Multi-Scalar Extensions of the Standard Model: Dark Matter and LHC

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"What is Dark Matter?"
Nordita, Stockholm, 29.05.2014

collaboration with M. Krawczyk, B. Świeżewska and P. Swaczyna
JHEP 09 (2013) 055 (arXiv:1305.6266)
Acta Phys. Polon. B44 (2013) 11, 2163-2170 (arXiv:1309.7880)
also work in progress with V. Keus, S. King, S. Moretti

Higgs particle discovered

- 2012 – a Higgs boson with mass $M_h \approx 125$ GeV discovered at the LHC
- **VERY** SM-like:

$$\text{ATLAS: } M_h = 125.5\,\text{GeV},\ \mu^{tot} = 1.30^{+0.18}_{-0.17}$$

$$\text{CMS: } M_h = 125.7\,\text{GeV},\ \mu^{tot} = 0.80^{+0.14}_{-0.14}$$

$$\Gamma_H < 4.2\ \cdot \Gamma_H^{SM}$$

$$h \text{ is a scalar } 0^+\text{; states } 0^-, 2^+ \text{ excluded at } > 3\sigma$$

$\Rightarrow$ strong constraints for extensions of the Standard Model...

- yet we do expect some New Physics to exist
  - neutrino masses
  - baryon asymmetry and baryogenesis
  - vacuum stability
  - Dark Matter
  - ...

Dark Matter

Evidence for Dark Matter at diverse scales:

- galaxy scales: rotational speeds of galaxies
- cluster scales: gravitational lensing at galaxy clusters
- horizon scales: anisotropies in the CMB

$\Rightarrow$ **around 25 % of the Universe is:**

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

$\Rightarrow$ **W**eakly **I**nteracting **M**assive **P**article

- stable due to the discrete symmetry
- standard particle physics' candidate: neutralino

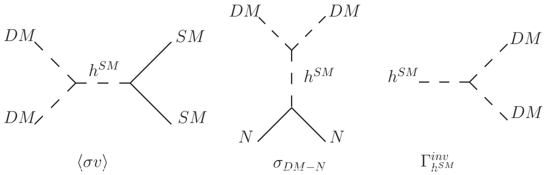
  $\rightarrow$ but no sign of SUSY at the LHC

  $\rightarrow$ a scalar candidate?

Two Higgs Doublet Model

- two scalar $SU(2)_W$ doublets Φ_S, Φ_D with the hypercharge $Y = +1$
- rich phenomenology: various Yukawa couplings, CP violation in the scalar sector, different types of vacua, breaking of $U(1)_{QED}$, phase transitions in the early Universe, baryogenesis,...
- 2HDM with an exact Z_2 symmetry: Inert Doublet Model (IDM)
  - $\rightarrow$ SM-like Higgs boson
    - $\rightarrow$ modifications of the diphoton decay rate possible
  - $\rightarrow$ a Dark Matter candidate
- the IDM as the Higgs portal model:

$$\text{SM sector} \overset{\text{Higgs}}{\longleftrightarrow} \text{DM sector}$$



Testing IDM

Current experiments impose constraints on the 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
- 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.

[N. G. Deshpande and E. Ma 1978, R. Barbieri, L. J. Hall and V. S. Rychkov '06, Q. H. Cao et al. '07, P. Agrawal et al. '09, E. M. Dolle and S. Su '09, C. Arina et al. '09, T. Hambye and M. H. G. Tytgat '08, E. Nezri et al. '09, S. Andreas et al. '09, L. Lopez Honorez et al. '07, L. L. Honorez and C. E. Yaguna '10, M. Gustafsson et al. '07, E. Lundstrom et a. '09, M. Krawczyk and D.S '09, I.F. Ginzburg, K.A. Kanishev, M. Krawczyk and D.S. '10, M. Krawczyk et al. '13, A. Arhrib et al. '13...]

Direct & indirect detection experiments

- direct detection signals (DAMA, CoGeNT, CRESST-II, CDMS-II)

→ light DM

→ **no agreement with exclusion limits** (XENON100, LUX)

- no indirect DM detection signals as of 2013:
  - γ-lines (INTEGRAL – 511 keV, Fermi-LAT – 130 GeV)

  → DM interpretation disfavored

  - e^+/e^- excess (Pamela, Fermi-LAT)

  → "signature not unique for DM, astrophysical explanation possible"

Direct & indirect detection experiments do not provide a coherent picture of Dark Matter.

