Hidden Higgs Boson at the LHC and Light Dark Matter Searches

Xiao-Gang He\(^1,2\) and Jusak Tandean\(^3\)

\(^1\)INPAC, Department of Physics, Shanghai Jiao Tong University, Shanghai, China

\(^2\)Department of Physics and Center for Theoretical Sciences, National Taiwan University, Taipei 106, Taiwan

\(^3\)Department of Physics and Center for Mathematics and Theoretical Physics, National Central University, Chungli 320, Taiwan

Abstract

Recent LHC searches have not found a clear signal of the Higgs boson \(h\) of the standard model (SM) with three or four families in the mass range \(m_h = 120\) - \(600\) GeV. If the Higgs had an unexpectedly large invisible branching ratio, the excluded \(m_h\) regions would shrink. This can be realized in the simplest weakly interacting massive particle dark matter (DM) model, which is the SM plus a real gauge-singlet scalar field \(D\) as the DM, via the invisible mode \(h \rightarrow DD\). Current data allow this decay to occur for \(D\)-mass values near, but below, \(m_h/2\) and those compatible with the light DM hypothesis. For such \(D\) masses, \(h \rightarrow DD\) can dominate the Higgs width depending on \(m_h\), and thus sizable portions of the \(m_h\) exclusion zones in the SM with three or four families may be recovered. Increased luminosity at the LHC may even reveal a Higgs having SM-like visible decays still hiding in the presently disallowed regions. The model also accommodates well the new possible DM hints from CRESST-II and will be further tested by improved data from future DM direct searches.
The hunt for the Higgs boson is an essential part of our effort to test the standard model (SM). Searches at the Tevatron [1] have ruled out the SM Higgs boson \( h \) with mass \( m_h \) between 156 and 177 GeV at 95% confidence level (CL). The latest results from the LHC have excluded most of the \( m_h \) range of 145 - 466 GeV [2, 3] at 95% CL. The LHC data are not yet sensitive to the region around \( m_h \sim 120 \) GeV favored by the SM fit to electroweak precision data [4].

The main production process for the SM Higgs at hadron colliders is the gluon fusion \( gg \rightarrow h \) arising from a top-quark loop [5]. This mechanism is thus sensitive to new physics which can affect the loop-induced \( gg \rightarrow h \) amplitude, such as extra heavy quarks. Especially in the SM with four sequential fermion families (SM4), the new heavy quarks can enhance the Higgs production cross-section by up to \( \sim 9 \) times [6] relative to that in the SM with three families (SM3). Reinterpreted in the SM4 context, the current LHC data then disallow \( m_h \) values from 120 to 600 GeV [2, 7], which form a sizable part of the range allowed by precision data [4], while Tevatron results exclude only \( m_h = 124 - 286 \) GeV [8].

Future LHC searches may well discover a Higgs within the SM (either SM3 or SM4) preference. However, if none is found between the LEP lower-bound and 1 TeV, physics beyond the SM may have to supply the explanation. New physics could offset the heavy-quark contribution to \( gg \rightarrow h \) [9], reducing the \( h \) production rate to below its SM value, and/or the couplings involved in the decays on which Higgs searches rely could be less than the corresponding couplings in the SM, as may occur in two-Higgs-doublet models [9]. Alternatively, it is of course possible that an elementary Higgs does not exist at all, if the electroweak symmetry breaking sector is a strongly correlated system [10], or that the Higgs is simply too heavy for LHC data to reveal. It may also be that the Higgs has an unexpectedly big branching-ratio \( B_{\text{inv}} \) into invisible particles [11, 12]. Even if its production mechanisms and decays into visible channels are not altered, a larger-than-expected \( B_{\text{inv}} \) will lower the event numbers of the Higgs decays used in the LHC analyses, due to the increased rate of the invisible mode. A sufficiently high \( B_{\text{inv}} \) will even make the present bounds on \( m_h \) disappear. In this paper we focus on this last possibility and demonstrate that it may indeed be realized in a particle physics model of cold dark matter we call SM+D. This illustrates the potential deep connection between dark matter and Higgs physics. The interplay between the two sectors might shine light on the still hidden elements in them.

The SM+D is one of the simplest models which can provide weakly interacting massive particle (WIMP) dark matter (DM). In addition to the SM particles, it has a real scalar field \( D \) dubbed darkon which is a singlet under the SM gauge group and acts as the WIMP. Beyond the SM (SM3 or SM4) part, the Lagrangian of the model has new renormalizable terms given by [13, 14]

\[
\mathcal{L}_D = \frac{1}{2} \partial^\mu D \partial_\mu D - \frac{1}{4} \lambda_D D^4 - \frac{1}{2} m_0^2 D^2 - \lambda D^2 H^\dagger H ,
\]

(1)

where \( \lambda_D, m_0, \) and \( \lambda \) are free parameters and \( H \) is the Higgs doublet containing the physical Higgs field \( h \), in the notation of Ref. [11] which gives some more details on the model. Its DM sector has a small number of free parameters, only two of which, besides \( m_h \), are relevant to our study: the Higgs-darkon coupling \( \lambda \) and the darkon mass \( m_D = (m_0^2 + \lambda v^2)^{1/2} \), where \( v = 246 \) GeV is the Higgs vacuum expectation value.

