Two photon decay rate of the Higgs boson in the Inert Doublet Model

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based on arXiv:1212.4100 [hep-ph], arXiv:1304.7757[hep-ph], arXiv:1303.7102[hep-ph]

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Outlook

- Motivation
- Introduction to IDM
- $h \to \gamma\gamma$ rate
- Numerical results
  - Bounds on scalars' masses
  - Bounds on couplings
- Summary and outlook

Why $h \to \gamma\gamma$?

- Important observation channel of the Higgs boson at the LHC
- Experimental hints on deviation from the SM value
- Sensitive to the existence of new charged particles – well suited for studying different 2HDMs
- Signal strength sensitive to the existence of invisible decay channels – can provide information about extra scalars

Why IDM?

- IDM - a simple extension of the Standard Model (a special 2HDM)
- Rich phenomenology
- $\rho = 1$ at the tree-level
- DM candidate
- Interesting framework for the study of the thermal evolution of the Universe

Lagrangian of the Inert Doublet Model

$$\mathcal{L} = \mathcal{L}_{\rm gf}^{\rm SM} + \mathcal{L}_{\rm H} + \mathcal{L}_{\rm Y}$$

- $\mathcal{L}_{\rm gf}^{\rm SM}$ – SM Lagrangian describing interactions of fermions and gauge bosons
- $\mathcal{L}_{\rm H}$ – Lagrangian of the scalar sector: ϕ_S and ϕ_D

$$\mathcal{L}_{\rm H} = (D^\mu \phi_S)(D_\mu \phi_S)^\dagger + (D^\mu \phi_D)(D_\mu \phi_D)^\dagger - \mathbf{V}$$

V – scalar potential

- $\mathcal{L}_{\rm Y}$ - Yukawa Lagrangian describing interactions of scalars with fermions – **only ϕ_S couples to fermions**

Scalar potential

[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, I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, D. Sokołowska, Phys. Rev. D 82 (2010) 123533]

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

$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D) + \lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) +$$

$$\frac{1}{2}\lambda_5\left[(\phi_S^\dagger\phi_D)^2 + (\phi_D^\dagger\phi_S)^2\right]$$

- **D symmetry**: $\phi_D \to -\phi_D$, $\phi_S \to \phi_S$
- $\mathcal{L}$ – D-symmetric
- D-symmetric vacuum state $\langle\phi_S\rangle = \frac{v}{\sqrt{2}}$, $\langle\phi_D\rangle = 0$

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: $0.1018 < \Omega_{DM} h^2 < 0.1234$):
  - $M_H \lesssim 10\,\text{GeV}$
  - $40\,\text{GeV} < M_H < 150\,\text{GeV}$
  - $M_H \gtrsim 500\,\text{GeV}$

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
- H **as DM** candidate: $M_H < M_A, M_{H^\pm}$
- **Electroweak Precision Tests** (EWPT): the values of S and T parameters lie within 2σ ellipses in the S, T plane, (central values: $S = 0.03 \pm 0.09$, $T = 0.07 \pm 0.08$, with correlation equal to 87%)
- **LEP bounds** on the scalars' masses
- **LHC**: $M_h \approx 125\,\text{GeV}$

2-photon decay rate 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, arXiv:1212.4100 [hep-ph]]

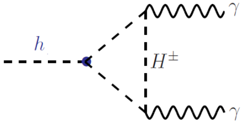
$R_{\gamma\gamma}$ – 2-photon decay rate

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

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

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

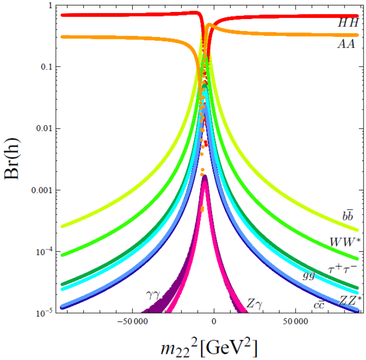
- **invisible decays** $h \to HH$, $h \to AA$ in $\Gamma(h)^{IDM}$
- **charged scalar loop** in $\Gamma(h \to \gamma\gamma)^{IDM}$



Invisible decays

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

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

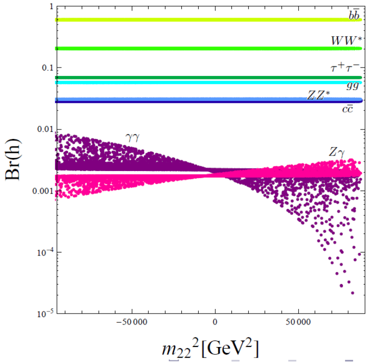


Charged scalar loop

[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 charged scalar contributions
- Controlled by $M_{H^\pm}$ and $2M_{H^\pm}^2 + m_{22}^2 \sim \lambda_3 \sim hH^+H^-$
- **If invisible channels closed charged scalar contribution visible**



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

If invisible channels closed

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

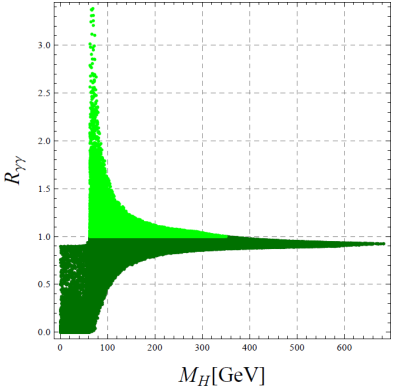
$\Rightarrow R_{\gamma\gamma} > 1$ can be solved analytically for $M_{H^\pm}$, m_{22}^2

