CDMS stands for
Constrained Dark Matter Singlet

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Abstract

Motivated by the two candidate Dark Matter events observed by the CDMS experiment, we consider a Constrained Dark Matter Singlet (CDMS) model that, with no free parameters, predicts the DM mass and the DM direct cross section to be in the range weakly favored by CDMS.

1 Introduction

The Cryogenic Dark Matter Search (CDMS) experiment reported 2 events possibly due to DM scattering, with an expected background of about 0.8 events \cite{1}. The statistical significance of the hint is so low, about 1.5\(\sigma\), that calling it excess would be an excess. It is further reduced by the bound of the XENON experiment \cite{2}, that also observed events, interpreted as background. However discoveries are first seen as hints, and the CDMS excess attracted theoretical interest \cite{3, 4}.

The event rate as well as the average energy of the two CDMS events give an indication on the DM cross section and on the DM mass: DM lighter than the nuclear mass gives less energetic scattering events. We determine the ‘favored’ region by performing an event-by-event fit, assuming a dominant spin-independent elastic DM/nucleon cross section \(\sigma_{\text{SI}}\), the ‘standard’ local DM density \(\rho_{\odot} = 0.3\text{ GeV/cm}^3\) (one should take into account that only the combination \(\rho_{\odot}\sigma_{\text{SI}}\) is determined and that values closer to 0.4 GeV/cm\(^3\) might actually be favored by Milky Way rotation curves \cite{5}) and for the DM velocity distribution (in the galactic...
Figure 1: Predictions of the CDMS model for spin-independent elastic scattering for $M$ and $\sigma_{SI}$ for a few values of the higgs mass $m_h$ compared to the region ‘favored’ at 78% CL ($\Delta \chi^2 < 3$ for 2 dof) by the CDMS experiment (green region), and to the regions disfavored at 90% CL by CDMS and XENON (upper red shaded regions). We assumed $\rho_\odot = 0.3$ GeV/cm$^3$.

frame, a Maxwellian $dN/d\vec{v} \propto e^{-v^2/(220\text{km/s})^2} \Theta(v - v_E)$ cutted at the escape velocity $v_E = 500$ km/s), and taking into account the energy-dependent CDMS signal efficiency (the correct likelihood for this purpose was described in [6]).

Fig. 1 shows the regions ‘favored’ by the two CDMS events at 78% confidence level (i.e. $\chi^2 - \chi^2_{\text{min}} < 3$ for 2 dof). Our results agree with those in [7]. Of course, any significantly higher confidence level would favor the whole parameter space not disfavored by CDMS and XENON data [2]. The two jumps in the bound reported by CDMS are due to the two events. We see that the CDMS events suggest $\sigma_{SI} \approx \text{few} \times 10^{-44}$ cm$^2$ and a DM mass $M$ around $40 \div 80$ GeV.

Perhaps, proposing DM models that predict $M$ and $\sigma_{SI}$ to be in the CDMS range, despite the weakness of its statistical significance, could maybe have some possible interest. At least, this is more interesting than proposing models where $M$ and $\sigma_{SI}$ can lie in the CDMS range, but suffer orders of magnitude uncertainties.

2 The model

The CDMS value of $\sigma_{SI}$ is characteristic of higgs-mediated DM/nucleon scattering. Thereby we consider a DM model obtained adding to the Standard Model a Dark Matter real singlet scalar field $S$ coupled to the Higgs doublet $H$ as described by the following Lagrangian invariant
under $S \rightarrow -S$:

$$
\mathcal{L} = \mathcal{L}_{SM} + \frac{(\partial_\mu S)^2}{2} - \lambda S^2 |H|^2.
$$

(1)

This is the well known scalar singlet model [8, 9, 10, 4], here with the additional constraint of setting to zero the mass term $m^2 S^2/2$ (and omitting the quartic coupling $S^4$, which is phenomenologically irrelevant). Inserting $H = (0, V + h)/\sqrt{2}$ in eq. (1), the higgs vev $V \approx 246$ GeV gives a DM mass $M = \sqrt{\chi V}$.

Phenomenologically, $m$ cannot be much larger than the Higgs mass $m_h$. Theoretically, $m$ (as well as $m_h$) has no reason to be much smaller than the Planck scale; both receive quadratically divergent quantum corrections so that their smallness is technically unnatural, giving rise to hierarchy problems. As well known, the smallness of $m_h$ could be related to the scale of supersymmetry breaking, with $m_h = 0$ in the supersymmetric limit. Maybe $m$ is similarly forbidden by some symmetry which does not need to be broken, such that $m = 0$. Alternatively, if $m$ and $m_h$ are small due to independent reasons, it is unlikely that they are comparable; one therefore expects that $m \ll m_h$ is ‘more likely’.

Whatever is its motivation, the model is phenomenologically interesting: it has only one parameter, $\lambda$, fixed by assuming that thermal freeze-out reproduces the observed cosmological DM abundance. Thereby both $M$ and $\sigma_{SI}$ are predicted, as we now compute. As both predictions lie within the region ‘favored’ by the CDMS experiment, we name this model Constrained Dark Matter Singlet (CDMS).

