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

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Abstract

In this short note 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.

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 \cite{4,5,6}. In this two Higgs doublet model a discrete $Z_2$ symmetry (called $D$-symmetry) is imposed, with the following transformation properties:

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

(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 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 \cite{4} and later in \cite{5,6}. The model was further studied in \cite{7,8,9,10,11}, followed with further analyses of the IDM at colliders \cite{11,32}.

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 \cite{23,31} 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 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 linear colliders.

2 The IDM

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

$$V = -\frac{1}{2} \left[ m_S^2 (\phi_S^\dagger \phi_S) + m_D^2 (\phi_D^\dagger \phi_D) \right] + \frac{\lambda_1}{2} (\phi_S^\dagger \phi_S)^2 + \frac{\lambda_2}{2} (\phi_D^\dagger \phi_D)^2 + \lambda_3 (\phi_S^\dagger \phi_S) (\phi_D^\dagger \phi_D) + \lambda_4 (\phi_S^\dagger \phi_D) (\phi_D^\dagger \phi_S) + \frac{\lambda_5}{2} \left[ (\phi_S^\dagger \phi_D)^2 + (\phi_D^\dagger \phi_S)^2 \right].$$

(2)

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\footnote{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 \cite{33}. Choosing $A$ instead of $H$ changes the meaning of $\lambda_5$, with rephasing of $\lambda_5 \rightarrow -\lambda_5$, but not the overall phenomenology of the model, cf. \cite{22}.}.

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

$$M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345},$$

(3)
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 (BP) for the IDM, taking all constraints viable at that time into account, have been presented in [23, 34], which focus on processes at the LHC; some of these were already investigated in a linear collider context in [24]. Ref. [31] 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 BP fulfil the latest experimental limits; following [23] (see also the discussion in [35]), 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 BP 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 $V \to -\infty$, resulting in tree-level relations [36]

\[ \lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0. \]  

(4)

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, 37].

**Perturbative unitarity**: we require the scalar $2 \to 2$ scattering matrix to be unitary, i.e. all eigenvalues of scattering matrices for scalars with specific hypercharge and isospin should satisfy $|L_i| \leq 16 \pi$ [38, 39]. 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

\[ \frac{m_{11}^2}{\lambda_1} \geq \frac{m_{22}^2}{\lambda_2}, \]  

(5)

the inert minimum is only a local one, with the global vacuum corresponding to the case of massless fermions [40]. 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 [41, 42], while the total width of the SM-like Higgs boson obeys an upper limit of [43]

\[ \Gamma_{\text{tot}} \leq 13 \text{ MeV}. \]  

(6)

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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, 31]. 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, 31]. The Run I combined ATLAS and CMS limit for $h \to \gamma \gamma$ signal strength is given by $\mu_{\gamma\gamma} = 1.14^{+0.38}_{-0.36}$ [44]. In our analysis we use both the upper limit and require agreement within 2$\sigma$ for the prediction of $h \to \gamma \gamma$. 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 [45], 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. [46]). To ensure that $W^\pm \to HH^\pm$ and $Z \to HA, H^+H^-$ decay channels are kinematically forbidden we set:

$$M_{A,H} + M_{H^\pm} \geq M_W, \quad M_A + M_H \geq M_Z, \quad 2M_{H^\pm} \geq M_Z.$$  \hspace{1cm} (7)

**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 $S, T, U$ [47–50]. In our work, calculations were done through the routine implemented in the Two Higgs Doublet Model Calculator (2HDMC) tool [51], which checks whenever model predictions fall within the observed parameter range [52].

**Charged scalar mass and lifetime**: we take a conservative lower estimate on the mass of $M_{H^\pm}$ following analysis in [53] to be

$$M_{H^\pm} \geq 70 \text{ GeV.}$$  \hspace{1cm} (8)

We also set an upper limit on the charged scalar lifetime of $\tau \leq 10^{-7} \text{ s}$, 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 $\Gamma_{\text{tot}} \geq 6.58 \times 10^{-18} \text{ GeV}$. 

**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]

$$M_A \leq 100 \text{ GeV, } M_H \leq 80 \text{ GeV, } \Delta M(A,H) \geq 8 \text{ GeV},$$  \hspace{1cm} (9)

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]:

$$\Omega_c h^2 = 0.1197 \pm 0.0022.$$  \hspace{1cm} (10)

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

$$\Omega_H h^2 < \Omega_c h^2$$  \hspace{1cm} (11)
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. These supersede previous bounds applied e.g. in 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, give less stringent constraints than collider and direct detection experiments discussed above. 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. Furthermore, if the reported gamma-ray excess from the Galactic center is of DM origin, it can be explained by the IDM with dark matter masses near the Higgs resonance or around 72 GeV. All dark matter variables were calculated with the use of micrOmegas version 4.3.5.

3.2 Scan setup and limits

After fixing the value of $M_h$, and hence both $\lambda_1$ and $m_1^2$, 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 a 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 $h \rightarrow \text{invisible}$, 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 the 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.\footnote{We use a digitized format of that data available from [59].}
(i) constraints on the masses of the dark scalars, with the constraint given in eqn. (11) 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. [35]) 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, 33, 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 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 eqn.(8), the measurement of \( h \to \gamma \gamma \) puts a lower limit on the charged Higgs mass as a function of \( \lambda_{345} \), cf. e.g. [31].

- masses of DM particles below 45 GeV are excluded [23, 35]. 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 significantly.

- for dark scalars with masses \( \lesssim 100 \) GeV, additional specific constraints are given by eqn.(9).

