Scalar Dark Matter in Multi-Inert Doublet Models

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based on
JHEP 1612 (2016) 014 and work in progress
with A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus,
S. F. King, S. Moretti, D. Rojas

The Standard Model

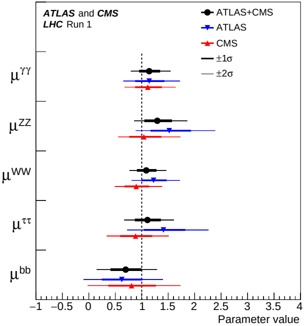
A rigorously tested Theory of Fundamental Interactions

From the LHC:

- a Higgs particle found in 2012
- no significant deviation from the SM
- no sign of New Physics

But no explanation for:

- Dark Matter
- neutrino masses
- baryon asymmetry and baryogenesis
- extra source of CP violation
- vacuum stability
- ...



JHEP 08 (2016) 045

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

$$\underbrace{\text{DM DM} \to \text{SM SM},}_{\text{pair annihilation}} \quad \underbrace{\text{DM} \not\to \text{SM}, \ldots}_{\text{stable}}$$

- annihilation cross-section $\langle \sigma v \rangle \propto$ EW interaction
- thermal evolution of DM density – a fixed value after freeze-out

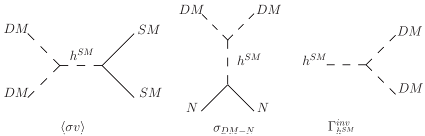
Higgs-portal DM

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

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

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - \frac{1}{2}m_{DM}^2 S^2 - \lambda_{DM} S^4 - \lambda_{SSh}\Phi_{SM}^2 S^2$$

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



given by the same coupling

Strong constraints from relic density + direct detection + Higgs decays

$\Rightarrow$ modified Higgs-portal-type DM candidates in multi-scalar models

*in this talk: focus on **DM phenomenology** in the I(2+1)HDM i.e.*
3HDM with Two Inert and One Higgs doublet

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:

$$V = \sum_i^3 \left[-|\mu_i^2|(\phi_i^\dagger \phi_i) + \lambda_{ii}(\phi_i^\dagger \phi_i)^2 \right] + \sum_{ij}^3 \left[\lambda_{ij}(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij}(\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right]$$
$$+ \left(-\mu_{12}^2(\phi_1^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_2)^2 + \lambda_2(\phi_2^\dagger \phi_3)^2 + \lambda_3(\phi_3^\dagger \phi_1)^2 + h.c. \right)$$
$$+ \Big(\lambda_4(\phi_3^\dagger \phi_1)(\phi_2^\dagger \phi_3) + \lambda_5(\phi_1^\dagger \phi_2)(\phi_3^\dagger \phi_3) + \lambda_6(\phi_1^\dagger \phi_2)(\phi_1^\dagger \phi_1)$$
$$+ \lambda_7(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_2) + \lambda_8(\phi_3^\dagger \phi_1)(\phi_3^\dagger \phi_2) + h.c. \Big)$$

- 21 parameters in V
- $\mu_{12}^2, \lambda_1, \lambda_2, \lambda_3$ are complex
- Yukawa interaction: "Model I"-type (only ϕ_3 couples to fermions)
- explicit Z_2-symmetry

Parameters of V

- $\mu_3^2 = v^2\lambda_{33} = m_h^2/2$ fixed from extremum conditions
- "dark democracy": $\mu_1^2 = \mu_2^2,\ \lambda_{13} = \lambda_{23},\ \lambda'_{13} = \lambda'_{23},\ \lambda_3 = \lambda_2$, e.g.

$$\lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c. \to \lambda_2\left((\phi_2^\dagger\phi_3)^2 + (\phi_3^\dagger\phi_1)^2 + h.c.\right)$$

- $\left(\lambda_4(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_3) + \lambda_5(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_3) + ...\right)$: no new phenomenology

$$\Rightarrow \lambda_{4-8} = 0$$

- $\lambda_1, \lambda_{11,22,12}, \lambda'_{12}$ – self-interactions of inert doublets

21 parameters → 7 important parameters

- μ_2^2 – mass scale of inert particles
- $\mu_{12}^2 = |\mu_{12}^2|e^{i\theta_{12}}, \lambda_2 = |\lambda_2|e^{i\theta_2}$ – mass splittings and CPv phase
- $\lambda_2, \lambda_{23}, \lambda'_{23}$ – DM-Higgs coupling