IDM in LHC

What can LHC tell us about the IDM & 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 Planck)

$$0.1118 < \Omega_{DM} h^2 < 0.128$$

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

$$\text{ATLAS} \quad : \quad R_{\gamma\gamma} = 1.57^{+0.33}_{-0.28}$$
$$\text{CMS} \quad : \quad R_{\gamma\gamma} = 0.77^{+0.27}_{-0.27}$$

Both values consistent with $R_{\gamma\gamma} = 1$, still room for "new physics"

Z_2-symmetric 2HDM

Scalar potential V invariant under a D-transformation of Z_2 type:

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

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

- all parameters $\in \mathbf{R}$ – no CP violation
- Yukawa interaction: Model I, only Φ_S couples to fermions
- whole Lagrangian explicitly D-symmetric

  $\to$ spontaneous violation by $\langle \Phi_D \rangle \neq 0$ still possible

The general type of EWSB v.e.v:

$$\langle \Phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ v_D \end{pmatrix}$$

IDM

Deshpande, Ma, ’78, Barbieri et al., ’06

$$\langle\Phi_S\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle\Phi_D\rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- Φ_S as in SM (SM-like Higgs boson h)

  Φ_D – "dark" or inert doublet with 4 dark scalars $(H, A, H^\pm)$, no interaction with fermions
- exact D-symmetry – both in Lagrangian and in the extremum
- only Φ_D has odd D-parity

  → the lightest scalar is **a candidate for the dark matter**

Constraints

(1) **Vacuum stability**: scalar potential V bounded from below

(2) **Existence of the Inert vacuum**: a *global* minimum of V

to avoid metastability issues at tree-level

(3) **Perturbative unitarity**: eigenvalues Λ_i of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$

(4) **Higgs mass**: $M_h = 125$ GeV

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

(5) **EWPT & LEP**: bounds on masses of the scalars

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

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

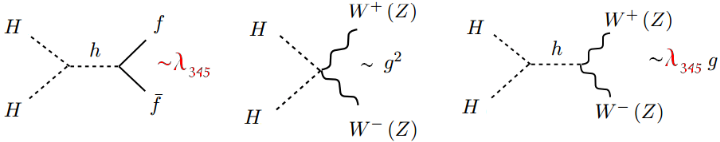
$$\delta_A = M_A - M_H < 8\,\text{GeV} \Rightarrow M_H + M_A > M_Z$$

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

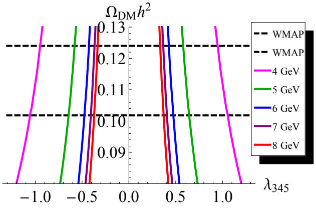
(6) ***H* as DM candidate**: $M_H < M_A, M_{H^\pm}$ with proper $\Omega_{DM} h^2$

$$\lambda_{345} \sim g_{HHh} \text{ and } M_i$$

λ_{345}: relic density constraints



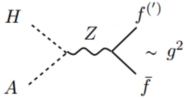
$$0.1118 < \Omega_{DM} h^2 < 0.128 \Rightarrow \lambda_{345}^{\min}, \lambda_{345}^{\max}$$



- **low DM mass** $M_H \lesssim 10$ GeV, $\lambda_{345} \sim \mathcal{O}(0.5)$
- **medium DM mass** $M_H \approx (40 - 160)$ GeV, $\lambda_{345} \sim \mathcal{O}(0.05)$
- **high DM mass** $M_H \gtrsim 500$ GeV, $\lambda_{345} \sim \mathcal{O}(0.1)$

Comment: coannihilation

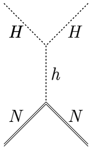
coannihilation (for $M_{A,H^\pm} - M_H \lesssim (10-20)$ GeV):



- constructive or destructive
- destroys the simple relation between $\Omega_{DM}h^2$ and $\sigma_{DM,N}$
- very important for the heavy DM mass region in the IDM
- important in 3HDM

λ_{345}: direct detection

λ_{345} – not just $\Omega_{DM} h^2$ but also direct detection:

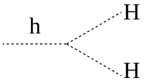


DM-scattering on nucleus through the Higgs exchange

$$\sigma_{DM,N} \propto \lambda_{345}^2/(M_H + M_N)^2$$

λ_{345}: invisible decays of the Higgs boson

- $h \to HH$ – invisible decay (H is stable)



- augmented total width of the Higgs boson

$$\Gamma(h \to HH) = \frac{\lambda_{345}^2 v^2}{32\pi M_h} \sqrt{1 - \frac{4M_H^2}{M_h^2}}$$

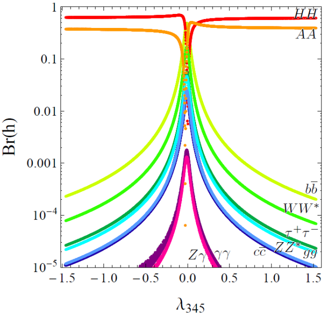
- LHC: $\mathrm{Br}(h \to \mathrm{inv}) < 37\%$

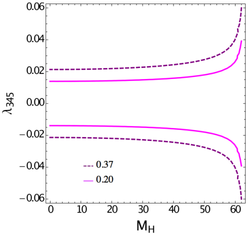
  global fit: $\mathrm{Br}(h \to \mathrm{inv}) \lesssim 20\% \Rightarrow$

  bounds on M_{DM} and λ_{345}

[G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, PLB 723 (2013) 340]

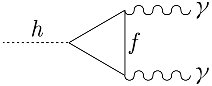
For $M_H = 50\,\mathrm{GeV}$, $M_A = 58\,\mathrm{GeV}$.



