Scalar Dark Matter beyond the IDM: I(2+1)HDM

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based on arXiv:1407.7859 [hep-ph]
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Higgs particle discovered

- a Higgs boson has been discovered at the LHC
- **VERY** SM-like:

  → Higgs signal strength ≈ 1 (within experimental accuracy)

  ATLAS: $M_h = 125.36\,\text{GeV}, \; \mu = 1.30 \pm 0.12(stat) \pm 0.10(th) \pm 0.09$

  CMS: $M_h = 125.03\,\text{GeV}, \; \mu = 1.00 \pm 0.13$

  → 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?

Higgs-portal DM

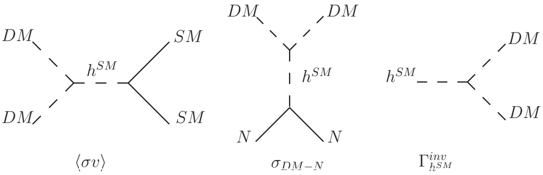
Simplest realization: the SM with Φ_{SM} + Z_2-odd scalar S:

$$S \to -S, \quad \text{SM fields} \to \text{SM fields}$$

$$\mathcal{L} = \mathcal{L}_{SM} + (\partial S)^2 - \lambda_{DM} \Phi_{SM}^2 S^2$$

Higgs-portal interaction:

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



given by the same coupling

Strong constraints from relic density + direct detection + Higgs decays

Multi-Higgs Doublet Models

- two or more scalar $SU(2)_W$ doublets
- **rich phenomenology**
  - → see all talks in this workshop
- 2HDM with an exact Z_2 symmetry: Inert Doublet Model (IDM)
  - → SM-like Higgs boson
    - → modifications of the diphoton decay rate possible
  - → a Dark Matter candidate
  - → see B. Świeżewska's talk
- 3HDM with an exact Z_2 symmetry
  - → many features of the IDM with new phenomena
  - → see also S. Moretti's talk on Friday on 3HDM/6HDM
- within the reach of current and future experiments

I(2+1)HDM

Z_2-symmetry in I(2+1)HDM:

$$\phi_1 \to -\phi_1,\ \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3,\ \text{SM fields} \to \text{SM fields}$$

Z_2-invariant potential:

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

- all parameters real
- Yukawa interaction: "Model I"-type (only ϕ_3 couples to fermions)
- explicit Z_2-symmetry
- $\mu_{12}^2 \neq 0 \Rightarrow$ mixing between ϕ_1 and ϕ_2

DM in I(2+1)HDM

Z_2-invariant vacuum state:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} H_3^+ \\ \frac{v + H_3^0 + iA_3^0}{\sqrt{2}} \end{pmatrix}$$

- ϕ_3 – SM-like doublet with SM-like Higgs H_3^0
- Z_2-odd doublets ϕ_1 and ϕ_2 mix:

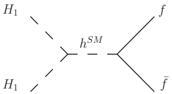
$$H_1 = \cos\alpha_H H_1^0 + \sin\alpha_H H_2^0, \quad H_2 = \cos\alpha_H H_2^0 - \sin\alpha_H H_1^0$$

  (similar for A_i and $H_i^\pm$)
- 4 neutral and 4 charged Z_2-odd particles (double the IDM)
- H_1 – **DM candidate**, other dark particles heavier
- Note: $V \ni \left(-\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c\right)$

  → term added to avoid $Z_2 \times Z_2$-symmetric V
  → lifts degeneracy between H_i and A_i!

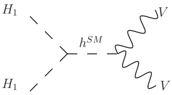
Dark Matter Annihilation

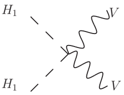
- annihilation through Higgs into fermions



depends on $g_{H_1 H_1 h}$ coupling; dominant channel for $M_{DM} < M_h/2$

- annihilation into gauge bosons (also into virtual states)





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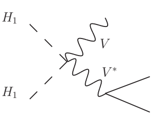
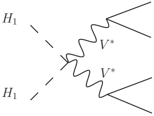
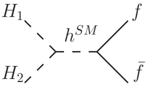
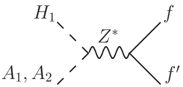


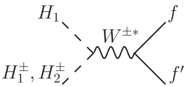


crucial for heavy masses; non-negligible for $M_h/2 < M_{DM} < M_W$

- coannihilation







very important when particles have similar masses

Constraints I

(1) **Vacuum stability**:

scalar potential V bounded from below

(2) **Perturbative unitarity**:

eigenvalues Λ_i of the high-energy scattering matrix fulfil $|\Lambda_i| < 8\pi$

(3) **Higgs mass**:

$$M_h = 125 \text{ GeV}$$

(4) **EWPT & LEP**:

$$M_{H_i^\pm} \gtrsim 70 - 90 \text{ GeV}, \quad M_{H_i} + M_{A_i} > M_Z$$

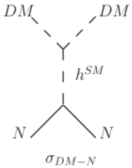
(5) ***H_1* as DM candidate**:

$$M_H < M_A, M_{H^\pm} \text{ and } 0.1118 < \Omega_{DM} h^2 < 0.128 \text{ (}3\sigma\text{ Planck)}$$

