Inert Doublet Model in light of new experimental results: combining astrophysical and the LHC data

Dorota Sokołowska

University of Warsaw, Faculty of Physics,
Institute of Theoretical Physics

SCALARS 2013
Warsaw, Poland, 12-16.09.2013

collaboration with M. Krawczyk, B. Świeżewska and P. Swaczyna
JHEP 09 (2013) 055 (arXiv:1305.6266 [hep-ph])

Motivation

Around 25 % of the Universe is:

→ cold, non-baryonic, neutral, very weakly interacting

→ particle physics' candidate: **WIMP**, stable due to the D symmetry

Two Higgs Doublet Model:

- two scalar $SU(2)_W$ doublets Φ_S, Φ_D with the same hypercharge $Y = 1$
- rich phenomenology: CP violation in the scalar sector, different types of vacua, breaking of $U(1)_{QED}$, phase transitions in the early Universe...
- 2HDM with an exact Z_2 symmetry: Inert Doublet Model (IDM)

→ a Dark Matter candidate

→ SM-like Higgs boson

→ modifications of the diphoton decay possible

Testing IDM

Collider constraints (LEP II, Tevatron, LHC)

$\rightarrow$ properties of SM-like Higgs h and dark scalars $H, A, H^{\pm}$

Relic density constraints

$\rightarrow$ masses and couplings ($g_{HHh} \sim \lambda_{345}$) of dark scalars

Direct & indirect detection of DM:

$\rightarrow$ further constraints for (M_H, g_{HHh})

IDM can be proven/excluded once an agreement in the experimental area is reached.

Lundstrom et al. '07, '08, Barbieri et al. '06, Lopez Honorez et al. '07, Hambye et al. '08,'09, Agrawal et al. '09, Dolle et al. '09, Arina et al. '09, ...

Direct & indirect detection experiments

- direct detection signals (DAMA, CoGeNT, CRESST-II, CDMS-II)

$\rightarrow$ light DM

$\rightarrow$ **no agreement with exclusion limits** (XENON10, XENON100)

- no indirect DM detection signals as of 2013:
  - γ-lines (INTEGRAL – 511 keV, Fermi-LAT – 130 GeV)

    $\rightarrow$ DM interpretation disfavored
  - e^+/e^- excess (Pamela, Fermi-LAT)

    $\rightarrow$ "signature not unique for DM, astrophysical explanation possible"

Direct & indirect detection experiments do not provide a coherent picture of Dark Matter.

IDM in LHC

What can LHC tell us about the IDM & scalar Dark Matter?

- mass of the Higgs boson: $M_h \approx 125$ GeV
- Higgs signal strength ≈ 1 (within experimental accuracy)
- Higgs phenomenology – diphoton channel sensitive to "new physics"
- IDM – a Higgs portal DM – interaction through h

Our goal:

Constrain the IDM independently of direct and indirect detection using:

(a) the relic density $\Omega_{DM} h^2$ (3σ WMAP from PDG)

$$0.1018 < \Omega_{DM} h^2 < 0.1234$$

(b) diphoton decay rate $R_{\gamma\gamma}$

$$\begin{aligned} \text{ATLAS} \quad &: \quad R_{\gamma\gamma} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst}) \\ \text{CMS} \quad &: \quad R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26} \end{aligned}$$

Both values consistent with $R_{\gamma\gamma} = 1$, still room for "new physics"

Inert Doublet Model

Scalar potential V invariant under a D-transformation of Z_2 type:

$$D: \quad \Phi_S \to \Phi_S, \quad \Phi_D \to -\Phi_D, \quad \text{SM fields} \to \text{SM fields}$$

$$V = -\frac{1}{2}\left[m_{11}^2 \Phi_S^\dagger \Phi_S + m_{22}^2 \Phi_D^\dagger \Phi_D\right] + \frac{1}{2}\left[\lambda_1 \left(\Phi_S^\dagger \Phi_S\right)^2 + \lambda_2 \left(\Phi_D^\dagger \Phi_D\right)^2\right]$$

$$+\lambda_3 \left(\Phi_S^\dagger \Phi_S\right)\left(\Phi_D^\dagger \Phi_D\right) + \lambda_4 \left(\Phi_S^\dagger \Phi_D\right)\left(\Phi_D^\dagger \Phi_S\right) + \frac{1}{2}\lambda_5\left[\left(\Phi_S^\dagger \Phi_D\right)^2 + \left(\Phi_D^\dagger \Phi_S\right)^2\right]$$

