Higgs physics and pseudo-Nambu-Goldstone dark matter in the S2HDM

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in collaboration with Pedro Gabriel, María Olalla Olea Romacho and Rui Santos

[2108.10864] [2207.04973]

Workshop on Multi-Higgs Models in Lisboa

August 31st 2022

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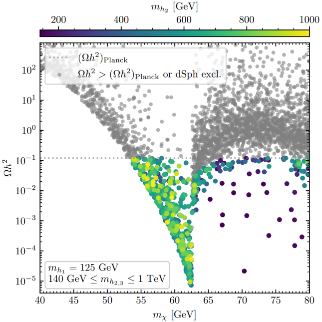
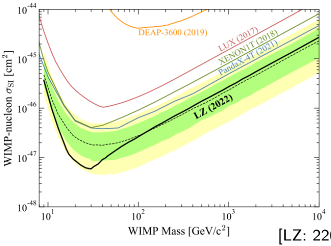
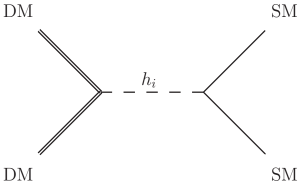
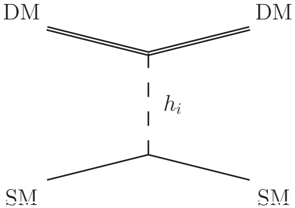
Higgs portal dark matter





[LZ: 2207.03764]





Can we have one without the other?

Pseudo-Nambu-Goldstone (pNG) dark matter

S: Complex field charged under a softly-broken global U(1)

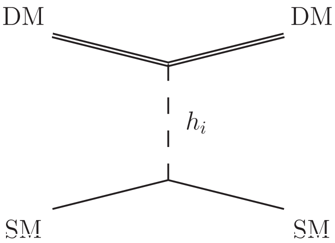
$$\mathcal{L} = (\partial_\mu S)^* \, \partial^\mu S - \, V(\phi_i, S)\big|_{\mathrm{U(1)}} - \, V(S)\big|_{\cancel{U(1)}-\mathrm{soft}}$$

$$S = \frac{1}{\sqrt{2}}\,(v_s + s)\,\mathrm{e}^{\mathrm{i}\,\frac{\chi}{v_s}} \quad \Rightarrow \quad \mathcal{L}_{\chi\chi s} = \frac{1}{2v_s}\,\left(\partial^2 s\right)\chi\chi - \frac{s}{v_s}\chi\left(\partial^2 + m_\chi^2\right)\chi$$

[2109.11499]

On-shell χ interactions with Higgs sector proportional to momentum of s

$$\sum_i$$



$$\sim t$$

Loop corrections → Non-vanishing corrections

Pseudo-Nambu-Goldstone dark matter (pNG)

Most studied case: $V = V_{\rm SM}(H) + V(H,S)|_{\rm U(1)} + \mu_\chi \left(S^2 + (S^*)^2\right)$

[0811.0393], [1609.07490], [1708.02253], [1812.05952], [1810.06105], [1810.08139], [1912.04008], [1906.02175], ...

- Predict DM relic abundance :)
- DM constrants: ID important, almost no sensitivity with DD
- Collider: h_{125}–s mixing, $E_T^{\rm miss}$ signatures

S2HDM: $V = V_{\rm 2HDM-\not{Z}_2}(\phi_1,\phi_2) + V(\phi_1,\phi_2,\phi_S)|_{\rm U(1)} + \mu_\chi \left(\phi_S^2 + (\phi_S^*)^2\right)$

- Sources of CP violation, 1st-order PT, GW, Susy, axion models
- DM: Richer DM-Higgs portal interactions
- Collider: More to search for

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1. Extensive exploration of h_{125}-funnel region

[TB, O. Olea: 2108.10864]

2. Can one really just forget about direct detection?

[TB, P. Gabriel, O. Olea, R. Santos: 2207.04973]

S2HDM: Singlet-extended 2 Higgs doublet model

ϕ_1, ϕ_2: SU(2) doublets, ϕ_S: SM singlet, charged under global U(1)

Scalar potential:

$$V = V_{\mathrm{2HDM}-\not{Z}_2}(\phi_1, \phi_2) + V(\phi_1, \phi_2, \phi_S)|_{\mathrm{U(1)}} - \frac{\mu_\chi^2}{4}\left(\phi_S^2 + (\phi_S^*)^2\right)$$

EW vacuum:

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}, \quad \langle\phi_S\rangle = v_S/\sqrt{2} \quad \in \mathbb{R}$$

BSM particles:

- $h_{1,2,3}$: CP-even Higgs bosons
- $H^\pm$: Charged Higgs bosons
- A: CP-odd Higgs boson
- χ: pNG DM

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R(\alpha_1, \alpha_2, \alpha_3) \cdot \begin{pmatrix} \mathrm{Re}(\phi_1^0) \\ \mathrm{Re}(\phi_2^0) \\ \mathrm{Re}(\phi_S^0) \end{pmatrix}$$

Singlet components: $\Sigma_{h_i} = R_{i3}^2$

Free parameters (Yukawa type II):

$$m_{h_{1,2,3}}, \quad m_A, \quad m_{H^\pm}, \quad m_\chi, \quad \alpha_{1,2,3}, \quad \tan\beta = v_2/v_1, \quad M = \sqrt{\mu_{12}^2/\left(s_\beta c_\beta\right)}, \quad v_S$$

μ_{12}^2 : Soft Z_2-breaking parameter

1. pNG dark matter in the h_{125}-funnel

[TB, O. Olea: 2108.10864]

Parameter Scan

S2HDM Type II:

$$1.5 \leq \tan\beta \leq 10 \;, \quad m_{h_1} = 125.09 \text{ GeV} \;, \quad 140 \text{ GeV} \leq m_{h_{2,3}} \leq 1 \text{ TeV} \;,$$
$$40 \text{ GeV} \leq m_\chi \leq 80 \text{ GeV} \;, \quad 40 \text{ GeV} \leq v_S \leq 1 \text{ TeV} \;, \quad -\pi/2 \leq \alpha_{1,2,3} \leq \pi/2 \;,$$
$$400 \text{ GeV} \leq M \leq 1 \text{ TeV} \;, \quad 600 \text{ GeV} \leq m_{H^\pm} \leq 1 \text{ TeV} \;, \quad m_A \leq 1 \text{ TeV} \;,$$

Second scan: $m_{h_1} = 96 \text{ GeV} \;, \; m_{h_2} = 125 \text{ GeV}$

Scanned the parameter space using **Genetic algorithm***

Why the h_{125}-funnel region?

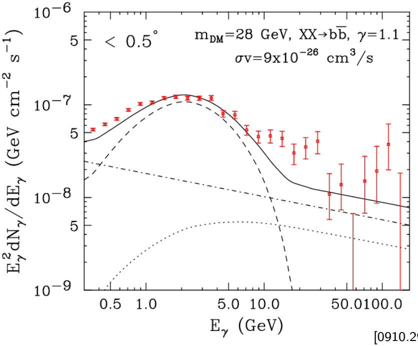
→ DM **indirect-detection** experiments probe the thermal relic XS **now**

→ Experimental anomalies can be explained: **Galactic center excess**

*Details appendix/questions

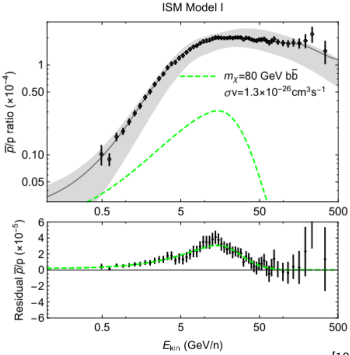
Galactic center excess and antiprotron excess

Fermi γ galactic-center excess



[0910.2998]

AMS $\bar{p}$ excess



[1903.02549]

Assuming that origin is DM annihilation:

1. Both excesses are compatible in terms of DM mass
2. They require annihilation XS of the order of the thermal relic XS
3. Both consistent with $b\bar{b}$ annihilation → Higgs portal DM
4. Currently probed by observation of dSph

DM in the h_{125}-funnel: Constraints

Theory:

Vacuum stability: Boundedness and global EW minimum (strict) [Hom4PS2]

Perturbativity: Upper limit on scalar $2 \to 2$ scattering amplitudes in large s limit

$$\to |\mathrm{Eig}[\mathcal{M}(\lambda_i)]| < 8\pi$$

RGE: Well behaved potential until at least 1 TeV [SARAH,PyR@TE]

Experiment:

Colliders: BSM Higgs boson searches, measurements of h_{125}
[N2HDECAY, SusHi, HiggsBounds, HiggsSignals]

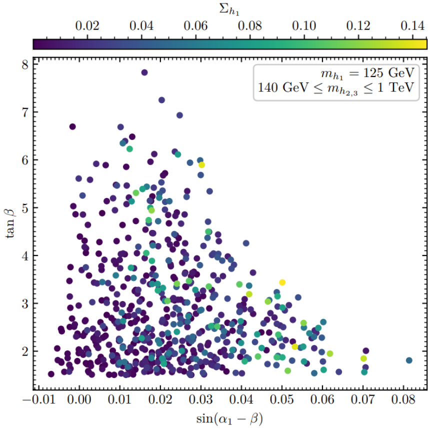
EWPO: STU parameters at one loop

Flavour: $\tan\beta > 1.5$ and $m_{H^\pm} > 600\ \mathrm{GeV}$ to avoid bounds (type II)

