Potential of LHC to determine DM properties in the IDM

Dorota Sokołowska

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

The 2013 EPS Conference on High Energy Physics
Stockholm, Sweden, 18-24 July, 2013

collaboration with M. Krawczyk, B. Świeżewska and P. Swaczyna
arXiv:1212.4100 and 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)

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

Relic density constraints

→ 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:

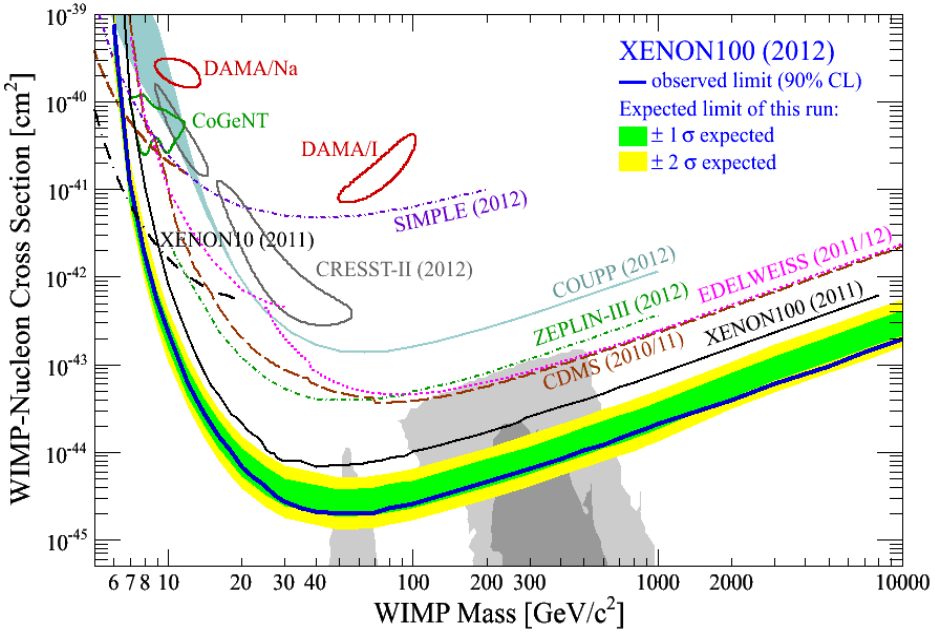
→ further constraints for (M_H, g_{HHh})

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

DM-nucleon scattering → 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, 1304.4279...

DM indirect detection experiments

annihilation of DM into SM particles (photons, antiparticles)

- INTEGRAL 511 keV γ-line from galactic 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"
- Fermi-LAT 130 GeV γ-line arXiv:1207.4466 [astro-ph.HE]
  $\rightarrow$ DM interpretation disfavored arXiv:1305.5597 [astro-ph.HE]

Direct and indirect detection summary: Lars Bergstrom, *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 conclusions in either directions."

IDM in LHC

What can LHC tell us about IDM & a 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 $R_{\gamma\gamma}$

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

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:

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

$$V = -\tfrac{1}{2}\left[m_{11}^2 \Phi_S^\dagger \Phi_S + m_{22}^2 \Phi_D^\dagger \Phi_D\right] + \tfrac{1}{2}\left[\lambda_1 \left(\Phi_S^\dagger \Phi_S\right)^2 + \lambda_2 \left(\Phi_D^\dagger \Phi_D\right)^2\right]$$
$$+ \lambda_3 \left(\Phi_S^\dagger \Phi_S\right)\left(\Phi_D^\dagger \Phi_D\right) + \lambda_4 \left(\Phi_S^\dagger \Phi_D\right)\left(\Phi_D^\dagger \Phi_S\right) + \tfrac{1}{2}\lambda_5 \left[\left(\Phi_S^\dagger \Phi_D\right)^2 + \left(\Phi_D^\dagger \Phi_S\right)^2\right]$$

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

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

(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

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

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

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

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

$R_{\gamma\gamma}$ – 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 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 $\Gamma(h \to \gamma\gamma)^{IDM}$

