Saving the Higgs Portal for Singlet Scalar Dark Matter.

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Introduction
Relation between Dark sector and SM
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Relation between Dark sector and SM

Dark matter sector \[\rightarrow\] Portal \[\rightarrow\] SM

Indirect detection

DM \[\rightarrow\] \[\rightarrow\] SM

DM production

Direct detection

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Saving the Higgs Portal for Singlet Scalar Dark Matter
Relation between Dark sector and SM

**Dark matter sector** → **Portal** → **SM**

**Indirect detection**

\[ DM \rightarrow SM \rightarrow_h \rightarrow \text{DM production} \]

**Direct detection**

Many candidates

- Singlet, Doublet…
- Scalar, fermionic…

Simplest:

Real singlet scalar DM
Higgs portal with a Real Singlet Scalar DM
$Z_2$ symmetry

$S \to -S \quad SM \to SM$
Higgs portal with a Real Singlet Scalar DM

$Z_2$ symmetry

$S \rightarrow -S \quad SM \rightarrow SM$

**Lagrangian**

$$\mathcal{L}_{HP} = \mathcal{L}_{SM} + \frac{1}{2} \partial_{\mu} S \partial^{\mu} S - \frac{1}{2} m_0^2 S^2 - \frac{1}{2} \lambda_S |H|^2 S^2 - \frac{1}{4} \lambda_4 S^4$$

Renormalizable
$Z_2$ symmetry

$S \rightarrow -S \quad SM \rightarrow SM$

**Lagrangian**

$$\mathcal{L}_{HP} = \mathcal{L}_{SM} + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_0^2 S^2 - \frac{1}{2} \lambda_S |H|^2 S^2 - \frac{1}{4} \lambda_4 S^4$$

*Renormalizable*

**After EWSB**

$$\mathcal{L}_{HP} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S \partial^\mu S - m_S^2 S^2) - \frac{1}{2} \lambda_S v h S^2 - \frac{1}{4} \lambda_4 h^2 S^2 - \frac{1}{4} \lambda_4 S^4$$

($v = 175$ GeV)
Higgs portal with a Real Singlet Scalar DM

After EWSB

\[ \mathcal{L}_{HP} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S \partial^\mu S - m_S^2 S^2) - \frac{1}{2} \lambda_S v h S^2 - \frac{1}{4} \lambda_S h^2 S^2 - \frac{1}{4} \lambda_4 S^4 \quad (v = 175 \text{ GeV}) \]

Processes DM-SM
Higgs portal with a Real Singlet Scalar DM

After EWSB

\[ L_{HP} = L_{SM} + \frac{1}{2}(\partial_{\mu}S\partial^{\mu}S - m_{S}^2 S^2) - \frac{1}{2}\lambda_{S}v h S^2 - \frac{1}{4}\lambda_{S} h^2 S^2 - \frac{1}{4}\lambda_{4} S^4 \] (\( v = 175 \) GeV)

Processes DM-SM

relevant parameters: \( m_{S}, \lambda_{S} \)
Higgs portal with a Real Singlet Scalar DM

After EWSB

\[ \mathcal{L}_{\text{HP}} = \mathcal{L}_{\text{SM}} + \frac{1}{2} (\partial_\mu S \partial^\mu S - m_S^2 S^2) - \frac{1}{2} \lambda_S v h S^2 - \frac{1}{4} \lambda_S h^2 S^2 - \frac{1}{4} \lambda_4 S^4 \]  \hspace{1cm} (v = 175 \text{ GeV})

Processes DM-SM

Relic density, \( \Omega h^2 \)

\[ \Omega h^2 < \Omega h^2_{\text{obs}} \]

\[ \Omega h^2 > \Omega h^2_{\text{obs}} \]
References on Real Singlet Scalar DM


References on Real Singlet Scalar DM


and many more…. 
Direct, indirect and Higgs Invisible Width constraints
Direct, indirect and Higgs Invisible Width constraints
Direct, indirect and Higgs Invisible Width constraints

\[ \Gamma_{H}^{inv} \]

Indirect detection

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Reopening the Higgs Portal for Singlet Scalar Dark Matter

Saving the Higgs Portal for Singlet Scalar Dark Matter
Direct, indirect and Higgs Invisible Width constraints

$$\Gamma_{H}^{inv}$$

Direct detection: LUX

Indirect detection

$${}$$

Opening the Higgs portal window

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Reopening the Higgs Portal for Singlet Scalar Dark Matter

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Saving the Higgs Portal for Singlet Scalar Dark Matter
Direct, indirect and Higgs Invisible Width constraints

- Masses over 500 GeV are allowed
- Small window in the resonance allowed
Future Direct Detection: LZ

Future constraints
Future Direct Detection: LZ

The only zone remaining will be the window in the resonance.
Future Direct Detection: LZ

The only zone remaining will be the window in the resonance.

