PROCEEDINGS OF SCIENCE

Inert Doublet Model in the light of LHC and astrophysical data

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We investigate the parameter space of the Inert Doublet Model, which is a straightforward extension of the SM in the scalar sector. We apply a set of constraints both from the theoretical and experimental side to extract and determine allowed regions of parameter space. These constraints put strong limits on both masses and couplings of the new particles. We also present a set of benchmarks for the current LHC run. This work is based on [1, 2].

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1. Introduction

The Inert Doublet Model (IDM) is one of the most straightforward extensions of the Standard Model. In this model, the scalar sector is augmented by a second complex doublet, and an exact Z_2 symmetry is imposed on the Lagrangian. The first doublet corresponds to the SM Higgs doublet with the Higgs particle, and is responsible for electroweak symmetry breaking (EWSB) in a standard way. The second doublet, called dark doublet, contains a stable dark matter candidate. The IDM was studied in context of LHC phenomenology, both with respect to the Higgs boson discovery [3, 4] as well as dark matter discovery, the latter e.g. in the two lepton + MET channel [5, 6]. Moreover the model offers also rich cosmological phenomenology, for a review of references see [2].

The discovery of a Higgs boson in 2012 basically fixes the particle content of the first doublet in the IDM, in analogy to the scalar sector of the SM. [1] In the light of LHC run II knowledge about regions of parameter space which are in agreement with all current constraints is imminent in order to correctly determine open search channels and their experimental signatures. We address this need by presenting a complete survey on the model's parameter space including a wide range of constraints, coming from theoretical bounds as well as collider and astrophysical data. We additionally provide a set of benchmark points and planes for the current LHC run.

2. The Model

The scalar sector of IDM consists of two doublets of complex scalar fields, which we label ϕ_S for the SM-like doublet, and ϕ_D - for the dark doublet. After EWSB, only ϕ_S acquires a nonzero vacuum expectation value (v). The Z_2 - symmetric potential reads:

$$\begin{aligned} V = & -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2 \\ & +\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right], \end{aligned} \tag{2.1}$$

with the Z_2 transformation being defined by $\phi_S \to \phi_S, \phi_D \to -\phi_D, SM \to SM$. Due to this symmetry the lightest particle of the dark sector is stable. In total, the dark sector contains 4 new particles: H, A and $H^\pm$. We here choose H to be the dark matter (DM) candidate[2].
The Higgs boson data and electroweak precision observables fixes the SM-like Higgs mass M_h and v, and we are left with 5 free parameters, for which we take:

$$M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345}, \tag{2.2}$$

where the $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$ describes coupling between SM-like Higgs and DM particle H and λ_2 corresponds to self-couplings of the dark scalars.

[1] After its discovery, several analyses studied the impact of this discovery as well as the signal strength measurements on the particles parameter space [7, 6, 8, 9].

[2] 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 [10]. Choosing A instead of H changes the meaning of λ_5, but not the overall phenomenology of the model, cf. [2].

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3. Scan Procedure

3.1 Constraints

Here we enumerate the constraints which were included in our analysis [2].

Theoretical constraints:

- positivity: potential is bounded from below at tree level
- perturbative unitarity of $2 \to 2$ scalar scattering matrix
- perturbativity of all couplings, (we chose 4π as upper limit)
- condition to be in the inert vacuum [11, 12].

Experimental constraints

- Mass of the SM-like Higgs boson h set to $M_h = 125.1\,\text{GeV}$ in agreement with results from the LHC experiments [13]
- Total width of the h obey an upper limit $\Gamma_{\text{tot}} \leq 22\,\text{MeV}$ [14, 15]
- Bounds provided by the total width of the electroweak gauge bosons:

$$M_{A,H} + M_H^{\pm} \geq m_W,\, M_A + M_H \geq m_Z,\, 2M_H^{\pm} \geq m_Z$$

- Bound on the lower mass of $M_H^{\pm} \geq 70\,\text{GeV}$ [16].
- Agreement with the current null-searches from the LEP, Tevatron, and LHC experiments using HiggsBounds [17, 18, 19]
- Agreement within 2σ for the 125 GeV Higgs signal strength measurements using HiggsSignals [20]
- 2σ agreement with electroweak precision observables, parameterized through the (correlated) electroweak oblique parameters S, T, U [21, 22, 23, 24].
- Upper limit of the H^+ lifetime $\tau \leq 10^{-7}\,s$, leading to $\Gamma_{\text{tot}} \geq 6.58 \times 10^{-18}\,\text{GeV}$.
- Upper limit on relic density within 2σ from measurement of the Planck experiment [25]: $\Omega_c h^2 \leq 0.1241$
- Respect direct detection limits from dark matter nucleon scattering: the most stringent bounds are provided by the LUX experiment [26]
- Obey exclusions from recasted SUSY LEP and LHC analyses [27, 28]