Dark matter: Relic abundance $h^2\Omega < 0.12$ [Micromegas]
Indirect detection limits from Fermi dSph observations [MadDM]
(No direct detection yet)

Properties of the Higgs boson $h_1 = h_{125}$

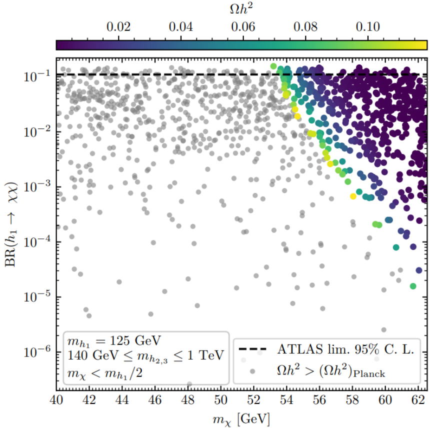
Σ_{h_1} : Singlet admixture of h_1



$\max(\Sigma_{h_1}) \simeq 0.14$ (in SM+S model $\simeq 0.07$)

Possibility to distinguish the models

χ : Dark matter particle

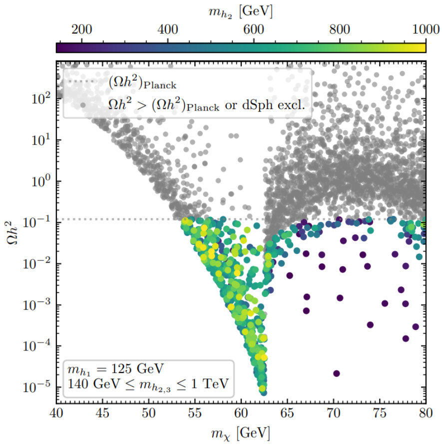


$m_\chi \gtrsim 54$ GeV (similar to SM+S limit)

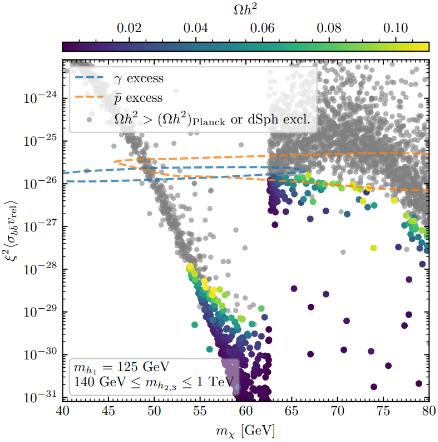
But depends on $m_{h_{2,3}} > m_{h_{125}}$

Thermal DM relics in the h_{125}-funnel

Relic abundance



Indirect detection ($\xi = \Omega h^2_{\rm pred} / \Omega h^2_{\rm Planck}$)



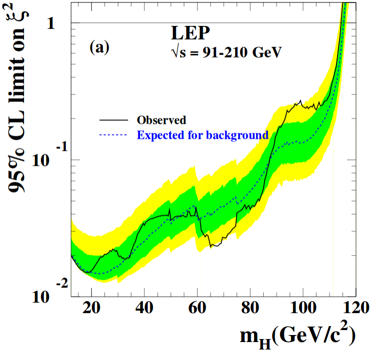
DM mass region at 62 GeV $\lesssim m_\chi \lesssim$ 65 GeV:

✓ Relic abundance ✓ Fermi γ excess* ✓ AMS $\bar{p}$ excess*

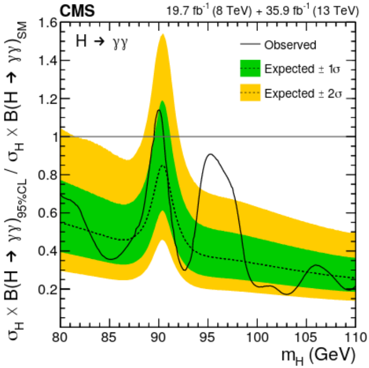
(✗) In tension with dSph exclusion limits (but there are large uncertainties)

*Preferred regions from [1409.0042,1903.02549]

"The 96GeV excesses" (LEP and CMS)



[LEP: hep-ex/0306033]



[CMS: 1811.08459]

$\mu_{\rm LEP}\left(e^+e^- \to Zh \to Zb\bar{b}\right) = 0.117 \pm 0.057$ [1612.08522]