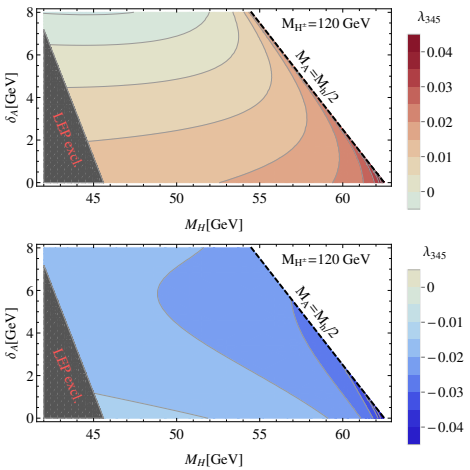
$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \mathcal{A}^{SM} + \frac{\lambda_3}{2v^2 M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$

    - 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 $\lambda_{345} = g_{HHh}$)

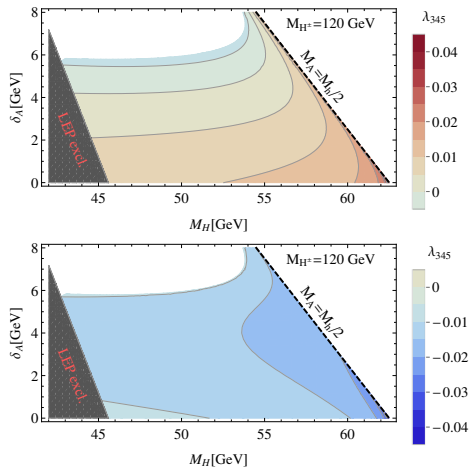
Q.-H. Cao et al '07, Posch '11, A. Arhrib et al '12, B.Swiezewska et al '12

$h \to HH, AA$ decay channels open

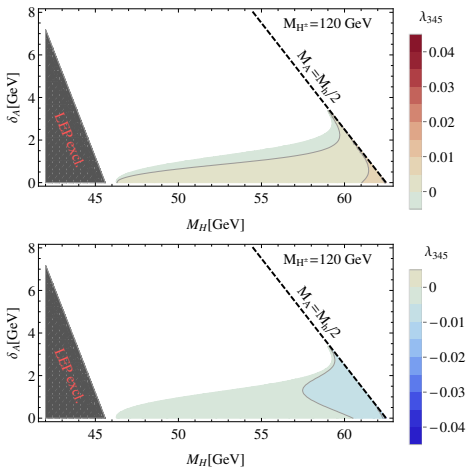
- invisible channels dominate, $H^\pm$ loop less relevant
- $0 < \delta_A < 8\,\text{GeV}$ (LEP), $M_{H^\pm} = 120$ GeV



$R_{\gamma\gamma} > 0.7$



$R_{\gamma\gamma} > 0.8$

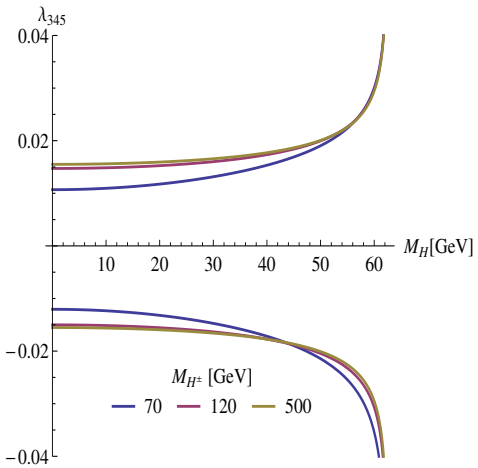


$R_{\gamma\gamma} > 0.9$

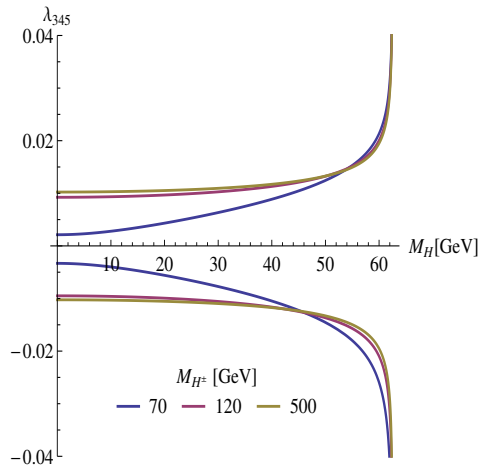
- bounds not symmetric due to AA contribution $\sim (\lambda_3 + \lambda_4 - \lambda_5)$
- $R_{\gamma\gamma} > 0.7 \Rightarrow \lambda_{345} \sim (-0.04, 0.04)$
- $R_{\gamma\gamma} > 0.8 \Rightarrow$ limits allowed masses, $\delta_A \lesssim 6$ GeV
- $R_{\gamma\gamma} > 0.9 \Rightarrow$ only $M_H \approx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

