental constraints

**Positivity constraints:** we require that the potential is bounded from below, therefore no field configuration leads to  $V \rightarrow -\infty$ , resulting in tree-level relations [35]

$$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0. \quad (3.1)$$

These relations hold on tree level and in this work we do not consider higher-order contributions, which in principle could lead to change in stability of the electroweak vacuum [10, 36].

**Perturbative unitarity:** we require the scalar  $2 \rightarrow 2$  scattering matrix to be unitary, i.e. all eigenvalues of scattering matrices for scalars with specific hypercharge and isospin should satisfy  $|L_i| \leq 16\pi$  [37, 38]. Furthermore, we require all quartic scalar couplings to be perturbative, i.e. to take absolute values  $\leq 4\pi$ .

**Global minimum:** in the IDM two neutral minima can coexist even at tree level. Unless the following relation is satisfied

$$\frac{m_{11}^2}{\sqrt{\lambda_1}} \geq \frac{m_{22}^2}{\sqrt{\lambda_2}}, \quad (3.2)$$

the inert minimum is only a local one, with the global vacuum corresponding to the case of massless fermions [39]. We impose the above relation in our scan.

**Higgs mass and signal strengths:** the mass of the SM-like Higgs boson  $h$  is set to

$$M_h = 125.1 \text{ GeV},$$

in agreement with limits from ATLAS and CMS experiments [40], while the total width of the SM-like Higgs boson obeys an upper limit of [41]

$$\Gamma_{\text{tot}} \leq 9 \text{ MeV}. \quad (3.3)$$

In the IDM, the total width of the SM-like state can obtain modifications from the following two contributions. For dark matter masses  $M_H \leq M_h/2$ , invisible decays of the 125 GeV resonance can lead to large additional contributions. Therefore, in these scenarios the above bound poses one of the most dominant constraints, especially affecting  $\lambda_{345}$  [23, 30]. Furthermore, the partial decay width of  $h$  to diphoton final states can be altered significantly [11, 19], as the new physics corrections are formally of the same order as the SM process. This leads to a clear distinction between allowed and forbidden regions in the  $(\lambda_{345}, M_{H^\pm})$  plane [23, 30]. The Run I combined ATLAS and CMS limit for  $h \rightarrow \gamma\gamma$  signal strength is given by  $\mu_{\gamma\gamma} = 1.14^{+0.38}_{-0.36}$  [42]. In our analysis we use both the upper limit (3.3) and require agreement within  $2\sigma$  for the prediction of  $h \rightarrow \gamma\gamma$ . We furthermore check agreement with all other branching ratios of the 125 Higgs on the  $2\sigma$  level using the publicly available tool `HiggsSignals-2.2.1beta` [43], and require  $\Delta\chi^2 \leq 11.31$ , corresponding to a 95% confidence level.

**Gauge bosons width:** introduction of light new particles could in principle significantly change the total width of electroweak gauge bosons (cf. e.g. [44]). To ensure that  $W^\pm \rightarrow HH^\pm$  and  $Z \rightarrow HA, H^+H^-$  decay channels are kinematically forbidden we set:

$$M_{A,H} + M_{H^\pm} \geq M_W, M_A + M_H \geq M_Z, 2M_{H^\pm} \geq M_Z. \quad (3.4)$$

**Electroweak precision tests (EWPT):** we call for a  $2\sigma$  (i.e. 95% C.L.) agreement with electroweak precision observables, parametrized through the electroweak oblique parameters  $S, T, U$  [45–48]. In our work, calculations were done through the routine implemented in the Two Higgs Doublet Model Calculator (2HDMC) tool [49], which checks whenever model predictions fall within the observed parameter range [50].

**Charged scalar mass and lifetime:** we take a conservative lower estimate on the mass of  $M_{H^\pm}$  following analysis in [51] to be

$$M_{H^\pm} \geq 70 \text{ GeV}. \quad (3.5)$$

We also set an upper limit on the charged scalar lifetime of

$$\tau \leq 10^{-7} \text{ s}, \quad (3.6)$$

in order to evade bounds from quasi-stable charged particle searches. This translates to a lower bound on the total decay width of the charged scalar  $H^\pm$  of  $\Gamma_{\text{tot}} \geq 6.58 \times 10^{-18} \text{ GeV}$ . In [52], the authors show that limits from a recast of heavy charged particle searches at the LHC [53] can set bounds on the lifetimes of  $H^\pm$  between  $10^{-9}$  and  $10^{-5} \text{ s}$ , with the lower value prevailing for charged masses  $M_{H^\pm} \lesssim 500 \text{ GeV}$ . For most of the parameter space, the limit (3.6) therefore corresponds to a conservative upper limit.

