

Constraining the Inert Doublet Model

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based on work with

A. Ilnicka, M. Krawczyk

[arXiv:1505.04734; arXiv:1508.01671; arXiv:1510.04159;
arXiv: 1705.00225]

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Inert doublet model: The model

- idea: take **two Higgs doublet model**, add additional Z_2 symmetry

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

(\Rightarrow implies CP conservation)

\Rightarrow obtain a **2HDM with (a) dark matter candidate(s)**

- potential

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

- only one doublet acquires VeV v , as in SM
(\Rightarrow implies analogous EWSB)

Number of free parameters

⇒ then, **go through standard procedure...**

⇒ minimize potential

⇒ determine number of free parameters

Number of free parameters here: 7

- e.g.

$$\mathbf{v}, M_h, M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345} [= \lambda_3 + \lambda_4 + \lambda_5]$$

- v, M_h fixed ⇒ left with **5 free parameters**

Constraints: Theory

⇒ **consider all current constraints on the model** ⇐

- Theory constraints: **vacuum stability, positivity, constraints to be in inert vacuum**
⇒ **limits on (relations of) couplings**, e.g.

$$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0$$

- **perturbative unitarity, perturbativity of couplings**
- **choosing** M_H as dark matter:

$$M_H \leq M_A, M_{H^\pm}$$

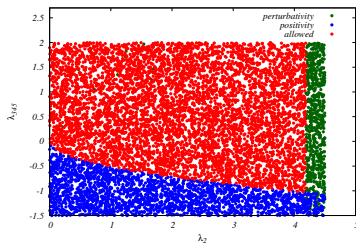
Constraints: Experiment

$$M_h = 125.1 \text{ GeV}, v = 246 \text{ GeV}$$

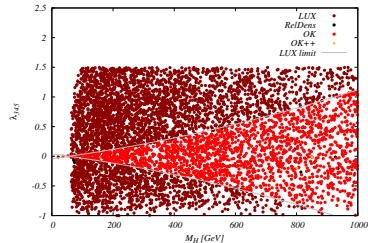
- total width of M_h ($\Gamma_h < 13 \text{ GeV}$); \Rightarrow JHEP, 09:051, 2016
 - total width of W, Z
 - collider constraints from signal strength/ direct searches;
 $R_{\gamma\gamma}$ and $\text{BR}_{h \rightarrow \text{inv}}$ from JHEP, 08:045, 2016
 - electroweak precision through S, T, U
 - unstable H^\pm
 - reinterpreted/ recastet LEP/ LHC SUSY searches (Lundstrom ea 2009; Belanger ea, 2015)
 - dark matter relic density (upper bound)
 - dark matter direct search limits (LUX)
- \Rightarrow **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

Obvious/ direct constraints on couplings

- some constraints \Rightarrow direct limits on couplings
- examples: limit on λ_2 from $HHHH$ coupling, limit on $\lambda_{345}(M_H)$ from direct detection



λ_2 , λ_{345} plane and limits from perturbativity, positivity

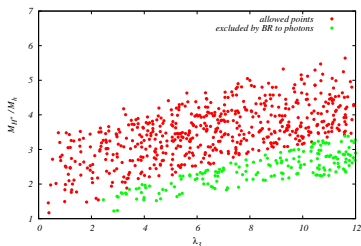


M_H , λ_{345} plane, limits from LUX^(*)

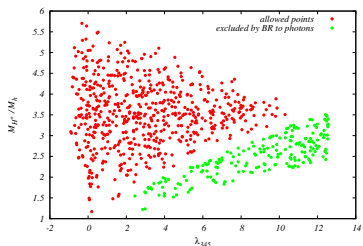
(*) updates not yet included

More direct constraints on couplings

- constraints on **combination of M_H^\pm/M_h and λ_3** from **one-loop corrected rate of $h \rightarrow \gamma\gamma$** (constraints: ratio too low !!)