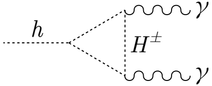


λ_{345}: Two-photon decay of the Higgs boson, $h \to \gamma\gamma$

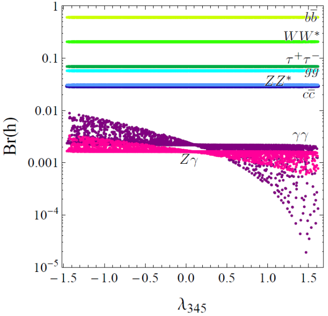
- $h\gamma\gamma$ not present at tree level
- At loop level in the SM



- In the IDM – additional $H^{\pm}$



- Width of $h \to \gamma\gamma$ modified



for invisible channels closed

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

$$\lambda_3 = \lambda_{345} - 2\frac{M_{H^\pm}^2 - M_H^2}{v^2}$$

Signal strength in the $h \to \gamma\gamma$ channel

$R_{\gamma\gamma}$ – signal strength

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

$R_{\gamma\gamma}$ can differ from the SM value $R_{\gamma\gamma} = 1$ because of:

- 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 $\Gamma(h \to \gamma\gamma)^{IDM}$
  - 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 $\lambda_{345} = g_{HHh}$)

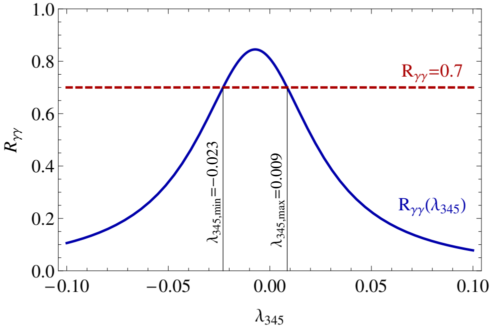
$$R_{\gamma\gamma} = 1.57^{+0.33}_{-0.28} \text{ (ATLAS)}, \; R_{\gamma\gamma} = 0.77 \pm 0.27 \text{ (CMS)}$$

[ATLAS Collaboration, PLB 726 (2013) 88, CMS Collaboration, CMS PAS HIG-13-005 (2013)]

$R_{\gamma\gamma}$ for the IDM

[M. Krawczyk, D.S, P. Swaczyna, B. Świeżewska, JHEP 09 (2013) 055]

Example: $R_{\gamma\gamma}(\lambda_{345})$ for $M_H = 55\,\text{GeV},\ M_A = 60\,\text{GeV},\ M_{H^\pm} = 120\,\text{GeV}$



$$R_{\gamma\gamma} > 0.7, 0.8, \ldots \Rightarrow \lambda_{345}^{\text{min}}, \lambda_{345}^{\text{max}}$$

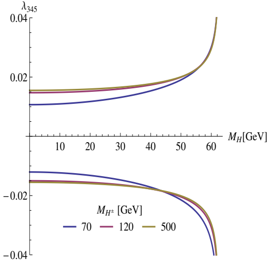
Do we get a proper relic density for those values?

Low DM mass

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

$h \to AA$ channel closed, $h \to HH$ channel open

main annihilation channel: $HH \to h \to b\bar{b}$



- Correct relic density

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

- CDMS-II reported event:

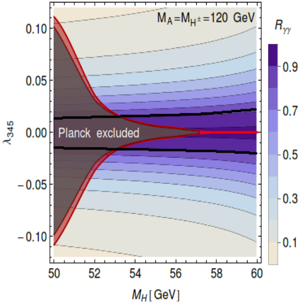
  $M_H = 8.6$ GeV $\Rightarrow |\lambda_{345}| \approx (0.3 - 0.4)$

- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02$

Low DM mass excluded

Medium DM mass (1) – HH channel open

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



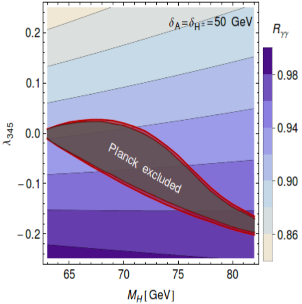
Red bound: $\Omega_{DM}h^2$ in agreement with Planck