**Collider searches for new physics:** we require agreement with the null-searches from the LEP, Tevatron, and LHC experiments. We use the publicly available tool `HiggsBounds-5.2.0beta` [54–57]. In addition the reinterpreted LEP II searches for supersymmetric particles analysis exclude the region of masses in the IDM where simultaneously [12]

$$M_A \leq 100 \text{ GeV}, M_H \leq 80 \text{ GeV}, \Delta M(A, H) \geq 8 \text{ GeV}, \quad (3.7)$$

as it would lead to a visible di-jet or di-lepton signal. After taking into account all the above limits we are outside of the region excluded due to the reinterpretation of the supersymmetry analysis from LHC Run I [21].

**Dark matter phenomenology:** we apply dark matter relic density limits obtained by the Planck experiment [3]:

$$\Omega_c h^2 = 0.1197 \pm 0.0022. \quad (3.8)$$

For a DM candidate that provides 100% of observed DM in the Universe we require the above bound to be fulfilled within the  $2\sigma$  limit. However, we also allow for the case where  $H$  is only a subdominant DM candidate, with

$$\Omega_H h^2 < \Omega_c h^2 \quad (3.9)$$

(see [23, 30, 34]). In such a scenario, additional dark matter candidates would be needed in order to account for the missing relic density. In the results presented here, we apply XENON1T limits [58].<sup>1</sup> These supersede previous bounds applied e.g. in [30] in relevant regions of parameter space, and are therefore crucial for a correct determination of the available parameter space, especially for low dark masses.

Results from indirect detection experiments, e.g. Fermi-LAT [60], give less stringent constraints than collider and direct detection experiments discussed above [10, 34]. A number of planned DM indirect detection experiments, mainly the Cherenkov Telescope Array, will be able to probe the heavy mass region, with DM particle heavier than 500 GeV [61]. Furthermore, if the reported gamma-ray excess from the Galactic center is of DM origin [62], it can be explained by the IDM with dark matter masses near the Higgs resonance or around 72 GeV [63]. All dark matter variables were calculated with the use of `micrOmegas` version 4.3.5 [64].

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<sup>1</sup>We use a digitized format of that data available from [59].

## 3.2 Scan setup and limits

After fixing the value of  $M_h$ , and hence both  $\lambda_1$  and  $m_{11}^2$ , we are left with five independent input parameters for the scan: three masses of dark scalars  $M_{A,H,H^\pm}$  and two couplings,  $\lambda_{345}, \lambda_2$ . In the initial setup of our scan, masses take values between 0 and 1 TeV, with  $M_H$  always being the lightest and  $M_{H^\pm} \geq 70$  GeV. Unless stated otherwise, scalar couplings fall in the range of  $\lambda_2 \in [0; 4.5]$ ,  $\lambda_{345} \in [-1.5; 4\pi]$ .

In order to get interesting benchmark points we follow the procedure described in [23]. All constraints described in the previous section are checked in steps, with the aid of publicly available tools. In the process we track the impact of each exclusion criterion.

The first step contains a check through the 2HDMC in order to establish agreement with theoretical constraints (positivity, stability, perturbative unitarity). The same code is used to check the SM-like Higgs and electroweak gauge bosons widths, the decay rates of  $h \rightarrow$  invisible, and  $h \rightarrow \gamma\gamma$ , properties of charged scalar (lifetime, mass) as well as the EWPT observables. Points that have passed the first step are then checked against limits from collider searches, in particular the Higgs signal strength limits, with the use of `HiggsBounds` and `HiggsSignals`. Points which passed the collider test are then confronted with limits from DM phenomenology, i.e. the relic density constraints with upper Planck bound (points that correspond to 100% of measured  $\Omega_c h^2$  are selected at later stage) and direct detection limits from XENON1T, with the use of `micrOmegas`.

Although the IDM is one of the simplest extensions of the SM and has a limited number of parameters, it is still difficult to establish which constraint has the greatest impact on excluding a given point in parameter space. In the following, we point to some generic features that however can be used for a clear distinction in the model parameters space (see also [23]).

It is important to emphasize that the couplings that govern the production and decay processes at  $e^+e^-$  colliders are mainly determined by the electroweak parameters of the SM; the additional parameters in the potential do not play any significant role for the allowed scenarios. On the other side, the parameter  $\lambda_{345}$  is especially sensitive to constraints from dark matter observations. This nicely demonstrates the important complementarity of collider and astrophysical measurements in constraining the IDM parameter space.

We divide the discussion in two different subsections

- (i) constraints on the masses of the dark scalars, with the constraint given in eq. (3.9) for the dark matter relic density;
- (ii) additional limits we obtain when requiring exact relic density.

