Status of Higgs Portal Dark Matter

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- Update on Higgs-nucleon coupling
- Scalar Higgs portal dark matter
- Vector Higgs portal dark matter
- CP even fermionic Higgs portal dark matter
- CP odd fermionic Higgs portal dark matter
- Mixed fermionic Higgs portal dark matter
- Conclusions

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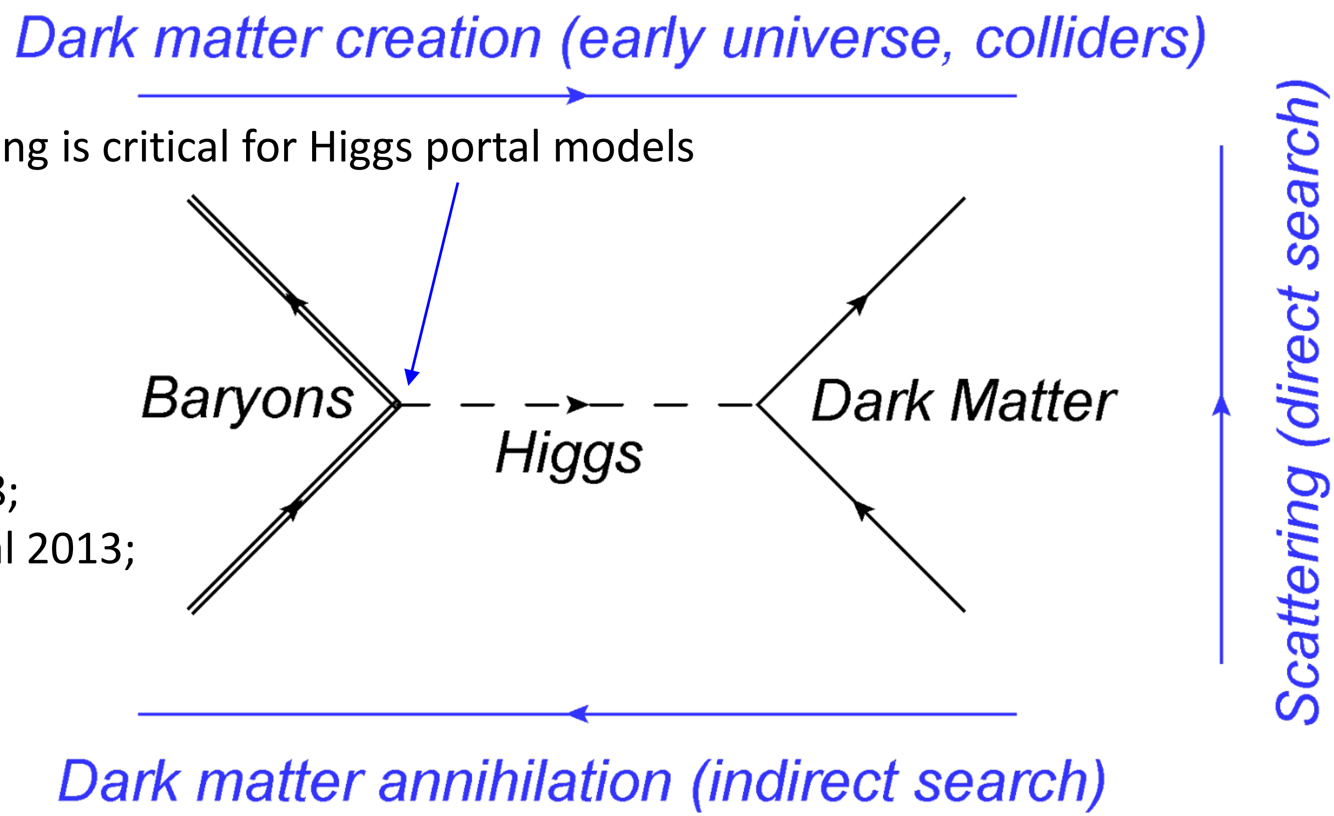
The Higgs-nucleon coupling $g_{hN} h \bar{N} N$

The Higgs-nucleon coupling is critical for Higgs portal models



Shifman, Vainshtein
& Zakharov 1978;
Ellis, Olive & Savage 2008;
Goudelis, Hermann & Stål 2013;
F.S. Sage & RD 2015;
Hoferichter et al. 2017.

$$g_{hN} v_h = \frac{7}{9}\left(1 + \frac{m_s y_N}{m_u + m_d}\right)\sigma_{\pi N} + \frac{2}{9} m_N = \frac{7}{9} \sum_{q=u,d,s} m_N f_q^N + \frac{2}{9} m_N = m_N f_N$$

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

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

This yields the very conservative estimate

$$210\ \mathrm{MeV} \leq g_{hN}v_h \leq 310\ \mathrm{MeV}$$

(comparable to range found by Alarcón et al. from pion-nucleon scattering)
We plot nuclear recoil cross sections for $g_{hN}v_h = 210\ \mathrm{MeV}$.
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

