An updated analysis of Inert Higgs Doublet Model in light of LUX, PLANCK, AMS02 and LHC

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This work (arXiv:1310.0358) is in collaboration with A. Arhrib, T.C Yuan and Q. Yuan
1. IHDM dark matter
2. IHDM Higgs search at the LHC
3. Impact of the direct and indirect detections
4. Prospect
5. Summary
## Dark Matter search

![Diagram of DM and SM interactions]

### Signals at Colliders

<table>
<thead>
<tr>
<th>Colliders</th>
<th>Experiments</th>
<th>DM Hints</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC, LEP, Tevatron, ...</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

### Direct detection

<table>
<thead>
<tr>
<th>Direct detection</th>
<th>Experiments</th>
<th>DM Hints</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUX, XENON100, CDMS, ...</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>DAMA, CoGeNT, CRESST, and CDMS* at low DM mass region.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Cosmic rays

<table>
<thead>
<tr>
<th>Cosmic rays</th>
<th>Experiments</th>
<th>DM Hints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Positrons</td>
<td>PAMELA, Fermi–LAT, AMS02...</td>
<td>1. High energy positron excess</td>
</tr>
<tr>
<td>2. antiprotons</td>
<td>PAMELA...</td>
<td>2. None</td>
</tr>
<tr>
<td>3. neutrinos</td>
<td>IceCube...</td>
<td>3. PeV neutrinos</td>
</tr>
</tbody>
</table>

### Gamma rays

<table>
<thead>
<tr>
<th>Gamma rays</th>
<th>Experiments</th>
<th>DM Hints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermi–LAT, ...</td>
<td>FERMI bubbles, Fermi Gamma ray line at 130 GeV...</td>
<td></td>
</tr>
</tbody>
</table>

### Radio

<table>
<thead>
<tr>
<th>Radio</th>
<th>Experiments</th>
<th>DM Hints</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMAP, Planck</td>
<td>WMAP (Planck) haze</td>
<td>WMAP (Planck) haze</td>
</tr>
</tbody>
</table>
Dark Matter in inert Higgs doublet Model
Inert Higgs doublet Model

\[ H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S + iA) \end{pmatrix} \]

\[ V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 \]
\[ + \frac{\lambda_5}{2} \left\{ (H_1^\dagger H_2)^2 + \text{h.c.} \right\}. \]

- h plays the role of SM higgs boson
- \( H_2 \) does not have vev: inert doublet
- In the dark sector (\( Z_2 \) odd), the lightest neutral particle (LOP) is DM, either S or A.

<table>
<thead>
<tr>
<th>Standard Model particles</th>
<th>Even</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP-even scalar S</td>
<td>Odd</td>
</tr>
<tr>
<td>pseudo-scalar A</td>
<td>Odd</td>
</tr>
<tr>
<td>Charged Higgs ( H^\pm )</td>
<td>Odd</td>
</tr>
</tbody>
</table>
Mass spectrum and scan ranges

\[ V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 \]
\[ + \frac{\lambda_5}{2} \left\{ (H_1^\dagger H_2)^2 + \text{h.c.} \right\} . \]

\[ m_h^2 = -2\mu_1^2 = 2\lambda_1 v^2 \]
\[ m_S^2 = \mu_2^2 + \frac{1}{2} (\lambda_3 + \lambda_4 + \lambda_5) v^2 = \mu_2^2 + \lambda_L v^2 \]
\[ m_A^2 = \mu_2^2 + \frac{1}{2} (\lambda_3 + \lambda_4 - \lambda_5) v^2 = \mu_2^2 + \lambda_A v^2 \]
\[ m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2} \lambda_3 v^2 \]

\[ \lambda_{L,A} = \frac{1}{2} (\lambda_3 + \lambda_4 \pm \lambda_5) . \]

Pertubativity and unitarity put very stringent constraints on couplings!!!