DM in I(2+1)HDM

Z_2-invariant vacuum state:

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

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

$$S_1 = \frac{\alpha H_1^0 + \alpha H_2^0 - A_1^0 + A_2^0}{\sqrt{2\alpha^2 + 2}}, \quad S_2 = \frac{-H_1^0 - H_2^0 - \alpha A_1^0 + \alpha A_2^0}{\sqrt{2\alpha^2 + 2}}$$

$$S_3 = \frac{\beta H_1^0 - \beta H_2^0 + A_1^0 + A_2^0}{\sqrt{2\beta^2 + 2}}, \quad S_4 = \frac{-H_1^0 + H_2^0 + \beta A_1^0 + \beta A_2^0}{\sqrt{2\beta^2 + 2}}$$

$$S_1^\pm = \frac{e^{\pm i\theta_{12}/2}}{\sqrt{2}}(S_1^\pm - S_2^\pm), \qquad S_2^\pm = \frac{e^{\mp i\theta_{12}/2}}{\sqrt{2}}(S_1^\pm + S_2^\pm)$$

- 4 neutral and 4 charged Z_2-odd particles (double the IDM)
- S_1 – **DM candidate**, other dark particles heavier

Physical Parameters

Parameters of V: $\mu_2^2, |\lambda_2|, |\mu_{12}^2|, \lambda_{23}, \lambda'_{23}, \theta_{12}, \theta_2$

Physical parameters:

DM mass:

m_{S_1}

Mass splittings:

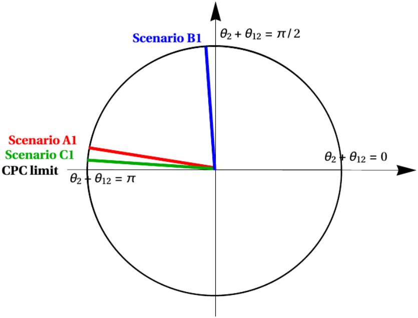
$$\delta_{12} = m_{S_2} - m_{S_1}$$
$$\delta_{1c} = m_{S_1^\pm} - m_{S_1}$$
$$\delta_c = m_{S_2^\pm} - m_{S_1^\pm}$$

Higgs-DM coupling:

$g_{S_1 S_1 h}$

CPv phases:

θ_{12}, θ_2



Benchmark scenarios

This talk: $m_{S_1} < m_Z$:

$$A1: \ \delta_{12} = 125\,\text{GeV}, \delta_{1c} = 50\,\text{GeV}, \delta_c = 50\,\text{GeV}, \theta_2 = \theta_{12} = 1.5$$

$$m_{S_1} < m_{S_{2,3,4}}, m_{S^\pm_{1,2}} \text{ (no coannihilation)}$$

$$B1: \ \delta_{12} = 125\,\text{GeV}, \delta_{1c} = 50\,\text{GeV}, \delta_c = 50\,\text{GeV}, \theta_2 = \theta_{12} = 0.82$$

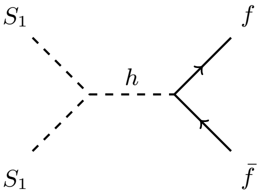
$$m_{S_1} \approx m_{S_3} < m_{S_{2,4}}, m_{S^\pm_{1,2}}$$

$$C1: \ \delta_{12} = 12\,\text{GeV}, \delta_{1c} = 100\,\text{GeV}, \delta_c = 1\,\text{GeV}, \theta_2 = \theta_{12} = 1.57$$

$$m_{S_1} \approx m_{S_3} \approx m_{S_4} \approx m_{S_2} < m_{S^\pm_{1,2}}$$

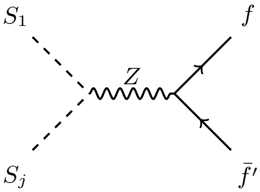
Checked against experimental and theoretical constraints:
details in JHEP 1612 (2016) 014

DM Annihilation for light DM



Higgs-mediated annihilation

depends on m_{S_1} and $g_{S_1 S_1 h}$



Z-mediated coannihilation

depends on $m_{S_j} - m_{S_1}$:

A1: no coannihilation

B1: $S_1 S_3$ coannihilation only

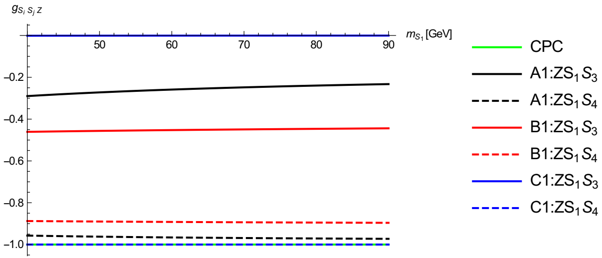
C1: $S_1 S_3$, $S_2 S_4$, $S_1 S_4$, $S_2 S_3$ coann.

depends on $Z S_i S_j$ couplings

Z-inert couplings

$$\chi_{ZS_1S_3} = \chi_{ZS_2S_4} = \frac{\alpha+\beta}{\sqrt{\alpha^2+1}\sqrt{\beta^2+1}}, \quad \chi_{ZS_1S_4} = \chi_{ZS_2S_3} = \frac{\alpha\beta-1}{\sqrt{\alpha^2+1}\sqrt{\beta^2+1}},$$

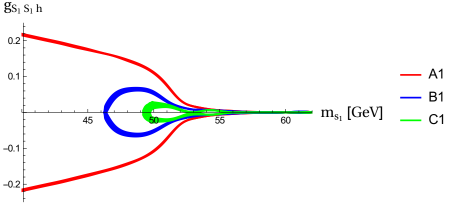
$$\chi^2_{ZS_1S_3} + \chi^2_{ZS_1S_4} = 1, \quad \chi^2_{ZS_2S_3} + \chi^2_{ZS_2S_4} = 1$$



- **mass order:** $m_{S_1} < m_{S_3} < m_{S_4} < m_{S_2}$
- CPc value $\chi_{ZS_1S_3} = -1, \chi_{ZS_1S_4} = 0$
- ZS_1S_3 – **reduced**; $20 - 50\%$ for **A1**, **B1**, ~ 0 for **C1**
- ZS_1S_4 – close to the CPc value → dominant channel for **C1**

Low DM mass

bounds: good relic density for A1, B1, C1



A1: mainly Higgs annihilation, large $g_{S_1 S_1 h}$

B1: Higgs annihilation (smaller $g_{S_1 S_1 h}$)

+ ZS_1S_3 coannihilation (reduced with respect to the CPc case)

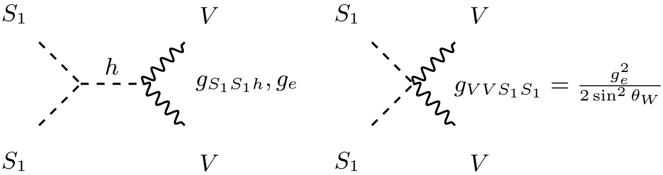
C1: mainly ZS_1S_4 coannihilation ($\chi_{ZS_1S_4} \approx -1$)

+ Higgs annihilation

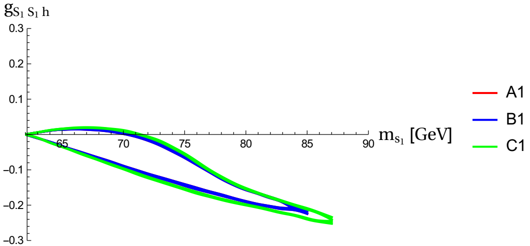
Tools used in calculation: LanHEP, arXiv:1412.5016 [physics.comp-ph]; CalcHEP 3.4, Comput. Phys. Commun. **184** (2013) 1729;micrOMEGAs 4.2 arXiv:1407.6129 [hep-ph]

Medium DM mass

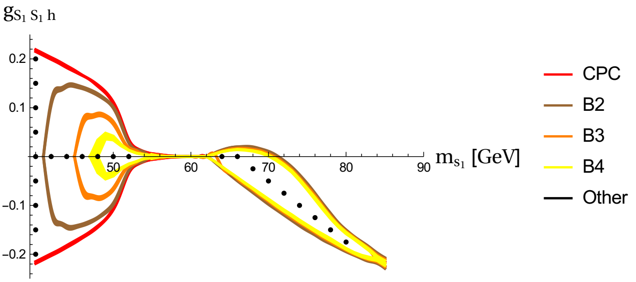
Main annihilation channels into gauge bosons $V = W^{\pm}, Z$:



no dependence on the benchmarks



Filling the plot



$m_{S_1} < m_h/2$: many new solutions:

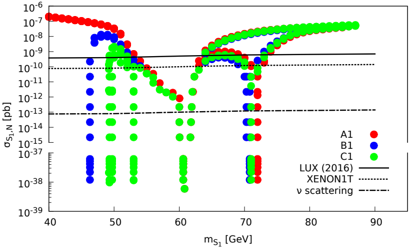
different mass splittings + ZS_iS_j interaction strength

$m_{S_1} > m_h/2$: less freedom but still new solutions:

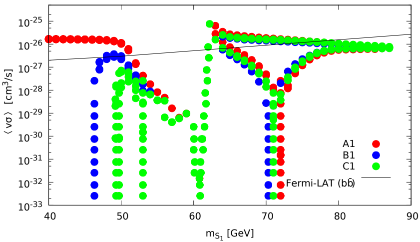
Higgs mediated coannihilation + sign of hS_3S_3 coupling

DM Detection Experiments

Direct Detection:



Indirect Detection:



Case **A1**: mostly excluded (large $g_{S_1 S_1 h}$)

Cases **B1** and **C1**: mostly within the limits

Access to region with very small $g_{S_1 S_1 h}$
$\Rightarrow$ not excluded by DM detection limits

LHC constraints

Higgs invisible decays

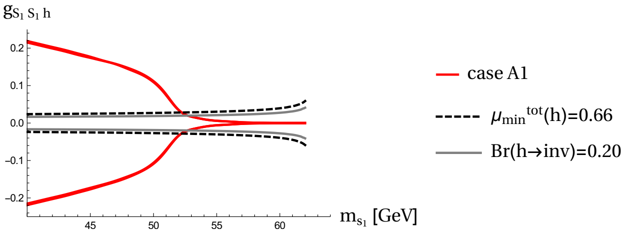
$$\Gamma(h \to S_1 S_1) = \frac{g^2_{S_1 S_1 h} v^2}{32\pi m_h}\left(1 - \frac{4m^2_{S_1}}{m_h^2}\right)^{1/2}, \quad \mathrm{Br}(h \to \mathrm{inv}) = \frac{\Gamma(h \to S_1 S_1)}{\Gamma_h^{\mathrm{SM}} + \Gamma(h \to S_1 S_1)}$$

Higgs total decay

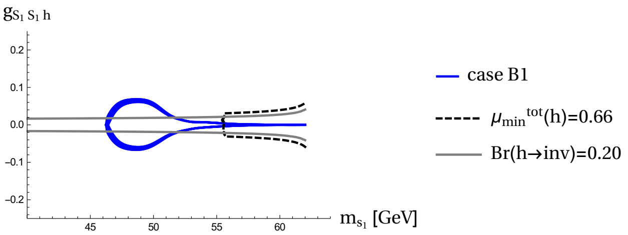
$$\mu_{tot} = \frac{\mathrm{BR}(h \to XX)}{\mathrm{BR}(h_{\mathrm{SM}} \to XX)} = \frac{\Gamma^{SM}_{tot}(h)}{\Gamma^{SM}_{tot}(h) + \Gamma^{inert}(h)}$$

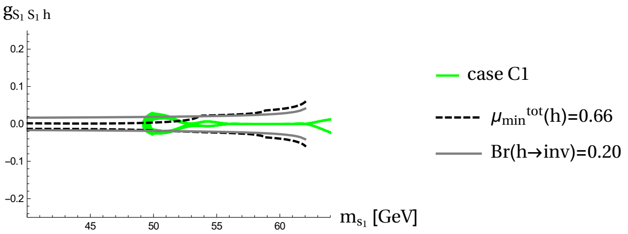
LHC limits

$$\mu_{tot} = 1.17 \pm 0.17 \text{ and } \mathrm{Br}(h \to \mathrm{inv}) < 0.2$$



LHC constraints





In general: scenarios of type C are the least constrained.

