Higgs decays to $\gamma\gamma$ and $Z\gamma$ in the Inert Doublet Model

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Phys. Rev. D 88, 035019 (2013), JHEP 09 (2013) 055

Outline

- Motivation
- Introduction to IDM
- $h \to \gamma\gamma,\ Z\gamma$ rates and their correlation
- $R_{\gamma\gamma} > 1$
  - Bounds on masses
- $1 > R_{\gamma\gamma} > 0.7 \to$ see the talk of D. Sokołowska
  - Implications for the DM
  - Combination with WMAP
- Summary

Why $h \to \gamma\gamma$?

- Important Higgs decay channel at the LHC
- Experimental hints on deviation from the SM value

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

- Sensitivity to new charged particles – well suited for studying different 2HDMs
- Sensitivity to invisible decay channels – information about extra states

$\to$ also $h \to Z\gamma$ interesting, but not enough data

Why Inert Doublet Model?

- Rich phenomenology
- $\rho = 1$ at the tree-level
- Viable DM candidate
- Thermal evolution of the Universe
  + some conditions for baryogenesis

Inert Doublet Model

[N. G. Deshpande, E. Ma, Phys. Rev. D 18 (1978) 2574, J. F. Gunion, H. E. Haber, G. Kane, S. Dawson, *The Higgs Hunter's Guide*, 1990 Addison-Wesley, R. Barbieri, L. J. Hall, V. S. Rychkov, Phys.Rev. D74 (2006) 015007, I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, D. Sokołowska, Phys. Rev. D 82 (2010) 123533]

IDM – a 2HDM with the scalar potential (real parameters):

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

- **D symmetry**: $\phi_D \to -\phi_D$, $\phi_S \to \phi_S$
- Yukawa interactions: type I (only ϕ_S couples to fermions)
- $\mathcal{L}$ – **D-symmetric**
- **D-symmetric vacuum state** $\langle\phi_S\rangle = \frac{v}{\sqrt{2}}$, $\langle\phi_D\rangle = 0$

$\Rightarrow$ **EXACT D-symmetry**

- Number of theoretical and experimental constraints

Particle spectrum of IDM

[E. M. Dolle, S. Su, Phys. Rev. D 80 (2009) 055012, L. Lopez Honorez, E. Nezri, F. J. Oliver, M. Tytgat, JCAP 0702 (2007) 028, D. Sokołowska, arXiv:1107.1991 [hep-ph]]

- 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
- D symmetry **exact** $\Rightarrow$ lightest D-odd particle stable $\Rightarrow$ **DM candidate**
- DM$= H$, so $M_H < M_{H^\pm}, M_A$
- Three regions of DM mass consistent with astrophysical observations (WMAP: $0.1018 < \Omega_{DM} h^2 < 0.1234$):
  - $M_H \lesssim 10\,\text{GeV}$
  - $40\,\text{GeV} < M_H < 150\,\text{GeV}$
  - $M_H \gtrsim 500\,\text{GeV}$

$\gamma\gamma$ and $Z\gamma$ decay rates of the Higgs boson

[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, BŚ, M. Krawczyk, Phys. Rev. D 88 (2013) 035019]

$R_{\gamma\gamma}$ – 2-photon decay rate, $R_{Z\gamma}$ – $Z\gamma$ decay rate

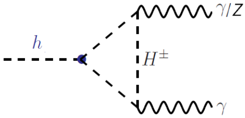
$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \to \gamma\gamma)^{IDM}}{\Gamma(h \to \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

$R_{Z\gamma}$ – treated analogously

- Largest contribution from gg fusion
- $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$ (not true in other 2HDMs)

Two sources of deviation from $R_{\gamma\gamma} = 1$:

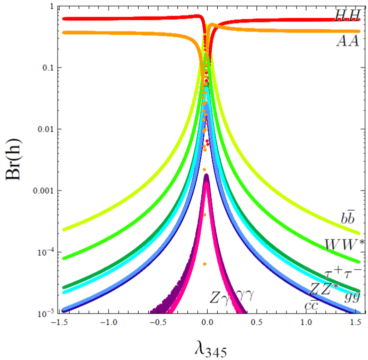
- **invisible decays** $h \to HH$, $h \to AA$ in $\Gamma(h)^{IDM}$
- **charged scalar loop** in $\Gamma(h \to \gamma\gamma)^{IDM}$



Invisible decays

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

- Controlled by: $\mathbf{M_H}$, $\mathbf{M_A}$, $\lambda_{345} \sim hHH$, $\lambda_{345}^- \sim hAA$
- Invisible decays, if kinematically allowed, dominate over SM channels.
- Plot for $M_A = 58$ GeV, $M_H = 50$ GeV