Black line: $R_{\gamma\gamma} = 0.7$

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

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

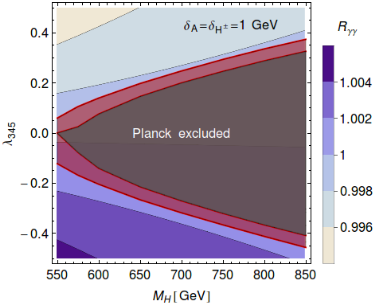


Red bound: $\Omega_{DM}h^2$ in agreement with Planck

- Max $R_{\gamma\gamma}$ in agreement with Planck $\Rightarrow$ $R_{\gamma\gamma} \lesssim 0.98 < 1$
- $R_{\gamma\gamma} > 1$ possible if $\Omega_H h^2 < \Omega_{DM} h^2$ (subdominant DM candidate)

High DM mass

$$M_H \gtrsim 550\,\text{GeV}, \quad M_A = M_{H^\pm} = M_H + 1\,\text{GeV}$$

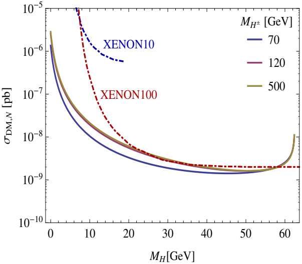


Red bound: $\Omega_{DM} h^2$ in agreement with Planck

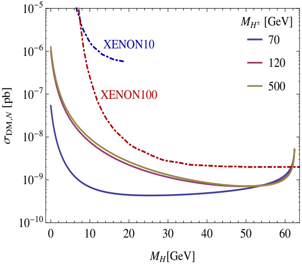
- $R_{\gamma\gamma}$ in agreement with Planck $\Rightarrow R_{\gamma\gamma} \approx 1$

Comparison with XENON

$$\sigma_{\rm DM,N} = \frac{\lambda_{345}^2}{4\pi M_h^4} \frac{m_N^4}{(m_N + M_H)^2} f_N^2$$



$R_{\gamma\gamma} = 0.7$

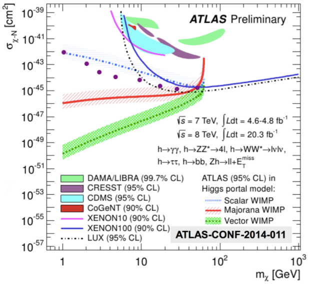


$R_{\gamma\gamma} = 0.8$

$R_{\gamma\gamma}$ bounds stronger than XENON10/100, comparable with LUX (2013) exclusion limits

The IDM: Summary

- $\Omega_{DM}h^2, \sigma_{DM,N}, R_{\gamma\gamma}, \Gamma(h)_inv$ depend on the same coupling
- $\Omega_{DM}h^2 + R_{\gamma\gamma}$: strong constraints for the IDM
- $R_{\gamma\gamma} < 1$ preferred
- $R_{\gamma\gamma} > 1$ then subdominant DM candidate
- currently also $Br(h \to inv)$:



(Z + MET, 2 jets + MET)

purple dots – our $R_{\gamma\gamma} = 0.7$ exclusion for the IDM

3HDM

Three $SU(2)$ doublets with Z_2-symmetry:

$$\phi_1 = \left(\begin{array}{c} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{array} \right), \quad \phi_2 = \left(\begin{array}{c} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{array} \right), \quad \phi_3 = \left(\begin{array}{c} H_3^+ \\ \frac{v + H_3^0 + iA_3^0}{\sqrt{2}} \end{array} \right)$$

$$V = \sum_i^3 \left[-|\mu_i^2| (\phi_i^\dagger \phi_i) + \lambda_{ii} (\phi_i^\dagger \phi_i)^2 \right] + \sum_{ij}^3 \left[\lambda_{ij} (\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij} (\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right]$$
$$+ \left(-\mu_{12}^2 (\phi_1^\dagger \phi_2) + \lambda_1 (\phi_1^\dagger \phi_2)^2 + \lambda_2 (\phi_2^\dagger \phi_3)^2 + \lambda_3 (\phi_3^\dagger \phi_1)^2 + h.c \right)$$

- ϕ_3 – SM-like doublet with SM-like Higgs H_3^0
- $\mu_{12}^2 \neq 0 \Rightarrow$ mixing between ϕ_1 and ϕ_2

$$H_1 = \cos\alpha H_1^0 + \sin\alpha H_2^0, \quad H_2 = \cos\alpha H_2^0 - \sin\alpha H_1^0$$

(similar for A_i and $H_i^\pm$)

- H_1 – **DM candidate**, other dark particles heavier

work in progress with V. Keus, S.F. King, S. Moretti

DM annihilation in 3HDM

- Possible scenarios for $M_{H_1} < M_W$:

(A) **no coannihilation effects**: $M_{H_1} < M_{H_2,A_1,A_2,H_1^\pm,H_2^\pm}$

(B) **coannihilation** with H_2: $M_{H_1} \approx M_{H_2} < M_{A_1,A_2,H_1^\pm,H_2^\pm}$

(C) **coannihilation** with A_1: $M_{H_1} \approx M_{A_1} < M_{H_2,A_2,H_1^\pm,H_2^\pm}$

(D) **coannihilation** with H_1, A_1, A_2:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} < M_{H_1^\pm,H_2^\pm}$$

- If M_{H_1} heavier (to escape LEP limit for $H^\pm$) also coannihilation with $H_i^\pm$.