The darkon model can yield the required WIMP relic density by means of Higgs-mediated darkon annihilation into kinematically allowed SM particles [13, 14]. Upon specifying \( m_D \) and \( m_h \), one can extract \( \lambda \) from the relic-density number \( \Omega_B h^2 = 0.1123 \pm 0.0035 \) [15]. Applying the procedure given in Ref. [11] to the SM3+D case for \( 2.5 \) GeV \( \leq m_D \leq 400 \) GeV and some illustrative values of \( m_h \), we present the results in Fig. 1(a), where the band widths reflect the relic-density
range. In the SM4+D, the $\lambda$ results are mostly somewhat lower than their SM3+D counterparts, by no more than $\sim 20\%$, similarly to what was found in Ref. [11]. The reason for the decrease is that the Higgs total width in the SM4 is enlarged relative to that in the SM3, mainly due to the rate of $h \rightarrow gg$ being enhanced by the new heavy quarks [11].

A number of underground experiments have been performed to detect WIMP DM directly by looking for the recoil energy of nuclei due to the scattering of a WIMP off a nucleon [16–22]. The acquired data impose additional constraints on the parameter space of the darkon models.

FIG. 1: (a) Darkon-Higgs coupling $\lambda$ as a function of darkon mass $m_D$ for Higgs mass values $m_h = 115, 150, 200, 450$ GeV in SM3+D. (b) The corresponding darkon-nucleon cross-section $\sigma_{el}$, compared to 90%-CL upper-limits from CoGeNT (magenta dotted curve) [17], CDMS (brown long-dashed curves) [18], XENON10 (green dot-dashed curve) [19], and XENON100 (black short-dashed curve) [20], as well as two (cyan) areas representing the new CRESST-II result [21] and a dark-gray patch fitting both DAMA/LIBRA [10] and CoGeNT [17] signal data [27]. The black-dotted sections of the curves in (a), and also in the following figures, are disallowed by the direct-search limits in (b) as discussed in the text.
The relevant observable is the spin-independent cross-section $\sigma_{el}$ of the darkon-nucleon elastic collision via $t$-channel Higgs-exchange \[13, 14\]. Thus to compute $\sigma_{el}$ requires knowing not only $\lambda$, but also the Higgs-nucleon coupling $g_{NNh}$. We again follow Ref. \[11\], but here employ a range of $g_{NNh}$ to account for its substantial uncertainty arising from its dependence on the pion-nucleon sigma term $\sigma_{\pi N}$ which is not well determined \[23\]. Since phenomenological analyses yield \[36\MeV \leq \sigma_{\pi N} \leq 71\MeV \[24\], while lattice calculation results have a wider spread from \[\sim 15\text{ to } 90\MeV \[23\], we can reasonably take \[30\MeV \leq \sigma_{\pi N} \leq 80\MeV\]. With the aid of formulas from Refs. \[11, 26\], this translates into \[0.0011 \leq g_{NNh}^{\text{SM3}} \leq 0.0032\] and \[0.0016 \leq g_{NNh}^{\text{SM4}} \leq 0.0033\].

We show in Fig.\[1\](b) the calculated $\sigma_{el}$ in the SM3+D for the same choices of $m_D$ and $m_h$ as in Fig.\[1\](a). Also shown are results of the latest direct-searches for DM, including CRESST-II which has reported fresh possible WIMP hints \[21\]. Evidently the $g_{NNh}$ uncertainties can make $\sigma_{el}$ vary by up to an order of magnitude \[23\]. Nevertheless, including them leads to a more complete picture of how the data confront the darkon model. In the SM4+D case, which is not shown, the majority of the predictions for $\sigma_{el}$ are higher by \(\sim\)50\%, and varying somewhat less, than their SM3+D counterparts.

Comparing the SM3+D predictions for $\sigma_{el}$ to the experimental bounds in Fig.\[1\](b), one can see that darkon masses \[\gtrsim 15\text{ GeV} \] up to \[\sim 80\text{ GeV}\] are disallowed except around $m_D \sim m_h/2$. We remark that these dips near $m_D = m_h/2$ are a common feature of $\sigma_{el}$ curves \[20\]. Specifically, we find \[54\text{ GeV} \lesssim m_D \lesssim 63\text{ GeV} \] is allowed for $m_h = 115\text{ GeV}$, and also $m_D \gtrsim 66, 75, 80\text{ GeV}$ for $m_h = 150, 200, 450\text{ GeV}$, respectively. Their counterparts in the SM4+D are \[54\text{ GeV} \lesssim m_D \lesssim 62\text{ GeV} \] for $m_h = 115\text{ GeV}$ and $m_D \gtrsim 67, 78, 81\text{ GeV}$ for $m_h = 150, 200, 450\text{ GeV}$, respectively. More generally, the direct searches to date have not yet probed the darkon model much beyond $m_D \sim 80\text{ GeV}$.