We only briefly discuss the second point here and refer to the literature (see e.g. [34]) for further details.

### 3.2.1 Limits on masses

The collider phenomenology of the IDM is mainly determined by the dark scalar masses, as all relevant production and decay channels are governed by electroweak couplings and the



corresponding SM parameters. As dominant constraints for the regions for  $M_H \leq M_h/2$  and  $M_H \geq M_h/2$  originate from different sources, we will discuss these separately.

- In general, constraints arising from EWPT are of a great importance to our studies. As found in [23, 34, 65], mass splittings between inert particles are heavily limited by the S,T,U parameters. First, only moderate mass splittings are allowed by EWPT data, with the preferred value of  $M_{H^\pm} - M_A$  below 100 GeV. Also, there is a hierarchy between masses, with the charged scalar being the heaviest particle. The reverse relation is not excluded, however it will lead to a larger tension with combined S and T limits. In general, points with moderate mass splittings are preferred, especially for dark matter candidates with masses  $\geq 300$  GeV, where splittings between  $M_A$  and  $M_H$  are typically of order 10 % or lower. For masses  $M_H \leq 100$  GeV, we found that relatively large mass differences are allowed between the two neutral scalars. The mass hierarchy and constraints on mass splittings can influence cascade decays of inert particles.
- In addition to eq. (3.5), the measurement of  $h \rightarrow \gamma\gamma$  puts a lower limit on the charged Higgs mass as a function of  $\lambda_{345}$ , cf. e.g. [30].
- Masses of DM particles below 45 GeV are excluded [23, 34]. For  $M_H \leq M_h/2$  limits from the invisible branching ratio of the SM Higgs lead to relatively low values of  $\lambda_{345}$ , which in turn result in the relic density exceeding the measured value by orders of magnitude or the mass splittings changing electroweak gauge bosons widths<sup>2</sup> significantly.
- For dark scalars with masses  $\lesssim 100$  GeV, additional specific constraints are given by eq. (3.7).

The parameters  $\lambda_2$  and  $\lambda_{345}$  are also constrained from combined positivity, unitarity and global minimum conditions [66]. The exact value of  $\lambda_2$  parameter would matter in studies that consider interaction between inert particles, for example for the astrophysical implications of self-interacting dark matter, or if the loop processes like  $HH \rightarrow \gamma\gamma$  through the  $H^+H^-$  loop are considered, this is however beyond the scope of this work.

Dark matter constraints give major bounds on allowed values of  $\lambda_{345}$ . In general,  $|\lambda_{345}| \lesssim 1.5$  for dark masses up to 1 TeV. For  $M_H \lesssim M_h/2$ , this limit decreases to  $|\lambda_{345}| \lesssim 0.006$ , due to the inclusion of results presented in [58]. Limits from Higgs signal strength measurements also limit this parameter, albeit less strongly than dark matter constraints. If we allow for a subdominant dark matter candidate, the parameter space largely opens up for regions where the dark matter relic density is much lower than the Planck value. Direct detection limits are then rescaled and therefore considerably relaxed (see also [23]). A prominent example for this is the region where  $M_H \sim M_h/2$ , leading to large annihilation cross sections. This broadens especially the allowed range for  $\lambda_{345}$ .

In summary,  $M_{H^\pm}$  and  $M_A$  are relatively degenerate throughout the allowed parameter space. The splittings between these and the dark matter candidate depend on the DM mass

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<sup>2</sup>See e.g. detailed discussions in [34].



and can become quite large, especially for low  $M_H$ . The couplings  $\lambda_2$  and  $\lambda_{345}$  do not play a significant role in collider phenomenology.

### 3.2.2 Requiring exact relic density

Requiring the model to render exact relic density, as specified by eq. (3.8), puts additional constraints on the model. These are mainly on the coupling combination  $\lambda_{345}$ , but also affect the values of possible dark scalar masses in such a scenario.

- If  $H$  is the only source of DM in the Universe then it is possible to find good points only for masses  $55 \text{ GeV} \lesssim M_H \lesssim 75 \text{ GeV}$ , where the allowed range of dark scalar masses is determined by electroweak constraints, without additional fine-tuning.
- In the region  $75 \text{ GeV} \lesssim M_H \lesssim 500 \text{ GeV}$  DM direct detection searches exclude all points that have exact relic density. Points that have passed all other constraints provide only a subdominant dark matter candidate.
- For  $M_H$  larger than  $500 \text{ GeV}$  extreme fine-tuning of the dark masses is required in order to obtain exact relic density; cf. the discussion in [34]. The authors of that reference find that  $\mathcal{O}(\text{GeV})$  mass splittings between the dark scalars would be required in order to obtain the correct relic density; in turn, this can lead to long-lived particles at the LHC, where minimal allowed mass splittings are  $\mathcal{O}(0.2 \text{ GeV})$  [52]. In our work, we do not study this particularly fine-tuned region in more detail.