$\mu_{\rm CMS}\left(gg \to h \to \gamma\gamma\right) = 0.6 \pm 0.2$

$\to \chi^2_{96}(\mu_{\rm LEP}, \mu_{\rm CMS})$ assuming no correlation between $\mu_{\rm LEP}$ and $\mu_{\rm CMS}$

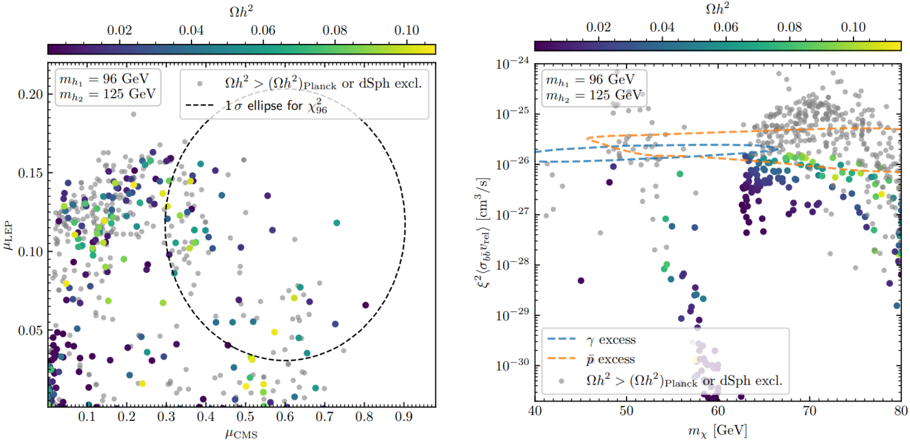
In the meantime a third (3σ local) excess appeared at $gg \to h \to \tau^+\tau^-$ at CMS

$\to$ Would point to type 4 interpretation

[TB, S. Heinemeyer, G. Weiglein: 2203.13180]

Higgs funnel DM and a Higgs boson at 96 GeV

Scan: As before, but with $m_{h_1} = 96$ GeV and $m_{h_2} = 125$ GeV



DM mass region at 62 GeV $\lesssim m_\chi \lesssim$ 65 GeV:

✓ Relic abundance ✓ Fermi γ excess ✓ AMS $\bar{p}$ excess ✓CMS excess ✓LEP excess

(✗) In tension with dSph exclusion limits (but there are large uncertainties)

2. Dark matter direct detection in the S2HDM

[TB, P. Gabriel, O. Olea, R. Santos: 2207.04973]

Origin of non-zero scattering cross sections

Exact U(1): NG boson χ

→ χ has only derivative couplings

→ χ-quark scattering vanishes for $p^2/m_{h_i}^2 \to 0$ to all orders of pert. theory

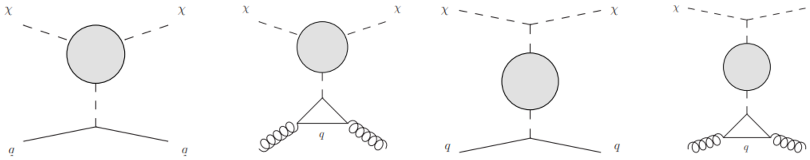
→ **BUT:** ξ is massless

Softly-broken U(1): pseudo-NG boson χ

→ χ has still only derivative couplings

→ χ-quark scattering vanishes for $p^2/m_{h_i}^2 \to 0$ only at the classical level

→ **BUT:** ξ is massive

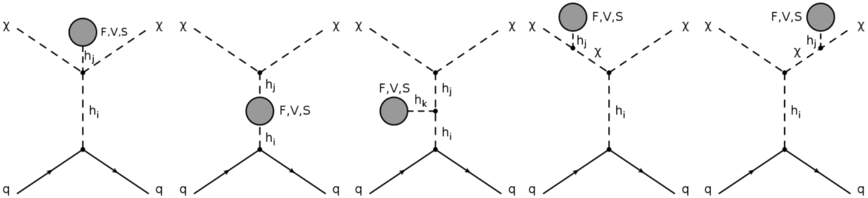


$$\sigma_{\chi N} = \frac{1}{\pi} \frac{m_N^4}{(m_N + m_\chi)^2} \left| \sum_{q=u,d,s} C_q^s f_{Tq}^N + \frac{2}{27} f_{Tg}^N \sum_{q=b,c,t} C_q^s \right|^2$$

C_q^s : Wilson coefficients (here one-loop) $\quad \mathcal{L}_{\rm eff} = m_q C_q^s \chi\chi \bar{q} q$

