Reconciling Higgs physics and pseudo-Nambu-Goldstone dark matter in the S2HDM using a genetic algorithm

[2108.10864]

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in collaboration with María Olalla Olea Romacho

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Helmholtz Alliance

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DESY.

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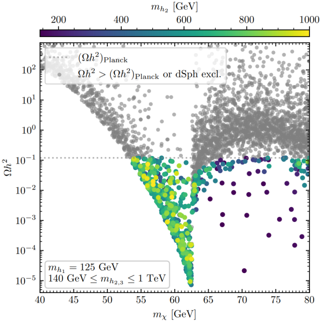
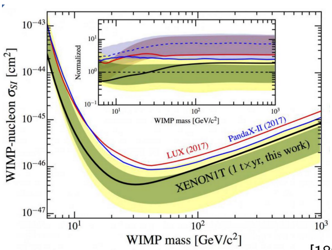
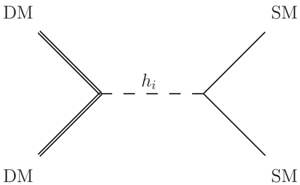
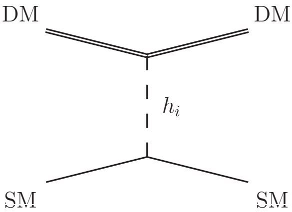
Higgs portal dark matter





[1805.12562]





Can we have one without the other?

Pseudo-Nambu-Goldstone dark matter (pNG)

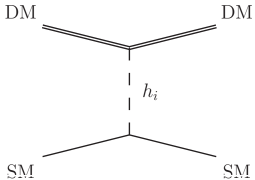
S: Complex field charged under a softly-broken global U(1)

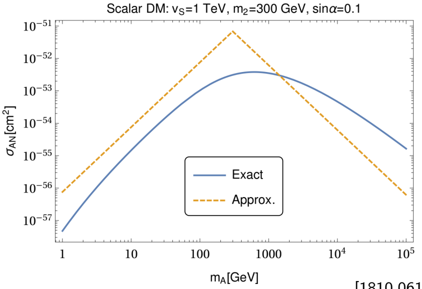
$$\mathcal{L} = (\partial_\mu S)^* \, \partial^\mu S - V(\phi_i, S)|_{\mathrm{U}(1)} - V(S)|_{\cancel{U(1)}-\mathrm{soft}}$$

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

[2109.11499]

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

$\sum_i$  $\sim t$



[1810.06105]

Direct detection constraints largely irrelevant

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, $E_{T_{\rm missing}}$ signatures

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Here: $V = V_{\rm 2HDM-II}(\phi_1,\phi_2) + V(\phi_1,\phi_2,\phi_S)|_{\rm U(1)} + \mu_\chi \left(\phi_S^2 + (\phi_S^*)^2\right)$ [2108.10864]

– 2HDM: First-order EW phase transitions, Susy, Axion models
– DM: Richer DM-Higgs portal interactions
– Collider: Richer mixing patterns and new states

Aim: Model exploration taking into account all constraints

We explore parameter region motivated by
(i) Cosmic ray excesses (Fermi and AMS)
(ii) collider excesses at 96 GeV

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:

$$V = V_{\mathrm{2HDM-II}}(\phi_1, \phi_2) + V(\phi_1, \phi_2, \phi_S)|_{\mathrm{U(1)}} + \mu_\chi \left(\phi_S^2 + (\phi_S^*)^2\right)$$

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):

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

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

Theoretical and experimental constraints

Theory:

Vacuum stability: EW minimum is global 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 evolution: Check for boundedness and perturbativity until at least $\mu_v = 1$ TeV

Experiment:

Colliders: Searches, measurements of h_{125} [N2HDECAY, HiggsBounds, HiggsSignals]

STU: EW precision observables (at one loop)

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

Dark matter: Relic abundance $h^2\Omega < 0.12$ [Micromegas]

Indirect detection limits from Fermi dSph observations [MadDM]

s2hdmTools

s2hdmTools Search GitLab ☆1 ⑂0

s2hdmTools
- Home
- API
- Example
- 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 software for a scientific publication, we kindly ask you to cite our paper:

- 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)

External software

`s2hdmTools` makes use of external software to perform some of the computations. Please also cite the relevant publications for the following software if it is relevant for your work:

- Vacuum stability: Hom4PS2
- Collider constraints: AnyHdecay, HiggsBounds, HiggsSignals
- Dark-matter constraints: MicrOmegas, MadDM

Installation

`s2hdmTools` can be installed by typing the following command from within the main directory:

```
make all PC2=/home/.../python2 F2PC2=/home/.../f2py2
```

The makefile uses `pip` to install the package to your python environment.