## 4 Benchmark points

As the aim of this note is to present benchmarks useful for further studies at linear colliders, we are particularly interested in points that provide an observable signal. For the possible signal we take the pair-production processes

$$e^+e^- \rightarrow H^+H^- \quad \text{and} \quad e^+e^- \rightarrow AH \quad (4.1)$$

for charged and neutral scalar production. The s-channel production  $e^+e^- \rightarrow h \rightarrow AA$  is also possible, however it is suppressed by a small electron Yukawa coupling. The dark scalars  $H^\pm$  and  $A$  will then decay into a virtual or on-shell electroweak gauge boson and the dark matter candidate. Here, we first concentrate on center-of-mass energies of  $\sqrt{s} \in \{250; 380; 500\} \text{ GeV}$ , therefore constraining ourselves to scenarios where either  $M_{H^\pm} \leq 250 \text{ GeV}$  or  $M_H + M_A \leq 500 \text{ GeV}$  (or both). In section 5, we extend the analysis to contain higher dark scalar masses, in order to investigate the collider reach of the high energy ILC at  $1 \text{ TeV}$  and higher energy stages of CLIC at  $1.5 \text{ TeV}$  and  $3 \text{ TeV}$  [67]. In this work, we consider benchmarks with both on-shell and off-shell intermediate gauge bosons, as these differ in the collider phenomenology, and different cut strategies have to be applied.

Our benchmark selection was done in the following steps:

1. Benchmark candidates were generated by employing the scan presented in [23], with updated experimental constraints as discussed above. We selected about 7500 bench-

mark candidates which fulfill all constraints (we allow for under-abundant dark matter, therefore relaxing bounds from direct detection considerably in certain regions of parameter space).

2. We then calculated the production cross sections at 250, 380 and 500 GeV center-of-mass energies for processes (4.1); we required a minimal production cross section of 10 fb to classify a point as “accessible” for a certain process/energy stage;
3. if possible, we required a high-enough relic density, providing at least 50% of the value observed by the Planck collaboration;
4. finally we selected benchmark points corresponding to different accessibility at the subsequent energy stages and different kinematical configurations, namely on-shell vs off-shell intermediate gauge bosons.

The calculation of cross sections was performed using input files generated by **SARAH** 4.13.0 [68–70] and **SPheno** 4.0.3 [71, 72], which were passed to **WHizard** 2.2.8 [73, 74]. Initial state radiation was taken into account but not the beam luminosity spectra.

Point 2 above allows us to categorize different classes of benchmarks, which we label “XYZ” in the following, with X=1(2) corresponding to 1 (2) production processes accessible at 250 GeV, while Y and Z are defined accordingly for 380 GeV and 500 GeV. Within a certain category, we then considered different mass splitting configurations, in order to cover all possible typical parameter configurations leading to distinct collider signatures that can be generated by the IDM. The final selection of benchmark points, focusing on kinematic properties and selection criteria, is given in table 1. The table also contains the complete set of independent parameters for each point, as well as the relic density.

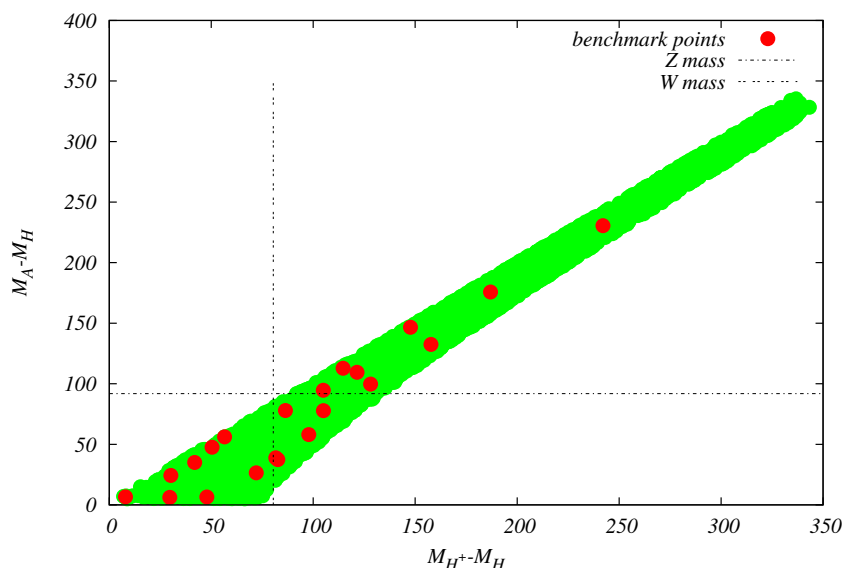
In our selection, BP1 is an example for a relatively small mass splitting, that forces the intermediate gauge boson to be off-shell. Other benchmark points, as e.g. BP9, allow for on-shell decays in both channels. However, these force the corresponding dark scalar masses to be  $\mathcal{O}(150 \text{ GeV})$ , therefore leading to smaller production cross sections.