Despite the soft breaking, the U(1) still helps

Loops with SM particles, A or $H^{\pm}$: $F \in \{u, c, s, c, b, t\}$, $V \in \{Z, W\}$ and $S \in \{G_0, G_{\pm}, A, H^{\pm}\}$

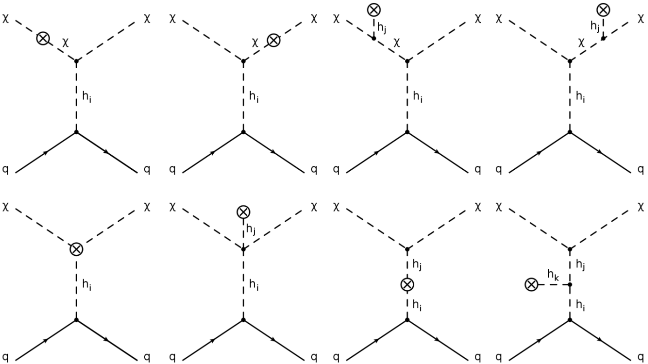


$$\sum_{\text{diags}} \mathcal{M}(t \to 0) = 0$$

(1PI diagrams don't know anything about the U(1)-breaking)

Despite the soft breaking, the U(1) still helps

Diagrams with counterterm insertions

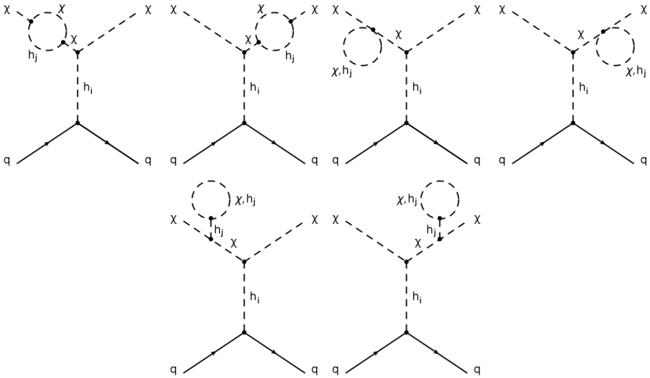


$$\sum_{\text{diags}} \mathcal{M}(t \to 0) = 0$$

(Tree-level amplitude is zero → one-loop amplitude is UV finite)

Despite the soft breaking, the U(1) still helps

Diagrams with external-leg corrections

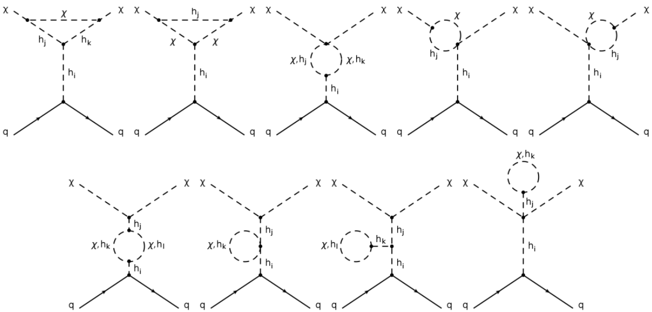


$$\sum_{\text{diags}} \mathcal{M}(t \to 0) = 0$$

(Factorize into tree-level amplitude times one-loop correction)