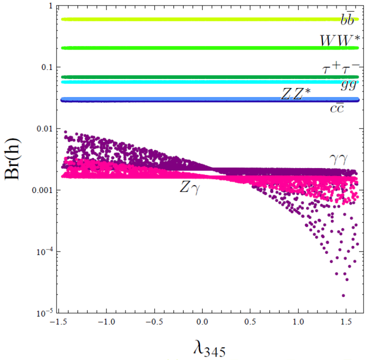


Charged scalar $H^\pm$ loop

[J. R. Ellis, M. K. Gaillard and D. V. Nanopoulos, Nucl. Phys. B 106 (1976) 292, M. A. Shifman, A. I. Vainshtein, M. B. Voloshin and V. I. Zakharov, Sov. J. Nucl. Phys. 30 (1979) 711 [Yad. Fiz. 30, 1368 (1979)]

$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \mathcal{A}^{SM} + \frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$

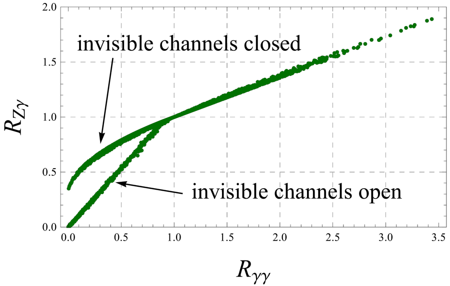
- Constructive or destructive interference between SM and $H^\pm$ contributions
- Controlled by $M_{H^\pm}$ and $2M_{H^\pm}^2 + m_{22}^2 \sim \lambda_3 \sim hH^+H^-$
- **Invisible channels closed $\Rightarrow H^\pm$ contribution visible**



$h \to \gamma\gamma$ vs $h \to Z\gamma$

[BŚ, M. Krawczyk, Phys. Rev. D 88 (2013) 035019, formulas for $h \to Z\gamma$: A. Djouadi, Phys.Rept. 459 (2008) 1, C.-S. Chen, C.-Q. Geng, D. Huang, L.-H. Tsai, Phys.Rev.D 87 (2013) 075019]

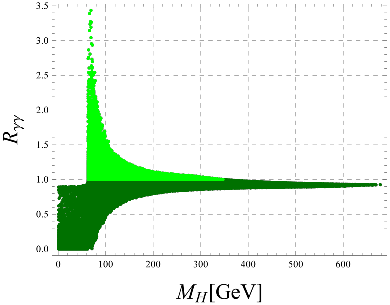
- Sensitivity to invisible channels
- $R_{\gamma\gamma}$ and $R_{Z\gamma}$ positively correlated
- $R_{\gamma\gamma} > 1 \Leftrightarrow R_{Z\gamma} > 1$



$R_{\gamma\gamma}$ vs Dark Matter (H) mass

[A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021, BŚ, M. Krawczyk, Phys. Rev. D 88 (2013) 035019]

- Invisible channels open $\Rightarrow$ **no enhancement in h $\to \gamma\gamma$ possible**
- Enhanced $R_{\gamma\gamma}$ for $M_H, M_{H^\pm}, M_A > 62.5$ GeV
- **$R_{\gamma\gamma} > 1 \Rightarrow$ very light DM excluded**

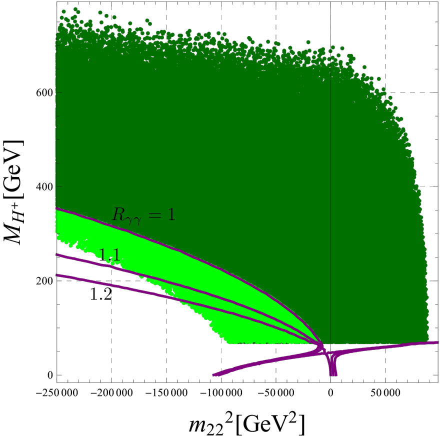


$R_{\gamma\gamma}$ vs charged scalar mass

Enhanced $R_{\gamma\gamma}$ even for big values of $M_{H^\pm}$

$\mathbf{R_{\gamma\gamma} > 1.2 \Rightarrow}$
$\mathbf{M_{H^\pm}, M_H \lesssim 154\,GeV}$