We expect **indirect detection** experiments to explore that remaining window.

- Feng et al: arXiv 1412:1105
- Duerr et al: arXiv 1509.04282
Future Direct Detection: LZ

The only zone remaining will be the window in the resonance.

We expect indirect detection experiments to explore that remaining window.

No positive detection.

Feng et al: arXiv 1412:1105
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Future Direct Detection: LZ

The only zone remaining will be the window in the **resonance**

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No positive detection

Scalar Higgs portal

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Opening the Higgs portal window

**Future constraints**
Future constraints

Future Direct Detection: LZ

The only zone remaining will be the window in the resonance

We expect indirect detection experiments to explore that remaining window.

Feng et al: arXiv 1412:1105
Duerr et al: arXiv 1509.04282

No positive detection

Scalar Higgs portal
“Rescuing” the Higgs portal

Original model

Real Singlet Scalar DM

Quarks

\( u \)
\( d \)
\( c \)
\( s \)
\( t \)
\( b \)
\( \bar{u} \)
\( \bar{d} \)
\( \bar{c} \)
\( \bar{s} \)
\( \bar{t} \)
\( \bar{b} \)

Leptons

\( \nu_e \)
\( \nu_\mu \)
\( \nu_\tau \)
\( \bar{\nu}_e \)
\( \bar{\nu}_\mu \)
\( \bar{\nu}_\tau \)

H

Z

W

\( \gamma \)
\( \text{gluon} \)
\( \text{Zboson} \)
\( \text{Wboson} \)

Saving the Higgs Portal for Singlet Scalar Dark Matter
“Rescuing” the Higgs portal

Original model

Real Singlet Scalar DM

Our proposal

Real Singlet Scalar DM

Extra real singlet scalar

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Reopening the Higgs Portal for Singlet Scalar Dark Matter

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Saving the Higgs Portal for Singlet Scalar Dark Matter
"Rescuing" the Higgs portal

Original model

Real Singlet Scalar DM

Our proposal

Real Singlet Scalar DM

Extra real singlet scalar
“Rescuing” the Higgs portal

Original model

Real Singlet Scalar DM

Our proposal

Real Singlet Scalar DM

Extra real singlet scalar

New scalar

- Heavier
- Decaying
“Rescuing” the Higgs portal

Original model

Real Singlet Scalar DM

Our proposal

Real Singlet Scalar DM

Extra real singlet scalar

New scalar

- Heavier
- Decaying

Only Singlet Scalar 1 remains
Higgs portal with two Real Singlet Scalars
Higgs portal with two Real Singlet Scalars

Global $Z_2$ symmetry

$S_1 \rightarrow -S_1 \quad S_1 S_2 \rightarrow S_1 S_2$

$S_2 \rightarrow -S_2 \quad SM \rightarrow SM$

$S_1$ DM candidate

$S_2$ Heavier scalar
Higgs portal with two Real Singlet Scalars

Global $Z_2$ symmetry

$S_1 \rightarrow -S_1$ \hspace{1cm} $S_1S_2 \rightarrow S_1S_2$

$S_2 \rightarrow -S_2$ \hspace{1cm} $SM \rightarrow SM$

$S_1$ DM candidate

$S_2$ Heavier scalar

Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \sum_{i=1,2} \left[ (\partial_\mu S_i)^2 - m_i^2 S_i^2 - \frac{1}{12} \lambda_{i4} S_i^4 \right] - \frac{1}{6} \lambda_{13} S_1 S_2^3 - \frac{1}{6} \lambda_{31} S_1^3 S_2 - \frac{1}{4} \lambda_{22} S_1^2 S_2^2$$

$$- \frac{1}{2} \lambda_1 S_1^2 |H|^2 - \frac{1}{2} \lambda_2 S_2^2 |H|^2 - \lambda_{12} S_1 S_2 \left( |H|^2 - \frac{v^2}{2} \right)$$

Renormalizable
Higgs portal with two Real Singlet Scalars

Global $Z_2$ symmetry

\[
S_1 \rightarrow -S_1 \quad S_1 S_2 \rightarrow S_1 S_2
\]

\[
S_2 \rightarrow -S_2 \quad SM \rightarrow SM
\]