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

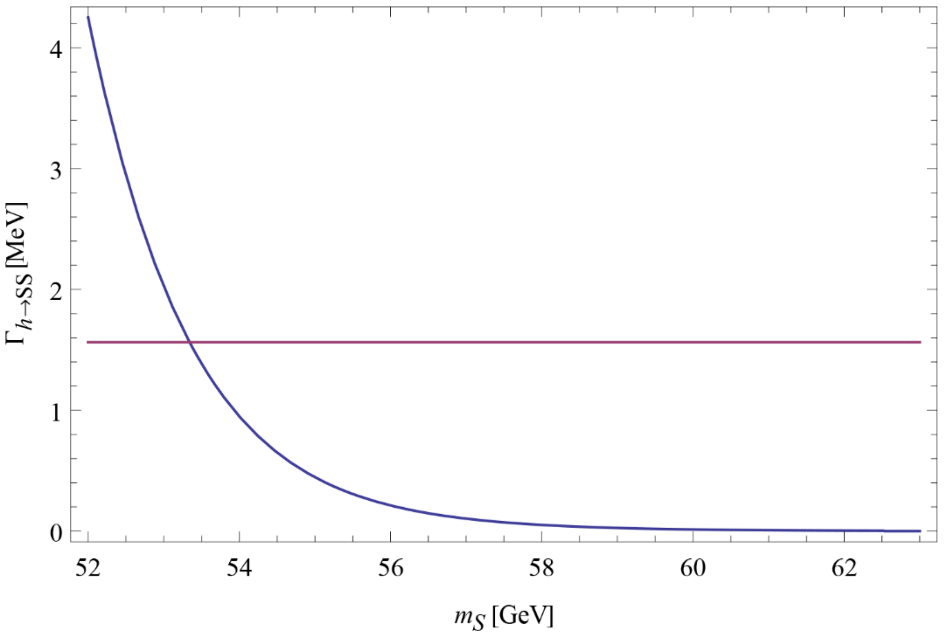
the minimal renormalizable addition to the Standard Model with an additional stable particle,

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

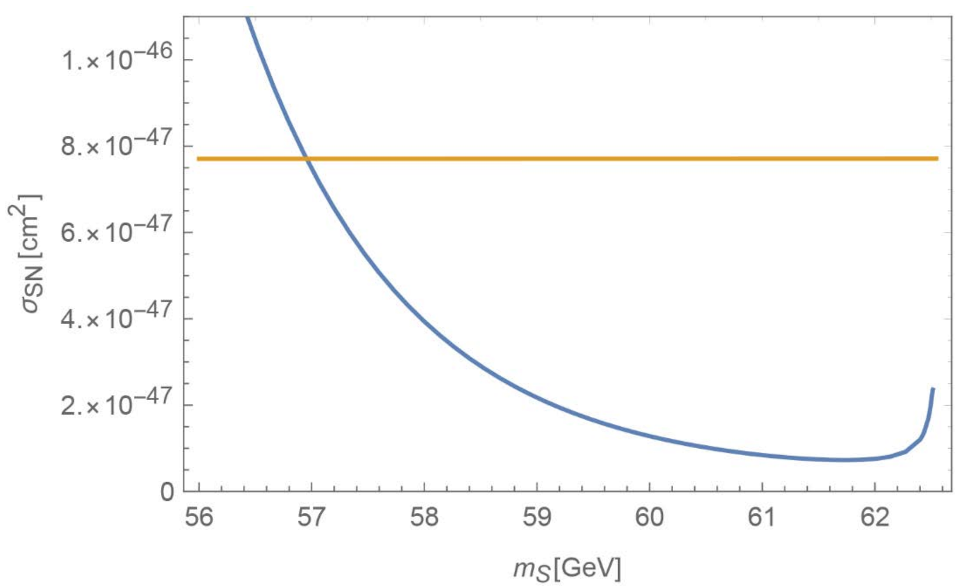
Silveira & Zee 1985; McDonald 1994; Bento *et al.* 2000; Burgess, Pospelov & ter Veldhuis 2001;…