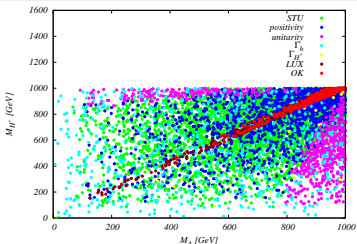


limits on λ_3 , M_H^\pm/M_h , plane

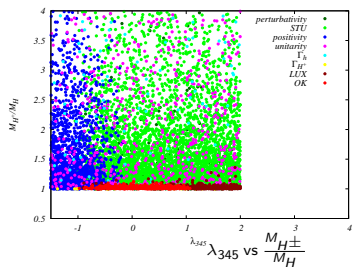
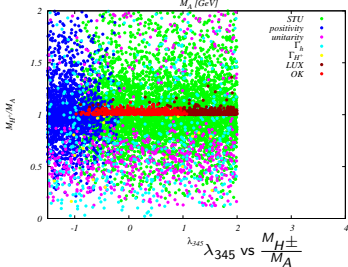


... translated to λ_{345} , M_H^\pm/M_h

Other constraints less obvious (interplay);
result \Rightarrow mass degeneracies



M_A vs M_{H^\pm} after all constraints



Benchmark selection for current LHC run

- ⇒ points need to **have passed all bounds**
- ⇒ total cross sections calculated using **Madgraph5, IDM model file from Goudelis ea, 2013 (LO)**
- ⇒ **effective ggH vertex implemented by hand**
 - highest production cross sections: HA ; $H^\pm H$; $H^\pm A$; $H^+ H^-$
 - decay $A \rightarrow HZ$ always 100 %
 - decay $H^\pm \rightarrow HW^\pm$ usually dominant

$$pp \rightarrow HA : \leq 0.03 \text{ pb,}$$

$$pp \rightarrow H^\pm H : \leq 0.03 \text{ pb,}$$

$$pp \rightarrow H^\pm A : \leq 0.015 \text{ pb,}$$

$$pp \rightarrow H^+ H^- : \leq 0.01 \text{ pb.}$$

Benchmark planes [old]

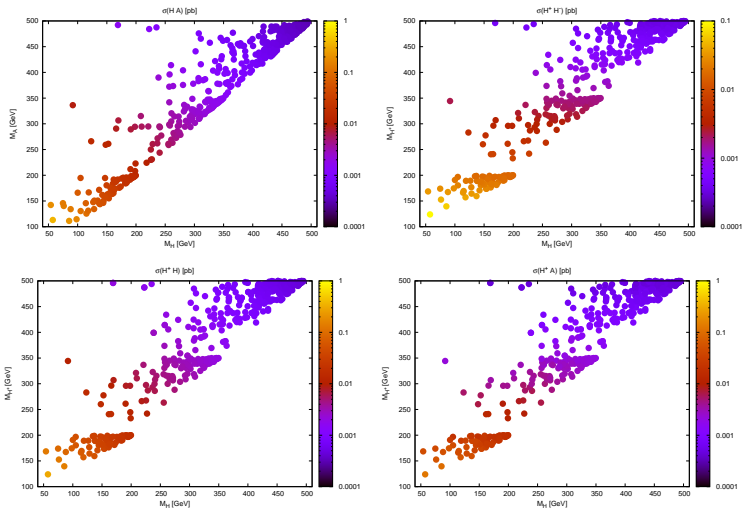


Figure 4: Production cross sections in pb at a 13 TeV LHC for the Inert Doublet Model. The plots show the dependence of the cross sections on the masses M_{H_1} and M_{H_2} (GeV).
 Tania Robens IDM Planck '17

Benchmark planes [new; LUX/ Signal rates improved]