$h \to AA$ decay channel closed

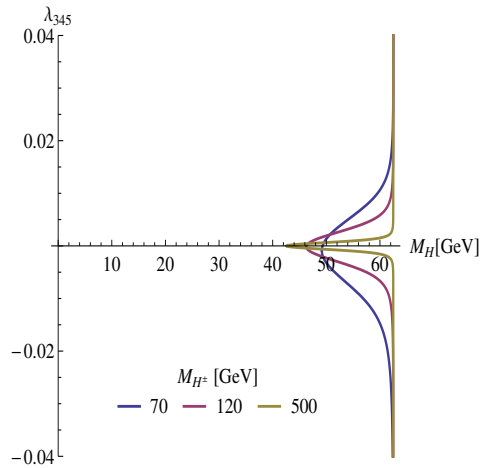
- $M_H < M_h/2$, HH channel open
- $M_A > M_h/2$, AA channel closed $\Rightarrow$
  value of M_A not important, $H^\pm$ loop more significant
- $M_{H^\pm} = 70, 120, 500$ GeV



$R_{\gamma\gamma} > 0.7$



$R_{\gamma\gamma} > 0.8$

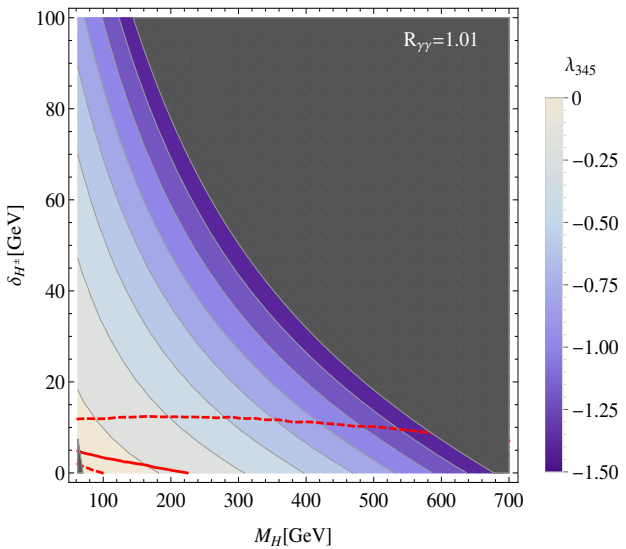


$R_{\gamma\gamma} > 0.9$

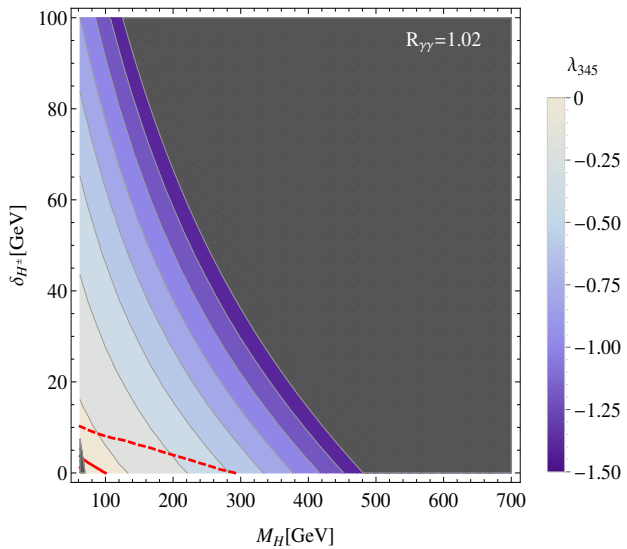
- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02$
- $R_{\gamma\gamma} > 0.8 \Rightarrow |\lambda_{345}| \lesssim 0.01$, smaller if $M_{H^\pm} = 70\,\text{GeV}$
- $R_{\gamma\gamma} > 0.9 \Rightarrow M_H \lesssim 43\,\text{GeV}$ excluded

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})



