Inert doublet model benchmarks for the 13 TeV run of the LHC

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based on work with

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A. Ilnicka, M. Krawczyk (arXiv:1505.04734; work in progress)

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Inert doublet model: The model

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

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

$\Rightarrow$ 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

- vacuum stability,
- constraints to be in inert vacuum
- perturbative unitarity
- perturbativity of couplings
- **choosing** M_H as dark matter: $M_H \leq M_A, M_{H^\pm}$

Constraints: Experiment

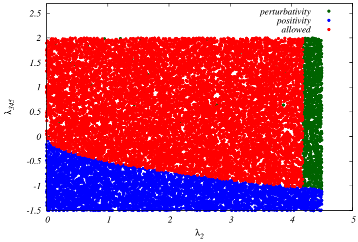
$$M_h = 125.1\,\mathrm{GeV},\ v = 246\,\mathrm{GeV}$$

- 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)

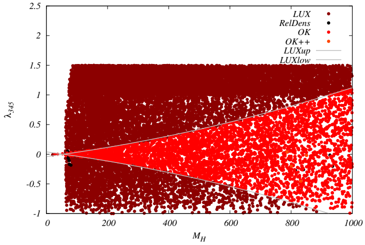
$\Rightarrow$ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

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

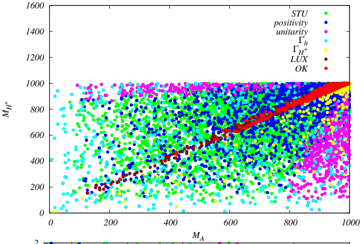


λ_2, λ_{345} plane and limits from perturbativity, positivity

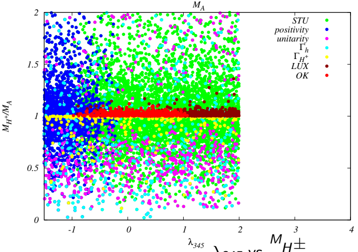


M_H, λ_{345} plane, limits from LUX

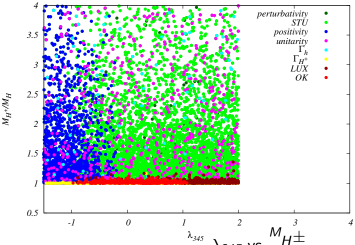
Other constraints less obvious (interplay); result ⇒ mass degeneracies



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



λ_{345} vs $\frac{M_{H\pm}}{M_A}$



λ_{345} vs $\frac{M_{H\pm}}{M_H}$

Benchmark selection

- ⇒ 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: $H\,A$; $H^+\,H^-$

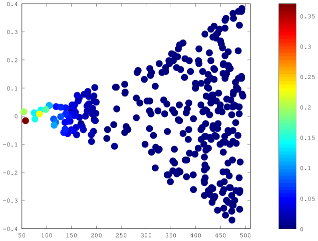


Figure : Production cross sections in pb at a 13 TeV LHC for *HA (left)* and $H^+\,H^-$ *(right)*, in the M_H, λ_{345} plane.

Benchmarks: low masses, $M_H \leq 90\,\mathrm{GeV}$

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

- **Benchmark I: low scalar mass**

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

$\lambda_{345} \in [-0.015;0.015]$

$HA : 0.371(4)\mathrm{pb},\ H^+ H^- : 0.097(1)\mathrm{pb}$
$H^+ \rightarrow W^+ H$ with a BR ≥ 0.99.

- **Benchmark II: low scalar mass**

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

$\lambda_{345} \in [-0.015;0.015]$

$HA : 0.226(2)\mathrm{pb}, H^+ H^- : 0.0605(9)\mathrm{pb}$
$H^+ \rightarrow W^+ H(A)$ with a BR $\sim 0.96(0.04)$.

relatively exceptional due to highly constrained parameter space; large production cross sections

Benchmark: intermediate mass, $M_H \geq 100\,\mathrm{GeV}$

- **Benchmark III: intermediate scalar mass**

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

$\lambda_{345} \in [-0.05; 0.05]$

$H\,A : 0.0765(7)\mathrm{pb},\; H^+\,H^- \; : 0.0259(3)\mathrm{pb};$
$H^+ \rightarrow\; W^+\,H(A)$ with a BR $\sim 0.66(0.34)$

interesting because less exceptional region, un typical decay of $H^\pm$

Benchmark: high masses, $M_H \geq 300\,\mathrm{GeV}$

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

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

  $\lambda_{345} \in [-0.25;0.25]$

  $H, A : 0.00122(1)\mathrm{pb},\ H^+H^- : 0.00124(1)\mathrm{pb}$
  $H^\pm$ 100 % to $W^\pm H$

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

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

  $\lambda_{345} \in [-0.19;0.19]$

  $H, A : 0.00129(1)\mathrm{pb},\ H^+H^- : 0.000553(7)\mathrm{pb}$
  $H^+ \rightarrow W^+ H$ with a BR $\gtrsim 0.99$

more typical, lowish cross sections
difference: production cross sections similar/ non similar, degeneracy (typical)/ non-degeneracy

Parameters tested at LHC

- dominant production cross sections and decays for LHC@13 TeV **do not depend on λ_2, only marginally on λ_{345}**

  $\Rightarrow$ mainly tested: masses $\Leftarrow$

- 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: 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**

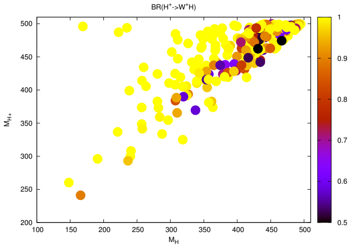
Appendix

Relevant couplings

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

Aside: typical BRs

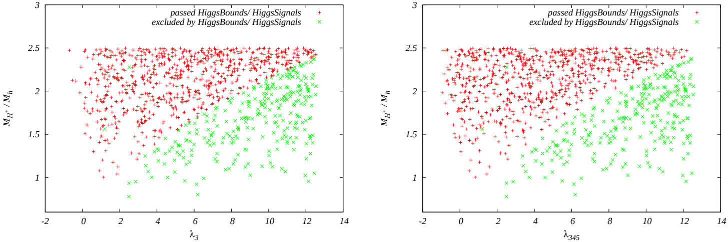
- decay $A \rightarrow H\,Z$ always 100 %
- decay $H^{\pm}$



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

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}, $M_H^{\pm}/M_h$