D-symmetric vacuum state (Inert vacuum):

$$\langle \Phi_S \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \Phi_D \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- Φ_S: h – SM-like Higgs boson,
  tree-level couplings to fermions and gauge bosons like in the SM,
  deviation from SM in loop couplings possible
- Φ_D: H, A, $H^\pm$ – dark scalars, no tree-level couplings to fermions
- exact D symmetry $\Rightarrow$ lightest D-odd particle stable $\Rightarrow$ DM candidate
- **Dark Matter candidate $\boldsymbol{H}$**, $M_H < M_{H^\pm}, M_A$

Constraints

(1) **Vacuum stability**: scalar potential V bounded from below

$$\lambda_{1,2} > 0, \quad \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1\lambda_2} > 0 \ \ (\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5)$$

(2) **Perturbative unitarity**: eigenvalues Λ_i of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$

(3) **Existence of the Inert vacuum**: a *global* minimum of V

(4) **Higgs mass**: $M_h = 125$ GeV

$$(1)\text{–}(4) \Rightarrow m_{22}^2 \lesssim 9{\cdot}10^4\,\text{GeV}^2,\ \lambda_1 = 0.258,\ \lambda_2 < 8.38,\ \lambda_3, \lambda_{345} > -1.47,$$

(5) **EWPT & LEP**: bounds on the scalars' masses

$$M_H \lesssim 10\,\text{GeV}, \quad 40\,\text{GeV} < M_H < 150\,\text{GeV}, \quad M_H \gtrsim 500\,\text{GeV}$$

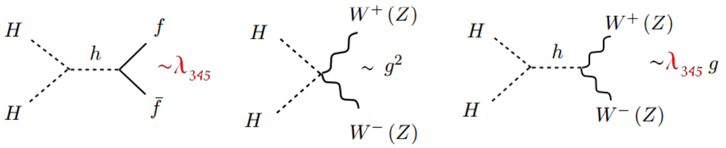
$$M_{H^\pm} \gtrsim 70 - 90\ \text{GeV}$$

$$\delta_A = M_A - M_H < 8\,\text{GeV} \Rightarrow M_H + M_A > M_Z$$

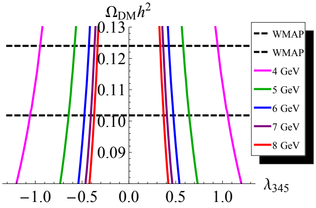
$$\text{excluded}: M_H < 80\ \text{GeV}, M_A < 100\ \text{GeV and } \delta_A > 8\ \text{GeV}$$

(6) ***H* as DM candidate** $M_H < M_A, M_{H^\pm}$ with proper $\Omega_{DM}h^2$

Relic density constraints



$$0.1018 < \Omega_{DM} h^2 < 0.1234 \Rightarrow \lambda_{345}^{\min}, \lambda_{345}^{\max}$$



- **low DM mass** $M_H \lesssim 10$ GeV, $\lambda_{345} \sim \mathcal{O}(0.5)$
- **medium DM mass** $M_H \approx (40 - 160)$ GeV, $\lambda_{345} \sim \mathcal{O}(0.05)$
- **high DM mass** $M_H \gtrsim 500$ GeV, $\lambda_{345} \sim \mathcal{O}(0.1)$

$R_{\gamma\gamma}$ – diphoton decay rate

$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \to \gamma\gamma)^{IDM}}{\Gamma(h \to \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

- Main production channel: gluon fusion, $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$
- Two sources of deviation from $R_{\gamma\gamma} = 1$:
  - invisible decays $h \to HH$, $h \to AA$ in total decay width $\Gamma(h)^{IDM}$:
    if kinematically allowed, dominate over SM channels $\Rightarrow \boldsymbol{R_{\gamma\gamma} < 1}$
  - **charged scalar $H^{\pm}$ loop** in $\Gamma(h \to \gamma\gamma)^{IDM}$

