Status of Higgs Portal Dark Matter

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The Higgs-nucleon coupling $g_{hN} h \bar{N} N$

**Dark matter creation (early universe, colliders)**

The Higgs-nucleon coupling is critical for Higgs portal models


\[
g_{hN} v_h = \frac{7}{9} \left( 1 + \frac{m_S y_N}{m_u + m_d} \right) \sigma_{\pi N} + \frac{2}{9} m_N = \frac{7}{9} \sum_{q=u,d,s} m_N f_q^N + \frac{2}{9} m_N = m_N f_N
\]
The Higgs-nucleon coupling $g_{hN} h N \bar{N} N$

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\]

Lattice calculations, chiral perturbation theory, and sum rules indicate $0 \leq y_N \leq 0.1$ and $\sigma_{\pi N} \leq 55$ MeV.

This yields the very conservative estimate

\[
210 \text{ MeV} \leq g_{hN} v_h \leq 310 \text{ MeV}
\]

(comparable to range found by Alarcón et al. from pion-nucleon scattering)

We plot nuclear recoil cross sections for $g_{hN} v_h = 210$ MeV.

Rationale: Most cautious approach to mass exclusion limits from the direct search experiments PandaX-II, LUX and XENON1T.
Scalar Higgs portal dark matter:

The coupling $g_S S^2 H^+ H$ between a scalar electroweak singlet $S$ and the Higgs doublet $H$ yields in unitary gauge

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu_H + h \end{pmatrix}$$

the minimal renormalizable addition to the Standard Model with an additional stable particle,

$$\mathcal{L}_S = -\frac{1}{2} \partial S \cdot \partial S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4} S^4 - g_S \nu_H h S^2 - \frac{g_S}{2} h^2 S^2$$

Silveira & Zee 1985; McDonald 1994; Bento et al. 2000; Burgess, Pospelov & ter Veldhuis 2001;...
“Low mass region” = resonance region $m_S \lesssim m_h/2 = 62.5$ GeV:

Scalar Higgs portal dark matter with $m_S < m_h/2$ is constrained by limits from ATLAS and CMS on the branching ratio into invisible Higgs decays $\mathcal{B} \leq 0.24$,

and by the exclusion limits from PandaX-II, LUX and XENON1T on nucleon recoil cross sections. XENONnT and LZ will have the potential to exhaust the resonance region.

Scalar Higgs portal matter in the high mass region is constrained by the direct search experiments PandaX-II, LZ and XENON1T to \( m_S \gtrsim 2.7 \text{ TeV} \) (or \( m_S \gtrsim 4.5 \text{ TeV} \) for \( g_{hN} \nu_h = 289 \text{ MeV} \)).

It should be detected or ruled out by DarkSide-20k and DARWIN

Vector Higgs portal dark matter:

The coupling $g_V V^\mu V_\mu H^+ H$ between an electroweak singlet vector field $V_\mu$ and the Higgs doublet $H$ yields in unitary gauge the vector Higgs portal addition to the Standard Model

$$\mathcal{L}_V = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} - \frac{1}{2} m^2 V^\mu V_\mu - \frac{\lambda_V}{4} (V^\mu V_\mu)^2 - g_V v_h h V^\mu V_\mu - \frac{g_v}{2} h^2 V^\mu V_\mu$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

Lebedev, Lee & Mambrini 2012; Djouadi, Lebedev, Mambrini & Quevillon 2012;...
“Low mass region” = resonance region $m_V \lesssim m_h/2 = 62.5$ GeV:

Vector Higgs portal dark matter with $m_V < m_h/2$ is constrained by limits from ATLAS and CMS on the branching ratio into invisible Higgs decays $\mathcal{B} \leq 0.24$,

and by the exclusion limits from PandaX-II, LUX and XENON1T on nucleon recoil cross sections. XENONnT and LZ will have the potential to exhaust the resonance region.

Vector Higgs portal matter in the high mass region is constrained by the direct search experiments PandaX-II, LZ and XENON1T to $m_V \gtrsim 6.4$ TeV (or $m_V \gtrsim 11.7$ TeV for $g_{hN\nu h} = 289$ MeV).

It should be detected or ruled out by DarkSide-20k and DARWIN.

Electroweak singlet fermions $\chi$ can couple through a Higgs portal

$$\mathcal{H}_{\chi h} = \frac{1}{M} \overline{\chi} \cdot \Gamma \cdot \chi \left( H^+ H - \frac{v_h^2}{2} \right) = \frac{1}{M} \overline{\chi} \cdot \Gamma \cdot \chi \left( v_h h + \frac{h^2}{2} \right)$$

$$\Gamma = a + ib\gamma_5$$

This can arise through a scalar mediator $\phi$

$$\mathcal{H}_\phi = \frac{1}{2} m_\phi^2 \phi^2 + g\phi \overline{\chi} \cdot \Gamma \cdot \chi + \lambda \phi \left( H^+ H - \frac{v_h^2}{2} \right)$$

with $M = -\frac{m_\phi^2}{g\lambda}$. Note that $|M| < m_\phi$ if $m_\phi < |g\lambda|$, i.e. the coupling scale $M$ in itself does not necessarily set the scale of new physics beyond the minimal fermionic Higgs portal.
The CP even model

