# Potential for Definitive Discovery of a 70 GeV Dark Matter WIMP with Only Second-Order Gauge Couplings

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## Abstract

As astronomical observations and their interpretation improve, the case for cold dark matter (CDM) becomes increasingly persuasive. A particularly appealing version of CDM is a weakly interacting massive particle (WIMP) with a mass near the electroweak scale, which can naturally have the observed relic abundance after annihilation in the early universe. But in order for a WIMP to be consistent with the currently stringent experimental constraints it must have relatively small cross-sections for indirect, direct, and collider detection. Using our calculations and estimates of these cross-sections, we discuss the potential for discovery of a recently proposed dark matter WIMP which has a mass of about 70 GeV/c$^2$ and only second-order couplings to $W$ and $Z$ bosons. There is evidence that indirect detection may already have been achieved, since analyses of the gamma rays detected by Fermi-LAT and the antiprotons observed by AMS-02 are consistent with 70 GeV dark matter having our calculated $\langle \sigma_{\text{ann}} v \rangle \approx 1.2 \times 10^{-26}\,\text{cm}^3/\text{s}$. The estimated sensitivities for LZ and XENONnT indicate that these experiments may achieve direct detection within the next few years, since we estimate the relevant cross-section to be slightly above $10^{-48}\,\text{cm}^2$. Other experiments such as PandaX, SuperCDMS, and especially DARWIN should be able to confirm on a longer time scale. The high-luminosity LHC might achieve collider detection within about 15 years, since we estimate a collider cross-section slightly below 1 femtobarn. Definitive confirmation should come from still more powerful planned collider experiments (such as a future circular collider) within 15–35 years.

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There are many aspects of the dark matter problem [1, 2] and a vast number of dark matter candidates [3, 4], with masses and couplings spanning many orders of magnitude. The cold dark matter (CDM) paradigm has, however, become increasingly compelling during the past quarter century, because of the growing sophistication of astronomical observations and their interpretation [4, 5]. A particularly appealing version of CDM continues to be weakly interacting massive particles (WIMPs), since a weakly interacting particle with a mass near the electroweak scale can naturally emerge from the early universe with about the observed relic abundance.

There are, however, stringent limits on the cross-sections for direct, indirect, and collider detection. Figure 1 shows the remarkable sensitivity achieved in direct detection experiments during the past few decades [6], which demonstrates that a viable dark matter candidate must have a very small cross-section for scattering off an atomic nucleus.

As can be seen in Figure 2, there are also strong bounds on the cross-section for annihilation in the present universe, determined by observations of dwarf spheroidal galaxies [7].

Finally, the hopes for collider detection at the LHC have not been realized, and strong limits have been placed on new particles of any kind, including dark matter particles [8, 9].

Here we will focus on the potential for detection of a new dark matter particle which is consistent with all experimental and observational limits, and which additionally appears to be the only viable candidate with a well-defined mass and well-defined couplings [10, 11, 12]. Since there are no free parameters, it is possible to determine the cross-sections for indirect, direct, and collider detection, providing clean experimental tests of the theory.

This candidate is a WIMP with a mass of about 70 GeV/c$^2$ and an annihilation cross section in the present universe given by $\langle \sigma_{\text{ann}} v \rangle \approx 1.2 \times 10^{-26}\,\text{cm}^3/\text{s}$, according to the calculations described below, if it is assumed to constitute 100% of the dark matter. It should be mentioned, however, that the present theory also predicts supersymmetry (susy) at some energy scale, and that the lightest superpartner [1, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23] can be a subdominant component in a multicomponent scenario.

The results above were obtained with MicrOMEGAs [24]. If we assume that the dark matter fraction $\Omega_{\text{DM}}$ is 0.27, that the present candidate constitutes all of the dark matter, and that the reduced Hubble constant $h$ is 0.73 [25], we obtain $\Omega_{\text{DM}} h^2 = 0.144$. If it is instead assumed that a few percent of the dark matter consists of other components, making $\Omega_{\text{DM}} \approx 0.26$ for the present candidate, and that $h = 0.68$ [26], one obtains $\Omega_{\text{DM}} h^2 \approx 0.120$. (This value is equal to that obtained by Planck for all dark matter in an analysis that confirms the consistency of standard $\Lambda$CDM cosmology [26].) Finally, as an extreme, we can consider $\Omega_{\text{DM}} = 0.22$ (for the present candidate) with $h = 0.68$, giving $\Omega_{\text{DM}} h^2 = 0.102$.