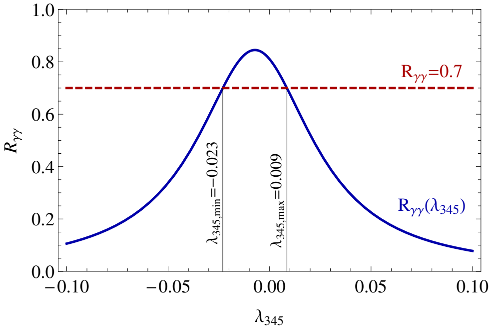
$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \mathcal{A}^{SM} + \frac{\lambda_3}{2v^2 M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right)\right|^2$$

  - visible if invisible channels closed
  - constructive ($\boldsymbol{R_{\gamma\gamma} > 1}$) or destructive ($\boldsymbol{R_{\gamma\gamma} < 1}$) interference
- $R_{\gamma\gamma} \Rightarrow$ bounds on masses and λ_3 (or $\lambda_{345} = g_{HHh}$)

Q.-H. Cao et al '07, Posch '11, A. Arhrib et al '12, B.Swiezewska et al '12

$R_{\gamma\gamma}$ for the IDM

Example: $R_{\gamma\gamma}(\lambda_{345})$ for $M_H = 55\,\mathrm{GeV},\ M_A = 60\,\mathrm{GeV},\ M_{H^\pm} = 120\,\mathrm{GeV}$

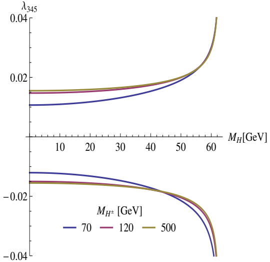


$$R_{\gamma\gamma} > 0.7, 0.8, ... \Rightarrow \lambda_{345}^{\mathrm{min}}, \lambda_{345}^{\mathrm{max}}$$

Do we get a proper relic density for those values?

Low DM mass

$$M_H \lesssim 10\,\text{GeV}, \quad M_A \approx M_{H^\pm} \approx 100\,\text{GeV}$$
$$h \to AA \text{ channel closed, } h \to HH \text{ channel open}$$

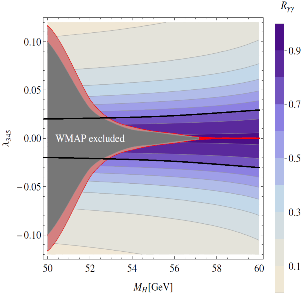


- Proper relic density
  $0.1018 < \Omega_{DM} h^2 < 0.1234 \Rightarrow |\lambda_{345}| \sim \mathcal{O}(0.5)$
- CDMS-II reported event:
  $M_H = 8.6$ GeV $\Rightarrow |\lambda_{345}| \approx (0.35 - 0.41)$
- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02$

Low DM mass excluded

Medium DM mass (1) – HH channel open

$$50\,\text{GeV} < M_H < M_h/2\,\text{GeV}, \quad M_A = M_{H^\pm} = 120\,\text{GeV}$$



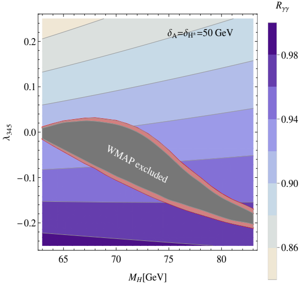
Red bound: $\Omega_{DM}h^2$ in agreement with WMAP

Black line: $R_{\gamma\gamma} = 0.7$

- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow M_H \lesssim 53\,\text{GeV}$ excluded
- $53\,\text{GeV} \lesssim M_H \lesssim M_h/2 \Rightarrow R_{\gamma\gamma} \approx (0.8 - 0.9)$

Medium DM mass (2) – HH channel closed

$$M_h/2 < M_H < 83\,\text{GeV}, \quad M_A = M_{H^\pm} = M_H + 50\,\text{GeV}$$

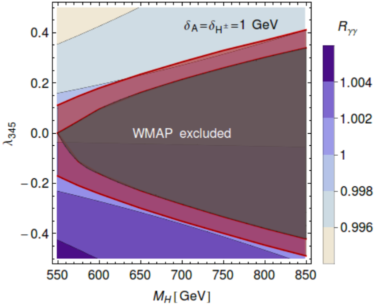


Red bound: $\Omega_{DM}h^2$ in agreement with WMAP

- Max $R_{\gamma\gamma}$ in agreement with WMAP $\Rightarrow R_{\gamma\gamma} \lesssim 0.98 < 1$
- $R_{\gamma\gamma} > 1$ possible if $\Omega_H h^2 < \Omega_{DM} h^2$ (subdominant DM candidate)