Despite the soft breaking, the U(1) still helps

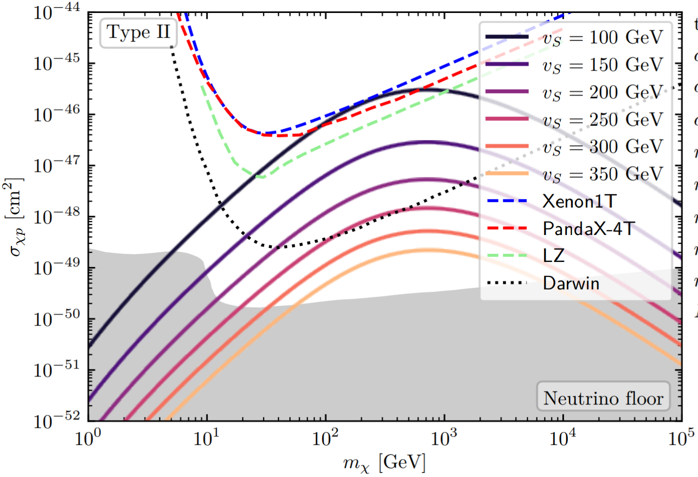
Actually contributing diagrams



$$\sum_{\text{diags}} \mathcal{M}(t \to 0) \neq 0$$

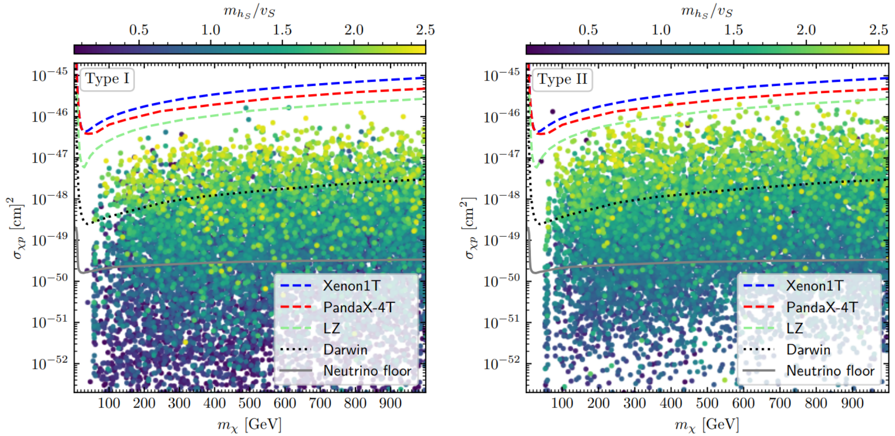
(diagrams with internal χ in 1PI part, UV divergences cancel)

Generic features of loop-corrected scattering XS



$\tan\beta = 2$
$\alpha_1 = \beta$
$\alpha_2 = 0.1$
$\alpha_3 = \pi/2 - 0.1$
$m_{h_a} = 125$ GeV
$m_{h_b} = 350$ GeV
$m_{h_c} = 500$ GeV
$m_A = 600$ GeV
$m_{H^\pm} = 700$ GeV
$M = 500$ GeV

Experimental prospects for a direct detection of χ

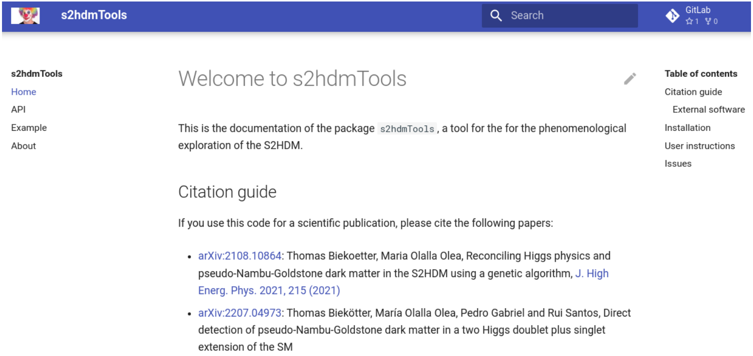


Type	m_{h_a}	$m_{h_b}, m_{h_c}, m_A, m_\chi$	$m_{H^\pm}$	$\alpha_{1,2,3}$	$\tan\beta$	M	v_S
I	125.09	[30,1000]	[150,1000]	$[-\pi/2, \pi 2]$	[1.5,10]	[20, 1000]	[30,1000]

Type	m_{h_a}	m_{h_b, m_A}	$m_{H^\pm}$	$m_{h_c,\chi}$	$\alpha_{1,2,3}$	$\tan\beta$	M	v_S
II	125.09	[200,1000]	[650,1000]	[30,1000]	$[-\pi/2, \pi 2]$	[1.5,10]	[450, 1000]	[30,1000]

Conclusions

If you are interested in the **S2HDM**: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About

Welcome to s2hdmTools

This is the documentation of the package `s2hdmTools`, a tool for the for the phenomenological exploration of the S2HDM.

Citation guide

If you use this code for a scientific publication, please cite the following papers:

- arXiv:2108.10864: Thomas Biekoetter, Maria Olalla Olea, Reconciling Higgs physics and pseudo-Nambu-Goldstone dark matter in the S2HDM using a genetic algorithm, J. High Energ. Phys. 2021, 215 (2021)
- arXiv:2207.04973: Thomas Biekötter, María Olalla Olea, Pedro Gabriel and Rui Santos, Direct detection of pseudo-Nambu-Goldstone dark matter in a two Higgs doublet plus singlet extension of the SM

Table of contents

Citation guide

External software

Installation

User instructions

Issues

`https://gitlab.com/thomas.biekoetter/s2hdmtools`

Thanks!