Figure 1 shows the initial benchmark candidates, that obey all current constraints, in the  $(M_{H^+} - M_H; M_A - M_H)$  plane. All points form a narrow band corresponding to  $M_A \lesssim M_{H^\pm}$ . Our chosen benchmark points, also indicated in figure 1 (red points) cover mass gaps up to about 250 GeV only, due to the required minimal cross section (see point 2 above). Notice that for most selected benchmark points the DM candidate is relatively light, with a mass below 80 GeV.

Tables 2 and 3 show the production cross sections at various center-of-mass energies for all benchmark scenarios. These indicate promising prospects of detection at future linear colliders. Because  $A$  is always a lighter particle, neutral channels are usually accessible at lower energies than charged ones. If both channels are accessible, the cross section for charged scalar pair-production is usually larger than for the neutral ones.

No.	$M_H$	$M_A$	$M_{H^\pm}$	$Z$ on-shell	$W$ on-shell	DM >50%	$\lambda_2$	$\lambda_{345}$	$\Omega_H h^2$
222									
<b>BP1</b>	72.77	107.803	114.639			✓	1.44513	-0.00440723	0.12007
BP2	65	71.525	112.85			✓	0.779115	0.0004	0.070807
BP3	67.07	73.222	96.73			✓	0	0.00738	0.061622
122									
BP4	73.68	100.112	145.728			✓	2.08602	-0.00440723	0.089249
<b>BP6</b>	72.14	109.548	154.761		✓	✓	0.0125664	-0.00234	0.11708
112									
BP7	76.55	134.563	174.367		✓		1.94779	0.0044	0.031402
<b>BP8</b>	70.91	148.664	175.89		✓	✓	0.439823	0.0051	0.124
BP9	56.78	166.22	178.24	✓	✓	✓	0.502655	0.00338	0.081268
BP23	62.69	162.397	190.822	✓	✓	✓	2.63894	0.0056	0.064038
022									
BP10	76.69	154.579	163.045		✓		3.92071	0.0096	0.028141
BP11	98.88	155.037	155.438				1.18124	-0.0628	0.0027369
BP12	58.31	171.148	172.96	✓	✓		0.540354	0.00762	0.0064099
012									
BP13	99.65	138.484	181.321		✓		2.46301	0.0532	0.001255
<b>BP14</b>	71.03	165.604	175.971	✓	✓	✓	0.339292	0.00596	0.11841
<b>BP15</b>	71.03	217.656	218.738	✓	✓	✓	0.766549	0.00214	0.12225
011									
<b>BP16</b>	71.33	203.796	229.092	✓	✓	✓	1.03044	-0.00122	0.12214
002									
BP18	147	194.647	197.403				0.387	-0.018	0.0017718
BP19	165.8	190.082	195.999				2.7675	-0.004	0.0028405
BP20	191.8	198.376	199.721				1.5075	0.008	0.008494
001									
<b>BP21</b>	57.475	288.031	299.536	✓	✓	✓	0.929911	0.00192	0.11946
<b>BP22</b>	71.42	247.224	258.382	✓	✓	✓	1.04301	-0.00406	0.12428

**Table 1.** In all benchmarks  $M_h = 125.1$  GeV. Bold font denotes BP with 100% DM relic density. Accessibility categories are also shown (see text for details). Note that BP5 and BP17 were excluded by the updated XENON1T limits [58].



**Figure 1.** Distribution of benchmark candidate points (green) in the  $(M_{H^+} - M_H; M_A - M_H)$  plane, after all constraints are taken into account, as well as selected benchmark points (red) in the same plane. The dashed lines indicate the electroweak gauge boson masses that distinguish between on- and off-shell decays of dark scalars. The relatively narrow band stems mainly from electroweak precision constraints.

## 5 Extending to higher mass scales

So far, we have discussed IDM scenarios that are accessible at center-of-mass energies up to 500 GeV, with a mass range of  $M \lesssim 250$  GeV for all dark scalars. However, the parameter space of the IDM largely opens up for higher dark scalar masses, especially as direct detection constraints are less strict and direct collider searches pose less stringent constraints.<sup>3</sup> Therefore, in this section we consider high-mass benchmark points (HP) that can be explored at higher center-of-mass energies, e.g. at 1 TeV ILC or at the high-energy stages of the CLIC collider, at 1.5 TeV or 3 TeV.

