Inert Doublet Model benchmarks for the 13 TeV run of the LHC

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Abstract

Benchmark points for the Inert Doublet Model, prepared for the Higgs Cross section working group, for the 13 TeV LHC run.

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1. MOTIVATION FOR MODEL

One of the simplest models for a scalar dark matter is the Inert Doublet Model (IDM), a version of a Two Higgs Doublet Model with an exact Z_2 symmetry [1]. It contains one SU(2) doublet of spin-0 fields, playing the same role as the corresponding doublet in the SM, with the SM-like Higgs particle, while the second Z_2-odd doublet, does not interact with fermions and is not involved in the mass generation. This so called inert or dark doublet contains 4 scalars, two charged and two neutral ones, with the lightest neutral scalar being a natural DM candidate. There are regions of parameter space where this model can account for the SM-like Higgs particle in agreement with the LHC results and at the same time for the correct relic density of dark matter, while fulfilling direct and indirect DM detection limits [see e.g. [2–7]]. It was found that additional scalars can have a strong impact on the vacuum stability in this model [5, 8, 9]. It leads to a interesting pattern of the Universe evolution, with one, two or three phase transitions [10]. Furthermore, the IDM can provide a strong first-order phase transition [11], which is one of the Sakharov conditions needed to generate a baryon asymmetry of the universe. Another Sakharov requirement, namely the large enough CP violation (CPV), the IDM fails to fulfil, so it has to be completed by some additional fields. Due to the Z_2 symmetry, all particles from the dark doublet are pair-produced.

2. THE MODEL

The D-symmetric potential of the IDM has the following form:

$$\begin{aligned} V = &-\tfrac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \tfrac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\tfrac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2 \\ &+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \tfrac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right], \end{aligned} \tag{1}$$

with all parameters real (see e.g. [10]). The vacuum state in the IDM is given by:[1]

$$\langle\phi_S\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \qquad \langle\phi_D\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ 0\end{pmatrix}, \tag{2}$$

where $v = 246\,\mathrm{GeV}$ denotes the vacuum expectation value (vev).

The first doublet, ϕ_S, contains the SM-like Higgs boson h with mass M_h equal to

$$M_h^2 = \lambda_1 v^2 = m_{11}^2 = (125\ \mathrm{GeV})^2\,. \tag{3}$$

The second doublet, ϕ_D, consists of four dark (inert) scalars H, A, $H^\pm$, which do not couple to fermions at the tree-level. Their masses are as follows

$$\begin{gathered} M_{H^\pm}^2 = \tfrac{1}{2}\left(\lambda_3 v^2 - m_{22}^2\right), \\ M_A^2 = M_{H^\pm}^2 + \tfrac{1}{2}\left(\lambda_4-\lambda_5\right)v^2 \;= \tfrac{1}{2}(\bar\lambda_{345}v^2 - m_{22}^2), \quad M_H^2 = M_{H^\pm}^2 + \tfrac{1}{2}\left(\lambda_4+\lambda_5\right)v^2 \;= \tfrac{1}{2}(\lambda_{345}v^2 - m_{22}^2). \end{gathered} \tag{4}$$

[1] In a 2HDM with the potential V given by eqn. (1) different vacua can exist, e.g. a mixed one with $\langle\phi_S\rangle \neq 0$, $\langle\phi_D\rangle \neq 0$, an inertlike vacuum with $\langle\phi_S\rangle = 0$, $\langle\phi_D\rangle \neq 0$, or even a charge breaking vacuum see [10, 12–14].

Due to an exact D symmetry the lightest neutral scalar H (or A) is stable and thereby it may serve as a good dark matter candidate.[2] We take H to be the DM candidate and so $M_H < M_A, M_{H^\pm}$ ($\lambda_5 < 0,\ \lambda_{45} = \lambda_4 + \lambda_5 < 0$).