S2HDM: Singlet-extended 2 Higgs doublet model

ϕ_1, ϕ_2: SU(2) doublets, ϕ_S: SM singlet, charged under global U(1)

Scalar potential:

$$V = \mu_{11}^2 \left(\phi_1^\dagger \phi_1\right) + \mu_{22}^2 \left(\phi_2^\dagger \phi_2\right) - \mu_{12}^2 \left(\left(\phi_1^\dagger \phi_2\right) + \left(\phi_2^\dagger \phi_1\right)\right) + \frac{1}{2}\mu_S^2 |\phi_S|^2 - \frac{1}{4}\mu_\chi^2 \left(\phi_S^2 + (\phi_S^*)^2\right)$$
$$+ \frac{1}{2}\lambda_1 \left(\phi_1^\dagger \phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\phi_2^\dagger \phi_2\right)^2 + \lambda_3 \left(\phi_1^\dagger \phi_1\right)\left(\phi_2^\dagger \phi_2\right) + \lambda_4 \left(\phi_1^\dagger \phi_2\right)\left(\phi_2^\dagger \phi_1\right)$$
$$+ \frac{1}{2}\lambda_5 \left(\left(\phi_1^\dagger \phi_2\right)^2 + \left(\phi_2^\dagger \phi_1\right)^2\right) + \frac{1}{2}\lambda_6 \left(|\phi_S|^2\right)^2 + \lambda_7 \left(\phi_1^\dagger \phi_1\right)|\phi_S|^2 + \lambda_8 \left(\phi_2^\dagger \phi_2\right)|\phi_S|^2$$

EW vacuum: $\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}$, $\langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}$, $\langle \phi_S \rangle = v_S/\sqrt{2} \quad \in \mathbb{R}$

BSM particles:

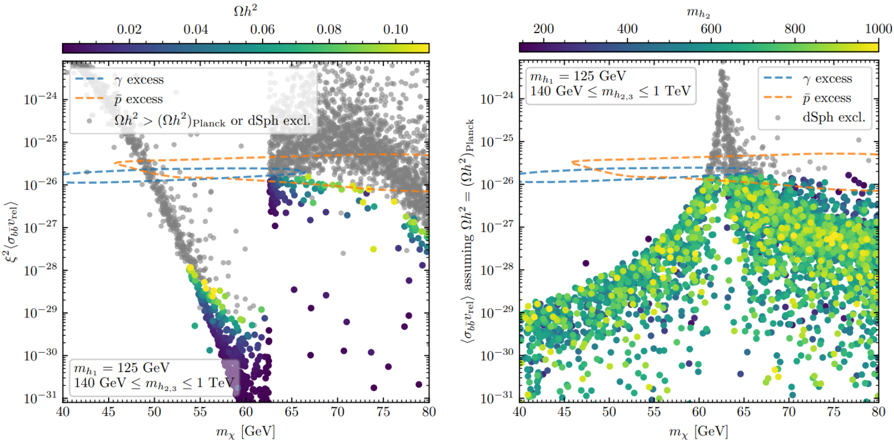
- $h_{1,2,3}$: CP-even Higgs bosons
- $H^\pm$: Charged Higgs bosons
- A: CP-odd Higgs boson
- χ: pNG DM

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R(\alpha_1, \alpha_2, \alpha_3) \cdot \begin{pmatrix} \mathrm{Re}(\phi_1^0) \\ \mathrm{Re}(\phi_2^0) \\ \mathrm{Re}(\phi_S^0) \end{pmatrix}$$

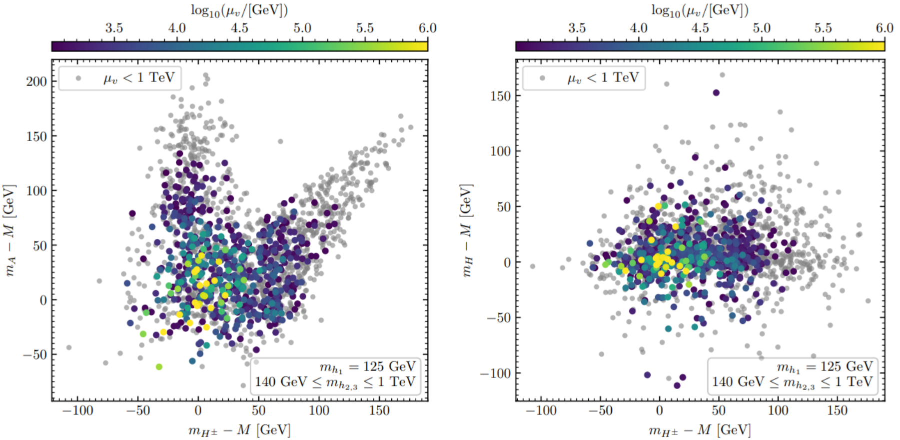
Free parameters (Yukawa type II):

$$m_{h_{1,2,3}} , \quad m_A , \quad m_{H^\pm} , \quad m_\chi , \quad \alpha_{1,2,3} , \quad \tan\beta , \quad M = \sqrt{\mu_{12}^2 / \left(s_\beta c_\beta\right)} , \quad v_S$$