$R_{\gamma\gamma} = 1.01$



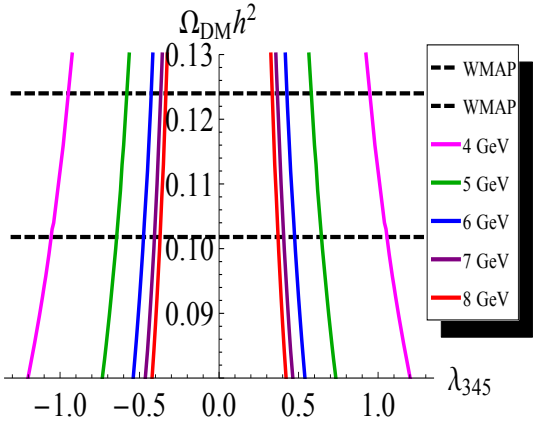
$R_{\gamma\gamma} = 1.02$

- $R_{\gamma\gamma} > 1$ 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

$$M_H \lesssim 10\,\text{GeV}, \quad M_A \approx M_{H^\pm} \approx 100\,\text{GeV}$$



- Proper relic density

  $0.1018 < \Omega_{DM}h^2 < 0.1234 \Rightarrow |\lambda_{345}| \sim \mathcal{O}(0.5)$

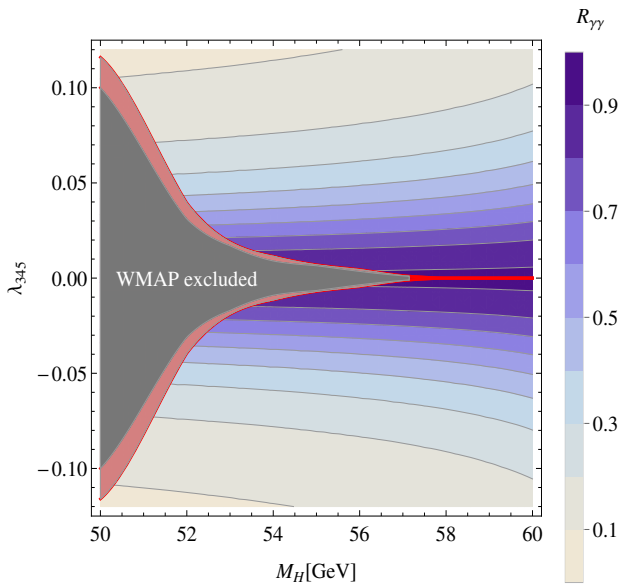
- CDMS-II reported event:

  $M_H = 8.6\ \text{GeV} \Rightarrow |\lambda_{345}| \approx (0.35 - 0.41)$

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

Medium DM mass (1) – HH channel open

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

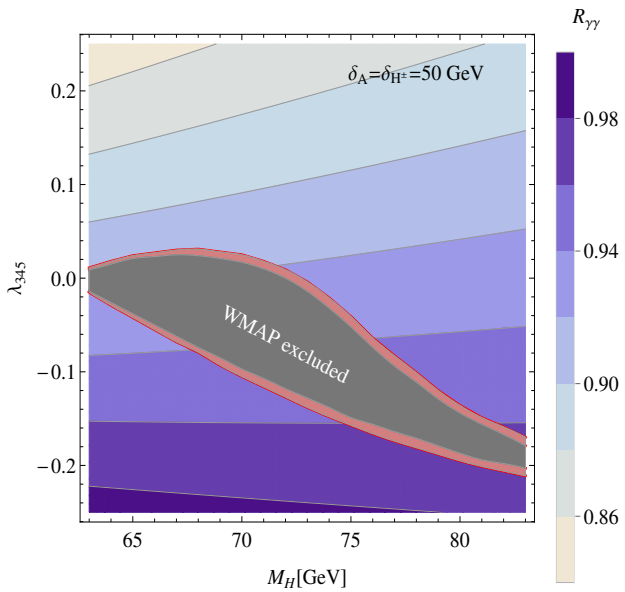


Red bound: $\Omega_{DM}h^2$ in agreement with WMAP

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

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

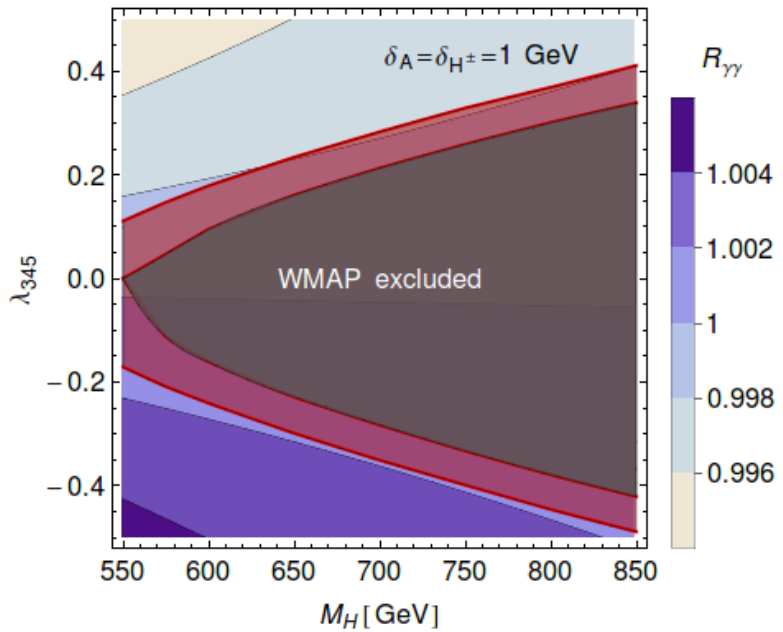


Red bound: $\Omega_{DM}h^2$ in agreement with WMAP

- 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)

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 $\Rightarrow R_{\gamma\gamma} \approx 1$

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 $\Rightarrow R_{\gamma\gamma} \approx 1$