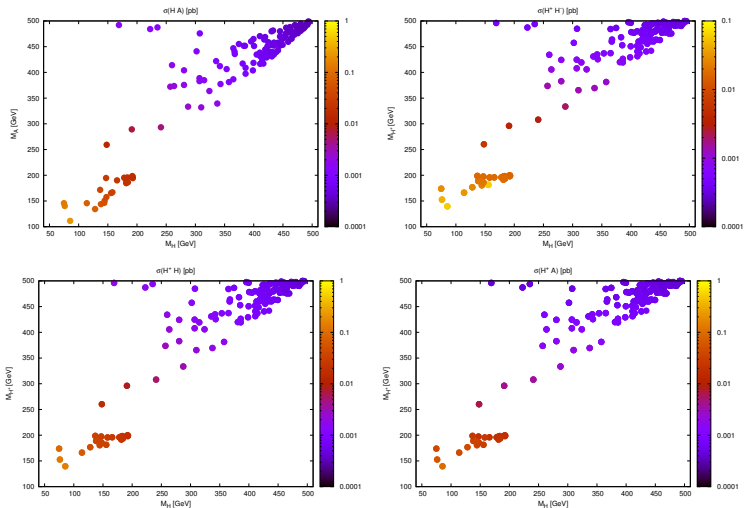


Figure : Production cross sections in pb at a 13 TeV LHC

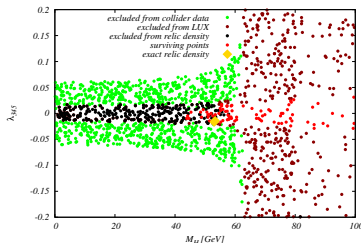
Parameters tested at LHC: masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
 - **LHC@13 TeV** does not depend on λ_2 , only marginally on λ_{345}
 - all **relevant couplings follow from ew parameters (+ derivative couplings)** \Rightarrow in the end a kinematic test
 - only in exceptional cases λ_{345} important; did not find such points
- \Rightarrow **high complementarity between astroparticle physics and collider searches**

(holds for $M_H \geq \frac{M_h}{2}$)

Last comment: cases where $M_H \leq M_h/2$ [old]

- **discussion so far:** decay $h \rightarrow HH$ kinematically not accessible
 - for these cases, **discussion along different lines**
- ⇒ **extremely strong constraints from signal strength, and dark matter requirements**

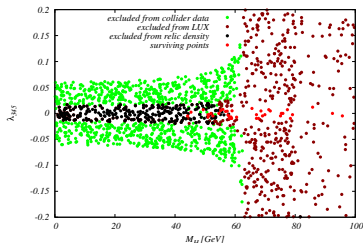


- additional constraints from combination of W, Z decays and recasted analysis at LEP

no allowed point with $M_H < 45$ GeV

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Summary

- **LHC run II in full swing** \Rightarrow **exciting times ahead of us**
- one important question: **test Higgs sector**, especially wrt **extensions/ additional matter content**
- from current **LHC and astrophysical data: models already highly constrained**
- discussion here: **2HDM with dark matter (IDM)**
- **identified viable regions in parameter space**
- from these: **predictions for current LHC run**
[A. Ilnicka, M. Krawzyk, TR, CERN Yellow Report]

!! stay tuned, and thanks for listening !!

Appendix

Last comments: publications where scan has been used

- **Production of Inert Scalars at the high energy e^+e^- colliders**, M. Hashemi ea, **JHEP 1602 (2016) 187**
- **Exploring the Inert Doublet Model through the dijet plus missing transverse energy channel at the LHC**, P. Poulose ea, **Phys.Lett. B765 (2017) 300-306**
- **Yellow Report IV of the Higgs Cross Section Working Group**, **arXiv:1610.07922**
- S. Moretti ea, *to appear*

Very brief: parameters determining couplings (production and decay)

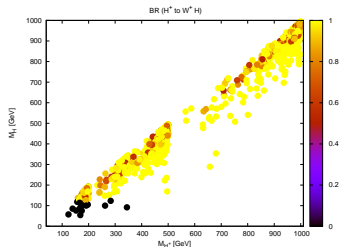
dominant production modes: through Z ; Z, γ, h for AH ; H^+H^-
important couplings:

- ZHA : $\sim \frac{e}{s_W c_W}$
- ZH^+H^- : $\sim e \coth(2\theta_w)$
- γH^+H^- : $\sim e$
- hH^+H^- : $\lambda_3 v$
- H^+W^+H : $\sim \frac{e}{s_W}$
- H^+W^+A : $\sim \frac{e}{s_W}$

!! mainly determined by electroweak SM parameters !!

