2-photon decay rate of the Scalar boson in the Inert Doublet Model

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05.03.2013
Recontres de Moriond, La Thuile, Italy

The Inert Doublet Model (IDM)

[N. G. Deshpande, E. Ma, Phys. Rev. D 18 (1978) 2574, R. Barbieri, L. J. Hall, V. S. Rychkov, Phys. Rev. D 74 (2006) 015007, Q.-H. Cao, E. Ma, G. Rajasekaran, Phys. Rev. D 76 (2007) 095011, 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]]

$\Rightarrow$ **For a review of IDM see the talk by M. Tytgat**

- Simple extension of the Standard Model (SM)
- Two scalar doublets ϕ_S and ϕ_D, $\langle \phi_S \rangle = \frac{v}{\sqrt{2}}$, $\langle \phi_D \rangle = 0$
- ϕ_S: h – SM-like scalar, 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: $\phi_D \rightarrow -\phi_D \Rightarrow$ lightest D-odd particle stable $\Rightarrow$ **DM candidate** (H)
  Three regions of masses (low, medium or large) consistent with astrophysical observations

2-photon decay rate of the SM-like scalar

[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)], P. Posch, Phys. Lett. B696 (2011) 447, A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021]

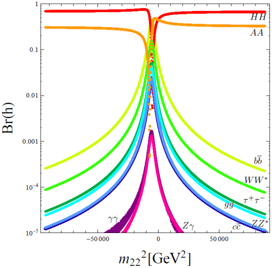
$R_{\gamma\gamma}$ – 2-photon decay rate

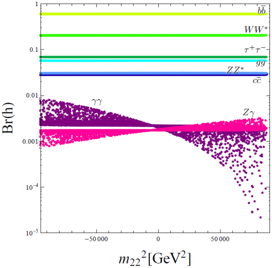
$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \to \gamma\gamma)^{IDM}}{\Gamma(h \to \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

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

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





Scan of the parameter space

Parameters: $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{22}^2)$ or $(M_h, M_H, M_A, M_{H^\pm}, m_{22}^2, \lambda_2)$

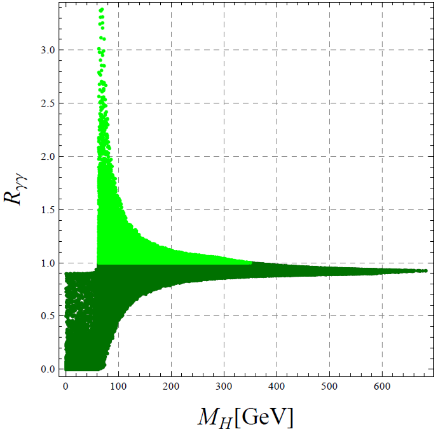
We took into account:

- Vacuum stability
- Perturbative unitarity
- Electroweak Precision Tests (EWPT)
- LEP bounds
- LHC data: $M_h = 125\,\mathrm{GeV}$
- H as DM candidate
- Existence of the Inert vacuum (new) $\Rightarrow$ $\mathbf{m_{22}^2 \lesssim 9 \cdot 10^4\ GeV^2}$

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

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

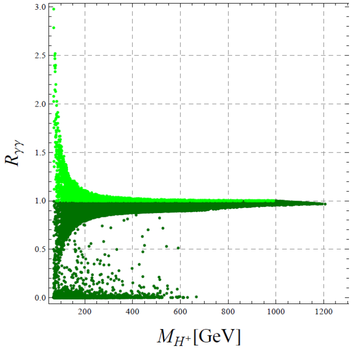
- Invisible channels open $\Rightarrow$ **no enhancement in $h \to \gamma\gamma$ possible**
- Enhanced $R_{\gamma\gamma}$ for $M_H, M_{H^\pm}, M_A > 62.5$ GeV

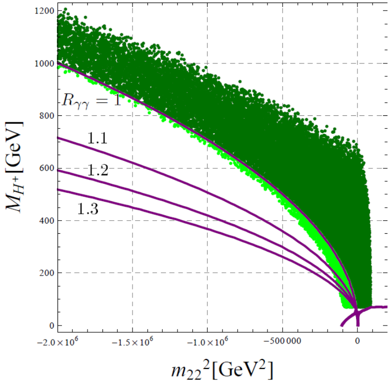


$R_{\gamma\gamma}$ vs charged scalar mass

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

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





If $R_{\gamma\gamma} > 1.3$, then:

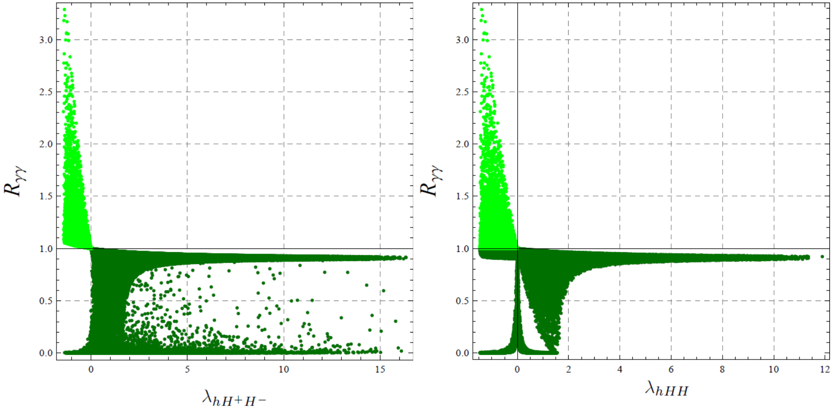
- $M_{H^\pm}, M_H \lesssim 135$ GeV
  Only medium DM mass!