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3.2 Scan setup

We have performed a flat scan over the input parameters as given in eq. (2.2), where we have run up 1 TeV with the mass of the DM candidate. We confronted these points with the above constraints (sec. 3.1), where for each point we memorised the exclusion criteria if applicable. Our scan is performed in several steps: first we check the theoretical constraints as well as S, T, U parameters and total widths using 2HDMC [29]. In a second step, points which pass these bounds were confronted with null searches and Higgs signal strength measurements using HiggsBounds and HiggsSignals, respectively [17, 18, 19, 20]. In the final step of the scan, the calculation of Dark Matter observables, i.e. the total relic density as well as the direct detection cross section, was performed using MicrOmegas [30] and confronted with Planck and LUX measurements [25, 26]. For points which are in agreement with all bounds, we provide cross sections for pair-production of dark scalars, where we employed MadGraph [31], using the IDM UFO model presented in [32].

4. Allowed Parameter Space of IDM

In this section, we present the results of our scans and we emphasise the source of the strongest bounds, following the order of checks as discussed above. In the left panel of Figure 1 we show the region of parameter space where the dark scalar mass M_H is smaller than the SM like Higgs mass of 125 GeV. This region is strongly constrained by the combination of the 125 GeV Higgs width and the signal strength, leaving a very narrow allowed stripe of λ_{345}, with absolute values $\lesssim 0.02$. Also astrophysical data pose important constraints in this region. Relic density requires the mass of the DM candidate to values $\gtrsim 45\,\text{GeV}$. In addition, LUX measurements narrow down the allowed values for the λ_{345} coupling. In the right panel of Figure 1, we display the whole region of mass values for M_H up to 1 TeV. Here, especially LUX data limit the models parameter space, reflecting the dependance of the direct detection cross section on these parameters.

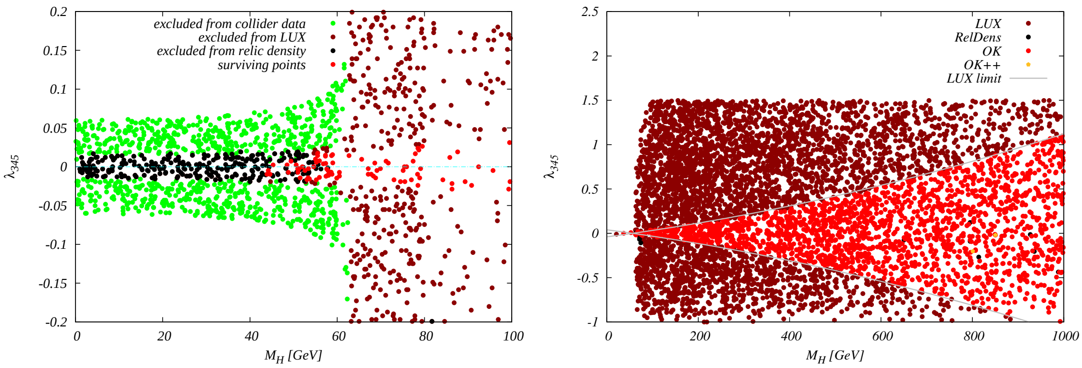

Figure 1: Dark matter mass vs DM-SM coupling planes: *(left)* a zoom into the low mass region, with $M_H \leq 100\,\text{GeV}$ showing the importance of constraints from LHC and astrophysical measurements; *(right)* the general case with M_H up tp 1 TeV, where bounds from direct detection are dominant.

The interplay of all constraints, presented in the left panel of Figure 2, leads to the strict mass hierarchy

$$M_H < M_A \leq M_{H^+}.$$

Also clearly visible is the preference for more degenerate masses in the dark sector and the more relaxed parameter space for high masses.

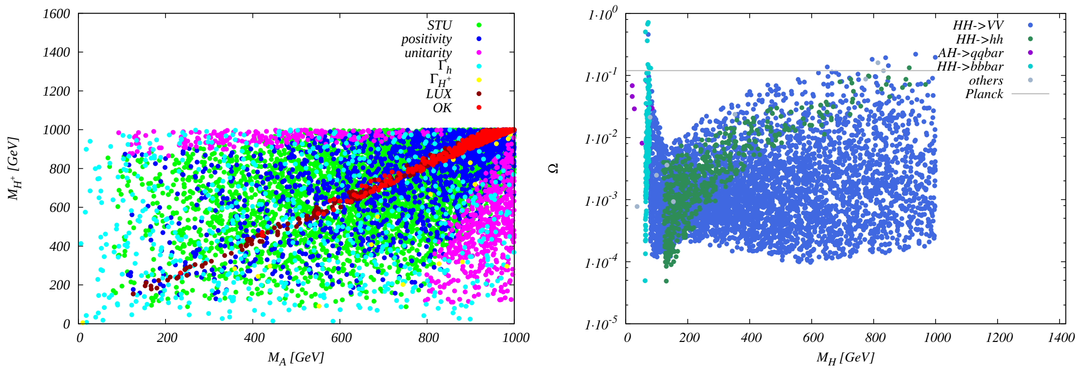

Figure 2: *(left)* The exclusion plot in M_A vs M_{H^+} plane. *(right)* The plot presents leading contribution to DM relic density in the DM mass vs relic density plane. (Exclusion from LUX not included).