“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 $\mathcal{B} \leq 0.24$,

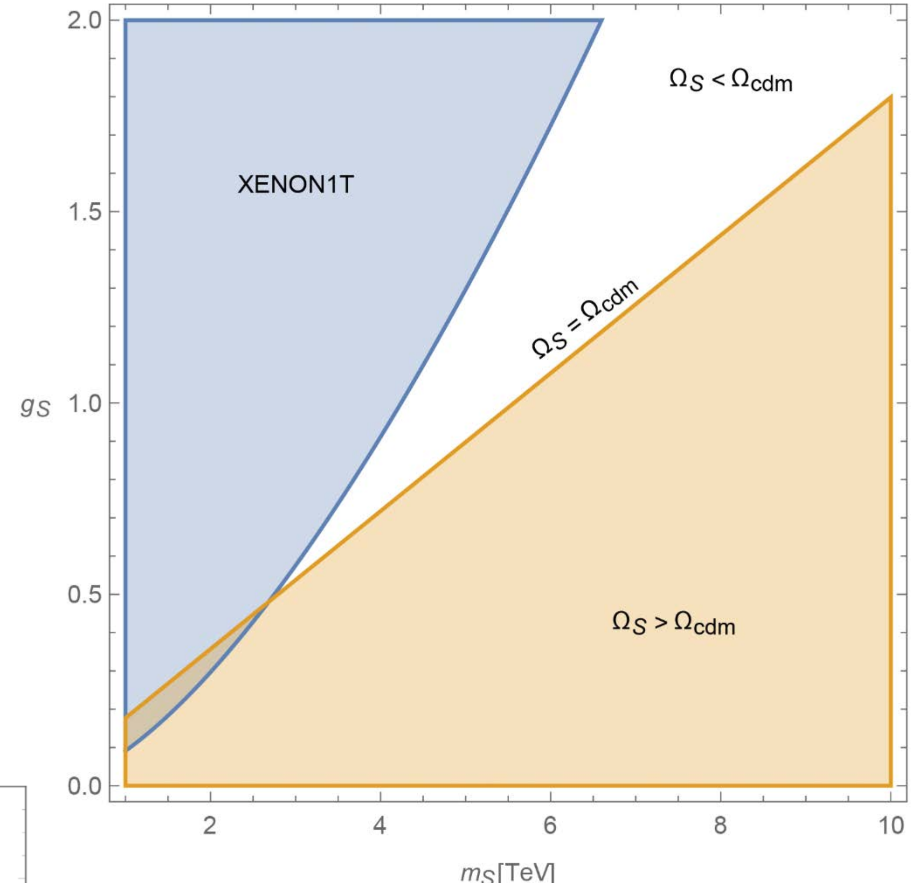


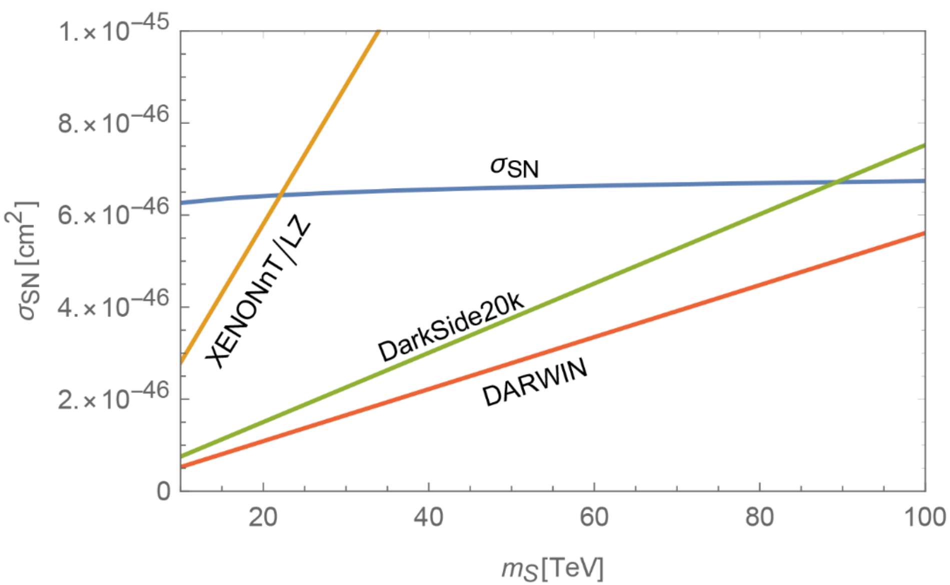
and by the exclusion limits from PandaX-II, LUX and XENON1T on nucleon recoil cross sections. XENONnT and LZ will have the potential to exhaust the resonance region.



RD, arXiv:1804.02604 [hep-ph]

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





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

arXix:1804.02604 [hep-ph]

Vector Higgs portal dark matter:

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

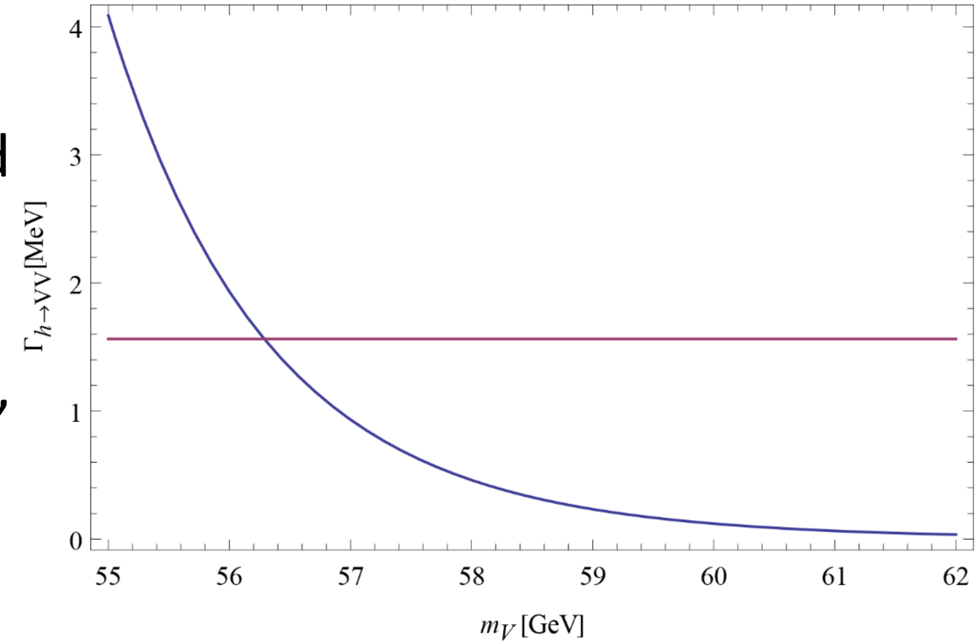
$$\mathcal{L}_V = -\frac{1}{4}V^{\mu\nu}V_{\mu\nu} - \frac{1}{2}m_V^2 V^\mu V_\mu - \frac{\lambda_V}{4}\left(V^\mu V_\mu\right)^2 - g_V v_h h V^\mu V_\mu - \frac{g_V}{2}h^2 V^\mu V_\mu$$