As before, all benchmark points have passed theoretical and experimental constraints discussed in section 3. We now consider the nominal collider energies of 1 TeV, 1.5 TeV and 3 TeV. From about 6000 parameter points, we selected 20 benchmark points. The selection was done analogously to the low-energy case, aiming in addition to cover the whole mass range of the dark scalars up to 1 TeV. Benchmark points are summarized in table 4 and the production cross sections for the considered IDM scalar pair-production processes in table 5. The maximum mass splitting between the dark scalars is about 140 GeV, as the relic density decreases rapidly with the increasing mass difference (see section 3.2.2).

<sup>3</sup>Constraints stemming from the diphoton range exclude certain ranges in the  $M_{H^+}, \lambda_{345}$  plane, cf. e.g. [30], leading to a lower limit on the dark charged scalar mass.

No.	$M_H$	$M_A$	$M_{H^\pm}$	$\sigma(250)$	$\sigma(380)$	$\sigma(500)$	$BR_{H^+ \rightarrow W^+ H}$
<b>BP1</b>	72.77	107.803	114.639	23.7	97.8	82.6	$> 0.99$
BP2	65	71.525	112.85	30.4	101	83.9	0.66
BP3	67.07	73.222	96.73	108	127	95.3	0.75
BP4	73.68	100.112	145.728	-	46.7	59.9	0.92
<b>BP6</b>	72.14	109.548	154.761	-	33.3	53.2	0.99
BP7	76.55	134.563	174.367	-	9.59	38.9	$> 0.99$
<b>BP8</b>	70.91	148.664	175.89	-	8.16	37.8	$> 0.99$
BP9	56.78	166.22	178.24	-	6.13	36.1	$> 0.99$
BP10	76.69	154.579	163.045	-	22.3	47.1	$> 0.99$
BP11	98.88	155.037	155.438	-	32.4	52.7	1
BP12	58.31	171.148	172.96	-	11	39.9	1
BP13	99.65	138.484	181.321	-	3.79	33.9	0.99
<b>BP14</b>	71.03	165.604	175.971	-	8.09	37.7	$> 0.99$
<b>BP15</b>	71.03	217.656	218.738	-	-	10.5	1
<b>BP16</b>	71.33	203.796	229.092	-	-	5.64	$> 0.99$
BP18	147	194.647	197.403	-	-	23.1	1
BP19	165.8	190.082	195.999	-	-	24	$> 0.99$
BP20	191.8	198.376	199.721	-	-	21.6	1
BP23	62.69	162.397	190.822	-	-	27.4	$> 0.99$

**Table 2.** Production cross sections in fb for on-shell charged scalar pair-production,  $e^+ e^- \rightarrow H^+ H^-$ , for the center-of-mass energies considered in this work. We only list benchmark points with at least one non-zero production cross section. We also display the branching ratio  $H^+ \rightarrow W^+ H$  (the other possible channel,  $H^+ \rightarrow W^+ A$ , is suppressed for most BPs). The displayed branching ratios were calculated using 2HDMC.

## 6 Prospects for future dark matter and LHC experiments

Experiments at future  $e^+ e^-$  colliders will be able to probe the described benchmark scenarios on the time scales of ten to twenty years. By that time, the sensitivity of direct DM search experiments will have improved significantly, and much larger samples of data will also be collected by the LHC experiments. It is therefore an important question whether the benchmarks presented here are already accessible at the LHC or via dark matter direct detection.

As already described above, significant constraints of the IDM scenarios are set by the recent XENON1T measurement [58]. The experiment continues to collect data and it is expected to improve its sensitivity by a factor of about 3 [75]. In this range, most of the points providing dominant contribution to the DM density in the Universe (see tables 1 and 4) can be probed. Four of these scenarios (BP6, BP16, BP21 and HP10) will remain

