The Inert Doublet Model
in the light of LHC and astrophysical data

Tania Robens

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based on work with

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A. Ilnicka, M. Krawczyk

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

TU Dresden

Workshop on Multi-Higgs Models
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Inert doublet model: The model

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

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

$\Rightarrow$ 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

$\Rightarrow$ then, **go through standard procedure...**

$\Rightarrow$ minimize potential

$\Rightarrow$ determine number of free parameters

Number of free parameters here: 7

- e.g.

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

- v, M_h fixed $\Rightarrow$ left with **5 free parameters**

Constraints: Theory

$\Longrightarrow$ **consider all current constraints on the model** $\Longleftarrow$

- Theory constraints: **vacuum stability, positivity, constraints to be in inert vacuum**
  $\Rightarrow$ **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

$$M_h = 125.1\,\mathrm{GeV},\; v = 246\,\mathrm{GeV}$$

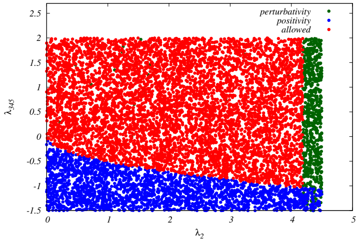
- total width of $M_h^{(*)}$
- total width of W, Z
- collider constraints from signal strength/ direct searches
- electroweak precision through S, T, U
- unstable $H^{\pm}$
- reinterpreted/ recastet LEP/ LHC SUSY searches (Lundstrom ea 2009; Belanger ea, 2015)
- dark matter relic density (upper bound)
- dark matter direct search limits $^{(*)}$ (LUX)

$\Rightarrow$ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

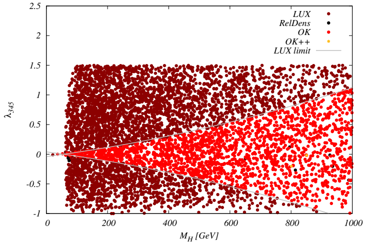
$^{(*)}$ updates not yet included

Obvious/ direct constraints on couplings

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



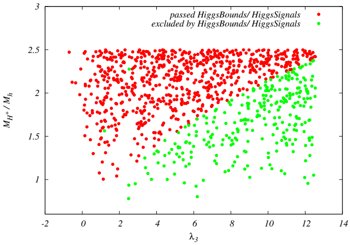
λ_2, λ_{345} plane and limits from perturbativity, positivity



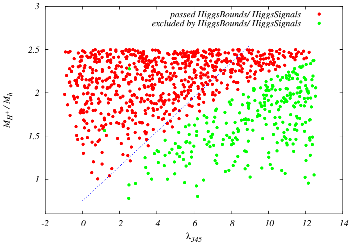
M_H, λ_{345} plane, limits from LUX$^{(*)}$

More direct constraints on couplings

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

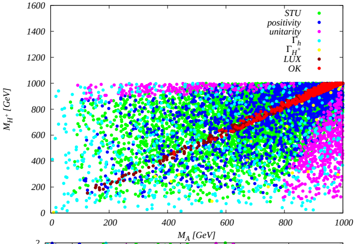


limits on λ_3, $M_H^{\pm}/M_h$, plane

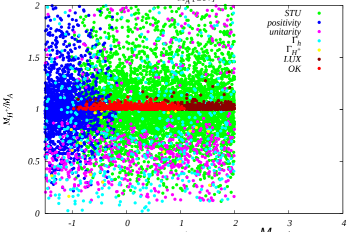


... translated to λ_{345}, $M_H^{\pm}/M_h$

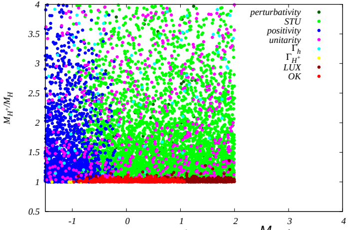
Other constraints less obvious (interplay); result $\Rightarrow$ mass degeneracies



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



λ_{345} vs $\frac{M_{H\pm}}{M_A}$



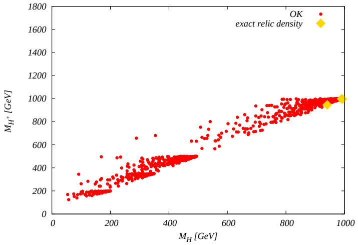
λ_{345} vs $\frac{M_{H\pm}}{M_H}$

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

[preliminary results]

E.g. **this means**

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



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

Benchmark selection for current LHC run

$\Rightarrow$ points need to **have passed all bounds**

$\Rightarrow$ total cross sections calculated using **Madgraph5, IDM model file from Goudelis ea**, 2013 (LO)

$\Rightarrow$ **effective ggH vertex implemented by hand**

- highest production cross sections: $H\,A$; $H^\pm\,H$; $H^\pm\,A$; $H^+\,H^-$
- decay $A\,\rightarrow\,H\,Z$ always 100 %
- decay $H^\pm\,\rightarrow\,H\,W^\pm$ usually dominant

$$
\begin{aligned}
p\,p\,\rightarrow\,H\,A &\quad : \quad \leq\,0.03\,\mathrm{pb},\\
p\,p\,\rightarrow\,H^\pm\,H &\quad : \quad \leq\,0.03\,\mathrm{pb},\\
p\,p\,\rightarrow\,H^\pm\,A &\quad : \quad \leq\,0.015\,\mathrm{pb},\\
p\,p\,\rightarrow\,H^+\,H^- &\quad : \quad \leq\,0.01\,\mathrm{pb}.
\end{aligned}
$$