High DM mass

$$M_H \gtrsim 550\,\text{GeV}, \quad M_A = M_{H^\pm} = M_H + 1\,\text{GeV}$$

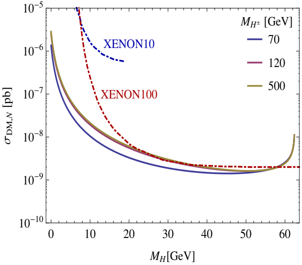


Red bound: $\Omega_{DM} h^2$ in agreement with WMAP

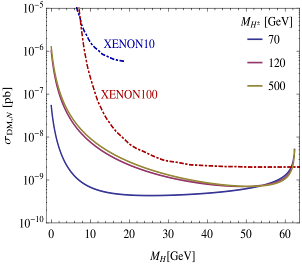
- $R_{\gamma\gamma}$ in agreement with WMAP $\Rightarrow R_{\gamma\gamma} \approx 1$

Comparison with XENON

$$\sigma_{\mathrm{DM,N}} = \frac{\lambda_{345}^2}{4\pi M_h^4}\frac{m_N^4}{(m_N+M_H)^2} f_N^2$$



$R_{\gamma\gamma} = 0.7$



$R_{\gamma\gamma} = 0.8$

$R_{\gamma\gamma}$ bounds stronger or comparable with XENON10/100 exclusion limits

Conclusions

- IDM – simple extension of SM with rich phenomenology
- $R_{\gamma\gamma}$ – sensitive to M_H and $M_{H^\pm}$ $\Rightarrow$ important information about IDM
- $R_{\gamma\gamma} + \Omega_{DM} h^2 \Rightarrow$ strong limits on IDM
  - Low DM mass excluded
  - $M_H < M_h/2$ excluded if $R_{\gamma\gamma} > 1$
  - $80 > M_H > M_h/2$ & H constitutes 100% of DM $\Rightarrow R_{\gamma\gamma} < 1$
  - $R_{\gamma\gamma} > 1$ possible if H is a subdominant DM candidate
  - Heavy DM particles $\Rightarrow R_{\gamma\gamma} \approx 1$

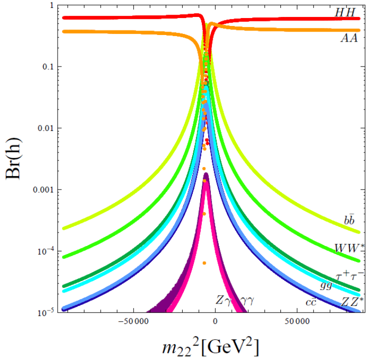
BACKUP SLIDES

Invisible decays

B. Swiezewska, Two photon decay rate of the Higgs boson in the Inert Doublet Model, Photon 2013

$$\begin{aligned}\Gamma(h) =&\Gamma(h\to b\bar{b}) + \Gamma(h\to WW^*) + \Gamma(h\to \tau^+\tau^-) + \Gamma(h\to gg)\\ &+ \Gamma(h\to ZZ^*) + \Gamma(h\to c\bar{c}) + \Gamma(h\to Z\gamma) + \Gamma(h\to \gamma\gamma)\\ &+ \Gamma(h\to HH) + \Gamma(h\to AA)\end{aligned}$$

- ATLAS: $\mathrm{Br}(h\to \mathrm{inv}) < 65\%$ (at 95% C.L.), but
- Invisible decays, if kinematically allowed, dominate over SM channels.