No.	$M_H$	$M_A$	$M_{H^\pm}$	$\sigma(250)$	$\sigma(380)$	$\sigma(500)$
<b>BP1</b>	72.77	107.803	114.639	77.2	65.9	45.7
BP2	65	71.525	112.85	155	85.1	53.4
BP3	67.07	73.222	96.73	149	83.5	52.8
BP4	73.68	100.112	145.728	89.2	69.1	46.9
<b>BP6</b>	72.14	109.548	154.761	75.1	65.4	45.4
BP7	76.55	134.563	174.367	31.2	52.3	40.1
<b>BP8</b>	70.91	148.664	175.89	20	47.5	38.1
BP9	56.78	166.22	178.24	14.1	43	36
BP10	76.69	154.579	163.045	9.44	43	36.2
BP11	98.88	155.037	155.438	-	35.6	33.2
BP12	58.31	171.148	172.96	9.01	40.4	34.8
BP13	99.65	138.484	181.321	5.17	42.5	36.2
<b>BP14</b>	71.03	165.604	175.971	5.13	39.6	34.7
<b>BP15</b>	71.03	217.656	218.738	-	18.2	24.2
<b>BP16</b>	71.33	203.796	229.092	-	23.3	26.9
BP18	147	194.647	197.403	-	6.14	18.7
BP19	165.8	190.082	195.999	-	3.02	16.6
BP20	191.8	198.376	199.721	-	-	11.3
<b>BP21</b>	57.475	288.031	299.536	-	2.66	12.6
<b>BP22</b>	71.42	247.224	258.382	-	8.94	18.6
BP23	62.69	162.397	190.822	13.2	43.3	36.2

**Table 3.** Production cross sections in fb for on-shell neutral scalar pair-production,  $e^+ e^- \rightarrow HA$ , for the center-of-mass energies considered in this work. We only list benchmark points with at least one non-zero production cross section. The branching ratio  $\text{BR}(A \rightarrow HZ^{(*)}) \approx 100\%$ .

inaccessible at XENON1T, but can be probed at XENONnT, when the sensitivity will be enhanced by another order of magnitude. Only one scenario, BP2, will not be probed after the future XENON detector upgrade.

Scenarios resulting in subdominant contribution to the relic density are less constrained by direct search experiments. Still, half of the presented benchmark points can be probed with the full XENON1T data and only four scenarios (BP18, BP19, BP20 and BP3) remain inaccessible at XENONnT. This shows that direct DM search experiments will continue to set important constraints on the proposed class of models and can result in the need to redefine the set of benchmark points in the future. On the other hand, if an excess in direct detection is observed in the XENON detector, the IDM scenarios will provide a perfect test framework for interpretation of these results. Direct searches will only indicate the possible mass and coupling range for the lightest IDM scalar. Other parameters of the model need to be constrained in collider experiments.

No.	$M_H$	$M_A$	$M_{H^\pm}$	$Z$ on-shell	$W$ on-shell	DM >50%	$\lambda_2$	$\lambda_{345}$	$\Omega_H h^2$
HP1	176	291.36	311.96	✓	✓		1.4895	-0.1035	0.00072156
HP2	557	562.316	565.417			✓	4.0455	-0.1385	0.072092
HP3	560	616.32	633.48				3.3795	-0.0895	0.001129
HP4	571	676.534	682.54	✓	✓		1.98	-0.471	0.00056347
HP5	671	688.108	688.437				1.377	-0.1455	0.024471
HP6	713	716.444	723.045				2.88	0.2885	0.035152
HP7	807	813.369	818.001				3.6675	0.299	0.032393
HP8	933	939.968	943.787			✓	2.9745	-0.2435	0.09639
HP9	935	986.22	987.975				2.484	-0.5795	0.0027958
<b>HP10</b>	990	992.36	998.12			✓	3.3345	-0.051	0.12478
HP11	250.5	265.49	287.226				3.90814	-0.150071	0.00535
HP12	286.05	294.617	332.457				3.29239	0.112124	0.00277
HP13	336	353.264	360.568				2.48814	-0.106372	0.00937
HP14	326.55	331.938	381.773				0.0251327	-0.0626727	0.00356
HP15	357.6	399.998	402.568				2.06088	-0.237469	0.00346
HP16	387.75	406.118	413.464				0.816814	-0.208336	0.0116
HP17	430.95	433.226	440.624				3.00336	0.082991	0.0327
HP18	428.25	453.979	459.696				3.87044	-0.281168	0.00858
HP19	467.85	488.604	492.329				4.12177	-0.252036	0.0139
HP20	505.2	516.58	543.794				2.53841	-0.354	0.00887

**Table 4.** High-mass benchmark points (HPs) accessible at linear colliders with  $\mathcal{O}(\text{TeV})$  center-of-mass energies.  $M_h = 125.1 \text{ GeV}$  for all points. HP10 provides exact relic density.

Searches for pair production of IDM scalars have also been considered for current and future runs of the LHC. Many different final states can be considered, including mono-jet, mono- $Z$ , mono-Higgs and Vector-Boson-Fusion + missing transverse energy signatures [25, 26, 29, 34, 76]. Especially multi-lepton final states [26] are promising.<sup>4</sup> In addition, also multi-jet final states [25, 76] and combinations [29] have been considered. For example, in [26, 29, 76] the authors present phenomenological studies that render scenarios with dark masses  $\lesssim 300 \text{ GeV}$  accessible at the HL-LHC.