\[ \mathcal{L}_\chi = \bar{\chi}(i\gamma^\mu \partial_\mu - m_\chi)\chi - \frac{\nu_h}{M} h\bar{\chi}\chi - \frac{1}{2M} h^2 \bar{\chi}\chi \]

would require coupling scales in the TeV range:
However, the CP even model

\[ \mathcal{L}_\chi = \bar{\chi}(i\gamma^\mu \partial_\mu - m_\chi)\chi - \frac{\nu^h}{M} h \bar{\chi} \chi - \frac{1}{2M} h^2 \bar{\chi} \chi \]

yields nucleon recoil cross sections

\[ \sigma_{\chi N} = \frac{g_{hN}^2 \nu_h^2}{\pi M^2 m_h^4} \left( \frac{m_\chi m_N}{m_\chi + m_N} \right)^2 \]

which are too large:
The CP odd model

\[ \mathcal{L}_\chi = \bar{\chi} (i \gamma^\mu \partial_\mu - m_\chi) \chi - i \frac{\nu_h}{\mu} h \bar{\chi} \gamma_5 \chi - \frac{i}{2 \mu} h^2 \bar{\chi} \gamma_5 \chi \]

would require larger coupling scales than the CP even model:
The CP odd model

\[ \mathcal{L}_\chi = \bar{\chi} \left( i \gamma^\mu \partial_\mu - m_\chi \right) \chi - i \frac{v_h}{\mu} h \bar{\chi} \gamma_5 \chi - \frac{i}{2\mu} h^2 \bar{\chi} \gamma_5 \chi \]

is constrained by the ATLAS and CMS limits on the branching ratio into invisible Higgs decays.

The invisible decay width for the CP odd model is

\[ \Gamma_{h \rightarrow \chi \chi} = \frac{v_h^2}{8\pi \mu^2} \sqrt{m_h^2 - 4m_\chi^2} \]
However, the CP odd model

\[
\mathcal{L}_\chi = \bar{\chi}(i\gamma^\mu \partial_\mu - m_\chi)\chi - i \frac{v_h}{\mu} h \bar{\chi} \gamma_5 \chi - \frac{i}{2\mu} h^2 \bar{\chi} \gamma_5 \chi
\]

yields nucleon recoil cross sections

\[
\sigma_{\chi N} = \frac{g_{hN}^2 v_h^2}{\pi \mu^2 m_h^4} \left( \frac{m_\chi m_N}{m_\chi + m_N} \right)^2 \frac{\beta_\chi^2}{2}
\]

which are too small to be tested by the direct search experiments. The difference between the CP odd and even couplings arises from

Even:

\[
\frac{1}{2} \sum_{s,s'} |\bar{u}(p, s') \cdot u(k, s)| = 2(m_\chi^2 - p \cdot k) \rightarrow 4m_\chi^2
\]

Odd:

\[
\frac{1}{2} \sum_{s,s'} |\bar{u}(p, s') \gamma_5 u(k, s)| = -2(m_\chi^2 + p \cdot k) \rightarrow (p - k)^2
\]
The fermionic model with a mixed CP even and odd Higgs portal

\[ H_{\chi h} = \bar{\chi} \left( \frac{\zeta}{M} + \frac{i}{\mu} \sqrt{1 - \zeta^2 \gamma_5} \right) \chi \left( H^+ H - \frac{v_h^2}{2} \right) \]

is constrained by the limits from PandaX-II, LUX and XENON1T.

RD, arXiv:1804.02604 [hep-ph]. Allowed values of \( \zeta \) are further reduced by a factor 0.727 if \( g_{hN} v_h = 289 \) MeV.
**Conclusion: Status of minimal electroweak singlet Higgs portal dark matter from thermal freeze-out**

<table>
<thead>
<tr>
<th>Type</th>
<th>Mass Range</th>
<th>Constraints</th>
<th>Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar</td>
<td>$57 \text{ GeV} \lesssim m \lesssim m_{h}/2$ or $m \gtrsim 2.7 \text{ TeV}$ ($m \gtrsim 4.5 \text{ TeV}$), will be further constrained by XENONnT and LZ.</td>
<td>Can be tested by DarkSide-20k and DARWIN.</td>
<td></td>
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<td>Vector</td>
<td>$58 \text{ GeV} \lesssim m \lesssim m_{h}/2$ or $m \gtrsim 6.4 \text{ TeV}$ ($m \gtrsim 11.7 \text{ TeV}$), will be further constrained by XENONnT and LZ.</td>
<td>Can be tested by DarkSide-20k and DARWIN.</td>
<td></td>
</tr>
<tr>
<td>Fermion, CP even</td>
<td>Appears to be ruled out by ATLAS and CMS at low masses, and by PandaX-II, LUX and XENON1T at high masses.</td>
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<tr>
<td>Fermion, CP odd</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Fermion, mixed</td>
<td>Recoil cross sections below the neutrino floor.</td>
<td>Constrained by ATLAS and CMS to $m \gtrsim 56 \text{ GeV}$; also needs further exploration at colliders.</td>
<td></td>
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