Implication on Higgs invisible width in light of the new CDMS result

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Abstract

With the assumption that the dominant diagram in supersymmetry for the spin-independent cross section of the dark matter particle is due to Higgs boson exchange, we obtain an upper limit on the Higgs-dark-matter coupling based on the new result of the CDMSII Collaborations. We then obtain an upper limit on the invisible width of the Higgs boson, numerically it is less than $20 - 120$ MeV for $m_h \simeq 120 - 180$ GeV. Implications for Higgs boson search are also discussed.
**Introduction.** The presence of cold dark matter (CDM) in our Universe is now well established by the very precise measurement of the cosmic microwave background radiation in the Wilkinson Microwave Anisotropy Probe (WMAP) experiment \[1\]. A nominal 3σ range of the CDM relic density is

\[
\Omega_{\text{CDM}} h^2 = 0.105^{+0.021}_{-0.030},
\]

where \(h\) is the Hubble constant in units of 100 km/Mpc/s.

One of the most appealing and natural CDM particle candidates is provided by supersymmetric models with \(R\)-parity conservation \[2\]. This \(R\)-parity conservation ensures the stability of the lightest supersymmetric particle (LSP) so that the LSP can be CDM. The LSP is in general the lightest neutralino, a linear combination of neutral electroweak (EW) gauginos and Higgsinos. Since the LSP nature depends on its compositions, its detection can vary a lot.

One of the most direct detection methods of the dark matter is through a set of direct search experiments. The CDMS is one of these. The dark matter particles move at a velocity relative to the detecting materials. It will recoil against the nucleons, and create a phonon-type signal, which can be amplified by electronics. Just very recently the CDMSII finalized their search in Ref. \[3\]. When they opened the black box in their blind analysis, they found two candidate events, which are consistent with background fluctuation at a probability level of about 23%. This exciting news already stimulates a large number of activities \[4\] in a very short period of time. Nevertheless, the signal is not conclusive. The CDMS then improves upon the upper limit on the spin-independent cross section \(\sigma_{\chi N}^{\text{SI}}\) to \(3.8 \times 10^{-44}\) cm\(^2\) for \(m_\chi \approx 70\) GeV. In the following, we use this new limit to put a new bound on the Higgs-dark-matter coupling, which is then implied to an upper limit on the Higgs boson invisible width. This is the main result of this work. Further implications for the Higgs boson search at colliders are also discussed.

**Direct Detection.** The spin-independent cross section between the dark matter particle (denoted by \(\chi\) in the following) and the nucleon is given by

\[
\sigma_{\chi N}^{\text{SI}} = \frac{\mu_{\chi N}^2}{\pi} |G_s|^2, \tag{1}
\]

where \(\mu_{\chi N} = m_\chi m_N/(m_\chi + m_N)\) is the reduced mass between the dark matter particle and
the nucleon, and

\[ G_s^N = \sum_{qq=u,d,s,c,b,t} \langle N|\bar{q}q|N \rangle \left( \frac{1}{2} \sum_q g_Lq\bar{q}g_Rq \frac{m_q^2}{m_h^2} - g_h\chi\chi \frac{m_p^2}{m_h^2} \right) \]  \tag{2}

Suppose the squarks are heavy, like that in split SUSY, the dominant diagram is the Higgs boson exchange diagram. The upper limit on the spin-independent cross section can imply an upper limit for the dark matter-Higgs coupling, which is more or less model independent. We shall ignore the squark exchange in the following.

Default values of the parameters used, e.g. in DarkSUSY [5] are (with \( \langle N|\bar{q}q|N \rangle = f_T T q_{m_N}/m_q \))

\[ f_T u = 0.023, \quad f_T d = 0.034, \quad f_T s = 0.14, \quad f_T c = f_T b = f_T t = 0.0595, \]
\[ f_T u = 0.019, \quad f_T d = 0.041, \quad f_T s = 0.14, \quad f_T c = f_T b = f_T t = 0.0592. \]  \tag{3}

We take the average between proton and neutron for \( \sigma_{\chi N}^{SI} \). Note that the \( m_q \) dependence in the Yukawa coupling \( g_{hqq} \) will be cancelled by the \( m_q \) dependence in \( \langle N|\bar{q}q|N \rangle \). Taking the average between proton and neutron the value of \( G_s^N \) is

\[ -G_s^N \simeq g_h\chi\chi \frac{g m_p}{2m_W m_h^2} \left( \frac{0.3766}{4\pi} \right). \]  \tag{4}

For \( m_\chi \sim O(100) \) GeV \( \mu_{xp} \approx m_p \). The spin-independent cross section is

\[ \sigma_{\chi N}^{SI} \approx \frac{g^2 m_p^4}{4\pi m_W^2 m_h^2} g_{h\chi\chi}^2 (0.3766)^2. \]  \tag{5}