Analytical solution

B. Swiezewska, Two photon decay rate of the Higgs boson in the Inert Doublet Model, Photon 2013

If invisible channels closed

$$R_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\text{IDM}}}{\Gamma(h \to \gamma\gamma)^{\text{SM}}}$$

$\Rightarrow R_{\gamma\gamma} > 1$ can be solved analytically

- Constructive interference:
  - $m_{22}^2 < -2M_{H^\pm}^2$ ($\Leftrightarrow \lambda_3 < 0$)
  - with LEP bound: $m_{22}^2 < -9.8 \cdot 10^3\,\text{GeV}^2$

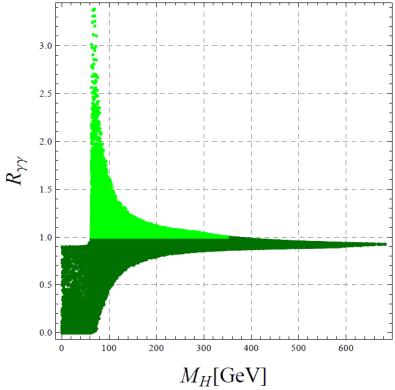
- Destructive interference
  - IDM contribution $\geqslant 2\times$ SM contribution
  - excluded by the condition for the Inert vacuum

$R_{\gamma\gamma}$ vs Dark Matter mass

[see also: A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021]

B. Swiezewska, Two photon decay rate of the Higgs boson in the Inert Doublet Model, Photon 2013

- $R_{\gamma\gamma}^{\max} \approx 3.4$
- Invisible channels open $\Rightarrow$ **no enhancement in $h \to \gamma\gamma$ possible**
- Enhanced $R_{\gamma\gamma}$ for $M_H, M_{H^\pm}, M_A > 62.5\,\text{GeV}$

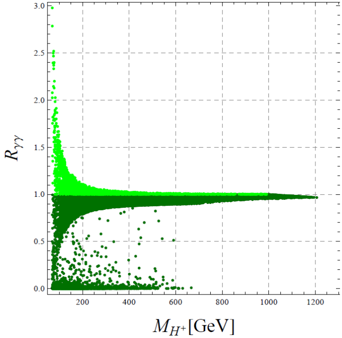


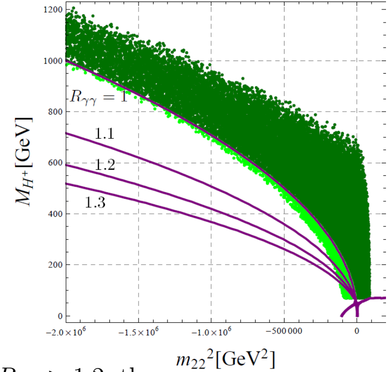
$R_{\gamma\gamma}$ vs charged scalar mass

B. Swiezewska, Two photon decay rate of the Higgs boson in the Inert Doublet Model, Photon 2013

Enhanced $R_{\gamma\gamma}$ possible for

- $m_{22}^2 < -9.8 \cdot 10^3\,\text{GeV}^2$
- any value of $M_{H^\pm}$





If $R_{\gamma\gamma} > 1.2$, then:

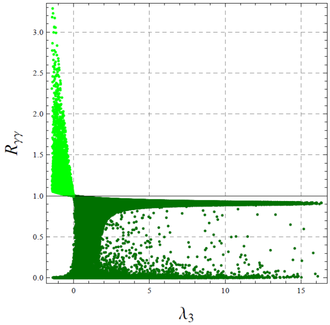
- $M_{H^\pm}, M_H \lesssim 154\,\text{GeV}$
  Only medium DM mass!

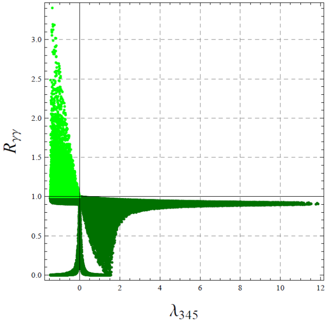
$R_{\gamma\gamma}$ vs couplings

B. Swiezewska, Two photon decay rate of the Higgs boson in the Inert Doublet Model, Photon 2013

$\lambda_3 \sim hH^+H^-$, $\lambda_{345} \sim hHH$

- In the IDM $\lambda_3, \lambda_{345} > -1.5$





- $R_{\gamma\gamma} > 1 \Rightarrow \lambda_3, \lambda_{345} < 0$
- $R_{\gamma\gamma} > 1.3 \Rightarrow -1.46 < \lambda_3, \lambda_{345} < -0.24$