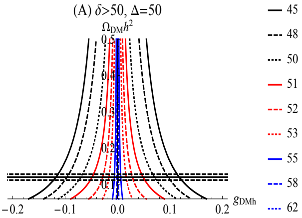
- **Toy Model** with additional "symmetry":

$$\mu_1^2 = \mu_2^2,\ \lambda_{13} = \lambda_{23},\ \lambda'_{13} = \lambda'_{23},\ \lambda_3 = \lambda_2$$

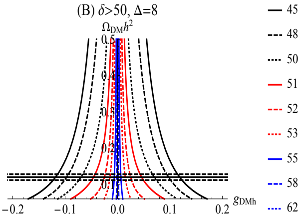
$$H_1 = \frac{1}{\sqrt{2}}(H_1^0 + H_2^0), \quad H_2 = \frac{1}{\sqrt{2}}(H_2^0 - H_1^0)$$

Relic density: $M_Z/2\,\text{GeV} < M_{DM} < M_h/2\,\text{GeV}$

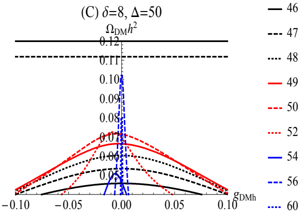
$$M_{A_1} = M_{H_1} + \delta \,;\, M_{H_2} = M_{H_1} + \Delta$$



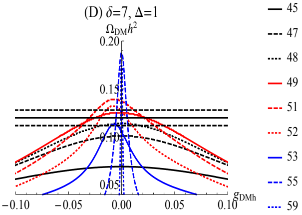
no coannhilation



coannhilation with H_2

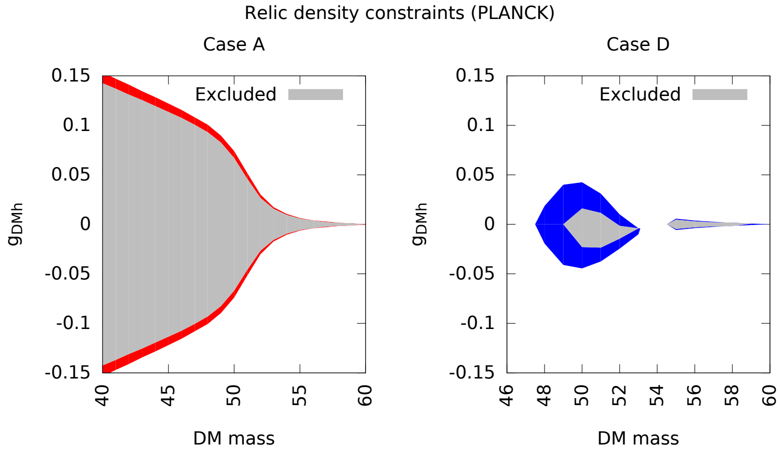


coannhilation with A_1



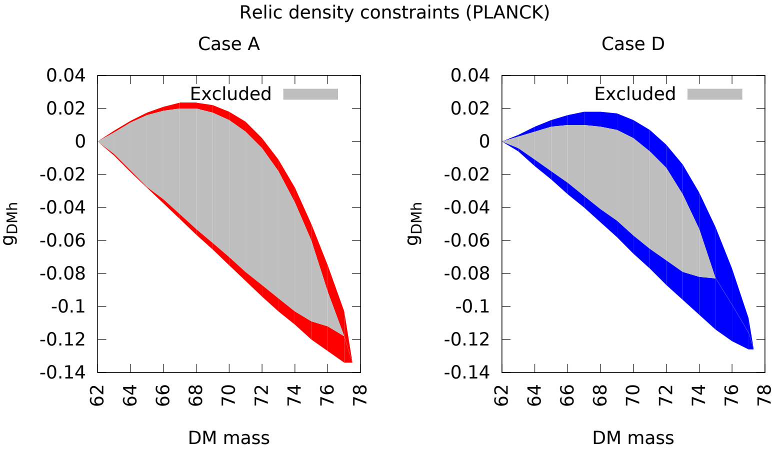
coannhilation with $H_2, A_{1,2}$

Planck constraints: $M_{DM} < M_h/2$



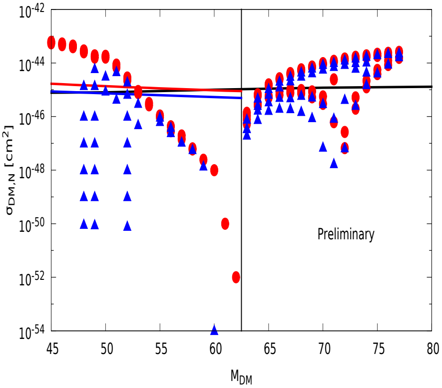
Case A (no coannhilation) – coupling generally bigger than in Case D (with coannihilation)

