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/c² 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 $\langle \sigma_{\text{ann}} v \rangle \approx 1.2 \times 10^{-26}$ cm³/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 $10^{-48}$ cm². 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.

Keywords: dark matter

There are many aspects of the dark matter problem and a vast number of dark matter candidates, 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. 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, 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 Fig. 2, there are also strong bounds on the cross-section for annihilation in the present universe, determined by observations of dwarf spheroidal galaxies.

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.

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. 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.

FIGURE 1: Reach of previous direct detection experiments. From Ref. [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 $10^{-48}$cm² in the case of Xe, so it lies below the sensitivities of earlier experiments. With a mass of about 70 GeV/c², it should barely be detectable by the LZ and XENONnT experiments, both of which estimate a reach down to about $1.4 \times 10^{-48}$cm² for a dark matter particle with a mass ~ 50 GeV/c². The current and projected sensitivities of LZ and XENONnT, shown in Figs. 3 - 6, demonstrate the grounds for this prediction in more detail.
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 \(<\sigma_{\text{ann}}v> \approx 1.2 \times 10^{-26} \text{ cm}^3/\text{s}\), 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 \(h = 0.73\) [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:
\[
\Omega_{\text{DM}}h^2 = 0.162, 0.147, 0.134, 0.121, 0.098 \text{ and } \\
<\sigma_{\text{ann}}v> = 1.08, 1.19, 1.30, 1.43, 1.73 \times 10^{-26} \text{ cm}^3/\text{s}, \text{ respectively, for } m_h = 69.5, 70.0, 70.5, 71.0, 72.0 \text{ GeV/c}^2.
\]

We can conclude that \(m_h = 70 - 72 \text{ GeV/c}^2\) and that \(<\sigma_{\text{ann}}v> \approx 1.2 - 1.7 \times 10^{-26} \text{ cm}^3/\text{s}\). 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) \(<\sigma_{\text{ann}}v> \approx 1.2 \times 10^{-26} \text{ cm}^3/\text{s}\).

It can be seen that our calculated \(<\sigma_{\text{ann}}v>\) with an approximately 70 GeV mass is well below the upper bounds of Fig. 2 for any of the above values of \(\Omega_{\text{DM}}h^2\).
Ref. [39] finds that “An excess of $\sim 10 - 20$ GeV cosmic-ray antiprotons has been identified in the spectrum reported 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 $\sigma v \approx (0.8 - 5.2) \times 10^{-26}$ cm$^3$/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 $\sim 800$ GeV or above. However, this interpretation has been ruled out by Planck [41].
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.
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 Figs. 8 and 9 have a cross-section given by $\langle \sigma_{\text{ann}}\vec{v} \rangle \approx 1.2 \times 10^{-26}$ cm$^3$/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 Refs. [43] and [44], where the action for scalar boson fields has the form

$$S_{\text{matter}} = \int d^4x \ e \ Z_{\text{scalar}}$$  \hspace{1cm} (A.1)

$$Z_{\text{scalar}} = \sum_R \phi_R^+(x) \left( D^\mu D_\mu - \frac{1}{4} R \right) \phi_R(x) + \sum_R F_R^+(x) F_R(x) + \sum_s \phi_s \left( \nabla^\mu \nabla_\mu - \frac{1}{4} R \right) \phi_s + Z_{h-\text{int}}$$  \hspace{1cm} (A.2)

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

$$D_\mu = \nabla_\mu - i A_\mu$$  \hspace{1cm} (A.3)

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

$$Z_{h-\text{int}} = \frac{s^2}{2(2 \cos \theta_W)^2} h_s Z^\mu Z_\mu h_s + \frac{s^2}{2} h_s W^{\mu+} W^-_{\mu} h_s$$  \hspace{1cm} (A.4)

in the electroweak sector, where it is assumed that there is no higgson condensate, so that $\phi_s = h_s$, 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 $\Phi_S^c$:

$$\Phi_S = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_S^c \\ \Phi_S \end{pmatrix}$$  \hspace{1cm} (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.

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