Dark Matter and 125 GeV Higgs for the IDM

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25th Rencontres de Blois: Particle Physics and Cosmology
Blois, 29.05.2013

collaboration with M. Krawczyk, B. Świeżewska and P. Swaczyna
arXiv:1212.4100 and 1305.6266 [hep-ph]

Motivation

25 % of the Universe is:

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

→ particle physics' candidate: **WIMP**, stable due to 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 $U(1)_{QED}$,...
- 2HDM with an exact Z_2 symmetry: Inert Doublet Model (IDM)

→ candidate for the dark matter

→ SM-like Higgs boson

→ modifications of the diphoton decay possible

Testing IDM

Collider constraints (LEP II, Tevatron, LHC)

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

Relic density constraints

$\longrightarrow$ masses and couplings (g_{HHh}) of dark scalars

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

Direct & indirect detection of DM:

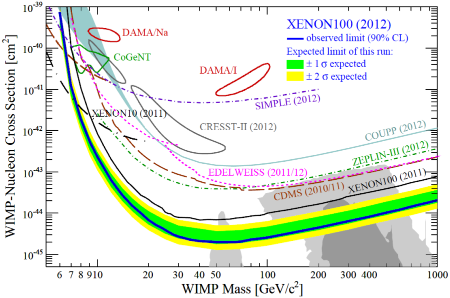
$\longrightarrow$ further constraints for (M_H, g_{HHh})

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, ...

DM direct detection experiments

dark matter – nucleon stattering → DM-quark interactions



Light DM is favoured by the reported detection signals

(DAMA, CoGeNT, CRESST-II, CDMS-II)

but there is no agreement with exclusion limits

(XENON10, XENON100)

arXiv:1109.0702,1207.5988[astro-ph]

DM indirect detection experiments

annihilation of DM into SM particles (photons, antiparticles)

- INTEGRAL 511 keV γ-line from galatic centre region astro-ph/0506026
- PAMELA: anomalous ratio of cosmic ray e^+/e^- arXiv:0810.4995 [astro-ph]
- Fermi-LAT e^+, e^- signal arXiv:0905.0025 [astro-ph.HE]

  $\rightarrow$ "signature not unique for DM, astrophysical explanation possible" arXiv:1205.4882 [astro-ph.HE]
- Fermi-LAT γ-line pointing to $M_{DM} \approx 130$ (or 150) GeV arXiv:1207.4466 [astro-ph.HE]

Direct and indirect detection summary: Lars Bergstrm, *Dark Matter Evidence, Particle Physics Candidates and Detection Methods*, arXiv:1205.4882 [astro-ph.HE]

"One should be aware, however, that this area of investigation is at present beset with large controversies, and one should allow the dust to settle before drawing strong conclussions in either directions."

LHC vs IDM

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

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

Goal:

Constrain the IDM independent of direct and indirect detection using:

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

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

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

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

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

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

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

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

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

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

$R_{\gamma\gamma}$ – 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 fussion, $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$
- 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 loop** in $\Gamma(h \to \gamma\gamma)^{IDM}$

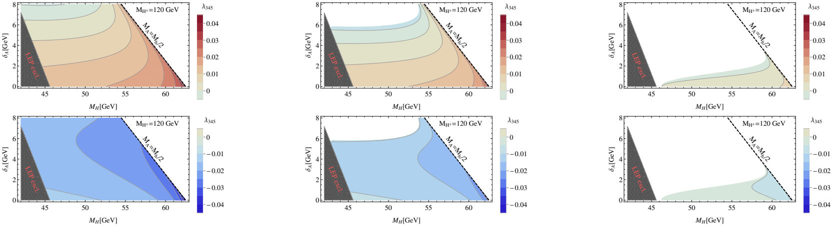
$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \mathcal{A}^{SM} + \frac{\lambda_3}{2v^2 M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$

    - 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, E. Ma, G. Rajasekaran, Phys. Rev. D 76 (2007) 095011, P. Posch, Phys. Lett. B696 (2011) 447, A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021, B.Swiezewska, M. Krawczyk, arXiv:1212.4100 [hep-ph]]

$h \to HH, AA$ decay channels open

- invisible channels dominate, $H^{\pm}$ loop less relevant
- $0 < \delta_A < 8\,\text{GeV}$ (LEP), $M_{H^\pm} = 120$ GeV