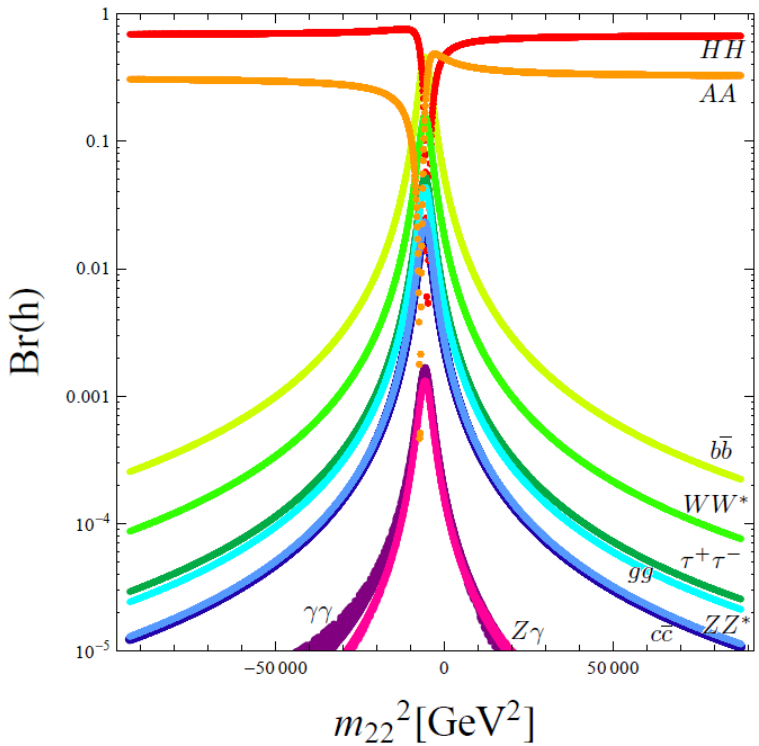
BACKUP SLIDES

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

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

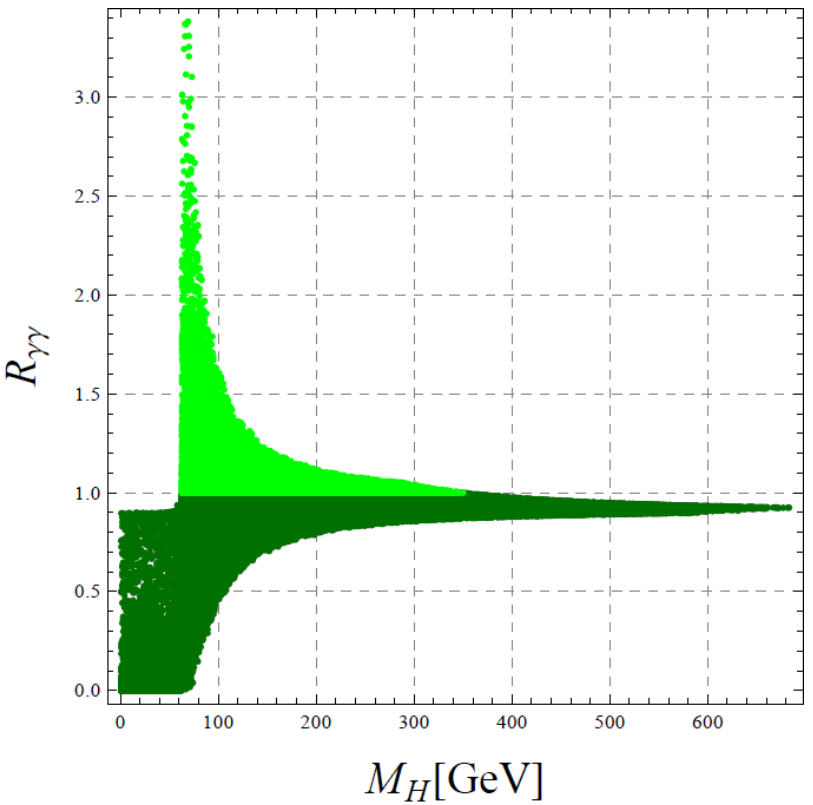
$\Rightarrow R_{\gamma\gamma} > 1$ can be solved analytically

- Constructive interference:
  - $m_{22}^2 < -2M_{H^\pm}^2 \ (\Leftrightarrow \lambda_3 < 0)$
  - with LEP bound: $m_{22}^2 < -9.8 \cdot 10^3\,\mathrm{GeV}^2$
- 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 $M_H, M_{H^\pm}, M_A > 62.5\,\text{GeV}$