In right panel of Figure 2 we present the leading contributions to the DM relic density. The relic density produced by IDM particles can be large for very low or relatively high DM masses. The dominant channel for most of the parameter space for mass of H above 100 GeV is annihilation into vector bosons.

5. Benchmarks

For the points allowed by all constraints the leading order cross section dark scalars pair-production [3] was calculated. The dominating channel leading to visible collider signatures is HA production [4], and Figure 3 shows its dependence on the masses and coupling of dark matter. Figure 3 shows that the production cross section is mainly driven by kinematics, and especially by particles masses. This follows from the fact that the dominant production mechanism, namely production via Z mediation in s-channel, only depends on kinematics and the SM electroweak couplings, but not on couplings of the extended scalar sector which are absent in the SM.

From the presented points, five were chosen as benchmarks [1, 33, 2], see Table 5. 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.

6. Conclusions

The Inert Doublet Model is a very promising extension of the SM in the scalar sector. Its parameter space is subject to several theoretical and experimental constraints. In a flat scan, high,

[3] Due to the Z_2 symmetry dark sector particles are always produced in pairs.

[4] As most DM models at colliders, the IDM will always lead to signatures including missing transverse energy.

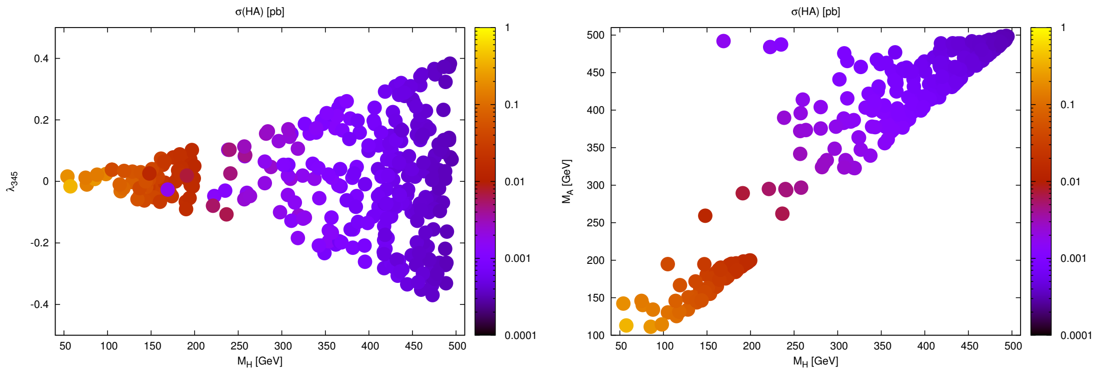

Figure 3: The planes of allowed points, with HA production cross sections (in pb) at a 13 TeV LHC.

BP	**BP I**	**BP II**	**BP III**	**BP IV**	**BP V**
$M_H[GeV]$	57.5	85.5	128.0	363.0	311.0
$M_A[GeV]$	113.0	111.0	134.0	374.0	415.0
$M_{H^\pm}[GeV]$	123.0	140.0	176.0	374.0	447.0
$\|\lambda_{345}\|$	[0.002;0.015]	[0;0.015]	[0;0.05]	[0,0.25]	[0;0.19]
$\|\lambda_2\|$	[0,4.2]	[0,4.2]	[0,4.2]	[0,4.2]	[0,4.2]
$\sigma(pp \to HA)[pb]$	0.371(4)	0.226 (2)	0.0765 (7)	0.00122(1)	0.00129 (1)
$\sigma(pp \to H^+H^-)[pb]$	0.097 (1)	0.0605 (9)	0.0259 (3)	0.00124 (1)	0.000553 (7)
$BR(H^+ \to HW^+$	0.99	0.96	0.66	1	0.99

Table 1: Benchmark points for dark scalars pair production at LHC run 2.

nearly degenerate masses of the dark particles are favoured, leaving however some viable parameter space for low dark matter masses ($M_H < \frac{M_h}{2}$). The pair production of dark particles at the LHC is mainly determined by their masses and regions with sizeable cross sections are subject to much more severe limits. The current LHC run will hopefully allow to provide more insight into this model, either by strengthening the above constraints or by means of a possible discovery.

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