Our calculations with MicrOMEGAs yield: $\Omega_{\text{DM}} h^2 = 0.162$, 0.147, 0.134, 0.121, 0.098 and $\langle \sigma_{\text{ann}} v \rangle = 1.08$, 1.19, 1.30, 1.43, $1.73 \times 10^{-26}\,\text{cm}^3/\text{s}$, respectively, for $m_h = 69.5$, 70.0, 70.5, 71.0, 72.0 GeV/c$^2$.

We can conclude that $m_h = 70$–$72\,\text{GeV/c}^2$ and that $\langle \sigma_{\text{ann}} v \rangle = 1.2$–$1.7 \times 10^{-26}\,\text{cm}^3/\text{s}$. It is then reasonable to say that $m_h$ is about 70 GeV/c$^2$ and that correspondingly (with some bias toward the measured value of $h = 0.73$ over the theoretical value of $h = 0.68$ in the context of the present universe) $\langle \sigma_{\text{ann}} v \rangle \approx 1.2 \times 10^{-26}\,\text{cm}^3/\text{s}$.

It can be seen that our calculated $\langle \sigma_{\text{ann}} v \rangle$ with an approximately 70 GeV mass is well below the upper bounds of Figure 2 for any of the above values of $\Omega_{\text{DM}} h^2$.

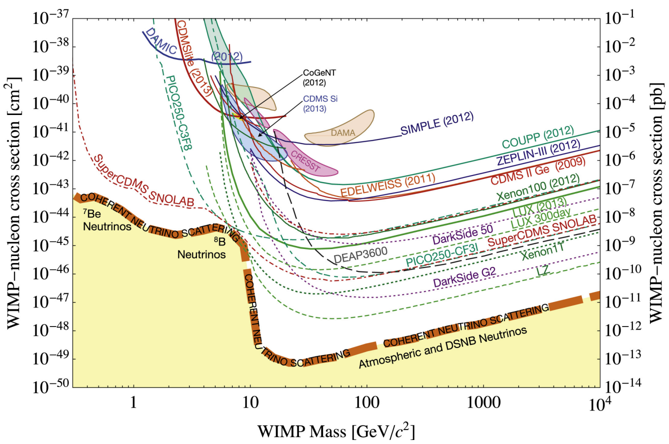


**FIGURE 1:** Reach of previous direct detection experiments. From [6], used with permission. The present dark matter candidate has couplings to only $W$ and $Z$ bosons, and these are only second-order. It consequently has only a small cross-section for scattering off atomic nuclei, estimated to be slightly above $10^{-48}$ cm$^2$ in the case of Xe [12], so it lies below the sensitivities of earlier experiments. With a mass of about 70 GeV/c$^2$, it should barely be detectable by the LZ and XENONnT experiments, both of which estimate a reach down to about $1.4 \times 10^{-48}$ cm$^2$ for a dark matter particle with a mass $\sim$50 GeV/c$^2$. The current and projected sensitivities of LZ and XENONnT, shown in Figures 3–6, demonstrate the grounds for this prediction in more detail.

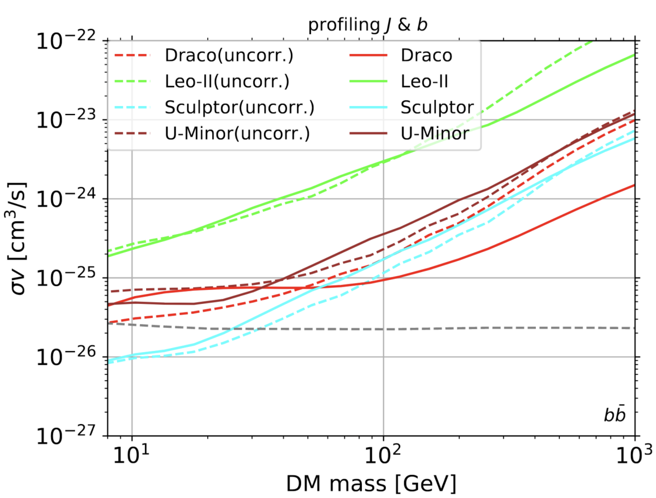


**FIGURE 2:** Upper bounds on $\langle \sigma_{\text{ann}} v \rangle$ from Fermi-LAT gamma-ray observations of dwarf spheroidal galaxies near the Milky Way. The solid and dashed curves are two limiting cases which "should bracket somewhat the real energy correlation". The dashed gray line indicates the thermal relic cross section inferred for generic WIMP models [13]. From [7], used with permission.