We can take \( m_h = 115 - 180 \) GeV for most general SUSY models and use the new CDMSII limit \( \sigma_{\chi N}^{SI} < 3.8 \times 10^{-44} \) cm\(^2\). We can obtain an upper limit on the Higgs-dark-matter coupling

\[ g_{h\chi\chi}^2 \lesssim 0.03 - 0.18 \]  \tag{6}

for \( m_h = 115 - 180 \) GeV, which takes into account the current Higgs mass lower limit and the predictions on the upper limit of the lightest Higgs boson in most SUSY models. We show in Fig. 1 the upper limit on \( g_{h\chi\chi}^2 \) versus \( m_h \) from the result \( \sigma_{\chi N}^{SI} < 3.8 \times 10^{-44} \) cm\(^2\).

Since the recoil energies of the two signal events recorded by the CDMSII were 10 – 15 keV, the mass of the dark matter particle is at most around 100 GeV. The lower limit on the the \( \sigma_{\chi N}^{SI} \) around 100 GeV is all about 3.8 – 5 \times 10^{-44} \) cm\(^2\), thus the lower limits on \( g_{h\chi\chi} \) for \( m_\chi \) around 100 GeV are about the same.
FIG. 1: Contour of $\sigma_{\chi N}^{SI} = 3.8 \times 10^{-44}$ cm$^2$ as function of $m_h^2$ and $g_{h\chi\chi}^2$. The curve is also the upper limit on the coupling $g_{h\chi\chi}$.

If the Higgs boson is heavy enough, say $150 - 180$ GeV and the dark matter particle is less than about 75 GeV, the Higgs boson can decay into a pair of dark matter particles. It will give rise to invisible width of the Higgs boson in collider experiments. Based on the upper limit that we obtain in Eq. (6), we can derive an upper limit on the Higgs invisible width

$$\Gamma_{\text{inv}} = \frac{g_{h\chi\chi}^2 m_h}{16\pi} \left(1 - \frac{4m_{\chi}^2}{m_h^2}\right)^{3/2},$$

(7)

where we assume dark matter particle is Majorana. Numerically, using the limit in Eq. (6) we obtain the upper limit on the invisible width of the Higgs boson for $m_h \approx 180$ GeV

$$\Gamma_{\text{inv}} < 20 - 120 \text{ MeV}.$$ 

(8)

Note that the signal events, if interpreted as signals, indicate a cross section of order $O(10^{-44})$ cm$^2$, which in turn gives rise to an invisible width of order $10 - 50$ MeV.

**Implications for Higgs search.** We assume the other SUSY particles are heavy such that the only SUSY particle that the lightest Higgs boson can decay into is the lightest neutralino – the dark matter particle that we denote by $\chi$. The mass range of the Higgs boson that we consider in this work is $120 - 180$ GeV, while the dark matter particle is less than $m_h/2$. The recoil energies of the signal events recorded by the CDMSII tell us that the mass of the dark matter particle is around 100 GeV. The dominant decay mode of the SM-like Higgs boson is either $b\bar{b}$ or the $WW^*$ in the range considered. The total decay width of the SM
Higgs boson is about a few MeV at $m_h = 120$ GeV and sharply rises to 1 GeV at $m_h = 180$ GeV, because of the opening of the $WW^*$ model. The SM-like lightest CP-even Higgs boson in SUSY models has a similar decay width. Therefore, the limit obtained in Eq. (8) is most relevant for the lower mass range, where the $WW$ or $WW^*$ mode is not yet open. If we take the invisible width to be of order of $O(10)$ MeV at $m_h = 120 - 140$ GeV, then the invisible decay of the Higgs boson can be dominant. This will have nontrivial effects on the search for the intermediate Higgs boson at colliders.

The search at the Tevatron is mostly based on associated $Wh, Zh$ production, followed by leptonic decays of the $W$ or $Z$ and the $b\bar{b}$ or $WW^*$ mode of the Higgs boson. If the invisible decay becomes significant, then the fraction into $b\bar{b}$ would be less, such that the search would be more difficult. Nevertheless, for $m_h > 140$ GeV the $WW^*$ mode opens and the invisible mode is less significant. The Higgs boson search at the LHC for $m_h = 120 - 140$ GeV is based on $gg \rightarrow h \rightarrow \gamma\gamma$. It may be worsened if the invisible mode becomes significant.

In summary, we have used the new CDMSII result on the spin-independent cross section to obtain an upper limit on the Higgs-dark-matter coupling, assuming the Higgs boson exchange is the dominant mechanism. We then derive an upper limit on the invisible width of the Higgs boson. If we take the two signal events seriously, the cross section of the order of $10^{-44}$ cm$^2$ implies an invisible width of order 10 MeV for the Higgs boson. Such an invisible width would have significant effects on search for intermediate Higgs boson of mass 120 – 140 GeV.
Acknowledgments

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