Planck constraints: $M_{DM} > M_h/2$



Case A and Case D slightly different

Direct detection

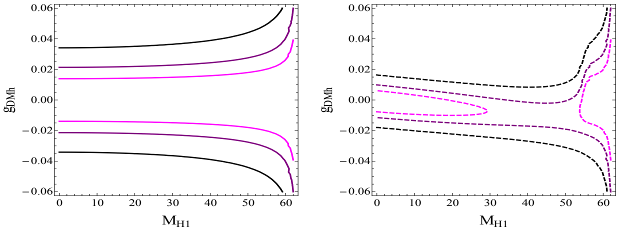


Case D: new region in agreement with LUX with respect to Case A

sign of coannhilation effects

LHC constraints

$$Br(h \to inv) \approx \frac{\sum_{i,j} \Gamma(h \to X_i X_j)}{\Gamma^{SM}(h) + \sum_{i,j} \Gamma(h \to X_i X_j)}$$



case A case D

- $BR(h \to inv) < 37\% \Rightarrow$
  - $|g_{DMh}| \lesssim 0.02$ for Case A
  - $\Omega_{DM} h^2 : M_{DM} > 53\,\text{GeV}$
  - $|g_{DMh}| \lesssim 0.015$ for Case D
  - all masses ok
- $BR(h \to inv) < 20\% \Rightarrow$
  - $|g_{DMh}| \lesssim 0.015$ for Case A
  - strong constraints for Case D!

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 $R_{\gamma\gamma} > 1$
    - $M_W > M_H > M_h/2$ & 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 $\Rightarrow R_{\gamma\gamma} \approx 1$
- **3HDM** – important coannhilation effects in $\Omega_{DM} h^2$
  - LHC constraints – strong for $M_{H_1} < M_h/2$
  - further study – heavy DM
  - additional symmetries? multi-component DM?

BACKUP SLIDES

Extrema

The EW symmetric extremum:

$$\langle \Phi_S \rangle = \langle \Phi_D \rangle = 0$$

- local minimum if $m^2_{11,22} < 0$, not realized today

Charge breaking extremum

$$\langle \Phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ 0 \end{pmatrix}$$

- $U(1)_{EM}$ symmetry broken by $u \neq 0$ – massive photon, not realized today

Mixed extremum:

$$\langle \Phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix}, \qquad \begin{array}{c} v^2 = v_s^2 + v_D^2 \\ \tan\beta = v_D/v_S \end{array}$$

- CP conserving, massive $Z^0, W^\pm$, massless photon,

5 physical Higgs bosons $H^\pm, A, H, h$, possible today but **no DM candidate**

Extrema: inert and inertlike

Deshpande, Ma, '78, Barbieri et al., '06

Inert extremum I_1:

$$\langle \Phi_S \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \Phi_D \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- Φ_S as in SM (SM-like Higgs boson h)

  Φ_D – "dark" or inert doublet with 4 dark scalars $(H, A, H^{\pm})$, no interaction with fermions
- exact D-symmetry – both in Lagrangian and in the extremum
- only Φ_D has odd D-parity

  $\rightarrow$ the lightest scalar is **a candidate for the dark matter**

Inertlike extremum I_2:

$$\langle \Phi_S \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad \langle \Phi_D \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

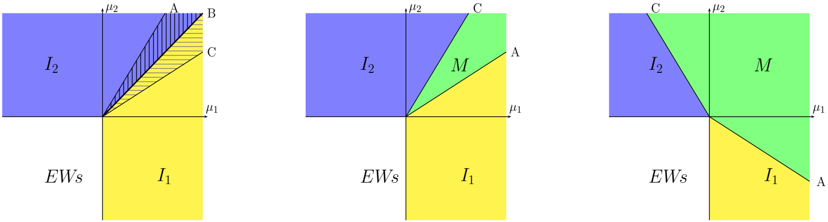
- Φ_S and Φ_D exchange roles
- fermions massless at tree-level (Model I, only Φ_S couples to fermions)
- **no DM candidate**

Coexisting minima

Stable vacuum:

$$\lambda_{1,2} > 0, \quad \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1\lambda_2} > 0 \;\; (\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5)$$

$$\mu_1 = m_{11}^2/\sqrt{\lambda_1}, \quad \mu_2 = m_{22}^2/\sqrt{\lambda_2}, \quad R = \lambda_{345}/\sqrt{\lambda_1\lambda_2}:$$



$R > 1$ $\quad$ $1 > R > 0$ $\quad$ $R < 0$

Coexistence of minima I_1 and I_2 at tree-level for $R > 1 \Rightarrow$ metastability at tree level.