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

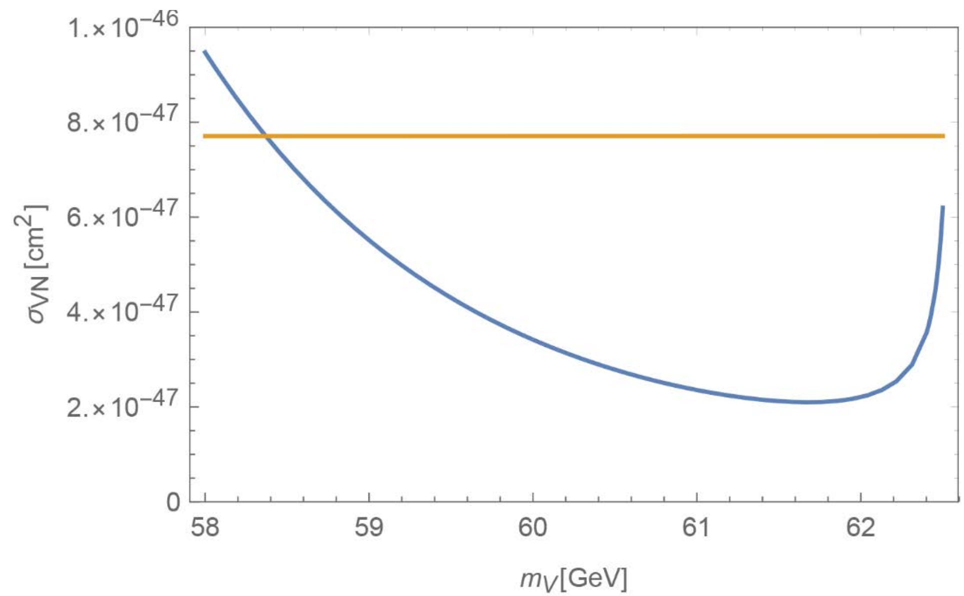
Lebedev, Lee & Mambrini 2012; Djouadi, Lebedev, Mambrini & Quevillon 2012;…