$\Rightarrow$ constraints for $g_{H_1 H_1 h}$

Constraints II

(6) DM direct detection:

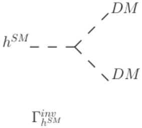


DM-scattering on nucleus through the Higgs exchange

$$\sigma_{DM-N} \propto g^2_{H_1 H_1 h}/(M_{H_1} + M_N)^2$$

Note: direct & indirect detection: not a coherent picture of Dark Matter

(7) LHC:



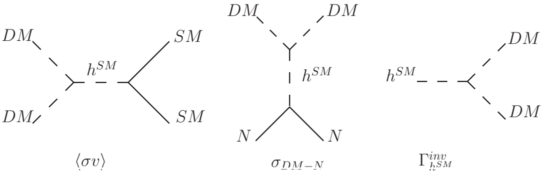
Higgs invisible decays for $M_{DM} < M_h/2$

$$\Gamma(h \to H_1 H_1) = \frac{g^2_{H_1 H_1 h} v^2}{32\pi M_h} \sqrt{1 - \frac{4M^2_{H_1}}{M^2_h}}$$

More LHC phenomenology: see S. Moretti's talk on Friday

I(2+1)HDM as (almost) Higgs portal model

For $M_{DM} < M_h/2$:



Tension:

- proper relic density $\leftrightarrow$ large $\langle\sigma v\rangle$ $\leftrightarrow$ large $g_{H_1 H_1 h}$
- direct detection $\leftrightarrow$ small σ_{DM-N} $\leftrightarrow$ small $g_{H_1 H1h}$
- LHC $\leftrightarrow$ small $Br(h \to inv)$ $\leftrightarrow$ small $g_{H_1 H1h}$

Solution:

destroy the Higgs-portal type relation between $\langle\sigma v\rangle, \sigma_{DM-N}, \Gamma(h \to inv)$

DM Annihilation Scenarios

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

usually relic density too big

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

usually relic density too small

(D) **coannihilation** with H_2, 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 $H_i^\pm$.

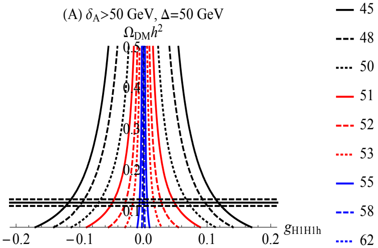
- **Toy Model** with additional "symmetry":

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

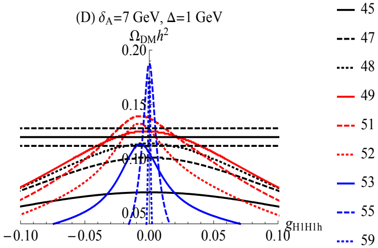
$$H_1 = \frac{1}{\sqrt{2}}(H_1^0 + H_2^0), \quad H_2 = \frac{1}{\sqrt{2}}(H_2^0 - H_1^0)$$