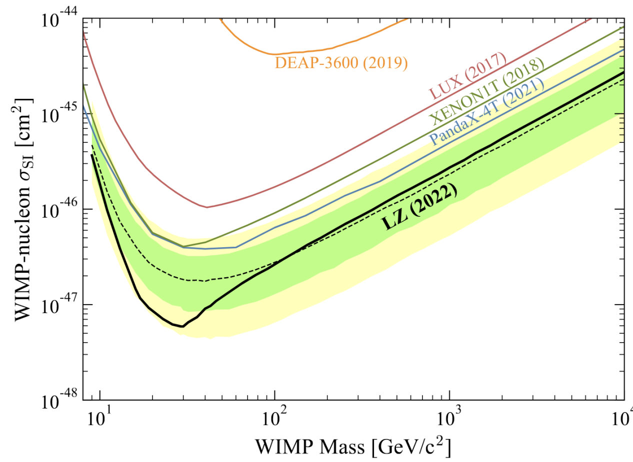


**FIGURE 3:** Reach of LZ in July 2022. From [27], used with permission.

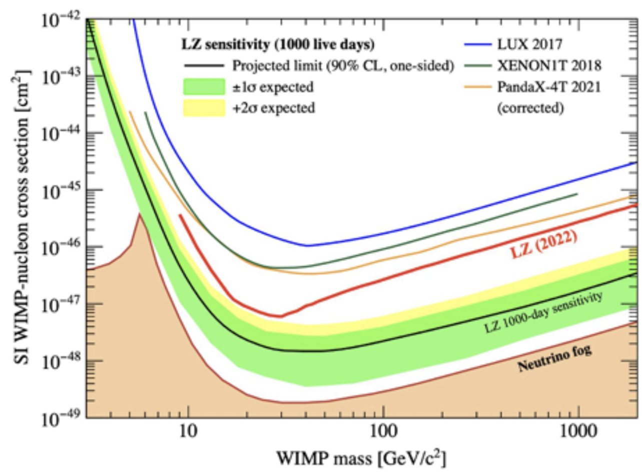


**FIGURE 4:** Reach of LZ with 1000 days of data. From [28], used with permission.

Our calculated mass and $\langle \sigma_{\text{ann}} v \rangle$ are also consistent with analyses of the Galactic center gamma ray excess observed by Fermi-LAT [30, 31, 32, 33, 34, 35] and the antiproton excess observed by AMS-02 [36, 37, 38, 39, 40].

Reference [33] concludes that "The center of the Milky Way is predicted to be the brightest region of $\gamma$-rays generated by self-annihilating dark matter particles. Excess emission about the Galactic center above predictions made for standard astrophysical processes has been observed in $\gamma$-ray data collected by the Fermi Large Area Telescope. It is well described by the square of a Navarro, Frenk, and White dark matter density distribution. Although other interpretations for the excess are plausible, the possibility that it arises from annihilating dark matter is valid.... Its spectral characteristics favor a dark matter particle with a mass in the range approximately from 50 to 190 (10 to 90) GeV and annihilation cross section approximately from $1 \times 10^{-26}$ to $4 \times 10^{-25}$ ($6 \times 10^{-27}$ to $2 \times 10^{-25}$) cm$^3$/s for pseudoscalar (vector) interactions."

Reference [39] finds that "An excess of $\sim$10–20 GeV cosmic-ray antiprotons has been identified in the spectrum reported