Conclusions and Outlook

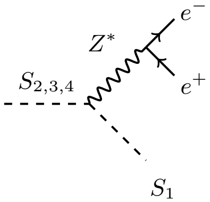
- **3HDM** with Z_2 symmetry: I(2+1)HDM
- viable DM candidate
- large dark sector: important coannhilation effects in $\Omega_{DM}h^2$
  - → varying strength of gauge-inert couplings
  - → new regions in agreement with Planck
- agreement with direct and indirect detection limits:

  $45\,\text{GeV} \lesssim m_{S_1} \lesssim 62.5\,\text{GeV}$, $64\,\text{GeV} \lesssim m_{S_1} \lesssim 74\,\text{GeV}$, $m_{S_1} \gtrsim 400\,\text{GeV}$
  - → **as long as DM is practically invisible**
  - → other detections prospects? LHC?

Inert cascade decays at the LHC

work in progress

$$pp \to Z \to S_{2,3,4} S_1 \to S_1 S_1 Z^* \to S_1 S_1 e^+ e^-$$

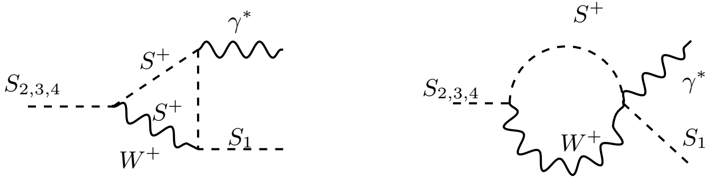


- signature: missing E_T and dilepton pair
- dominant if there is a **large mass splitting** between DM and other inert particles
- process present in the IDM (through HAZ vertex)
- note: possible differences with respect to the IDM due to varying strength of $S_1 S_j Z$ vertex

Inert cascade decays at the LHC

work in progress

$$pp \to h \to S_{2,3,4}S_1 \to S_1S_1\gamma^* \to S_1S_1e^+e^-$$

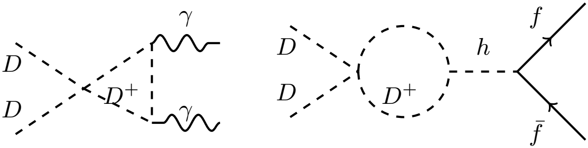


- signature: missing E_T and dilepton pair
- important if there is a **small mass splitting** between DM and other inert particles → scenario C is preferred anyway
- process absent in the IDM (no $A \to H\gamma^*$ loop)
- promising preliminary results $\sigma \sim 10^{-5}$ pb

DM self-couplings

Dark self-couplings – no impact on standard DM and LHC phenomenology

- In the I(1+1)HDM – λ_2
- In the I(2+1)HDM – $\lambda_1, \lambda_{11,22,12}, \lambda'_{12}$
- Possible relevant corrections to loop processes, e.g.:



D – DM matter, $D^{\pm}$ – charged dark scalar

- Astrophysical DM detection experiments:

  DM very weakly coupled to the visible sector

  $\Rightarrow$ **loop corrections can be important!**

Final Summary

Scalar DM models:

- interesting phenomenology
- strong constraints on g_{DMh} from DM experiments
- need to move away from Higgs-portal
- solution: rich particle spectrum & coannihilation effects
- interesting LHC signatures – a tool for testing DM models?
- loop processes & role of self-couplings – can be important
- **Further work needed!**

References

- Higgs-portal DM models

  [B. Patt and F. Wilczek, hep-ph/0605188, X. Chu, T. Hambye, and M. H. Tytgat, JCAP 1205 (2012) 034, A. Djouadi, O. Lebedev, Y. Mambrini, and J. Quevillon, Phys.Lett. B709 (2012) 65–69]

- 3HDM

  [V. Keus, S. King, S. Moretti JHEP 1401 (2014) 052, arXiv:1408.0796; V. Keus, S. F. King, S. Moretti and D. Sokolowska, JHEP **1411** (2014) 016, JHEP **1511**, 003 (2015)]

- Experimental constraints

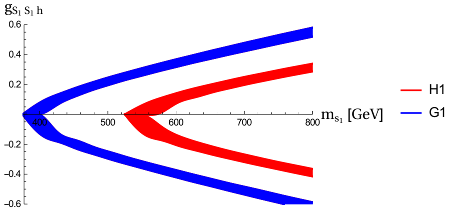
  [ATLAS and CMS collaborations, JHEP 08 (2016) 045; http://lux.brown.edu/LUX_dark_matter/Talks_files/LUX_NewDarkMatterSearchResult_332LiveDays_IDM2016_160721.pdf ("Dark-matter results from 332 new live days of LUX data, Identification of Dark Matter, The University of Sheffield, Sheffield, UK, 21 July, 2016"), M. Ackermann *et al.* [Fermi-LAT Collaboration], Phys. Rev. Lett. **115** (2015) 23, 231301, XENON1T Collaboration, Springer Proc. Phys. **148** (2013) 93]