According to the standard approximation for cosmological thermal freeze-out, the DM relic
abundance \( \Omega_{\text{DM}} = \rho_{\text{DM}}/\rho_c \) is given by:

\[
\Omega_{\text{DM}} h^2 = \frac{1.1 z_f}{\sqrt{g_{\text{SM}} M_{\text{Pl}} \sigma v \text{eV}}}, \quad z_f \approx \ln \frac{0.038 M_{\text{Pl}} M \sigma v}{\sqrt{g_{\text{SM}} z_f}} \approx \frac{1}{23}
\]  

(2)

where \( g_{\text{SM}} \sim 80 \) is the effective number of relativistic degrees of freedom at the freeze-out temperature \( T_f = M z_f \sim 10 \text{ GeV} \). The non-relativistic s-wave SS annihilation cross section into SM particles is given by \cite{8, 9, 10, 4}

\[
\sigma v = \frac{8 \lambda^2 V^2}{[4 M^2 - m_h^2]^2 + m_h^2 [\Gamma(m_h) + \Gamma_S]^2} \frac{\Gamma(2M)}{2M}
\]  

(3)

where \( \Gamma(m) \) is the decay width of a Higgs boson with mass \( m \) into SM particles, and \( \Gamma_S = \lambda^2 V^2 \text{Re} \sqrt{1 - 4 M^2/m_h^2}/8 \pi m_h \) is the higgs decay width into SS.

Fig. 2 shows the values of \( M \) compatible with the measured cosmological DM density, \( \Omega_{\text{DM}} h^2 = 0.110 \pm 0.005 \) \cite{11}. We plot the 3\( \sigma \) band, assuming a 5\% uncertainty in the theoretical prediction of eq. (2), that accounts for the p-wave contribution to \( \sigma v \), suppressed by a \( \mathcal{O}(z_f) \) factor.

We see that multiple solutions are possible:

i) with \( m_h < 2M \), such that the higgs is standard, \( \Gamma_S = 0 \). This solution exists only for \( m_h \lesssim 115 \text{ GeV} \), and seems excluded by LEP searches, possibly unless \( m_h \) is just around the LEP bound, \( m_h > 114 \text{ GeV} \) \cite{12}.

ii) with \( m_h > 2M \), such that \( h \rightarrow 2S \) decays are kinematically allowed. Fig. 2b compares the prediction for the visible higgs branching ratio with the LEP bounds: this solution is allowed for \( m_h \gtrsim 105 \text{ GeV} \) \cite{13}. The predicted coupling, \( \lambda \sim 0.05 \), is perturbative.

Furthermore, within the SM as well as within the CDMS model, precision data favor \( m_h = (87 \pm 35) \text{ GeV} \) \cite{12}, and, together with TeVatron higgs searches, suggest \( m_h \lesssim 160 \text{ GeV} \) at 90\% confidence level \cite{12}.

We now compute the spin-independent DM/nucleon elastic scattering mediated by tree-level higgs exchange (see also \cite{8, 9, 10, 4}). The interactions \( \lambda V S^2 h \) and \( m_q h \bar{q} q/V \) give the effective operator \( \lambda S^2 m_q \bar{q} q/m_h^2 \). Its nucleon matrix element is

\[
\langle N | \sum_q m_q \bar{q} q | N \rangle \equiv f m_N |\bar{N} N \rangle
\]  

(4)

where the sum runs over \( u, d, s, c, b, t \) and, according to recent analyses, \( f = 0.56 \pm 0.11 \) \cite{14} or \( f = 0.30 \pm 0.01 \) \cite{15} using lattice results. The prediction for the conventional spin-independent DM/nucleon cross section is:

\[
\sigma_{\text{SI}} = \frac{\lambda^2 m_N^4 f^2}{8 \pi M^2 m_h^4}.
\]  

(5)

Fig. 1 shows the numerical prediction for both \( M \) and \( \sigma_{\text{SI}} \) as function of the Higgs mass \( m_h \). The central values assumes \( f = 1/3 \) (as in \cite{16}) and the size of the bands indicates the
uncertainty in the nuclear matrix element. The disfavored solution with \( m_h \approx 115 \text{ GeV} \) would give a larger \( \sigma_{SI} \approx 10^{-43} \text{ cm}^2 \), a value disfavored also by CDMS and XENON direct searches. Indirect DM signals are compatible with existing bounds.

A related model is obtained assuming that the scalar singlet is complex under some dark U(1), with Lagrangian \( \mathcal{L} = \mathcal{L}_{SM} + |\partial_\mu S|^2 - 2\lambda |S|^2 |H|^2 \). As this model is equivalent to having two real singlets, \( S = (S_1 + iS_2)/\sqrt{2} \), the only modification is an extra factor of 2 in \( \Omega_{DM} \) in eq. (2), as well as a doubling of the invisible higgs width. The predictions for \( M \) and \( \sigma_{SI} \) remain very similar as in the real case of fig. 1. Furthermore the cosmological solution with \( M > m_h/2 \) becomes marginally allowed.

3 Conclusions

We have shown in fig. 1 the range of DM mass \( M \) and of the DM/nucleon cross section \( \sigma_{SI} \) ‘favored’ (at weak confidence level) by the weak excess reported by the CDMS experiment. This motivated us to look for DM models that predict both \( M \) and \( \sigma_{SI} \) to be within the CDMS range. DM could be a scalar singlet with just a quartic coupling \( \lambda \) to the Higgs. Assuming that the free parameter \( \lambda \) is determined from the cosmological freeze-out DM abundance, \( M \) and \( \sigma_{SI} \) are univocally predicted. Such predictions depend on the higgs mass, not yet precisely known. The predictions are shown in fig. 1. Furthermore, the model predicts that higgs decays are mostly invisible, \( \text{BR}(h \rightarrow SS) \approx 0.8 \).

Acknowledgements We thank Gino Isidori for discussions. This work is supported by the Swiss National Science Foundation under contract No. 200021-116372.

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