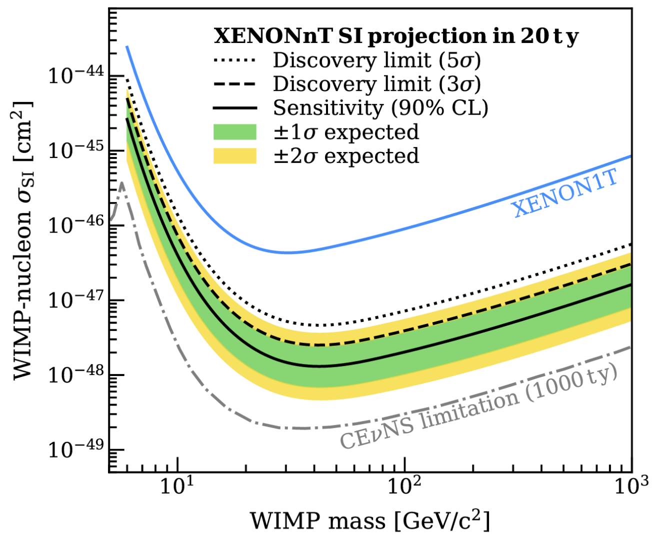


**FIGURE 5:** Reach of XENONnT with 5 years of data. From [29], used with permission.

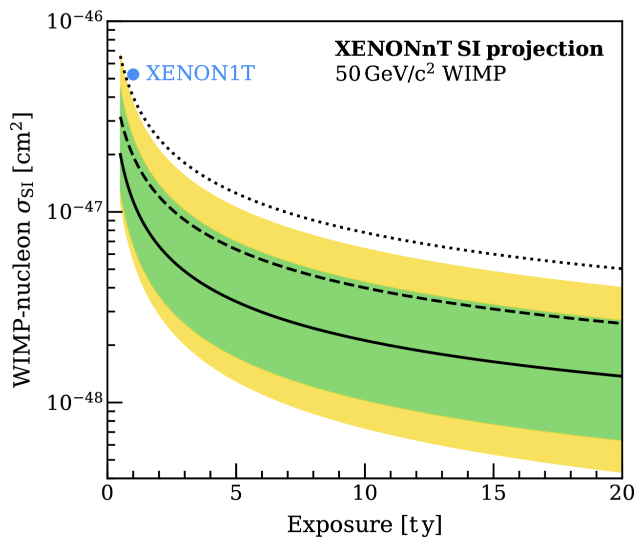


**FIGURE 6:** Reach of XENONnT for a 50 GeV WIMP in ton-years, with 4 tons fiducial mass. From [29], used with permission.

by the AMS-02 Collaboration.... After accounting for these uncertainties, we confirm the presence of a 4.7$\sigma$ antiproton excess, consistent with that arising from a $m_\chi \approx$ 64–88 GeV dark matter particle annihilating to $b\bar{b}$ with a cross section of $\sigma v = (0.8\text{–}5.2) \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$."

Other analyses have yielded similar results, which are not very sensitive to the specific annihilation channel.

At one time it may have appeared that a positron excess from AMS-02 and other experiments was evidence for a dominant dark matter particle at an energy of ~800 GeV or above. However, this interpretation has been ruled out by Planck,[1] as shown in Figure 7, and the excess has been attributed to pulsars [41].

[1]See Figure 46 of [26].

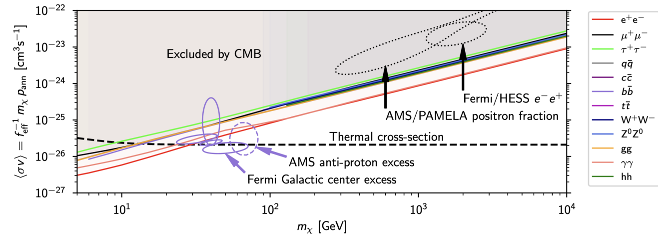


**FIGURE 7:** A high-mass dark matter candidate with high annihilation cross-section, which might have explained a positron excess observed by AMS-02 and other experiments, is excluded by the Planck data. The present candidate has a mass and cross-section consistent with this data. Figure credit: reference [26], Figure 46, reprinted with permission from ESO.

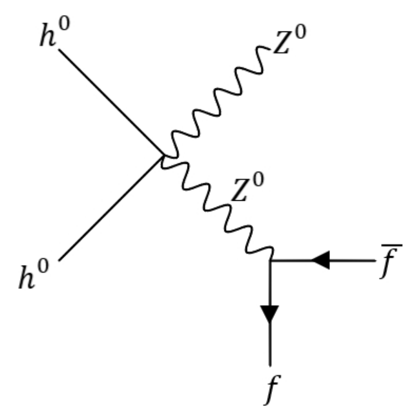


**FIGURE 8:** Representative diagram for annihilation of the present dark matter candidate via creation of $Z$ bosons.

The present dark matter candidate, with a mass of about 70 GeV and roughly a thermal cross-section, is fully consistent with the observations and conclusions represented by Figure 7.

The present candidate results from an extended Higgs sector, which is an inevitable consequence of a broader fundamental theory [42, 43]. This candidate is one member of a class of particles which we have called "higgsons" [10, 11, 12], represented by $h$, to distinguish them from Higgs bosons $H$ and higginos $\widetilde{h}$.