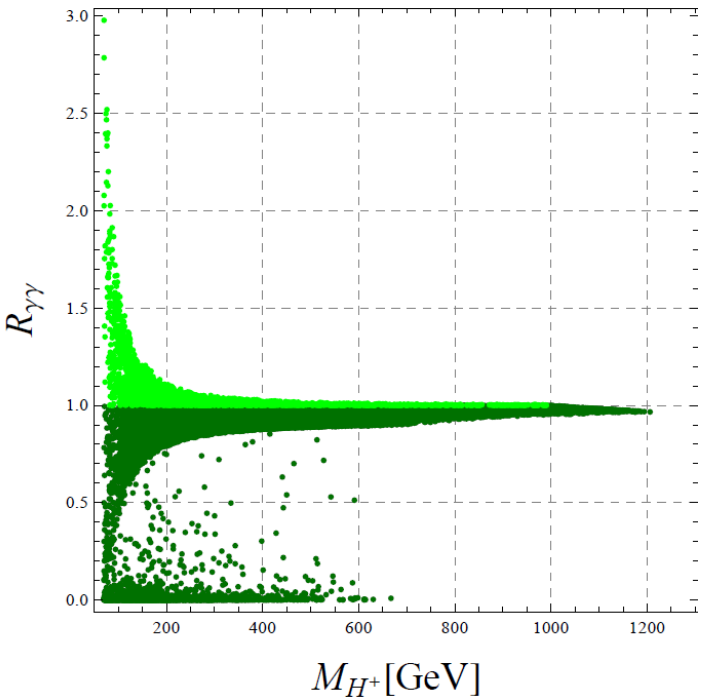


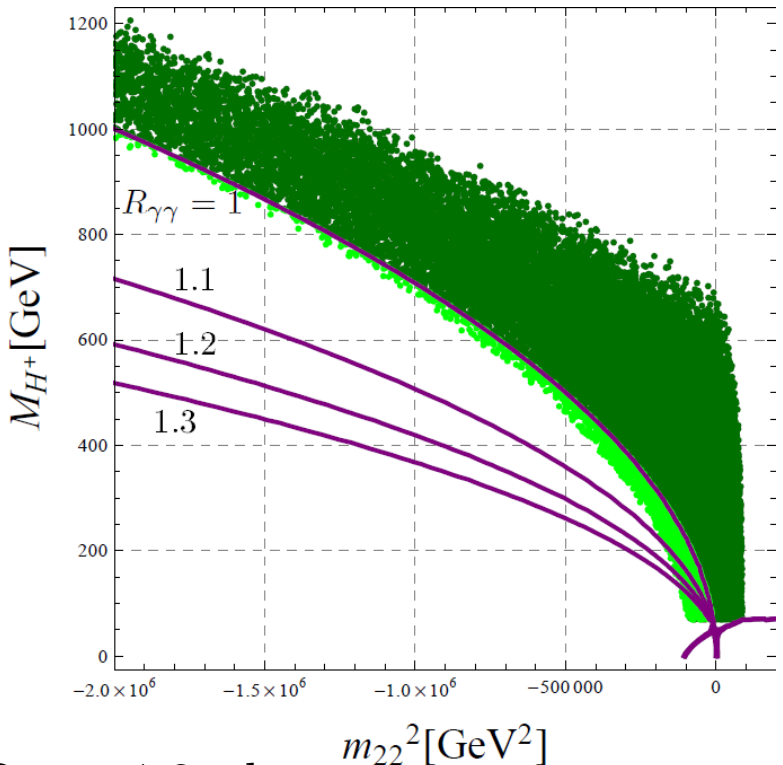
$R_{\gamma\gamma}$ vs charged scalar mass

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

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

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





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

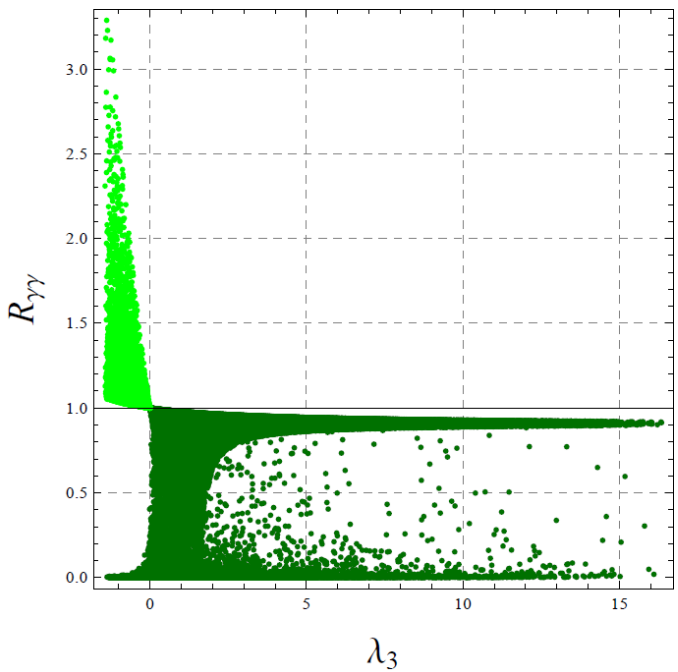
- $M_{H\pm}, M_H \lesssim 154\,\mathrm{GeV}$
  Only medium DM mass!

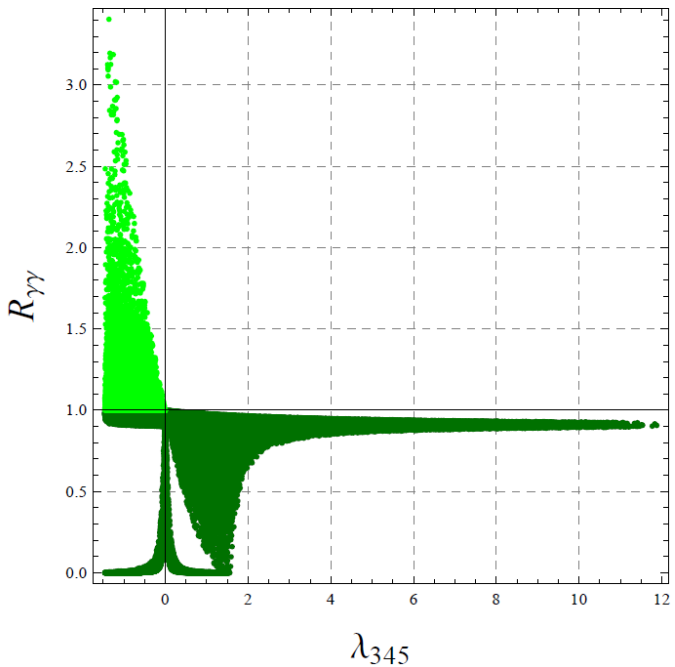
$R_{\gamma\gamma}$ vs couplings

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





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