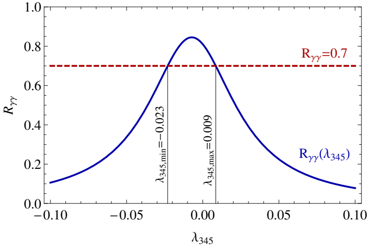
- Only medium DM mass
- Light charged scalar

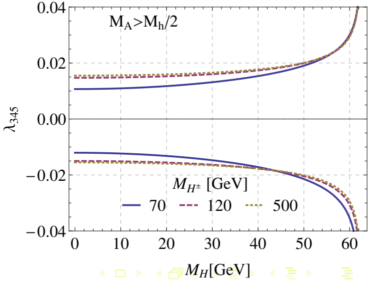


$R_{\gamma\gamma}$ constraints on $\lambda_{345} \sim hHH$

[M. Krawczyk, D. Sokołowska, P. Swaczyna, BŚ, JHEP 09 (2013) 055]

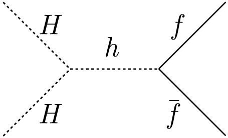
- Setting a lower limit on $R_{\gamma\gamma}$ constrains λ_{345}
- Upper and lower limits on λ_{345} depend on M_H
- Stronger than limits on $\mathrm{Br}(h \to \mathrm{inv})$ from LHC
- Stronger than limits from XENON100

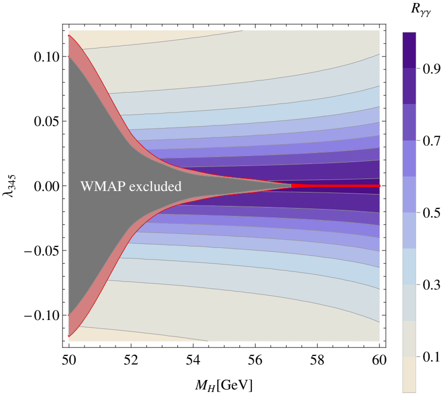




WMAP constraints on λ_{345}

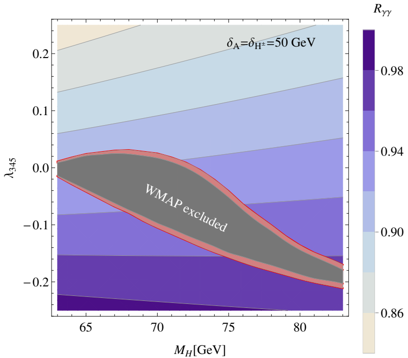
λ_{345} controls the annihilation of the DM $HH \to h \to f\bar{f} \Rightarrow$ important for the relic density of the DM

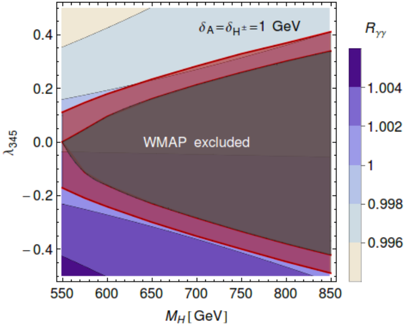




- $R_{\gamma\gamma} > 0.7$ inconsistent with WMAP for $M_H < 53\,\mathrm{GeV}$
- **Light DM excluded!**

Intermediate and heavy DM





- H of intermediate mass can constitute 100% of DM
- H constituting 100% DM inconsistent with $R_{\gamma\gamma} > 1$

- For heavy DM $R_{\gamma\gamma} \approx 1$ only very small deviations allowed

Summary

- IDM in agreement with the data (LEP, LHC and WMAP)
- $R_{\gamma\gamma}$ and $R_{Z\gamma}$ positively correlated, $R_{\gamma\gamma} > 1 \Leftrightarrow R_{Z\gamma} > 1$
- $h \to \gamma\gamma$ can provide important information about IDM, because it is sensitive to M_H and $M_{H^\pm}$
- If substantial enhancement of $R_{\gamma\gamma}$
  - Only medium masses of DM
  - Light charged scalar
  - H – subdominant component of the DM
- If H constitutes 100% of DM
  - Light DM excluded
  - Intermediate DM can accommodate only $R_{\gamma\gamma} < 1$
  - For heavy DM $R_{\gamma\gamma} \approx 1$