We recall that there are three kinds of particles in the Standard Model. After the first spin 1/2 fermion was discovered in 1897 (by J. J. Thompson), and the first spin 1 gauge boson was postulated in 1905 (by Einstein), many surprises lay ahead with major extensions of these two sectors. It is reasonable that similar surprises and extensions may lie ahead after the 2012 discovery of a scalar boson (by the CMS and ATLAS collaborations).

In the present theory, there are both complex scalar Higgs fields, having their standard interactions, and real scalar higgson fields, each of which interacts only with itself and gauge bosons, via second-order interactions like those of equation (A.4).

The lightest higgson $h^0$ is stable because of the form of the interaction in equation (A.4): It can radiate gauge bosons, annihilate into gauge bosons as in Figures 8 and 9, scatter via exchange of gauge bosons as in Figures 10 and 11, and be created in pairs as in Figure 12, but not decay, since a single initial $h^0$ implies a final state containing $h^0$ and two gauge bosons.

With $R$-parity conserved, the lightest superpartner (LSP) is stable for a different reason, so the lightest higgson can coexist with the LSP (and with other particles stable for other reasons, such as axions [44, 45]). The present theory unavoidably predicts (broken) susy at some energy scale, and is compatible with well-motivated hypothetical particles such as axions.

However, the lightest higgson is assumed to be the dominant constituent, because it is difficult to reconcile the LSP in natural susy with the various experimental limits [19, 20, 21, 22, 23, 46, 47, 48] and the other candidates tend not to have well-defined masses or couplings.

The present dark matter WIMP should be barely detectable by existing experiments, but certainly detectable with planned experiments such as DARWIN [49].

When a dark matter particle is discovered, rival claims to its nature can ultimately be determined by its properties (principally mass and interactions) and the general phenomenology associated with it. For example, various *ad hoc* extended Higgs models tend to predict processes that do not exist in the present theory, with one example (the inert doublet model) discussed in detail in [10].

To summarize the most important points: the present candidate is consistent with all current experimental and observational data.

The scattering processes of Figures 10 and 11 lead to a cross-section for direct detection in Xe based experiments which we estimate to be slightly above $10^{-48}\,\mathrm{cm}^2$, placing it barely within reach of LZ and XENONnT within about the next 5 years, and definitely within reach of DARWIN.

The creation processes of Figure 12 lead to a cross-section for collider detection which we estimate to be $\sim$1 femtobarn, which may place it barely within reach of the high-luminosity LHC within about 15 years, and definitely within reach of still more powerful colliders on a longer time scale. The signature in a proton collider is $>$140 GeV of missing transverse energy with two quark jets.

The annihilation processes of Figures 8 and 9 have a cross-section given by $\langle \sigma_{\text{ann}} v \rangle \approx 1.2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$. The mass and annihilation cross-section inferred in careful analyses of the gamma rays observed by Fermi-LAT and the antiprotons observed by AMS-02 are consistent with those calculated here, so indirect detection may already have been achieved.

## Appendix A. ACTION FOR SCALAR BOSONS AND AUXILIARY FIELDS

In this appendix we quote some relevant results of [42] and [43], where the action for scalar boson fields has the form

$$S_{\text{matter}} = \int d^4 x e \overline{\mathcal{L}}_{\text{scalar}} \tag{A.1}$$

$$\overline{\mathcal{L}}_{\text{scalar}} = \sum_R \phi_R^\dagger(x) \left( D^\mu D_\mu - \frac{1}{4} R \right) \phi_R(x) + \sum_R F_R^\dagger(x) F_R(x) + \sum_s \varphi_s \left( \nabla^\mu \nabla_\mu - \frac{1}{4} R \right) \varphi_s + \overline{\mathcal{L}}_{\text{h-int}} \tag{A.2}$$

in a general coordinate system, but before masses and further interactions result from symmetry breakings and other effects. The $\phi_R$ are complex one-component Higgs fields, the $F_R$ are the one-component auxiliary fields of supersymmetry, and the $\varphi_s$