Benchmark planes

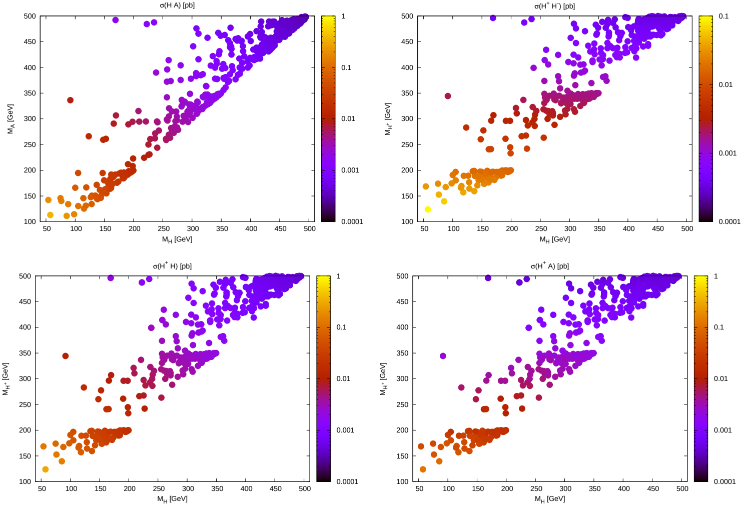


Figure: Production cross sections in pb at a 13 TeV LHC

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 expectional cases λ_{345} important; did not find such points

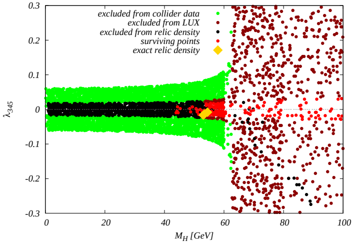
$\Rightarrow$ **high complementarity between astroparticle physics and collider searches**

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

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

- **discussion so far:** decay $h \rightarrow H\,H$ kinematically not accessible
- for these cases, discussion along different lines

$\Rightarrow$ **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 $M_H < 45\,\mathrm{GeV}$

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, **arXiv:1604.03045**
- **Yellow Report IV of the Higgs Cross Section Working Group**, *to appear*
- S. Moretti ea, *to appear*

Summary

- **LHC run II just started** $\Rightarrow$ **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: 2 models: **2HDM with dark matter (IDM)**
- **identified viable regions in parameter space**
- from these: **predictions for current LHC run**
  [A. Ilnicka, M. Krawzyk, TR, *"IDM benchmarks for the 13 TeV run of the LHC"*, for CERN Yellow Report]

!! stay tuned, and thanks for listening !!

Appendix

Very brief: parameters determining couplings (production and decay)

dominant production modes: through Z; $Z,\,\gamma,\,h$ for AH; H^+H^-

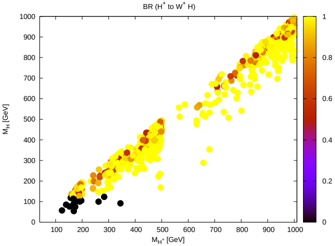
important couplings:

- $Z\,H\,A$: $\sim\;\frac{e}{s_W\,c_W}$
- $Z\,H^+\,H^-$: $\sim\;e\,\coth\,(2\,\theta_W)$
- $\gamma\,H^+\,H^-$: $\sim\;e$
- $h\,H^+\,H^-$: $\lambda_3\,v$
- $H^+\,W^+\,H$: $\sim\;\frac{e}{s_W}$
- $H^+\,W^+\,A$: $\sim\;\frac{e}{s_W}$

!! mainly determined by electroweak SM parameters !!

Aside: typical BRs

- decay $A \to H\,Z$ always 100 %
- decay $H^{\pm} \to H\,W^{\pm}$



second channel $H^{\pm} \to A\,W^{\pm}$

$\Longrightarrow$ collider signature: SM particles and MET $\Longleftarrow$

Total widths in IDM scenario

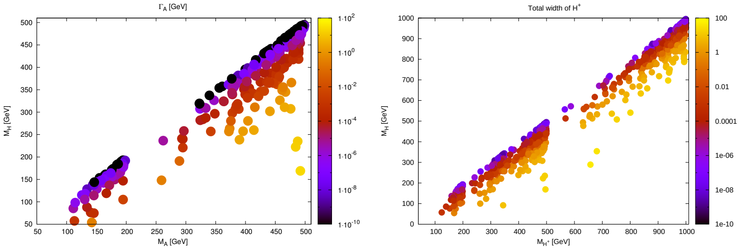
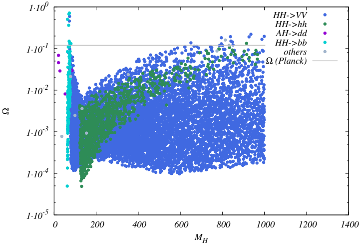
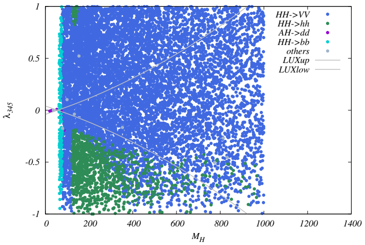


Figure: Total widths of unstable dark particles: A and $H^{\pm}$ in plane of their and dark matter masses.

Dark matter relic density



all but DM constraints



all but DM constraints

Benchmarks submitted to Higgs Cross Section Working Group

all benchmarks: $A \to Z\,H = 100\,\%$

- **Benchmark I: low scalar mass**

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

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

- **Benchmark II: low scalar mass**

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

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

- **Benchmark III: intermediate scalar mass**

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

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

Benchmark: high masses

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

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

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

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

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

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

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)

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

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

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**