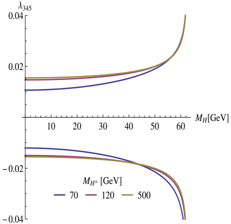


$R_{\gamma\gamma} > 0.7$ $R_{\gamma\gamma} > 0.8$ $R_{\gamma\gamma} > 0.9$

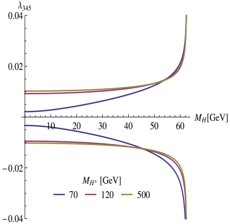
- bounds not symmetric due to AA contribution $\sim (\lambda_3 + \lambda_4 - \lambda_5)$
- $R_{\gamma\gamma} > 0.7 \Rightarrow \lambda_{345} \sim (-0.04, 0.04)$
- $R_{\gamma\gamma} > 0.8 \Rightarrow$ limits allowed masses, $\delta_A \lesssim 6$ GeV
- $R_{\gamma\gamma} > 0.9 \Rightarrow$ only $M_H \approx M_A$ possible

$h \to AA$ decay channel closed

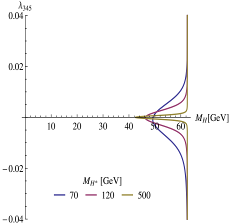
- $M_H < M_h/2$, HH channel open
- $M_A > M_h/2$, AA channel closed $\Rightarrow$ value of M_A not important, $H^\pm$ loop more significant
- $M_{H^\pm} = 70, 120, 500$ GeV



$R_{\gamma\gamma} > 0.7$



$R_{\gamma\gamma} > 0.8$

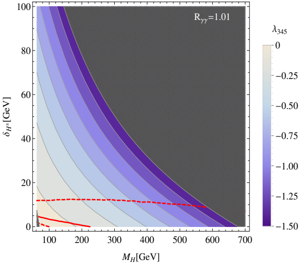


$R_{\gamma\gamma} > 0.9$

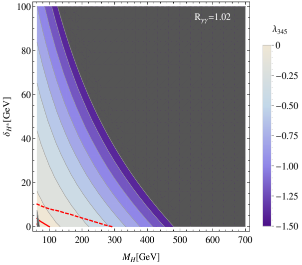
- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02$
- $R_{\gamma\gamma} > 0.8 \Rightarrow |\lambda_{345}| \lesssim 0.01$, smaller if $M_{H^\pm} = 70\,\text{GeV}$
- $R_{\gamma\gamma} > 0.9 \Rightarrow M_H \lesssim 43\,\text{GeV}$ excluded

Invisible channels closed

- $M_H, M_A > M_h/2 \Rightarrow$ charged loop contribution
  most relevant parameters: $M_{H^\pm}, \lambda_3$ (or λ_{345})



$R_{\gamma\gamma} = 1.01$



$R_{\gamma\gamma} = 1.02$

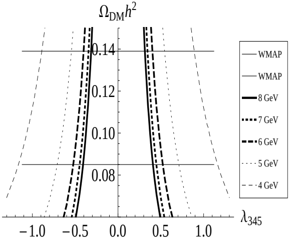
- $R_{\gamma\gamma} > 1$ and $\lambda_{345} \sim \mathcal{O}(0.1) \Rightarrow$ almost degenerated M_H and $M_{H^\pm}$
- unitarity constraints $\Rightarrow$ strong bounds on $M_{H^\pm}$:

$$R_{\gamma\gamma} = 1.01 \Rightarrow M_{H^\pm} \lesssim 700\,\text{GeV}$$

$$R_{\gamma\gamma} = 1.02 \Rightarrow M_{H^\pm} \lesssim 480\,\text{GeV}$$

$$R_{\gamma\gamma} = 1.2 \Rightarrow M_{H^\pm} \lesssim 150\,\text{GeV}$$

Low DM mass

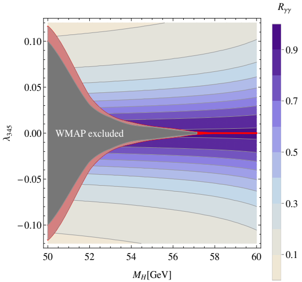


- $M_H \lesssim 10$ GeV
- $M_A \approx M_{H\pm} \approx 100$ GeV
- $0.1018 < \Omega_{DM} h^2 < 0.1234 \Rightarrow$ $|\lambda_{345}| \sim \mathcal{O}(0.5)$
- CDMS-II: $M_H = 8.6$ GeV $\Rightarrow |\lambda_{345}| \approx (0.35 - 0.41)$