Lagrangian

\[
\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \sum_{i=1,2} \left( (\partial_\mu S_i)^2 - m_i^2 S_i^2 - \frac{1}{12} \lambda_{i4} S_i^4 \right) - \frac{1}{6} \lambda_{13} S_1 S_2^3 - \frac{1}{6} \lambda_{31} S_1^3 S_2 - \frac{1}{4} \lambda_{22} S_1^2 S_2^2
\]

\[- \frac{1}{2} \lambda_1 S_1^2 |H|^2 - \frac{1}{2} \lambda_2 S_2^2 |H|^2 - \lambda_{12} S_1 S_2 \left( |H|^2 - \frac{v^2}{2} \right)
\]

Renormalizable

After EWSB

\[
\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \sum_{i=1,2} \left( (\partial_\mu S_i)^2 - m_i^2 S_i^2 - \frac{1}{12} \lambda_{i4} S_i^4 \right) - \frac{1}{6} \lambda_{13} S_1 S_2^3 - \frac{1}{6} \lambda_{31} S_1^3 S_2 - \frac{1}{4} \lambda_{22} S_1^2 S_2^2
\]

\[- \frac{1}{2} \lambda_1 \nu S_1^2 h - \frac{1}{2} \lambda_2 \nu S_2^2 h - \lambda_{12} \nu S_1 S_2 h - \frac{1}{4} \lambda_1 S_1^2 h^2 - \frac{1}{4} \lambda_2 S_2^2 h^2 - \frac{1}{2} \lambda_{12} S_1 S_2 h^2
\]

\[(v = 175 \text{ GeV})\]
Higgs portal with two Real Singlet Scalars

After EWSB

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \sum_{i=1,2} \left[ (\partial_{\mu} S_i)^2 - m_{S_i}^2 S_i^2 - \frac{1}{12} \lambda_{i4} S_i^4 \right] - \frac{1}{6} \lambda_{13} S_1 S_2^3 - \frac{1}{6} \lambda_{31} S_1^3 S_2 - \frac{1}{4} \lambda_{22} S_1^2 S_2^2 \\
- \frac{1}{2} \lambda_1 v S_1^2 h - \frac{1}{2} \lambda_2 v S_2^2 h - \lambda_{12} v S_1 S_2 h - \frac{1}{4} \lambda_1 S_1^2 h^2 - \frac{1}{4} \lambda_2 S_2^2 h^2 - \frac{1}{2} \lambda_{12} S_1 S_2 h^2 \quad (v = 175 \text{ GeV})
\]

Processes DM-SM

\[ S_j \rightarrow h \]

\[ S_j \rightarrow h \quad S_k \]

\[ S_i \rightarrow h \quad i, j, k = 1, 2 \]
Coannihilation and eff. operator

To avoid constraints we need low values of $\lambda_1$

$$-\frac{1}{2} \lambda_1 v S_1^2 h - \frac{1}{4} \lambda_1 S_1^2 h^2$$
Coannihilation and eff. operator

To avoid constraints we need low values of $\lambda_1$

$$-\frac{1}{2} \lambda_1 v S_1^2 h - \frac{1}{4} \lambda_1 S_1^2 h^2$$

To test coannihilation effects we are imposing low values of $\lambda_2$

$$-\frac{1}{2} \lambda_2 v S_2^2 h - \frac{1}{4} \lambda_2 S_2^2 h^2$$
Higgs portal with two Real Singlet Scalars

Coannihilation and eff. operator

To avoid constraints we need low values of $\lambda_1$

$$-\frac{1}{2} \lambda_1 v S_1^2 h - \frac{1}{4} \lambda_1 S_1^2 h^2$$

To test coannihilation effects we are imposing low values of $\lambda_2$

$$-\frac{1}{2} \lambda_2 v S_2^2 h - \frac{1}{4} \lambda_2 S_2^2 h^2$$

For low values of $\lambda_1, \lambda_2$ the coupling $\lambda_{12}$ becomes relevant.

$$-\lambda_{12} v S_1 S_2 h - \frac{1}{2} \lambda_{12} S_1 S_2 h^2$$
Coannihilation and eff. operator

To avoid constraints we need low values of $\lambda_1$

$$-\frac{1}{2} \lambda_1 v S_1^2 h - \frac{1}{4} \lambda_1 S_1^2 h^2$$

To test coannihilation effects we are imposing low values of $\lambda_2$

$$-\frac{1}{2} \lambda_2 v S_2^2 h - \frac{1}{4} \lambda_2 S_2^2 h^2$$

For low values of $\lambda_1, \lambda_2$ the coupling $\lambda_{12}$ becomes relevant.

$$-\lambda_{12} v S_1 S_2 h - \frac{1}{2} \lambda_{12} S_1 S_2 h^2$$

To analyze the effect of the coannihilation and effective operators we set $\lambda_1, \lambda_2$ to

$$\lambda_1 = \lambda_2 = \frac{\lambda_{12}^2}{(4\pi)^2}$$

(radiative corrections), and we study the relevance of the coupling $\lambda_{12}$
Coannihilation and eff. operator

\[ \lambda_1 = \lambda_2 = \frac{\lambda_{12}^2}{(4\pi)^2} \]