\[ 122.0 \leq m_h / \text{GeV} \leq 129.0 , \]
\[ 5.0 \leq m_S / \text{GeV} \leq 4 \times 10^3 , \]
\[ 5.0 \leq m_A / \text{GeV} \leq 4 \times 10^3 , \]
\[ 70.0 \leq m_{H^\pm} / \text{GeV} \leq 4 \times 10^3 , \]

\[ -2.0 \leq \lambda_L \leq 2.0 , \]
\[ 0.0 \leq \lambda_2 \leq 4.2 . \]
Constraints

Theoretical constraints:
- Pertubativity and unitarity
- Vacuum Stability

PLUS LEP CONSTRAINTS:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean</th>
<th>Error: exp., th.</th>
<th>Distribution</th>
</tr>
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<tbody>
<tr>
<td>$m_h$ (by CMS)</td>
<td>125.8 GeV</td>
<td>0.6 GeV, 0.0 GeV</td>
<td>Gaussian</td>
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<tr>
<td>$\Omega h^2$</td>
<td>0.1199</td>
<td>0.0027, 10%</td>
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<tr>
<td>BR($h \rightarrow$ invisible) (by ATLAS)</td>
<td>0.65</td>
<td>5%, 10%</td>
<td>Error Func.</td>
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<td>$R_{\gamma\gamma}$</td>
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<td>See text.</td>
<td>Poisson</td>
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<td>dSphs $\gamma$-ray</td>
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<tr>
<td>GC $\gamma$-ray flux</td>
<td>See text.</td>
<td>See text.</td>
<td>Half Poisson</td>
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## Constraints

### Theoretical constraints:
- Pertubativity and unitarity
- Vacuum Stability

### Plus LEP constraints:
- $m_h$ (by CMS)
- $\Omega h^2$
- $S$
- $T$
- $BR(h \rightarrow \text{invisible})$ (by ATLAS)
- $R_{\gamma\gamma}$
- Monojet (by CMS 19.5 fb$^{-1}$)

### LUX(2013)
- dSphs $\gamma$-ray
- GC $\gamma$-ray flux
- $e^+$ fraction, $e^++e^-$ flux
- $p$ flux

### Measurement Table

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Gustafsson, Lundström, Bergström, Edsjo (2009)
Impact of relic density

Relic density is dominant the likelihood function.
Impact of relic density

Profile Likelihood
IHDM

$\chi = S$

$10^2$ $10^3$

$m_A$ (GeV)

$10^2$ $10^3$

$m_S$ (GeV)

$\delta \chi^2$ (RC) < 5.99
Best fit

Higgs resonance

Profile Likelihood
IHDM

$\delta \chi^2$ (RC) < 5.99
Best fit
Impact of relic density

Coannihilation
Impact of relic density

Because $W^+W^-$ final state opens, $m_X$ is either lower than 100 GeV or greater than 500 GeV in 2 sigma significance.
Impact of relic density

- $m_x < 63 \text{ GeV}$, small lambda is allowed by invisible higgs decay.
- $76 \text{ GeV} < m_x < 100 \text{ GeV}$, only the negative lambda is allowed because of the cancellation condition at $m_x$ far from the Higgs resonance.
- $m_x > 500 \text{ GeV}$, lambda is increasing with respect to $m_x$ in order to maintain correct relic density.

$$g_{n\chi\chi} = -2\nu \lambda_{\chi\chi} \text{ with } \lambda_{\chi\chi} = \begin{cases} \lambda_L & \text{if } \chi = S, \\ \lambda_A & \text{if } \chi = A. \end{cases}$$
IHDM Higgs search at the LHC
The impact of 125 GeV Higgs mass

Characterization of the excess: mass

To reduce model dependence, allow for free cross sections in three channels and fit for the common mass:

$$m_X = 125.3 \pm 0.6 \text{ GeV}$$

04th July 2012, CMS and ATLAS
The impact of 125 GeV Higgs mass

Characterization of the excess: mass

2013 Nobel Prize in Physics

Francois Englert
Peter W. Higgs

F. Englert and P. Higgs
Photo: Wikimedia Commons

2013 Nobel Prize in Physics

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider"
The impact of 125 GeV Higgs mass

Characterization of the excess: mass

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Time to celebrate?
Hold on a moment,
is Higgs Standard Model like?