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 \( HH \to \gamma \gamma \) 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

\[^3\text{See e.g. detailed discussions in [32].}\]
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 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 eqn. (10), 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 \( M_H \gtrsim 55 \text{ GeV} \);
- good points can then be obtained for \( M_H \lesssim 75 \text{ GeV} \).
- For \( M_H \) larger than 500 GeV extreme fine-tuning of the dark masses is required in order to
  obtain exact relic density; cf. the discussion in [35]. The authors of that reference find that
  \( O(\text{GeV}) \) 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. 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

\[
e^{+}e^{-} \rightarrow H^{+}H^{-} \quad \text{and} \quad e^{+}e^{-} \rightarrow AH
\]  

(12)

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 \( M_{H^{+}} \leq 250 \text{ GeV} \) or \( M_H + M_A \leq 500 \text{ GeV} \) (or both). In section
\ref{sec: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 TeV and higher energy stages of CLIC at 1.5 TeV and 3 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 benchmark 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 (12); 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 kinematical 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 ($M_{H^+} - M_{H^0}$; $M_A - M_{H^0}$) plane. All points form a narrow band corresponding to $M_A \lesssim M_{H^\pm}$. Our chosen benchmark points, also indicated in Fig. 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.

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 $M \lesssim 250 \text{ GeV}$ for all dark scalars. However, the parameter space of the IDM
| No. | \(M_H\) | \(M_A\) | \(M_{H^\pm}\) | \(Z\) on-shell | \(W\) on-shell | \(\text{DM} > 50\%\) | \(\lambda_2\) | \(\lambda_{345}\) | \(\Omega_H h^2\) |
|-----|---------|---------|-------------|----------------|----------------|-----------------|----------|----------|-------------|
| 222 | BP1     | 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    |
|     | BP6     | 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    |
|     | BP8     | 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    |
|     | BP14    | 71.03   | 165.604     | 175.971        | ✓              | ✓               | 0.339292 | 0.00596   | 0.11841     |
|     | BP15    | 71.03   | 217.656     | 218.738        | ✓              | ✓               | 0.766549 | 0.00214   | 0.12225     |
| 011 | BP16    | 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 | BP21    | 57.475  | 288.031     | 299.536        | ✓              | ✓               | 0.929911 | 0.00192   | 0.11946     |
|     | BP22    | 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.\[58\]
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.

| No. | $M_H$  | $M_A$  | $M_{H^\pm}$ | $\sigma(250)$ | $\sigma(380)$ | $\sigma(500)$ | $BR_{H^+H^-\rightarrow W^+H}$ |
|-----|---------|---------|-------------|------------|------------|------------|-------------------------------|
| BP1 | 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                         |
| BP6 | 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                       |
| BP8 | 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                         |
| BP14| 71.03   | 165.604 | 175.971     | -          | 8.09       | 37.7       | > 0.99                       |
| BP15| 71.03   | 217.656 | 218.738     | -          | -          | 10.5       | 1                            |
| BP16| 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 3: Production cross sections in fb for on-shell neutral scalar pair-production, $e^+ e^- \rightarrow H A$, 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 $BR(A \rightarrow HZ^{(*)}) \approx 100\%$. 

| No. | $M_H$ | $M_A$ | $M_{H\pm}$ | $\sigma(250)$ | $\sigma(380)$ | $\sigma(500)$ |
|-----|-------|-------|------------|--------------|--------------|--------------|
| BP1 | 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 |
| BP6 | 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 |
| BP8 | 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 | 163.945 | 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 |
| BP14 | 71.03 | 165.604 | 175.971 | 5.13 | 39.6 | 34.7 |
| BP15 | 71.03 | 217.656 | 218.738 | - | 18.2 | 24.2 |
| BP16 | 71.33 | 203.796 | 229.092 | - | 23.3 | 26.9 |
| BP18 | 147 | 194.647 | 197.303 | - | 6.14 | 18.7 |
| BP19 | 165.8 | 190.082 | 195.999 | - | 3.02 | 16.6 |
| BP20 | 191.8 | 198.376 | 199.721 | - | - | 11.3 |
| BP21 | 57.475 | 288.031 | 299.536 | - | 2.66 | 12.6 |
| BP22 | 71.42 | 247.224 | 258.382 | - | 8.94 | 18.6 |
| BP23 | 62.69 | 162.397 | 190.822 | 13.2 | 43.3 | 36.2 |
largely opens up for higher dark scalar masses, especially as direct detection constraints are less strict and direct collider searches pose less stringent constraints. 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. The maximum mass splitting between the dark scalars is about 140 GeV, as the relic density decreases rapidly with the increasing mass difference (see sec. 3.2.2).

6 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

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4 Constraints stemming from the diphoton range exclude certain ranges in the \( M_{H^+}, \lambda_{345} \) plane, cf. e.g. [31], leading to a lower limit on the dark charged scalar mass.
| No. | $M_H$ | $M_A$ | $M_{H^\pm}$ | $Z_{\text{on-shell}}$ | $W_{\text{on-shell}}$ | 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   |
| **HP10** | **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 colliders with $\mathcal{O}$ (TeV) center-of-mass energies. $M_h = 125.1$ GeV for all points. HP10 provides exact relic density.
No. | $M_H$ [GeV] | $M_A$ [GeV] | $M_{H\pm}$ [GeV] | $\sigma(e^+e^-\rightarrow H^+H^-)$ | $\sigma(e^+e^-\rightarrow AH)$
--- | --- | --- | --- | --- | ---
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
HP10 | 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.
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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