Regarding other channels, the analysis of mono-jet signature considered in [31, 34] indicates that LHC has limited sensitivity to probe the IDM. Additional assumptions are needed to set the scalar mass limits and they range only up to about  $200 \text{ GeV}$  for HL-LHC. Also for the di-jet plus missing transverse energy signature, as studied e.g. in [25], LHC sensitivity is significantly affected by the large background, which can not be sufficiently

<sup>4</sup>A discussion on regions accessible at Run I can e.g. be found in [21].



No.	$M_H$ [GeV]	$M_A$ [GeV]	$M_{H^\pm}$ [GeV]	$\sigma(e^+e^- \rightarrow H^+H^-)$			$\sigma(e^+e^- \rightarrow AH)$		
				1 TeV	1.5 TeV	3 TeV	1 TeV	1.5 TeV	3 TeV
HP1	176	291.36	311.96	13	9.9	3.4	8.6	5.1	1.6
HP2	557	562.316	565.417	-	3.1	2.6	-	1.4	1.1
HP3	560	616.32	633.48	-	1.6	2.4	-	1.1	1.1
HP4	571	676.534	682.54	-	0.68	2.2	-	0.77	1.1
HP5	671	688.108	688.437	-	0.59	2.2	-	0.32	0.98
HP6	713	716.444	723.045	-	0.16	2.1	-	0.11	0.93
HP7	807	813.369	818.001	-	-	1.8	-	-	0.79
HP8	933	939.968	943.787	-	-	1.4	-	-	0.6
HP9	935	986.22	987.975	-	-	1.2	-	-	0.57
<b>HP10</b>	990	992.36	998.12	-	-	1.2	-	-	0.52
HP11	250.5	265.49	287.226	15	11	3.5	7.8	4.9	1.6
HP12	286.05	294.617	332.457	11	9.4	3.3	6.5	4.6	1.5
HP13	336	353.264	360.568	8.5	8.6	3.3	4.3	3.9	1.4
HP14	326.55	331.938	381.773	6.7	8	3.2	4.9	4.1	1.5
HP15	357.6	399.998	402.568	5	7.5	3.1	3	3.5	1.4
HP16	387.75	406.118	413.464	4.2	7.2	3.1	2.4	3.3	1.4
HP17	430.95	433.226	440.624	2.4	6.4	3	1.3	2.9	1.3
HP18	428.25	453.979	459.696	1.3	5.9	3	1	2.8	1.3
HP19	467.85	488.604	492.329	0.09	5	2.8	0.21	2.4	1.3
HP20	505.2	516.58	543.794	-	3.7	2.7	-	2	1.2

**Table 5.** Production cross sections in fb for high-mass benchmark points at 1 TeV, 1.5 TeV and 3 TeV, for the production processes considered here.

suppressed even with strong kinematic selection. For the benchmark scenarios considered, the maximum signal significance at an integrated luminosity of  $3000 \text{ fb}^{-1}$  was about  $2\sigma$ . However, we want to state that these analyses have not been on the same level as the current study, as they did not make use of more advanced analysis techniques. In general, production cross sections can be in the  $\mathcal{O}(500 - 700 \text{ fb})$  range for a center-of-mass energy of 13 TeV [77]. Without detailed analyses, projections of reachability are however difficult to make. We therefore strongly encourage the experimental collaborations to investigate the benchmark points presented here at current and future LHC runs.

## 7 Conclusions

In this paper we have revisited and updated the available parameter space of the Inert Doublet Model. The model features an exact  $Z_2$  symmetry which results in dark scalars that do not interact with SM fermions, and the lightest neutral scalar can serve as a

promising dark matter particle. We took into account most recent experimental constraints from relic density and direct dark matter searches, including the latest XENON1T 2018 results, as well as collider bounds and theoretical constraints. Based on these updated results, we have provided benchmark scenarios accessible at the initial stages of future linear  $e^+e^-$  colliders (250 and 500 GeV ILC and 380 GeV CLIC) as well as benchmarks that can be tested at high-energy stages (1 TeV ILC and 1.5 and 3 TeV CLIC). In doing so we pursued the philosophy of covering the widest range of parameters and experimental signatures. We provide predictions of production cross sections at these energies, and supplement these with information about the branching fractions of the relevant decay modes. We encourage the LC groups to make use of these benchmark scenarios. Although the benchmarks have been defined with  $e^+e^-$  physics in mind, we strongly encourage our LHC experimental colleagues to consider these scenarios in the analysis of the current and upcoming LHC data.

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