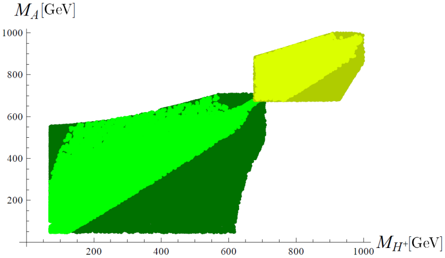
Back up

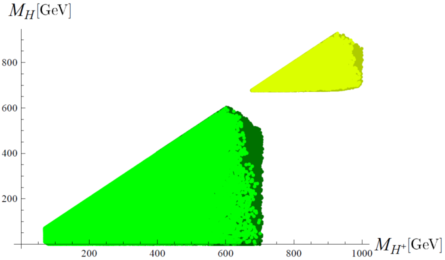
Constraints

- **Vacuum stability**: scalar potential V bounded from below
- **Perturbative unitarity**: eigenvalues Λ_i of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$
- **Existence of the Inert vacuum**: Inert state – a global minimum of the scalar potential $\Rightarrow m_{22}^2 \lesssim 9 \cdot 10^4 \text{ GeV}^2$
- **H as DM** candidate: $M_H < M_A, M_{H^\pm}$ and WMAP
- **Electroweak Precision Tests** (EWPT): S and T within 2σ ($S = 0.03 \pm 0.09$, $T = 0.07 \pm 0.08$, with correlation of 87%)
- **LEP bounds** on the scalars' masses
- **LHC**: $M_h \approx 125$ GeV

Masses of the scalars

$$
\begin{aligned}
M_h^2 &= m_{11}^2 = \lambda_1 v^2 \\
M_{H^\pm}^2 &= \frac{1}{2}(\lambda_3 v^2 - m_{22}^2) \\
M_A^2 &= \frac{1}{2}(\lambda_{345}^- v^2 - m_{22}^2) \\
M_H^2 &= \frac{1}{2}(\lambda_{345} v^2 - m_{22}^2)
\end{aligned}
$$





$R_{\gamma\gamma} > 1$ – analytical solution

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 for $M_{H^\pm},\ m_{22}^2$

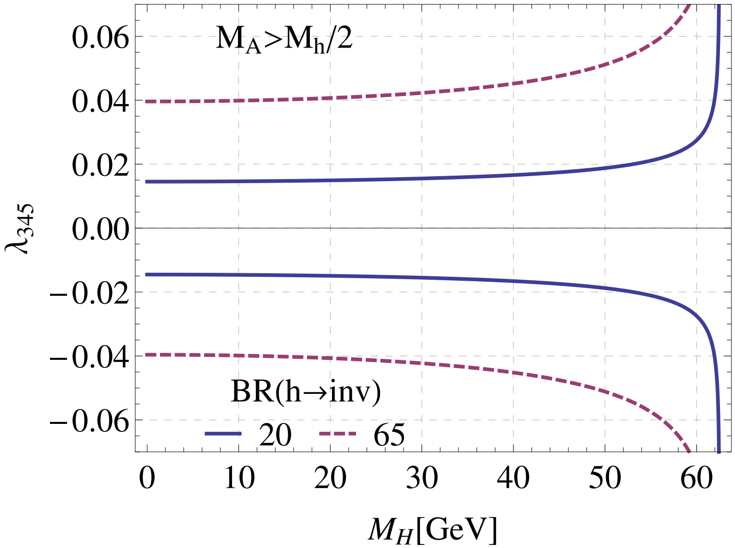
- **Constructive interference**
  - $m_{22}^2 < -2M_{H^\pm}^2$ $(\Leftrightarrow \boldsymbol{\lambda_3 < 0})$
  - with LEP bound on $M_{H^\pm} \Rightarrow$ $\mathbf{m_{22}^2 < -9.8 \cdot 10^3}$ $\mathbf{GeV^2}$
- **Destructive interference**
  - IDM contribution $\geqslant 2\times$ SM contribution
  - big m_{22}^2 required: $m_{22}^2 \gtrsim 1.8 \cdot 10^5$ GeV^2
  - **excluded** by the condition for the Inert vacuum $m_{22}^2 \lesssim 9 \cdot 10^4$ GeV^2

DM signals

[see e.g.: M. Gustafsson, S. Rydbeck, L. Lopez Honorez, E. Löndstrom, Phys. Rev. D 86 (2012) 075019]

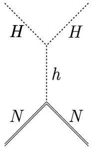
- gamma-ray lines
- cosmic and neutrino fluxes
- direct detection signals

Limits on λ_{345} from $\mathrm{Br}(h \to \mathrm{inv})$



Comparison with XENON

DM-nucleon scattering cross section $\sigma_{\mathrm{DM},N} \sim \lambda_{345}^2$



- $R_{\gamma\gamma}$ bounds on λ_{345} translated to the $(\sigma_{\mathrm{DM},N},\ M_H)$ plane
- Upper limits are stronger than those provided by XENON100