Aside: typical BRs

- decay $A \rightarrow HZ$ always 100 %
- decay $H^\pm \rightarrow HW^\pm$



second channel $H^\pm \rightarrow AW^\pm$

\Rightarrow collider signature: SM particles and MET \Leftarrow

Total widths in IDM scenario

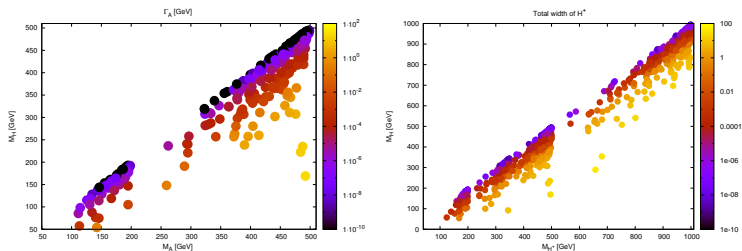
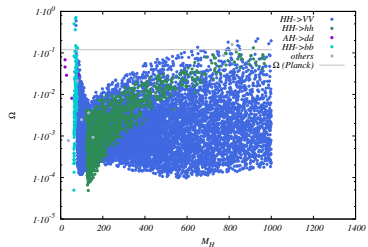
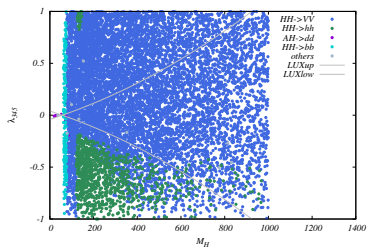


Figure : Total widths of unstable dark particles: A and H^\pm in plane of their and dark matter masses.

Dark matter relic density



all but DM constraints



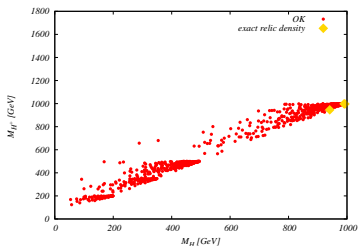
all but DM constraints

... and what if I want exact DM relic density ??

[preliminary results]

E.g. **this means**

- $m_{H^\pm} \in [100 \text{ GeV}; 620 \text{ GeV}]$ or $> 840 \text{ GeV}$
- $m_H \notin [75 \text{ GeV}; 120 \text{ GeV}]$ or $\sim 54 \text{ GeV}$
- ...



sample plot, M_H vs. M_{H^\pm}

Benchmarks submitted to Higgs Cross Section Working Group

all benchmarks: $A \rightarrow ZH = 100\%$

- **Benchmark I: low scalar mass**

$$M_H = 57.5 \text{ GeV}, M_A = 113.0 \text{ GeV}, M_{H^\pm} = 123 \text{ GeV}$$

$$HA : 0.371(4)\text{pb}, H^+ H^- : 0.097(1)\text{pb}$$

- **Benchmark II: low scalar mass**

$$M_H = 85.5 \text{ GeV}, M_A = 111.0 \text{ GeV}, M_{H^\pm} = 140, \text{ GeV}$$

$$HA : 0.226(2)\text{pb}, H^+ H^- : 0.0605(9)\text{pb}$$

- **Benchmark III: intermediate scalar mass**

$$M_H = 128.0 \text{ GeV}, M_A = 134.0 \text{ GeV}, M_{H^\pm} = 176.0, \text{ GeV}$$

$$HA : 0.0765(7)\text{pb}, H^+ H^- : 0.0259(3)\text{pb};$$

Benchmark: high masses

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

$$M_H = 363.0 \text{ GeV}, M_A = 374.0 \text{ GeV}, M_{H^\pm} = 374.0 \text{ GeV}$$

$$H, A : 0.00122(1)\text{pb}, H^+H^- : 0.00124(1)\text{pb}$$

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

$$M_H = 311.0 \text{ GeV}, M_A = 415.0 \text{ GeV}, M_{H^\pm} = 447.0 \text{ GeV}$$

$$H, A : 0.00129(1)\text{pb}, H^+H^- : 0.000553(7)\text{pb}$$

Combination of ew gauge boson total widths and LEP recast

- decays widths W, Z : **kinematic regions**

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

- **LEP recast** (Lundstrom 2008)

$$M_A \leq 100 \text{ GeV}, M_H \leq 80 \text{ GeV}, \Delta M \geq 8 \text{ GeV}$$

- **combination leads to**

- $M_H \in [0; 41 \text{ GeV}]$: $M_A \geq 100 \text{ GeV}$,
- $M_H \in [41; 45 \text{ GeV}]$: $M_A \in [m_Z - M_H; M_H + 8 \text{ GeV}]$ or $M_A \geq 100 \text{ GeV}$
- $M_H \in [45; 80 \text{ GeV}]$: $M_A \in [M_H; M_H + 8 \text{ GeV}]$ or $M_A \geq 100 \text{ GeV}$

Last comment: IDM tools for LHC phenomenology

- leading order production and decay: Madgraph5, + (currently) private version for ggh (top loop in $m_{\text{top}} \rightarrow \infty$ limit)
- in principle available: gg @ NLO, MG5 (needs however modification of current codes, not straightforward)
- IMHO: **currently LO sufficient**