The coupling \( \lambda_{12} \) is in charge of the annihilation of DM
Coannihilation and eff. operator

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The coupling \( \lambda_{12} \) is in charge of the annihilation of DM.
Coannihilation and eff. operator

\[ \lambda_1 = \lambda_2 = \frac{\lambda_{12}^2}{(4\pi)^2} \]

The coupling \( \lambda_{12} \) is in charge of the annihilation of DM
Higgs portal with two Real Singlet Scalars

Coannihilation and eff. operator

\[ \lambda_1 = \lambda_2 = \frac{\lambda_{12}^2}{(4\pi)^2} \]

The coupling \( \lambda_{12} \) is in charge of the annihilation of DM

\[ \Omega h^2 < \Omega h_{\text{obs}}^2 \]
\[ \Omega h^2 > \Omega h_{\text{obs}}^2 \]
Parameter space of the new model

Random scan: $m_{S_1}, m_{S_2}, \lambda_1, \lambda_{12}$
Parameter space of the new model

Random scan: \( m_{S_1}, m_{S_2}, \lambda_1, \lambda_{12} \)

Conditions: \( \lambda_2 = \frac{\lambda_{12}^2}{(4\pi)^2} \quad \lambda_1 > \frac{\lambda_{12}^2}{(4\pi)^2} \quad m_{S_2} > m_{S_1} \)
Higgs portal with two Real Singlet Scalars

Parameter space of the new model

Random scan: \( m_{S_1}, m_{S_2}, \lambda_1, \lambda_{12} \)

Conditions:
\[
\lambda_2 = \frac{\lambda_{12}^2}{(4\pi)^2} \\
\lambda_1 > \frac{\lambda_{12}^2}{(4\pi)^2} \\
m_{S_2} > m_{S_1}
\]

\[\lambda_{12} = 0.01\]

\[\lambda_{12} = 0.1\]

\[\lambda_{12} = 1\]

- 0.116 > \( \Omega h^2 \)
- 0.116 < \( \Omega h^2 < 0.122 \)
Higgs portal with two Real Singlet Scalars

Constraints
- $\tau_{S_2} < 1s$ (BBN)
- LUX
- $\Gamma_{H}^{inv}$
- dwarf spheroidal galaxies
- gamma-ray
Higgs portal with two Real Singlet Scalars

Constraints
- $\tau_{S_2} < 1\, s$ (BBN)
- dwarf spheroidal galaxies
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- $0.116 > \Omega h^2$
- $0.116 < \Omega h^2 < 0.122$
Higgs portal with two Real Singlet Scalars

Constraints

- $\tau_{S_2} < 1s$ (BBN)
- dwarf spheroidal galaxies
- LUX
- $\Gamma_{H}^{inv}$
- gamma-ray

For masses above 50 GeV we can find values of $m_{S_2}$, $\lambda_1$, $\lambda_{12}$ with the correct relic density that survive all the constraints.

$0.116 > \Omega h^2$

$0.116 < \Omega h^2 < 0.122$
Higgs portal with two Real Singlet Scalars

Future DD constraints (LZ)
Higgs portal with two Real Singlet Scalars

Future DD constraints (LZ)

- $\tau_{S_2} < 1\text{s}$ (BBN)
- dwarf spheroidal galaxies
- $\Gamma_{H}^{\text{inv}}$
- LUX
- gamma-ray

$\xi = \Omega h^2 / \Omega h_{\text{obs}}^2$

- $0.116 > \Omega h^2$
- $0.116 < \Omega h^2 < 0.122$
Future DD constraints (LZ)

- $\tau_{S_2} < 1\text{s}$ (BBN)
- dwarf spheroidal galaxies
- $\Gamma_{H}^{inv}$
- LUX
- gamma-ray

There are points in the parameter space that avoid also future LZ constraints

$$\xi = \Omega h^2 / \Omega_{obs}^2$$

- $0.116 > \Omega h^2$
- $0.116 < \Omega h^2 < 0.122$
Summary
1 real scalar singlet Higgs portal has been almost completely explored

Future DD and ID experiments will finish exploring the model

A DM sector with two scalars can enlarge the allowed region in the parameter space

If there is a positive detection in a zone where there would be more DM than the observed in the model with one scalar, could be allowed in this new model

If the model with one scalar is completely ruled out by future DD and ID detection, the Higgs portal can live in this minimal extended version

The model with 2 scalars is the most economical way to rescue the real singlet scalar model, which is the simplest model and renormalizable
Thanks for your attention!