The parameters

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5,\ \bar{\lambda}_{345} = \lambda_3 + \lambda_4 - \lambda_5 \tag{5}$$

are related to the triple and quartic coupling between the SM-like Higgs h and the DM candidate H or a scalar A, respectively, while λ_3 describes the h interaction with the charged scalars $H^\pm$. The parameter λ_2 gives the quartic self-couplings of dark particles. The parameter m_{22} sets here a common mass scale for the dark sector particles. Note that an equivalent choice would be to take A as the lightest neutral dark scalar and therefore as the dark matter candidate, which implies $\lambda_5 > 0$. In this case, the discussion below remains valid by replacing

$$\lambda_5 \longleftrightarrow -\lambda_5,\ \lambda_{345} \longleftrightarrow \bar{\lambda}_{345}.$$

After electroweak symmetry breaking, the model has seven free parameters. However, the values of the vev and the SM-like Higgs mass fixed by the experiments, and therefore there are in total 5 free parameters characterising the scalar sector of the IDM. Typical choices are either *(i)* physical parameters ($M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345}$) or *(ii)* potential parameters ($m_{22}, \lambda_2, \lambda_3, \lambda_4, \lambda_5$). We here choose to work in the physical basis *(i)*.

3. CONSTRAINTS

All benchmark points here have been subject to a dedicated scan [16] taking all current theoretical and experimental constraints into account, such as

- positivity of the potential, as well as boundedness from below
- perturbative unitarity in the scalar sector
- perturbativity of the couplings, i.e. we require them to be $< |4\,\pi|$
- globalness of the vacuum according to [17]
- total width of the 125 GeV Higgs
- decay width of electroweak gauge bosons
- reinterpreted LEP limits from [18]

[2] Charged DM has been strongly limited by astrophysical analyses [15].

- direct search limits from colliders using HiggsBounds [19–21]
- agreement with signal strength of 125 GeV Higgs using [22]
- agreement with S, T, U [23]
- exclusion of stable $H^{\pm}$
- upper limit from relic density from Planck [24] using MicrOmegas [25]
- agreement with LUX data [26],

where agreement/ exclusion always correspond to a 95 % confidence level limit.

4. BENCHMARKS

From all points above, we have chosen 5 benchmark points. We here keep the masses of all particles fixed, and allow for variation of λ_2, λ_{345} as allowed by the above scan. The main motivation for the points is the total production cross section at a 13 TeV LHC for $H\,A$ final states, which has been calculated at leading order using Madgraph5 [27]. The effective $g\,g\,h$ coupling was implemented adapting the implementation in [28]. For $M_H \leq 200\,\text{GeV}(500\,\text{GeV})$, we found production cross sections to be $\lesssim 0.05 - 0.35\text{pb}\,(0.005 - 0.35\text{pb})$. The next dominant production channel, $H^+\,H^-$, was found to be $\lesssim 0.02 - 0.09\text{pb}(0.001 - 0.09\text{pb})$. Our benchmark points are optimized to maximize $H\,A$ production which is purely gauge induced, while also commenting on H^+H^- production. In all points, we fix $M_h = 125.1\,\text{GeV}$, and allow λ_{345} and λ_2 to float. λ_{345} influences the production cross section for $H^+\,H^-$ (in the ranges allowed by the scan, this however is marginal[3]). For the scenarios considered here, λ_2 has no effect on either production cross sections or decays, but we prefer to keep it in the allowed range for consistency reason. We also list the relic density Ω for all points.

- **Benchmark I: low scalar mass**

  $$M_H = 57.5\,\text{GeV},\; M_A = 113.0\,\text{GeV}, M_{H^\pm} = 123,\;\text{GeV},\; \lambda_2\,\in[0;4.2],\; \lambda_{345}\,\in[-0.015;0.015]$$

  $HA : 0.371(4)\text{pb}$, $H^+\,H^- : 0.097(1)\text{pb}$
  $\Omega = 0.0042509$
  A decays 100 % to $Z\,H$, and $H^+ \rightarrow W^+\,H$ with a BR $\geq$ 0.99.