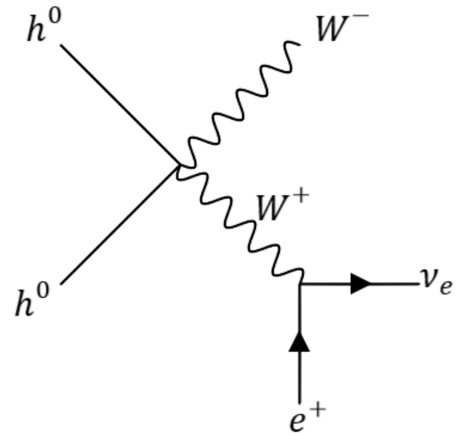


**FIGURE 9:** Representative diagram for annihilation of the present dark matter candidate via creation of $W$ bosons.

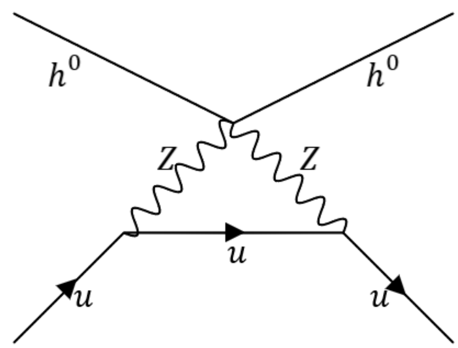


**FIGURE 10:** Representative diagram for direct detection of the present dark matter candidate with scattering via exchange of $Z$ bosons.

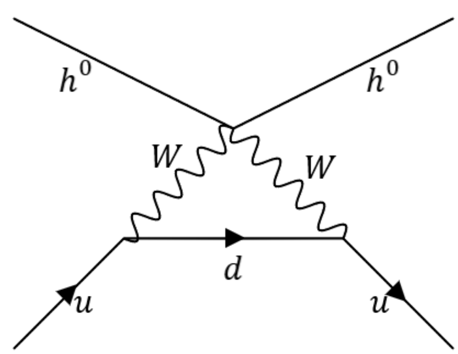


**FIGURE 11:** Representative diagram for direct detection of the present dark matter candidate with scattering via exchange of $W$ bosons.

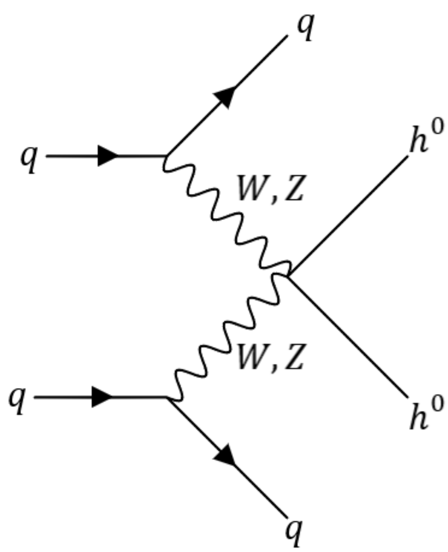


**FIGURE 12:** Representative diagram for collider detection of the present dark matter candidate via vector-boson fusion, with $>$140 GeV of missing energy accompanied by two jets.

are real one-component higgson fields. Each higgson field can be treated (and quantized) like a standard real scalar field, but with no quantum numbers and only second-order interactions.

Here

$$D_\mu = \nabla_\mu - iA_\mu \tag{A.3}$$

is the full covariant derivative, including the effects of both gravitational and gauge curvature, $R$ is the gravitational (Ricci) curvature scalar, and $e = |\det e^\alpha_\mu| = (-\det g_{\mu\nu})^{1/2}$. The second-order gauge interactions of the higgson fields have been isolated in the last term, which can be written explicitly as

$$\overline{\mathcal{L}}_{\text{h-int}} = \frac{g^2}{(2\cos\theta_W)^2} h_s Z^\mu Z_\mu h_s + \frac{g^2}{2} h_s W^{\mu+} W^-_\mu h_s \tag{A.4}$$

in the electroweak sector, where it is assumed that there is no higgson condensate, so that $\varphi_s = h_s$, with the convention that $h_s$ is used to represent both a field and the particle which is an excitation of that field.

The higgson fields have only second-order interactions because they are the amplitude modes for Majorana-like bosonic fields that are constructed from primitive fields $\Phi_S$ and their charge conjugates $\Phi_S^c$:

$$\Phi_S = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_S \\ \Phi_S^c \end{pmatrix}. \tag{A.5}$$

The first-order terms then cancel [10]. In addition, Yukawa couplings cannot exist and there is no mechanism for higgson-Higgs couplings. As a result, the cross-sections for annihilation, scattering, and creation are relatively small, making them consistent with current experimental and observational limits, while still within reach of experiments that have recently begun taking data or else are planned for the foreseeable future.

## CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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