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

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

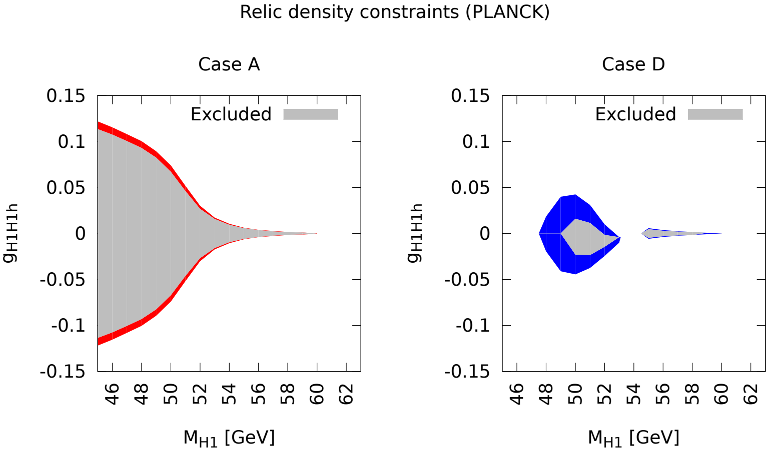


no coannhilation



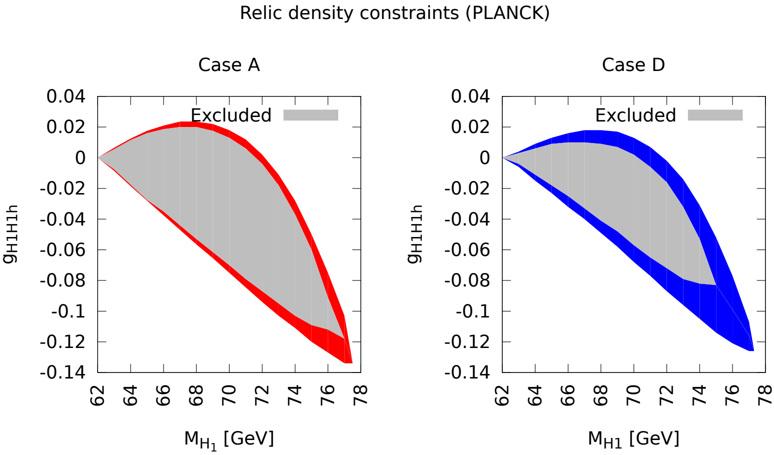
coannhilation with $H_2, A_{1,2}$

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



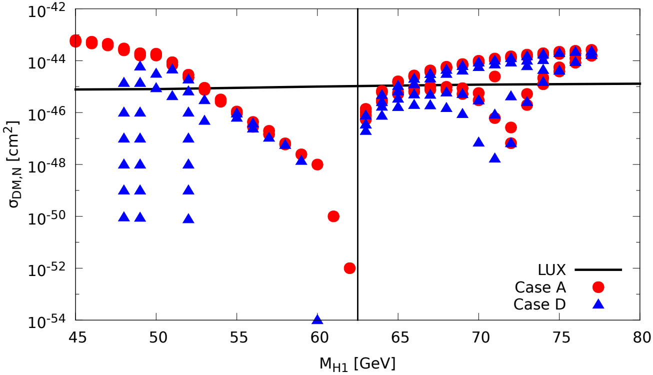
Case A (no coannhilation) – coupling bigger than in Case D (with coannihilation)

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



Case A and Case D slightly different

Direct detection

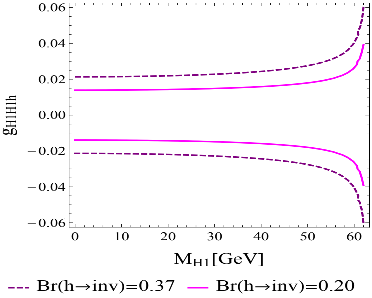


Case D: new region in agreement with LUX with respect to Case A

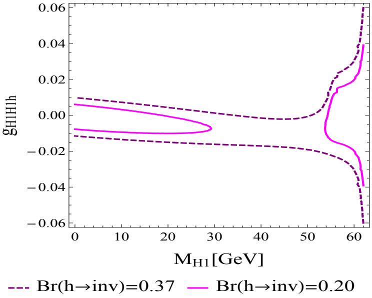
sign of coannhilation effects

LHC constraints

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



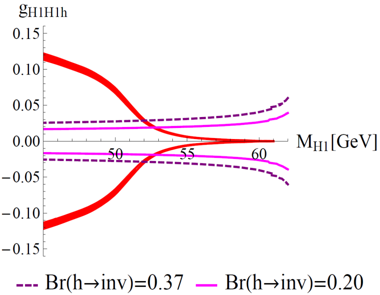
case A



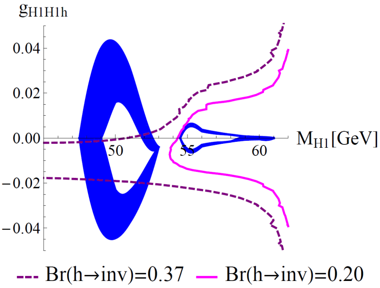
case D

- $Br(h \to inv) < 37\% \Rightarrow$
  - $|g_{H_1H1h}| \lesssim 0.02$ for Case A
  - $-0.015 \lesssim g_{DMh} \lesssim 0$ for Case D
- $Br(h \to inv) < 20\% \Rightarrow$
  - $|g_{H_1H1h}| \lesssim 0.015$ for Case A
  - strong constraints for Case D!

LHC vs Planck



case A



case D

- $Br(h \to inv) < 37\%$ & $\Omega_{DM}h^2 \Rightarrow$
    - $M_{DM} \gtrsim 53\,\text{GeV}$ for Case A
    - almost all masses ok for Case D
- $Br(h \to inv) < 20\%$ & $\Omega_{DM}h^2 \Rightarrow$
    - $M_{DM} \gtrsim 53\,\text{GeV}$ for Case A
    - $M_{DM} \gtrsim 53\,\text{GeV}$ for Case D

Conclusions

- **3HDM** with Z_2 symmetry: I(2+1)HDM
- viable DM candidate
- large dark sector

  → important coannhilation effects in $\Omega_{DM} h^2$
- Case D with multiple coannihilation channels

  → new viable region in agreement with LUX
- LHC constraints – strong for $M_{H_1} < M_h/2$

  → **stronger than direct detection limits!**
- further study – heavy DM
- additional symmetries? multi-component DM?

BACKUP SLIDES

References

- Higgs-portal DM models

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- 3HDM

  [V. Keus, S. King, S. Moretti JHEP 1401 (2014) 052, V. Keus, S. King, S. Moretti arXiv:1408.0796]
- Experimental constraints

  [G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, PLB 723 (2013) 340; ATLAS-CONF-2014-010, 2014; CMS-PAS-HIG-14-002]