“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 $\mathcal{B} \leq 0.24$,

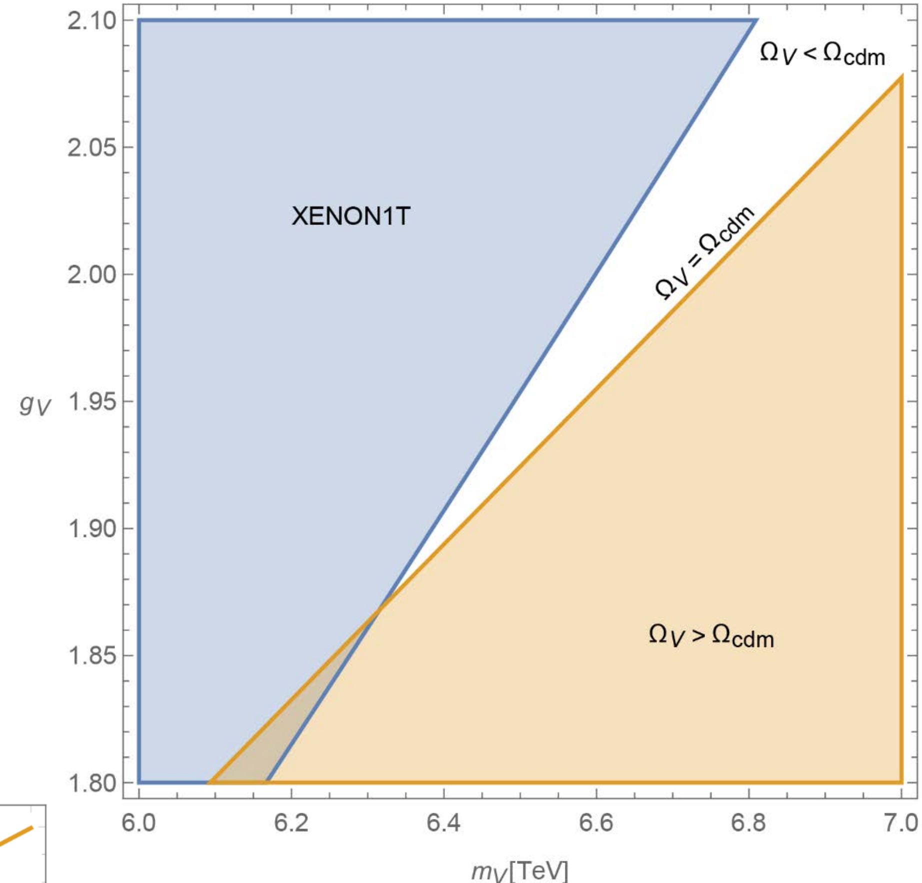


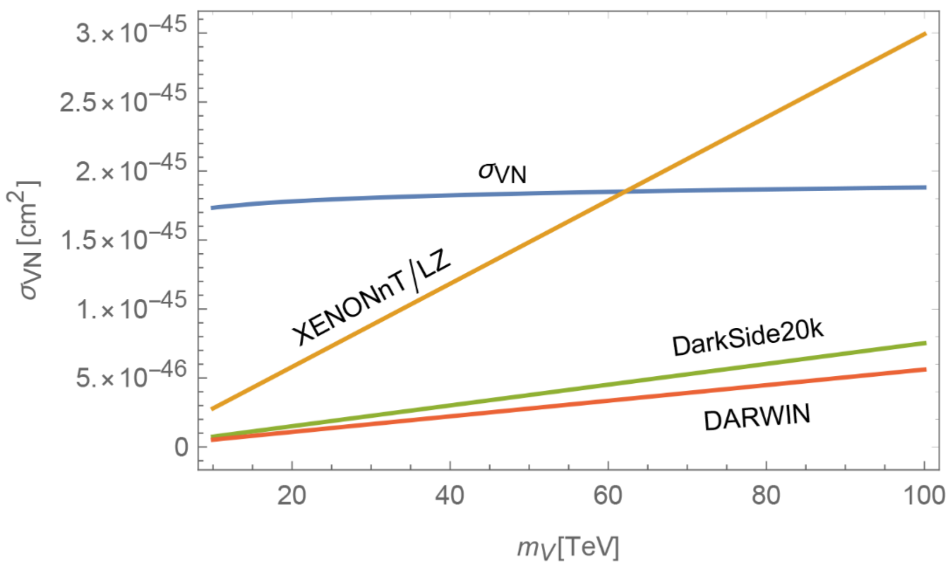
and by the exclusion limits from PandaX-II, LUX and XENON1T on nucleon recoil cross sections. XENONnT and LZ will have the potential to exhaust the resonance region.



RD, arXiv:1804.02604 [hep-ph]

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





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

arXix:1804.02604 [hep-ph]

Electroweak singlet fermions χ can couple through a Higgs portal

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

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

This can arise through a scalar mediator ϕ

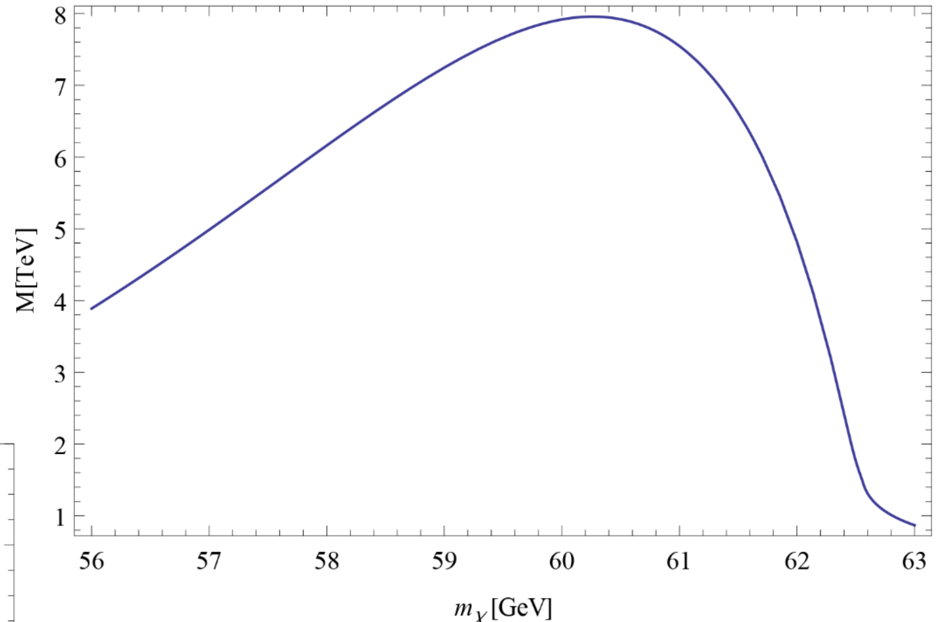
$$\mathcal{H}_{\phi} = \frac{1}{2}m_\phi^2\phi^2 + g\phi\bar{\chi}\cdot\Gamma\cdot\chi + \lambda\phi\left(H^{+}H - \frac{v_h^2}{2}\right)$$

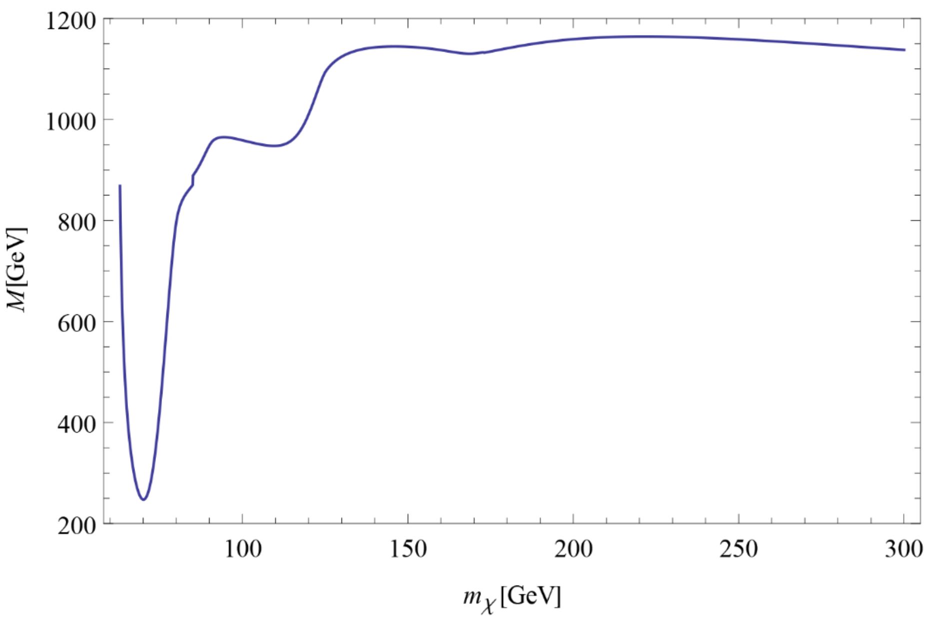
with $M = -m_\phi^2/g\lambda$. Note that $|M| < m_\phi$ if $m_\phi < |g\lambda|$, i.e. the coupling scale M in itself does not necessarily set the scale of new physics beyond the minimal fermionic Higgs portal.