- Numerical Tools

  [LanHEP, arXiv:1412.5016 [physics.comp-ph]; CalcHEP 3.4, Comput. Phys. Commun. **184** (2013) 1729; micrOMEGAs 4.2 arXiv:1407.6129 [hep-ph]]

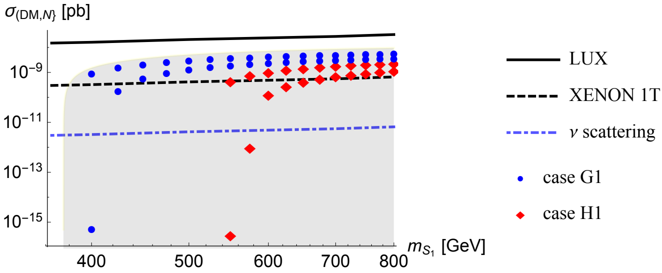
BACKUP SLIDES

Heavy DM



- $g_{S_1 S_1 h}$ in Case G > $g_{S_1 S_1 h}$ Case H
- The same behaviour in both cases
- Lower m_{S_1} for Case G
- Not really different from the CPc case

$$\sigma_{DM,N} \propto \frac{g^2_{S_1 S_1 h}}{(M_{S_1}+M_N)^2}$$



- in agreement with LUX
- within the reach of XENON-1T
- case G (bigger couplings) easier to see/exclude than case H (smaller couplings)

Mass formulas

$$m^2_{S_1^\pm} = (-\mu_2^2 - |\mu_{12}^2|) + \frac{1}{2}\lambda_{23}v^2, \quad m^2_{S_2^\pm} = (-\mu_2^2 + |\mu_{12}^2|) + \frac{1}{2}\lambda_{23}v^2.$$

$$m^2_{S_1} = \frac{v^2}{2}(\lambda'_{23} + \lambda_{23}) - \Lambda - \mu_2^2,$$

$$m^2_{S_2} = \frac{v^2}{2}(\lambda'_{23} + \lambda_{23}) + \Lambda - \mu_2^2,$$

$$m^2_{S_3} = \frac{v^2}{2}(\lambda'_{23} + \lambda_{23}) - \Lambda' - \mu_2^2,$$

$$m^2_{S_4} = \frac{v^2}{2}(\lambda'_{23} + \lambda_{23}) + \Lambda' - \mu_2^2,$$

$$\Lambda = \sqrt{v^4|\lambda_2|^2 + |\mu_{12}^2|^2 - 2v^2|\lambda_2||\mu_{12}^2|\cos(\theta_{12} + \theta_2)},$$

$$\Lambda' = \sqrt{v^4|\lambda_2|^2 + |\mu_{12}^2|^2 + 2v^2|\lambda_2||\mu_{12}^2|\cos(\theta_{12} + \theta_2)}.$$

$$\alpha = \frac{-|\mu_{12}^2|\cos\theta_{12} + v^2|\lambda_2|\cos\theta_2 - \Lambda}{|\mu_{12}^2|\sin\theta_{12} + v^2|\lambda_2|\sin\theta_2}, \qquad \beta = \frac{|\mu_{12}^2|\cos\theta_{12} + v^2|\lambda_2|\cos\theta_2 - \Lambda'}{|\mu_{12}^2|\sin\theta_{12} - v^2|\lambda_2|\sin\theta_2}.$$

Physical Basis

$$|\mu_{12}^2| = \frac{1}{2}(m^2_{S_2^\pm} - m^2_{S_1^\pm}),$$

$$\lambda_{23} = \frac{2\mu_2^2}{v^2} + \frac{m^2_{S_2^\pm} + m^2_{S_1^\pm}}{v^2},$$

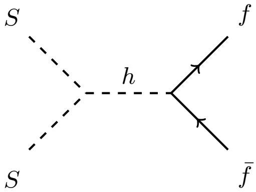
$$\lambda'_{23} = \frac{1}{v^2}(m^2_{S_2} + m^2_{S_1} - m^2_{S_2^\pm} - m^2_{S_1^\pm}),$$

$$\mu_2^2 = \frac{v^2}{2} g_{S_1 S_1 h} - \frac{v^2|\lambda_2|}{2(1+\alpha^2)}\left(4\alpha\sin\theta_2 + 2(\alpha^2 - 1)\cos\theta_2\right) - \frac{m^2_{S_2} + m^2_{S_1}}{2},$$