Safe approach: make sure I_1 is a global minimum.

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

If invisible channels closed

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

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

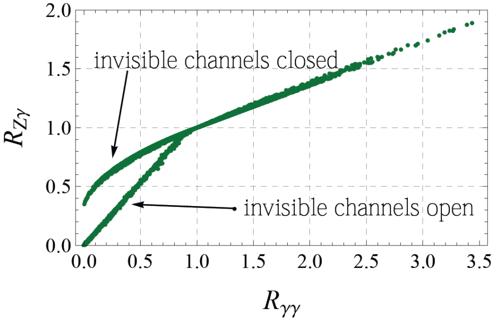
- **Constructive interference**
  - $m_{22}^2 < -2M_{H^\pm}^2$ ($\Leftrightarrow \lambda_3 < 0$)
  - with LEP bound on $M_{H^\pm}$
    $\Rightarrow m_{22}^2 < -9.8 \cdot 10^3\,\mathrm{GeV}^2$

- **Destructive interference**
  - IDM contribution $\geqslant 2\times$ SM contribution
  - big m_{22}^2 required:
    $m_{22}^2 \gtrsim 1.8 \cdot 10^5\,\mathrm{GeV}^2$
  - excluded by the condition for the Inert vacuum
    $m_{22}^2 \lesssim 9 \cdot 10^4\,\mathrm{GeV}^2$

[B. Świeżewska, M. Krawczyk, PRD 88 (2013) 035019]

Comment: $h \to \gamma\gamma$ vs $h \to Z\gamma$

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

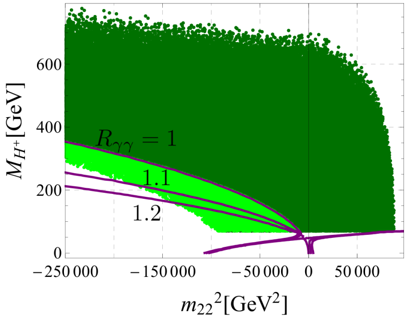


[B. Świeżewska, M. Krawczyk, Phys. Rev. D 88 (2013) 035019, formulas for $h \to Z\gamma$: A. Djouadi, Phys.Rept. 459 (2008) 1, C.-S. Chen, C.-Q. Geng, D. Huang, L.-H. Tsai, Phys.Rev.D 87 (2013) 075019]

(But: current LHC limits for $R_{Z\gamma}$ not strong enough yet)

$R_{\gamma\gamma} > 1$ and the masses of the dark scalars

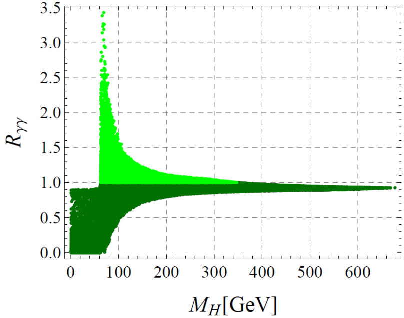
Mass of the charged scalar



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

- $M_H, \ M_{H^\pm} \lesssim 154\,\text{GeV}$.
- Relatively light charged scalar

Mass of the DM candidate



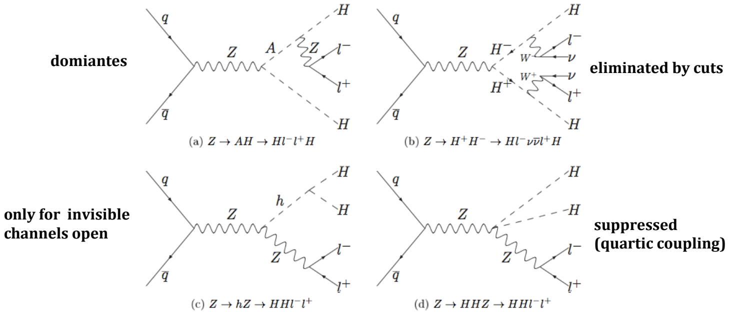
If $R_{\gamma\gamma} > 1$:

- $M_H > M_h/2$
- Light ($\lesssim 63\,\text{GeV}$) DM excluded

[A. Arhrib, R. Benbrik, N. Gaur, PRD 85 (2012) 095021, B. Świeżewska, M. Krawczyk, PRD 88 (2013) 035019]

Detection at the LHC

Processes with monojet / monophoton / **two leptons**
+ missing transverse energy in the final state