The CP even model

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

would require coupling scales in the TeV range:





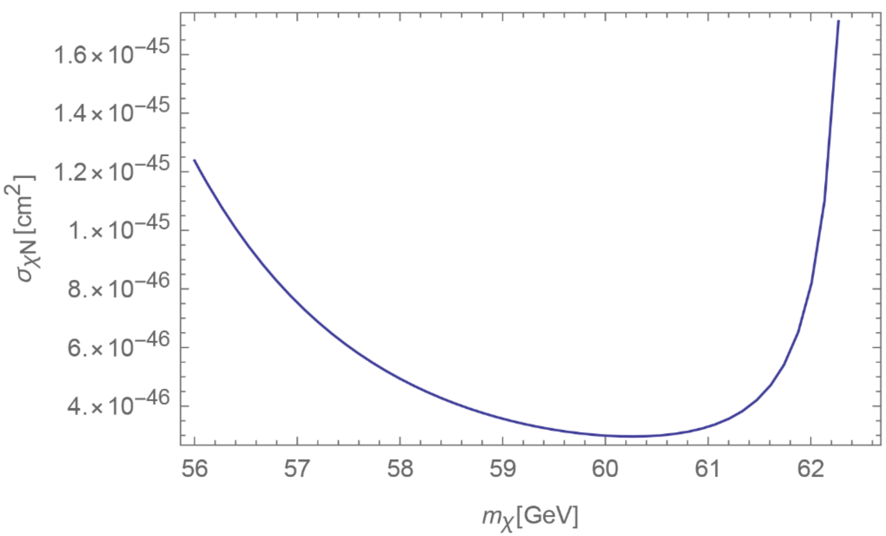
However, the CP even model

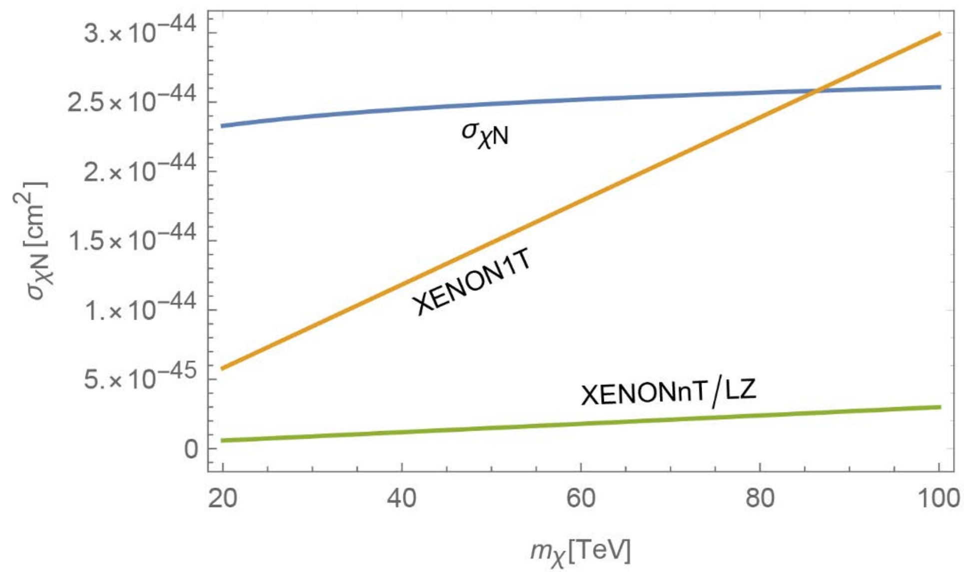
$$\mathcal{L}_\chi = \bar{\chi}(i\gamma^\mu \partial_\mu - m_\chi)\chi - \frac{v_h}{M} h\bar{\chi}\chi - \frac{1}{2M} h^2 \bar{\chi}\chi$$

yields nucleon recoil cross sections

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

which are too large:

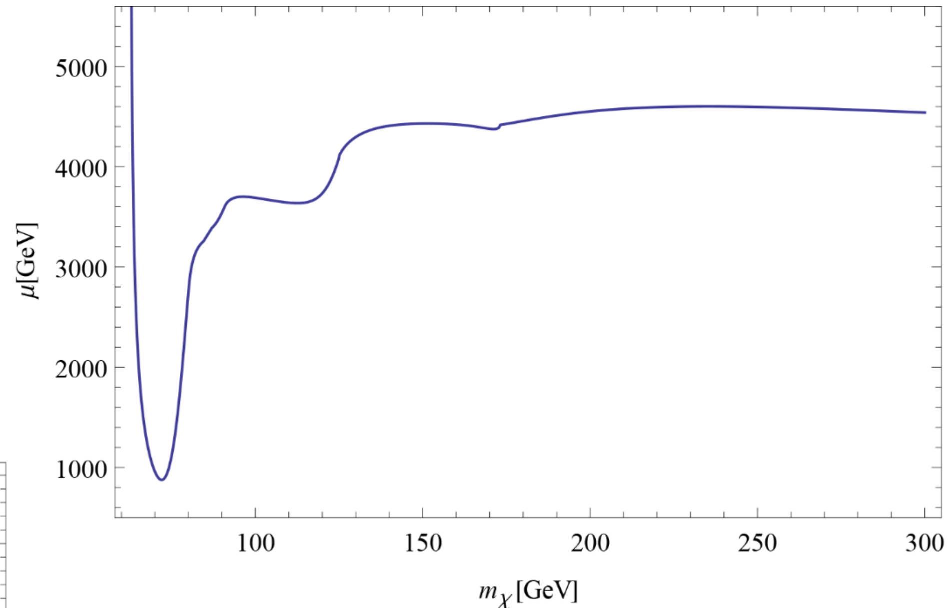


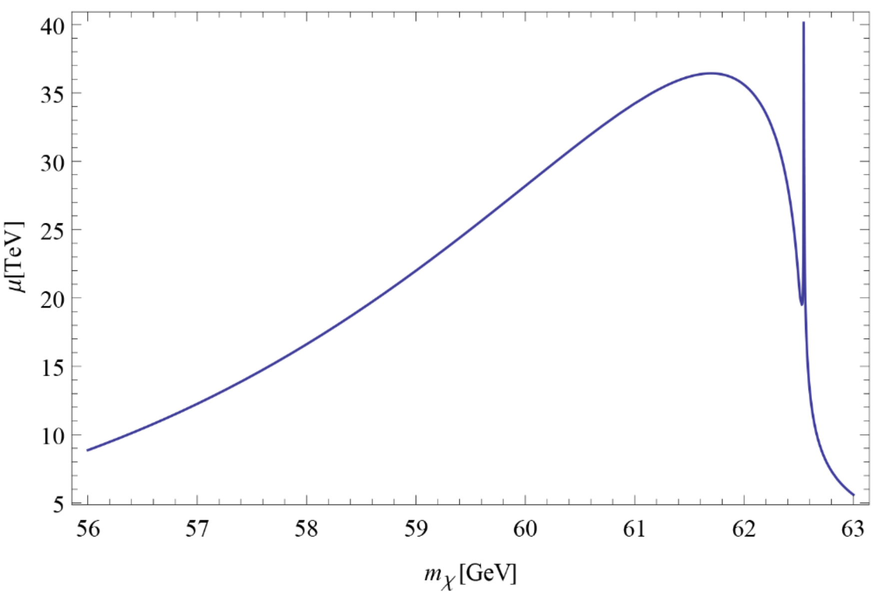


The CP odd model

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

would requires larger coupling scales than the CP even model:





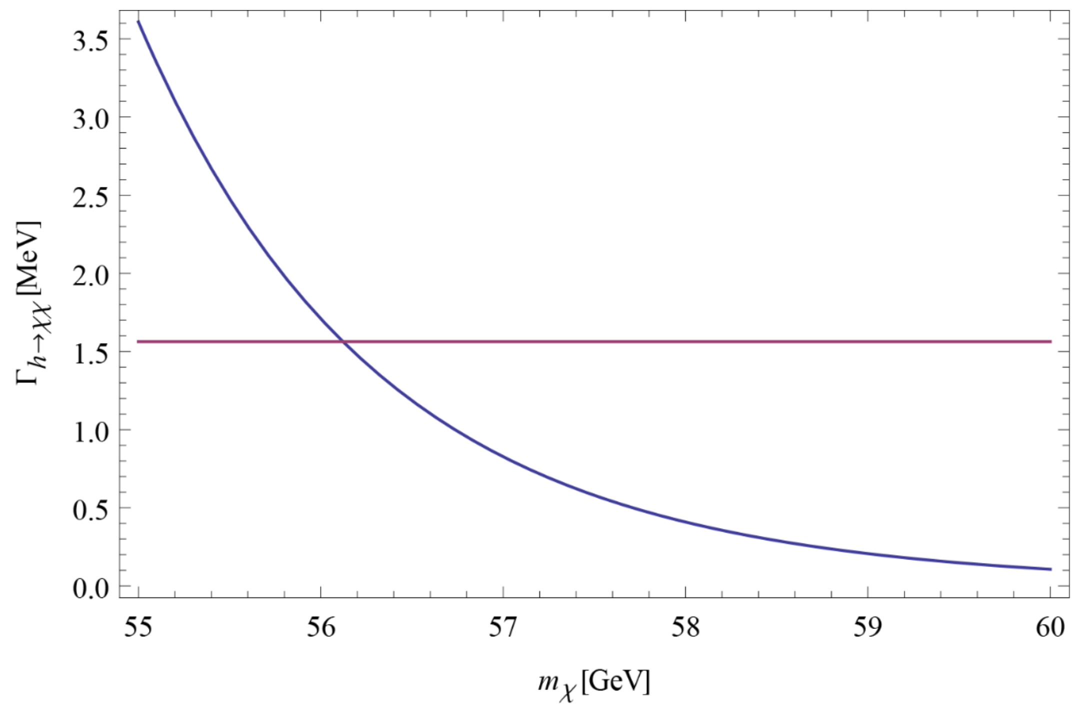
The CP odd model

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

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

$$\Gamma_{h\to\chi\chi} = \frac{v_h^2}{8\pi\mu^2}\sqrt{m_h^2 - 4m_\chi^2}$$



However, the CP odd model

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

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:

$$\frac{1}{2}\sum_{s,s\prime}\left|\bar{u}(\boldsymbol{p}, s'\,)\cdot u(\boldsymbol{k}, s\,)\right| = 2\left(m_\chi^2 - p\cdot k\right) \to 4m_\chi^2$$

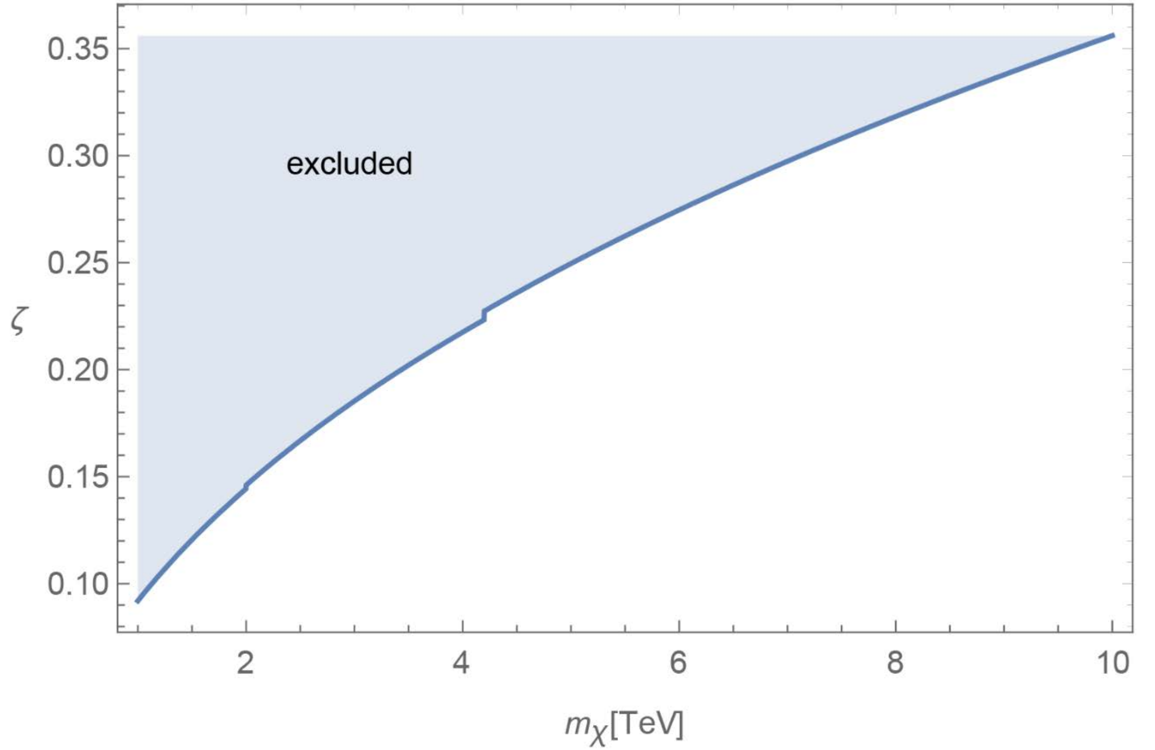
Odd:

$$\frac{1}{2}\sum_{s,s\prime}\left|\bar{u}(\boldsymbol{p}, s'\,)\gamma_5 u(\boldsymbol{k}, s\,)\right| = -2\left(m_\chi^2 + p\cdot k\right) \to (\boldsymbol{p} - \boldsymbol{k})^2$$

The fermionic model with a mixed CP even and odd Higgs portal

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

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



RD, arXiv:1804.02604 [hep-ph]. Allowed values of ζ 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

Scalar	$57\ \mathrm{GeV} \lesssim m \lesssim m_h/2$ or $m \gtrsim 2.7\ \mathrm{TeV}$ ($m \gtrsim 4.5\ \mathrm{TeV}$), will be further constrained by XENONnT and LZ.	Can be tested by DarkSide-20k and DARWIN.
Vector	$58\ \mathrm{GeV} \lesssim m \lesssim m_h/2$ or $m \gtrsim 6.4\ \mathrm{TeV}$ ($m \gtrsim 11.7\ \mathrm{TeV}$), will be further constrained by XENONnT and LZ.	Can be tested by DarkSide-20k and DARWIN.
Fermion, CP even	Appears to be ruled out by ATLAS and CMS at low masses, and by PandaX-II, LUX and XENON1T at high masses.	
Fermion, CP odd	Recoil cross sections below the neutrino floor.	Constrained by ATLAS and CMS to $m \gtrsim 56\ \mathrm{GeV}$; also needs further exploration at colliders.
Fermion, mixed	CP even part will be further constrained by direct search experiments.	

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