- **Benchmark II: low scalar mass**

  $$M_H = 85.5\,\text{GeV},\; M_A = 111.0\,\text{GeV}, M_{H^\pm} = 140,\;\text{GeV},\; \lambda_2\,\in[0;4.2],\; \lambda_{345}\,\in[-0.015;0.015]$$

[3] For first 3 scenarios

$H\,A: 0.226(2)\text{pb}, H^+H^-: 0.0605(9)\text{pb}$
$\Omega = 0.0033836$
A decays 100 % to $Z\,H$, $H^+ \to W^+\,H(A)$ with a BR $\sim 0.96(0.04)$.

- **Benchmark III: intermediate scalar mass**

  $M_H = 128.2\,\text{GeV},\ M_A = 134.303\,\text{GeV}, M_{H^\pm} = 176.665,\ \text{GeV},\ \lambda_2 \in [0; 4.2],\ \lambda_{345} \in [-0.025; 0.025]$

  Production cross sections: $H\,A: 0.0765(7)\text{pb},\ H^+\,H^-: 0.0259(3)\text{pb};$
  Dark matter relic density $\Omega = 0.0023045$
  A decays 100 % to $Z\,H$, $H^+ \to W^+\,H(A)$ with a BR $\sim 0.66(0.34)$

- **Benchmark IV: high scalar mass, mass degeneracy**

  $M_H = 363.5\,\text{GeV}, M_A = 373.738\,\text{GeV}, M_{H^\pm} = 373.874\,\text{GeV},\ \lambda_2 \in [0; 4.2],\ \lambda_{345} \in [-0.25; 0.25]$

  $H, A: 0.00122(1)\text{pb},\ H^+H^-: 0.00124(1)\text{pb}$
  $\Omega = 0.011737$
  A decays 100 % to $Z\,H$, and $H^\pm$ 100 % to $W^\pm H$

- **Benchmark V: high scalar mass, no mass degeneracy**

  $M_H = 311\,\text{GeV}, M_A = 415.706\,\text{GeV}, M_{H^\pm} = 447.269\,\text{GeV}, \lambda_2 \in [0; 4.2],\ \lambda_{345} \in [-0.25; 0.25]$

  $H, A: 0.00129(1)\text{pb},\ H^+H^-: 0.000553(7)\text{pb}$
  $\Omega = 0.00047379$
  A decays 100 % to $Z\,H$, $H^+ \to W^+\,H$ with a BR $\gtrsim 0.99$

While benchmarks I and II are exceptional points in a sense that the allowed parameter space is extremely constrained in the low mass region, benchmarks III to V are more typical, as these parts of the parameter space are more highly populated. Furthermore, for scenario IV the production cross sections for HA and H^+H^- have similar order of magnitude.

As an example, we give a survey of the production cross sections in figure 1.

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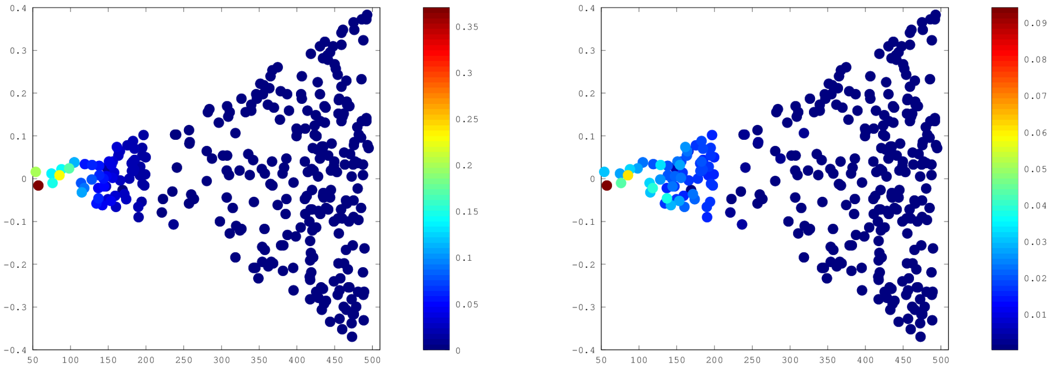

FIG. 1: Production cross sections in pb at a 13 TeV LHC for HA *(left)* and $H^+ H^-$ *(right)*, in the M_H, λ_{345} plane.

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