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

[A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021, BŚ, M. Krawczyk, arXiv:1212.4100 [hep-ph]]

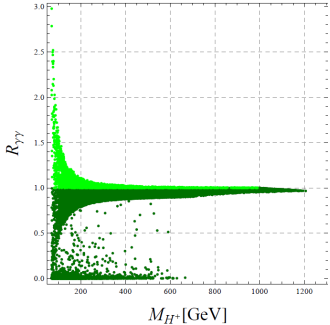
- $R_{\gamma\gamma}^{\max} \approx 3.4$
- Invisible channels open $\Rightarrow$ **no enhancement in h $\to \gamma\gamma$ possible**
- Enhanced $R_{\gamma\gamma}$ for $M_H, M_{H^\pm}, M_A > 62.5$ GeV
- **$R_{\gamma\gamma} > 1 \Rightarrow$ very light DM excluded**

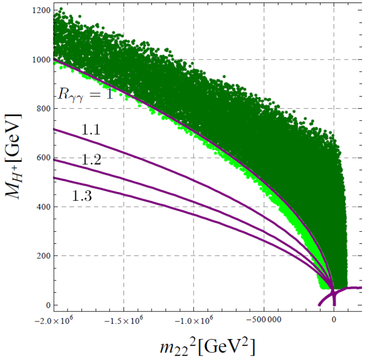


$R_{\gamma\gamma}$ vs charged scalar mass

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

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





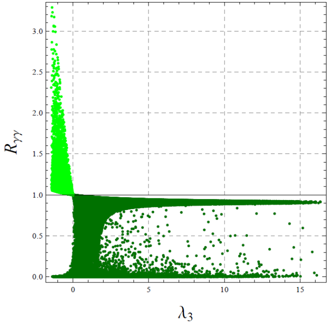
If $R_{\gamma\gamma} > 1.2$, then:

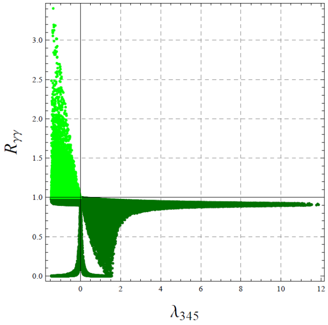
- $M_{H^\pm}, M_H \lesssim 154$ GeV
- **Only medium DM mass!**
- **Light charged scalar!**

$R_{\gamma\gamma}$ vs couplings

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

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





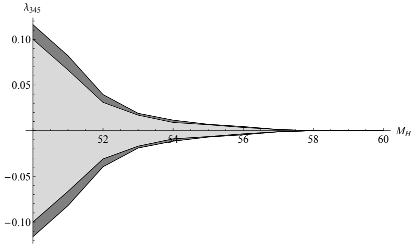
- $R_{\gamma\gamma} > 1 \Rightarrow \lambda_3, \lambda_{345} < 0$
- $R_{\gamma\gamma} > 1.3 \Rightarrow -1.46 < \lambda_3, \lambda_{345} < -0.24$

What if $R_{\gamma\gamma} < 1$ – Preliminary

[M. Krawczyk, D. Sokołowska, P. Swaczyna, B. Ś., work in progress]

Example: $0.7 < R_{\gamma\gamma} < 1$ and light DM ($M_H \lesssim 10\,\mathrm{GeV}$) $\Rightarrow$ $|\lambda_{345}| \lesssim 0.04$

- λ_{345} controls the annihilation of DM, e.g. $HH \to h \to f\bar{f}$
- Too low relic abundance of DM to fit WMAP observations



Low DM region excluded

Summary

- IDM in agreement with the data (LEP, LHC and WMAP)
- $h \to \gamma\gamma$ can provide important information about IDM, because it is sensitive to M_H and $M_{H^\pm}$
- If substantial enhancement of $R_{\gamma\gamma}$
  - $\Rightarrow$ Only medium masses of DM
  - $\Rightarrow$ Light charged scalar
  - $\Rightarrow$ Constrained couplings λ_{hHH}, $\lambda_{hH^+H^-}$
- If $0.7 < R_{\gamma\gamma} < 1$ and $M_H \lesssim 10\,\mathrm{GeV}$
  - $\Rightarrow$ $|\lambda_{345}| \lesssim 0.04$
  - $\Rightarrow$ light DM excluded by WMAP

Back up

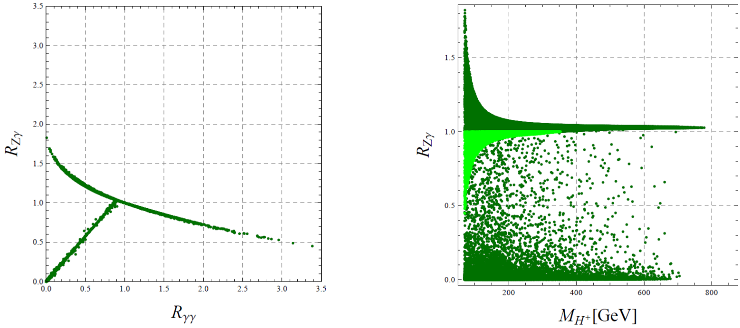
DM signals

[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

$h \to Z\gamma$ – Preliminary

[formulas: A. Djouadi, Phys.Rept. 459, 1 (2008), arXiv:hep-ph/0503173 [hep-ph]]



- $R_{Z\gamma} \lesssim 1.9$
- The straight line – invisible channels open
- $R_{Z\gamma}$ anticorrelated with $R_{\gamma\gamma}$.