Table of contents
- Citation guide
  - External software
- Installation
- User instructions
- Issues

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

Parameter Scan

S2HDM Type II:

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

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

Genetic algorithm:* Minimizing the loss function L

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

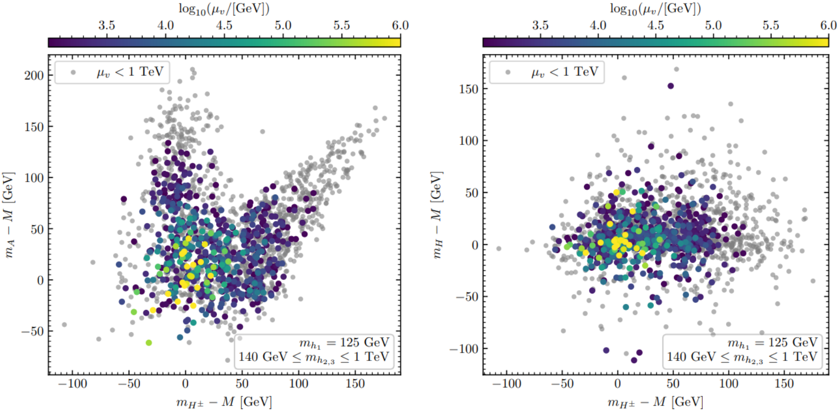
$\Rightarrow$ Points that fulfill theory constraints at $\mu = v_{\text{EW}}$ and are allowed by collider measurements

$\rightarrow$ Check theory constraints including **RGE evolution**
$\rightarrow$ Calculate **DM observables**

*Details appendix/questions

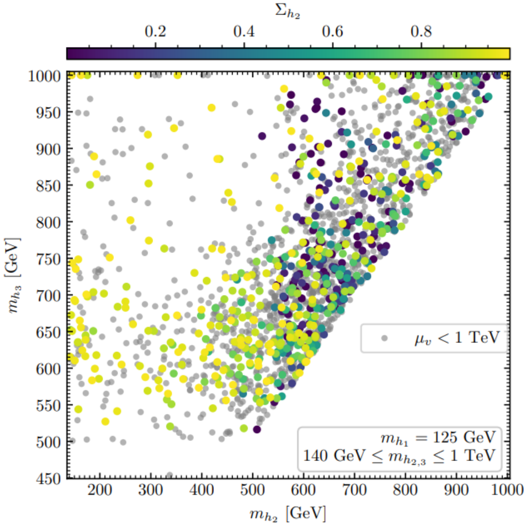
Theoretical constraints: Impact of RGE running

μ_v: Energy scale until the model is theoretically **viable**



⚠ First-order EW phase transitions (baryogenesis and GW) require sizable mass splittings

Scalar spectrum



Most common:

$m_H \sim m_A \sim m_{H^\pm} \sim M \gtrsim 500$ GeV

$m_{h_i} \lesssim v_S$ for $\Sigma_{h_i} \sim 1$

→ Higgs cascade decays

→ SM decay modes of $H, A, H^\pm$ can be suppressed w.r.t. 2HDM

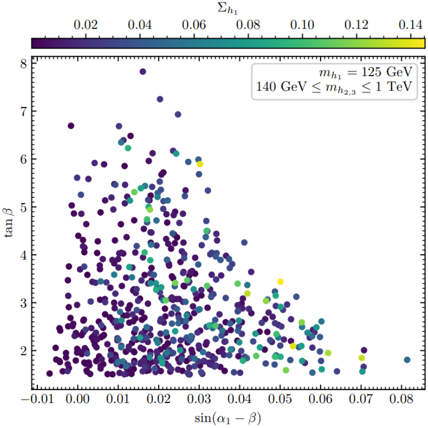
→ Spectrum can be somewhat lighter

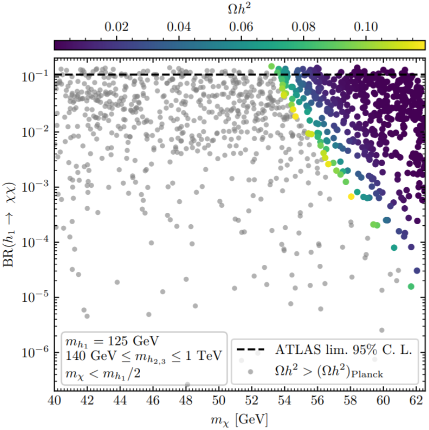
DM: Here $M \gg m_\chi$

→ Annihilation via $h_{1,2} = h_{125,S}$

SM-like Higgs boson at 125 GeV

$$h_1 = h_{125}$$





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

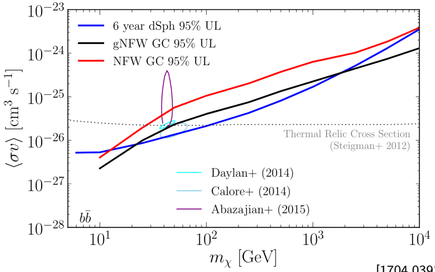
Possibility to distinguish the models

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

But depends on $m_{h_S} > m_{h_{125}}$

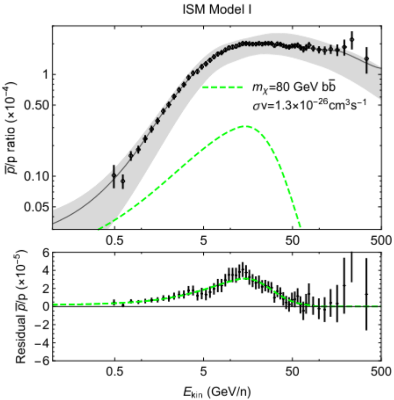
Galactic center excess and antiproton excess

Fermi γ excess



[1704.03910]

AMS $\bar{p}$ excess



[1903.02549]

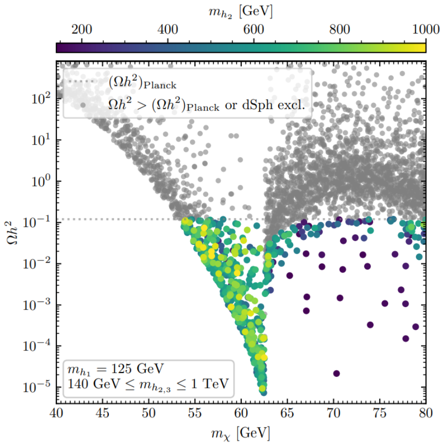
Assuming that origin is DM annihilation:

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

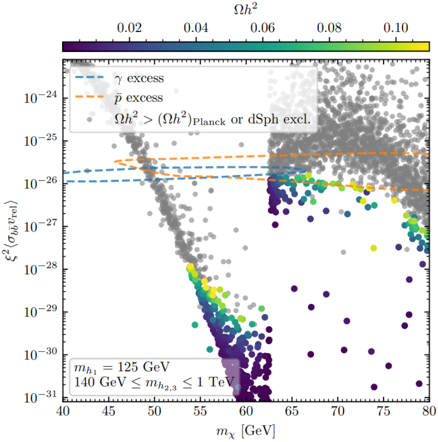
Exciting :)

Thermal DM relics in the Higgs funnel region

Relic abundance



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



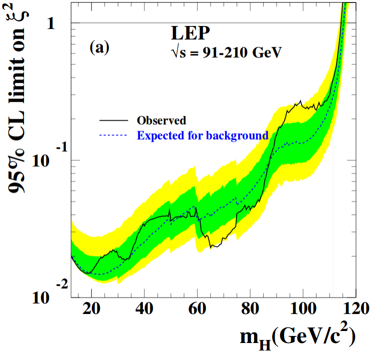
Very interesting region at 62 GeV $\lesssim m_\chi \lesssim$ 65 GeV:

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

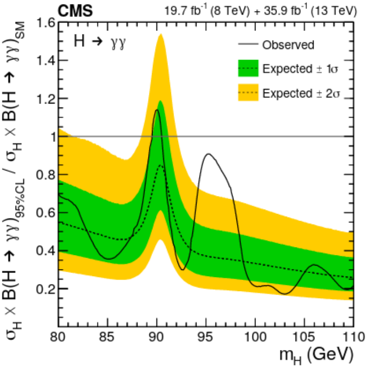
(✗) In tension with dSph exclusion limits (but there are large uncertainties)

*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]

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

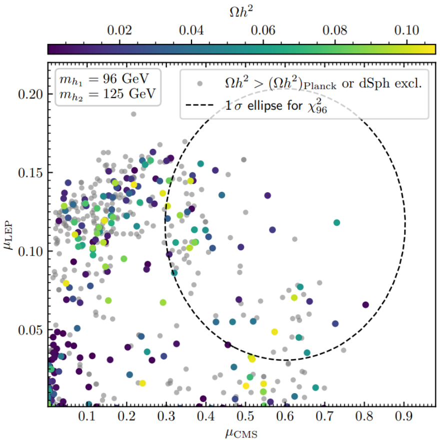
$\to \chi^2_{96}(\mu_{\rm LEP}, \mu_{\rm CMS})$ assuming no correlation between $\mu_{\rm LEP}$ and $\mu_{\rm CMS}$

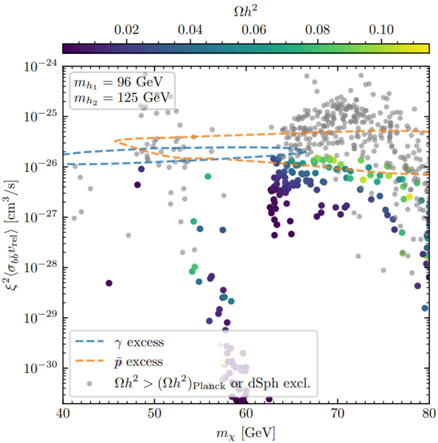
Many model interpretations with common origin of both excesses, including N2HDM and NMSSM

see [2003.05422] for a list models

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





Very interesting region at $62 \text{ GeV} \lesssim m_\chi \lesssim 65 \text{ GeV}$:

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

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

Summary and outlook

- The S2HDM is theoretically well motivated and has a rich Higgs and DM phenomenology
- We demonstrated that important (theoretical) constraints have been overlooked so far
- We provide the public code `s2hdmTools` for model explorations

In the Higgs funnel region recent experimental anomalies can be explained:

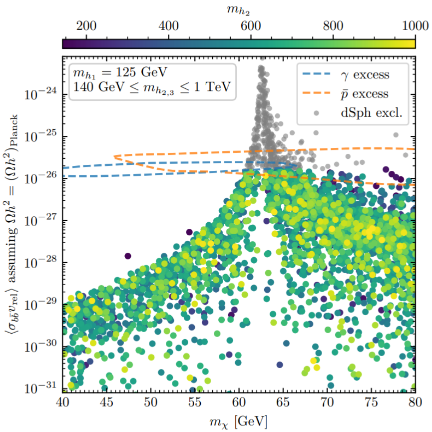
✓ Relic abundance ✓ Fermi γ excess ✓ AMS $\bar{p}$ excess ✓CMS excess ✓LEP excess

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

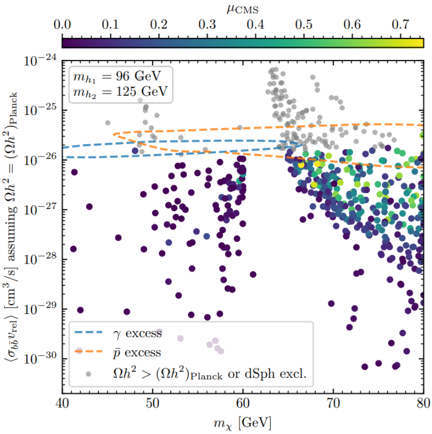
Thanks for your attention!