Summary

- IDM in agreement with the data (LHC and WMAP)
- $h \to \gamma\gamma$ can provide important information about IDM, because is sensitive to M_H and $M_{H^\pm}$
- If $R_{\gamma\gamma} > 1.3$
  - $62.5\,\text{GeV} < M_{H^\pm}, M_H \lesssim 135\,\text{GeV}$
    $\Rightarrow$ Only medium masses of DM!
    $\Rightarrow$ Light charged scalar!
  - $-1.46 < \lambda_{hH^+H^-}, \lambda_{hHH} < -0.24$
- **I eagerly wait for the experimental results!**

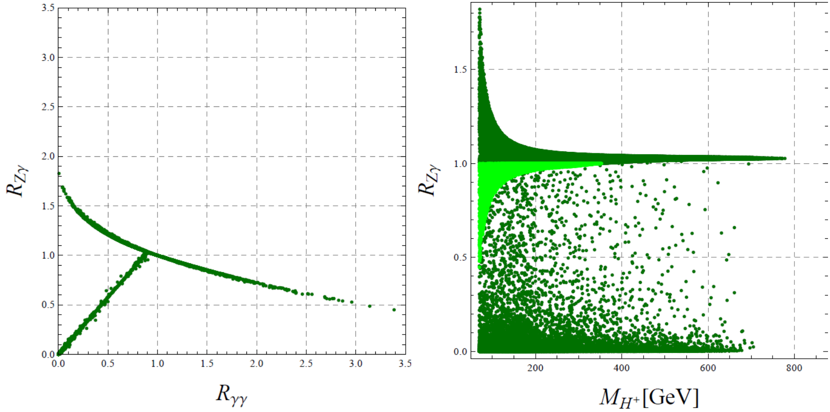
Back up

$R_{\gamma\gamma}$ vs λ_{hHH} and λ_{hH^+H}



$h \to Z\gamma$ - Preliminary

[See also talk by A. Arhrib at Toyama Conference 02.2013]



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]

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

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

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

- $\mathbb{Z}_2$ symmetry (D symmetry): $\phi_D \to -\phi_D$, $\phi_S \to \phi_S$
- Positivity constraints:
  a) $\lambda_1 > 0$, $\lambda_2 > 0$, b) $\lambda_3 + \sqrt{\lambda_1\lambda_2} > 0$,
  c) $\lambda_3 + \lambda_4 + \lambda_5 + \sqrt{\lambda_1\lambda_2} > 0$

Constraints

- Vacuum stability: For a stable vacuum state to exist it is necessary that the potential V is bounded from below, which leads to:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1\lambda_2} > 0.$$

- Perturbative unitarity: For the theory to be perturbatively unitary it is required that the eigenvalues Λ_i of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$.
- Existence of the Inert vacuum: The Inert vacuum can be realized only if the following conditions are fulfilled:

$$M_h^2,\ M_H^2,\ M_A^2,\ M_{H^\pm}^2 \geqslant 0, \qquad \frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$

From the existence of the Inert vacuum and the Higgs boson with mass $M_h = 125\,\text{GeV}$, and unitarity bounds on λ_2, follows a bound on m_{22}^2:

$$m_{22}^2 \lesssim 9 \cdot 10^4\ \text{GeV}^2.$$

Constraints

- H as DM candidate: We assume that H is the DM candidate, so $M_H < M_A, M_{H^\pm}$. Studies of the DM in the IDM show that if H is to account for the observed relic density of DM, it should have mass in one of the three regions: $M_H < 10\,\text{GeV}$, $40\,\text{GeV} < M_H < 80\,\text{GeV}$ or $M_H > 500\,\text{GeV}$.
- Electroweak Precision Tests (EWPT): We demand that the values of S and T parameters calculated in the IDM lie within 2σ ellipses in the S, T plane, with the following central values: $S = 0.03 \pm 0.09$, $T = 0.07 \pm 0.08$, with correlation equal to 87%.
- LEP: We use the LEPI and LEPII bounds on the scalar masses:

$$M_{H^\pm} + M_H > M_W, \quad M_{H^\pm} + M_A > M_W,$$
$$M_H + M_A > M_Z, \quad 2M_{H^\pm} > M_Z, \quad M_{H^\pm} > 70\,\text{GeV}$$

and exclude the region where:
$M_H < 80\,\text{GeV}$ and $M_A < 100\,\text{GeV}$ and $M_A - M_H > 8\,\text{GeV}$.

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