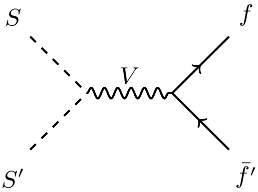
$$|\lambda_2| = \frac{1}{v^2}\left[|\mu_{12}^2|\cos(\theta_2 + \theta_{12}) + \sqrt{|\mu_{12}^2|^2\cos^2(\theta_2+\theta_{12}) + \left(\frac{m^2_{S_2} - m^2_{S_1}}{2}\right)^2 - |\mu_{12}^2|^2}\,\right].$$

DM annihilation diagrams

Light DM annihilation:

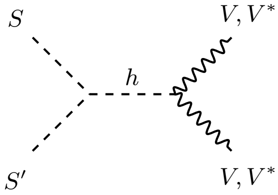


(a)

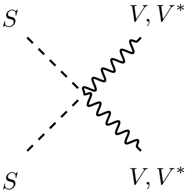


(b)

Virtual gauge bosons:

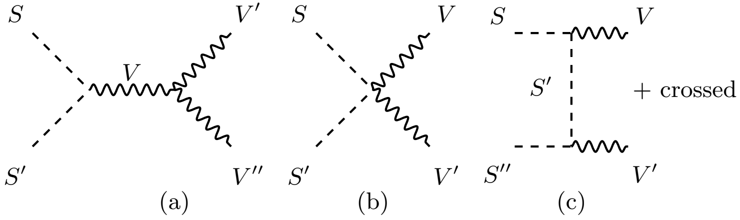


(a)



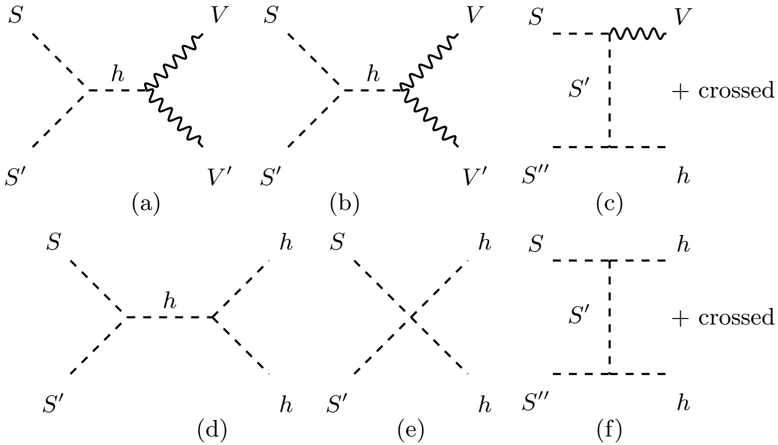
(b)

Heavy DM (co)annihilation diagrams with pure gauge boson final states:

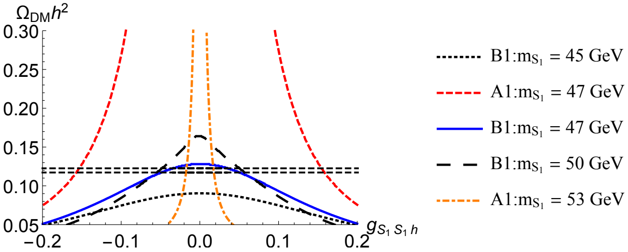


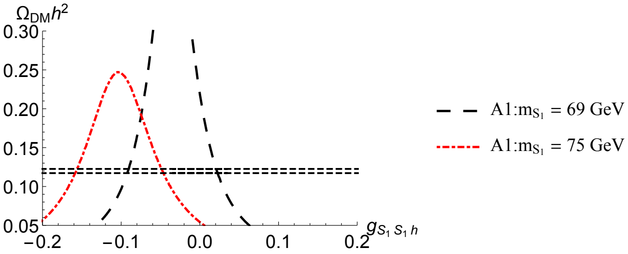
DM annihilation diagrams

Heavy DM (co)annhilation channels involving the SM-like Higgs boson:



Relic density





Higgs-inert couplings