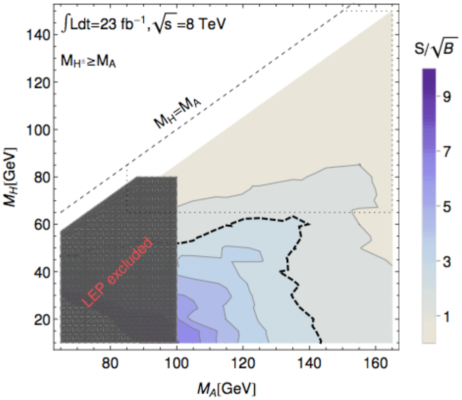


Comparision of the IDM signal with the SM background from:
$pp \to W^+W^- \to l^+\nu l^-\bar{\nu}$, $pp \to ZZ \to \nu\bar{\nu}l^+l^-$, production of WZ, $t\bar{t}$, (Wt).

[P. Swaczyna, Master Thesis at the University of Warsaw, 2013, J. Bogdanowicz, Detector study, work in progress]

Signal

for $\int L dt = 23 \mathrm{fb}^-1$, $M_{H\pm} \geqslant M_A$,
similar results for $M_{H\pm} = 70\,\mathrm{GeV}$



If $S/\sqrt{B} \geqslant 2$ the signal should be visible

[P. Swaczyna, Master Thesis at the University of Warsaw, 2013, J. Bogdanowicz, Detector study, work in progress]

I level cuts

All the events underwent these cuts:

- transverse momentum of leptons $p_{T,l} \geqslant 15\,\mathrm{GeV}$, pseudorapidity $\eta_l \leqslant 2.5$
- spatial separation of leptonic and jet pairs $\Delta R_{ij} \geqslant 0.4$
- no jets with $p_{T,\mathrm{jet}} > 20\,\mathrm{GeV}$ and $|\eta_{\mathrm{jet}}| < 3.0$
- missing transverse energy $E_{T,\mathrm{miss}} > 30\,\mathrm{GeV}$

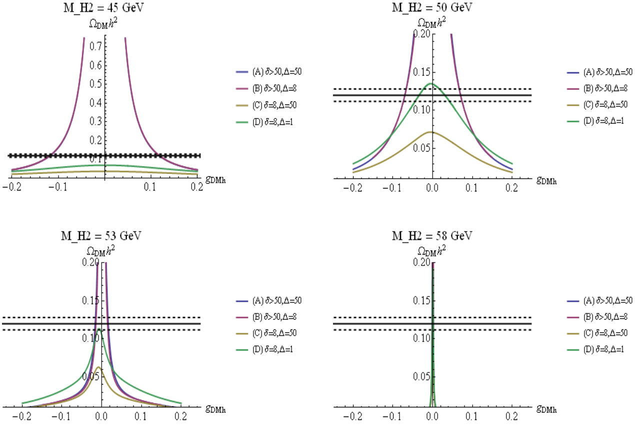
II level cuts

Maximisation of the ratio (no. HA production events / no. $\sqrt{\text{SM background events}}$) with the use of these cuts:

- minimal and maximal invariant mass of the lepton pair $M_{ll}^{\min} \leqslant M_{ll} \leqslant M_{ll}^{\max}$
- maximal spatial separation of leptons $\Delta R_{ll} \leqslant \Delta R_{ll}^{\max}$
- minimal value of cos of the azimuthal angles difference $\cos(\phi_i - \phi_j) \geqslant \cos\phi_{ll}^{\max}$
- minimal value of $p_{T,\mathrm{miss}} + p_{T,1} + p_{t,2} \geqslant H_T^{\min}$
- minimal missing transverse energy $E_{T,\mathrm{miss}} \geqslant E_{T,\mathrm{miss}}^{\min}$
- maximal transverse leptons momenta $p_{T,1}, p_{T,2} \leqslant p_{Tl}^{\max}$

Relic density – difference between cases (A)-(D)

$$M_{A_2} = M_{H_2} + \delta \; ; M_{X_1} = M_{X_2} + \Delta$$



Vacuum instability

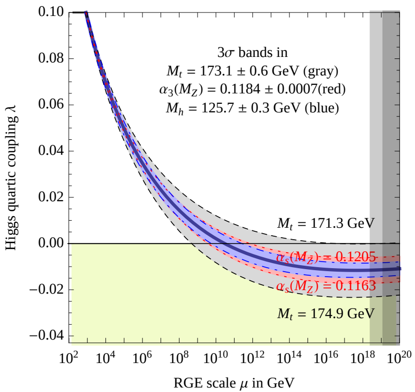
[Butazzo et al (arXiv:1307.3536)]

For the SM:

$$V = \lambda\phi^4$$

$$\beta_\lambda \sim (\lambda^2 - y_t^4 + \ldots) \Rightarrow$$

λ negative at large scales



Additional scalar states $\Rightarrow$
additional **positive** contributions to β_λ

[for example: SM + singlet, arXiv:0910.3167]