Assuming $\Omega h^2 = \Omega h^2_{\rm Planck}$ – Non-standard cosmological history

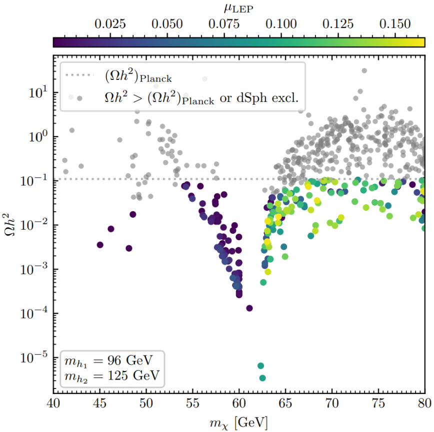
$m_{h_1} = 125$ GeV , $m_{h_2} > 140$ GeV

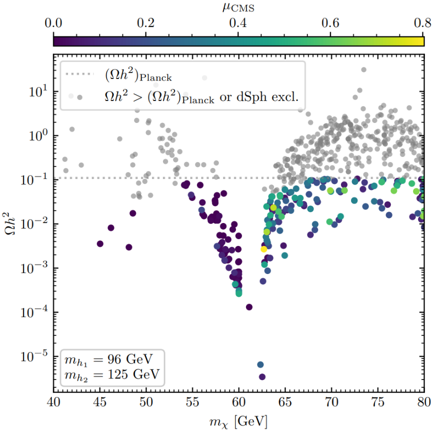


$m_{h_1} = 96$ GeV , $m_{h_2} = 125$ GeV

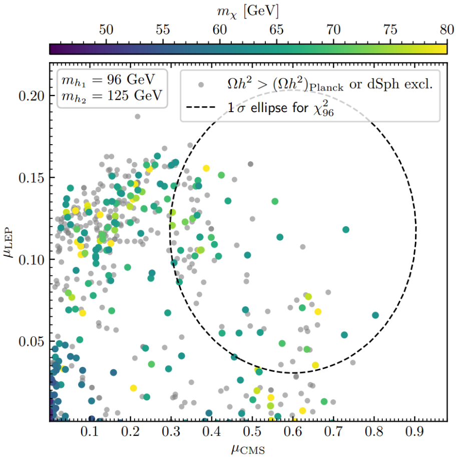


Higgs funnel DM and a Higgs boson at 96 GeV





Higgs funnel DM and a Higgs boson at 96 GeV



S2HDM Type II:

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

Genetic algorithm: Minimizing the loss function L

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

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

Population: 50 000 individuals, randomly generated

Evolution: Selection: Tournament selection with size 3

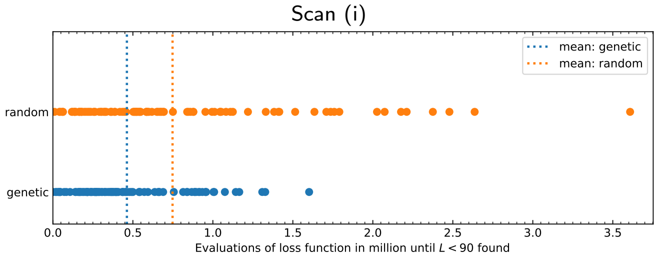
Mating: Uniform crossover of 2 individuals with $p = 20\%$, mating probability 80%

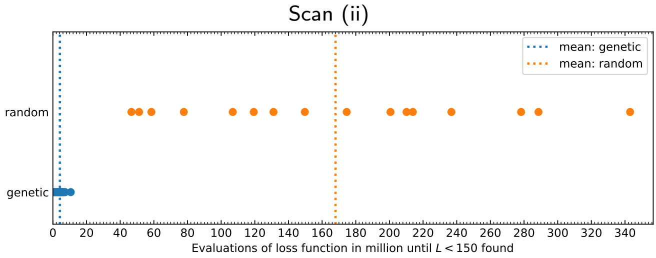
Mutation: Float uniform mutator with $p = 10\%$, mutation probability 20%

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

$\rightarrow$ For the resulting points calculate **DM observables**

Performance of genetic algorithm





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):

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