$R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow$ **Low DM mass excluded**

Medium DM mass (1) – HH channel open

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

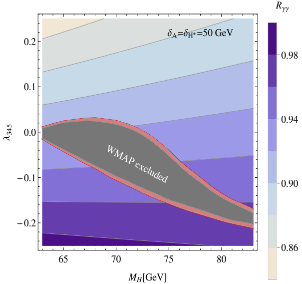


Red bound: $\Omega_{DM}h^2$ in agreement with WMAP

- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow M_H \lesssim 53\,\text{GeV}$ 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)

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 $R_{\gamma\gamma} > 1$
  - $M_H \lesssim 53\,\text{GeV}$ excluded if $R_{\gamma\gamma} > 0.7$
  - H constitutes 100% of DM $\Rightarrow R_{\gamma\gamma} < 1$
  - $R_{\gamma\gamma} > 1$ possible if H is a subdominant DM candidate

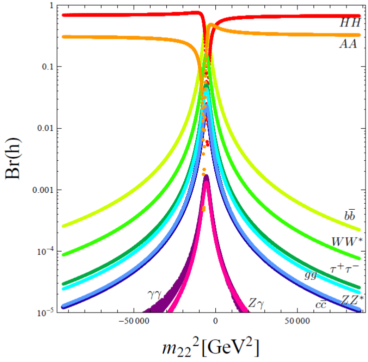
BACKUP SLIDES

Invisible decays

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

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

- 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

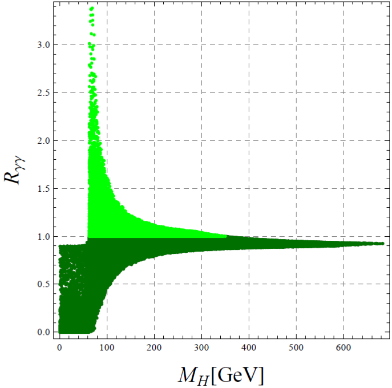
- Constructive interference:
  - $m_{22}^2 < -2M_{H^\pm}^2$ ($\Leftrightarrow \lambda_3 < 0$)
  - with LEP bound: $m_{22}^2 < -9.8 \cdot 10^3\,\text{GeV}^2$

- 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 $M_H, M_{H^\pm}, M_A > 62.5\,\mathrm{GeV}$

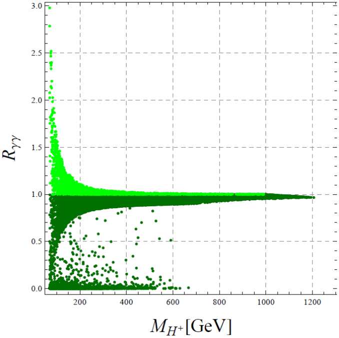


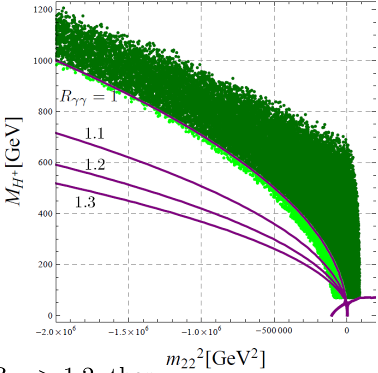
$R_{\gamma\gamma}$ vs charged scalar mass

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

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

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





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

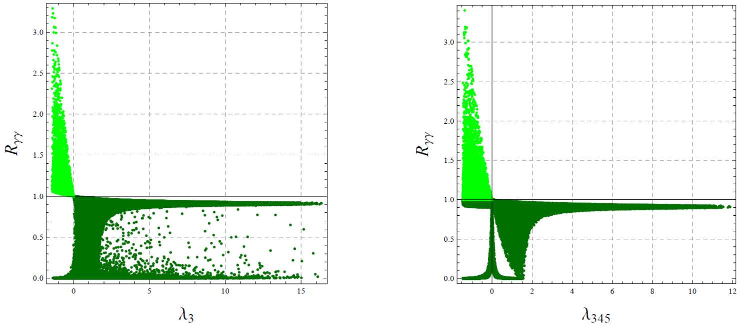
- $M_{H^\pm}, M_H \lesssim 154\,\mathrm{GeV}$
  Only medium DM mass!

$R_{\gamma\gamma}$ 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 $\lambda_3, \lambda_{345} > -1.5$



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