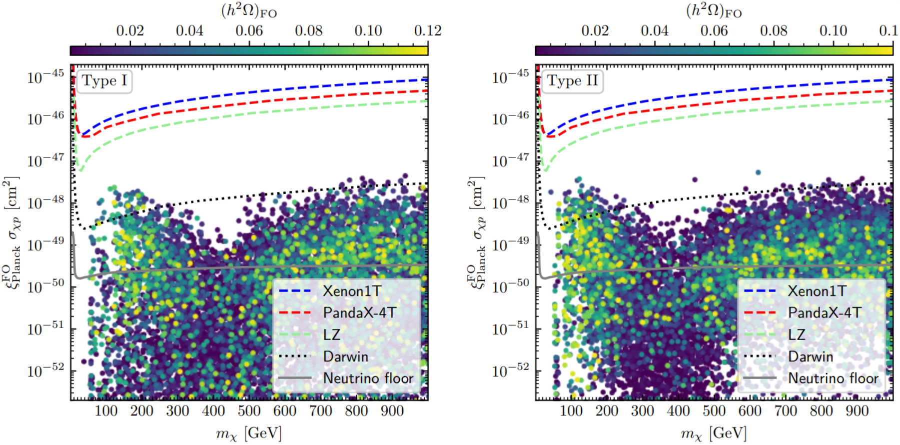
GCE and non-standard cosmological histories



RGE evolution and mass splittings



Experimental prospects for a direct detection of χ



Type	m_{h_a}	$m_{h_b}, m_{h_c}, m_A, m_\chi$	$m_{H^\pm}$	$\alpha_{1,2,3}$	$\tan\beta$	M	v_S
I	125.09	[30,1000]	[150,1000]	$[-\pi/2, \pi 2]$	[1.5,10]	[20, 1000]	[30,1000]

Type	m_{h_a}	m_{h_b, m_A}	$m_{H^\pm}$	$m_{h_c,\chi}$	$\alpha_{1,2,3}$	$\tan\beta$	M	v_S
II	125.09	[200,1000]	[650,1000]	[30,1000]	$[-\pi/2, \pi 2]$	[1.5,10]	[450, 1000]	[30,1000]

S2HDM Type II:

$$1.5 \leq \tan\beta \leq 10 \;, \quad m_{h_1} = 125.09\ \mathrm{GeV} \;, \quad 140\ \mathrm{GeV} \leq m_{h_{2,3}} \leq 1\ \mathrm{TeV} \;,$$
$$40\ \mathrm{GeV} \leq m_\chi \leq 80\ \mathrm{GeV} \;, \quad 40\ \mathrm{GeV} \leq v_S \leq 1\ \mathrm{TeV} \;, \quad -\pi/2 \leq \alpha_{1,2,3} \leq \pi/2 \;,$$
$$400\ \mathrm{GeV} \leq M \leq 1\ \mathrm{TeV} \;, \quad 600\ \mathrm{GeV} \leq m_{H^\pm} \leq 1\ \mathrm{TeV} \;, \quad m_A \leq 1\ \mathrm{TeV} \;,$$
$$\Delta M_{\mathrm{max}} = \max\left(|m_H - M|, |m_A - M|, |m_{H^\pm} - M|\right) < 200\ \mathrm{GeV} \;,\; m_H = m_{h_2} \text{ or } m_{h_3}$$

Genetic algorithm: Minimizing the loss function L

$$L = \chi^2_{125}(+\chi^2_{96}) + \max\left[0, (r^{\mathrm{HB}}_{\mathrm{obs}} - 1)\cdot 100\right] + \begin{cases} C \;, & \chi^2_{ST} > 5.99 \text{ or theo. constr. } ↯ \\ 0 \;, & \text{otherwise} \end{cases}$$

Individuals: $[n_1, n_2, \ldots, n_{14}]$, $0 < n_i < 1$ $\Rightarrow \tan\beta(n_i)$, $m_{h_i}(n_i)$, ...

Population: 50 000 individuals, randomly generated

Evolution: Selection: Tournament selection with size 3

Mating: Uniform crossover of 2 individuals with $p = 20\%$, mating probability 80%

Mutation: Float uniform mutator with $p = 10\%$, mutation probability 20%

Generations: Maximum 40, or until individual with $L \leq L_{\mathrm{threshold}}$ has been found

→ For the resulting points calculate **DM observables** and check RGE evolution

Performance of genetic algorithm