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The impact of 126 GeV Higgs Boson

- Agree with CMS!
- Enhancement is found at negative lambda_3 and small charged higgs mass.
- Gamma-gamma rate should greater than 0.7 for invisible decay less than 0.2.
Considering relic density and DM DD, invisible higgs decay can be constrained less than ~0.2. This is a more stringent limit than the one given by ATLAS, ~0.6.
Impact of the direct and indirect detection
## Fermi DM gamma ray search

<table>
<thead>
<tr>
<th>Source</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic Center</td>
<td>Strong DM signal, good statistics</td>
<td>High astrophysics background, unclear source</td>
</tr>
<tr>
<td>Milky Way Halo</td>
<td>Large statistics</td>
<td>High astrophysics background</td>
</tr>
<tr>
<td>dSphs</td>
<td>Low astrophysics background</td>
<td>Low statistics</td>
</tr>
<tr>
<td>Gamma-ray line</td>
<td>No similar astrophysical signal</td>
<td>Low statistics</td>
</tr>
<tr>
<td>Extragalactic gamma-ray background</td>
<td>Large statistics</td>
<td>Huge astrophysical uncertainties</td>
</tr>
<tr>
<td>Galaxy Clusters</td>
<td>Low astrophysics background</td>
<td>Low statistics and astrophysical uncertainties</td>
</tr>
</tbody>
</table>

Fermi LAT data taken from 4 August 2008 to 2 August 2012 with the pass 7 photon selection, and energy from 200 MeV to 500 GeV
Almost no room for DM antiproton but positron.
We fit data with pulsar+DM.
The impact of indirect detection

- ID cannot constrain at the region $m_X > 500$ GeV.
- Some higgs resonance region with high annihilation is disfavored by ID constraints.
Detect DM elastic scattering

\[ \sigma_0 = \frac{m_u + m_d}{2} \langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle, \]
\[ \Sigma_{\pi N} = \frac{m_u + m_d}{2} \langle N|\bar{u}u + \bar{d}d|N\rangle. \]

From quark level to parton level

Varying sigma-term between 32 MeV to 52 MeV, Stahov et al (2012). 
spin-independent cross-section can vary by \sim factor 3.

Most important channel

Irrelevant if \( m_{A^0} - m_{H^0} \gtrsim 100 \text{ keV} \)
Impact of XENON100

- Most WW final state is disfavored!
- $m_x > 500$ GeV is still allowed by XENON100.
Prospect
LHC Monojet 14 TeV

- $|\lambda| < 0.01$ if LHC reaches 100 fb$^{-1}$.
- $|\lambda| < 0.006$ if LHC reaches 300 fb$^{-1}$.
The exclusion power for future 1-yr AMS02 antiproton data is more sensitive at higgs resonance region.
We can expect that the next generation of ton-sized detector for DM direct detection can probe most of the parameter space, especially for large $m_x$ region.
Comparing with current experimental data, these three future experiments sensitivities are robust but neither the lower \( m_x \) region nor the larger \( m_x \) region can be entirely ruled out.
Summary and Conclusion

1. A global Statistical Analysis of the IHDM with Dark matter candidate, S or A.
2. No preference of DM is S or A in our study.
3. In 95% C.L. of RC+DD+ID constraints, \( m_x > 52 \) GeV.
4. The current ID and DD data are only sensitive to Higgs resonance region.
5. No current constraint can probe \( m_x > 500 \) GeV region but one expects future XENON1T can probe this region.