For lighter darkons, it may seem from Fig.\[1\](b) that almost all masses down to $m_D \sim 5\text{ GeV}$ are already excluded by the CDMS, XENON10, and XENON100 limits. However, their results for WIMP masses \[\lesssim 15\text{ GeV} \] have been seriously disputed in the literature \[22, 27, 28\]. Furthermore, other recent searches by DAMA/LIBRA \[16\], CoGeNT \[17\], and CRESST-II \[21\] have turned up potential evidence for DM under 30 GeV. In particular, the excess events newly observed at CRESST-II may have been caused by WIMPs of mass about 12 or 25 GeV \[21\]. Pending a general consensus on this matter, it is not impossible that the DM masses suggested by DAMA/LIBRA, CoGeNT, or CRESST-II are still viable. One should therefore keep an open mind that this light-WIMP region is not totally ruled out. It is then interesting to see that the SM3+D predictions in Fig.\[1\](b) overlap well with the 2$\sigma$-confidence (cyan) areas compatible with the CRESST-II result \[21\], especially the lower mass region around 12 GeV. The predictions also cover part of the dark-gray area that can fit both the DAMA/LIBRA and CoGeNT data at 99\% CL according to Ref. \[27\]. The same can be said of the corresponding results in the SM4+D.

For even lower masses, the available data on $B$-meson decay $B \to KE$ and kaon decay $K \to \pi E$ with missing energy $E$ imply stringent restrictions excluding most of the $m_D < (m_B - m_K)/2 \simeq 2.4\text{ GeV}$ region \[11, 29\]. In contrast, bounds on $B \to E$ and the bottomonium decay $\Upsilon \to \gamma E$ are still too weak \[30\] to probe higher masses up to $m_D \sim m_\Upsilon/2 \sim 5\text{ GeV}$.

Based on the preceding considerations, we regard the range $2.5\text{ GeV} \leq m_D \leq 15\text{ GeV}$ as still viable in the SM3+D and SM4+D. It accommodates the WIMP masses hinted at by CoGeNT as well as the smaller values of those suggested by DAMA/LIBRA and CRESST-II. The various allowed ranges of $m_D$ discussed above are depicted for the SM3+D in Fig.\[1\](a), where the black-dotted sections of the $\lambda$ curves are disallowed.
Now if \( m_h > 2m_D \), the branching ratio of the invisible decay \( h \to DD \) is \( \mathcal{B}(h \to DD) = \Gamma(h \to DD)/\Gamma_h^{SM+D} \), where \( \Gamma(h \to DD) = \lambda^2 v^2 (1 - 4m_D^2/m_h^2)^{1/2}/(8\pi m_h) \) and \( \Gamma_h^{SM+D} = \Gamma_h^{SM} + \Gamma(h \to DD) \) includes the Higgs total width \( \Gamma_h^{SM} \) in the SM3 or SM4 without the darkon. To illustrate how large \( \mathcal{B}(h \to DD) \) can be, we use the \( \lambda \) values obtained earlier to draw the plots in Fig. 2 where the black-dotted areas are again excluded. Obviously, in the viable \( m_D \) zones of the SM3+D or SM4+D the additional process \( h \to DD \) can greatly enhance the Higgs invisible branching ratio \( \mathcal{B}_{\text{inv}} \simeq \mathcal{B}(h \to DD) \). Needless to say, this implies potentially significant changes to the Higgs branching ratios assumed in LHC analyses [31].

The impact of the enlarged \( \mathcal{B}_{\text{inv}} \) on Higgs searches can be quantified in a different way. Since the darkon has no gauge interactions or mixing with the Higgs, the rates of Higgs decays into \( \gamma\gamma, \tau^+\tau^-, bb, WW^{(*)}, \) and \( ZZ^{(*)} \), which are employed in LHC searches [2, 3, 7], are not modified in the SM+D with respect to the SM alone. It follows that their branching ratios in the SM+D are all subject to the same reduction factor [14]

\[
\mathcal{R} = \frac{\mathcal{B}(h \to X\bar{X})}{\mathcal{B}(h \to XX)_{\text{SM}}} = \frac{\Gamma_h^{SM}}{\Gamma_h^{SM} + \Gamma(h \to DD)}.
\]

Since the \( gg \to h \) expectation is unchanged by the darkon’s presence, the cross-section of \( gg \to h \to X\bar{X} \) is then decreased by the same factor \( \mathcal{R} \), as are the cross sections of other Higgs production modes. Hence the assumed event rate for each production channel in the SM Higgs searches would be overestimated by \( 1/\mathcal{R} \) times.

In Fig. 3 we plot \( \mathcal{R} \) for the same \( m_D \) and \( m_h \) choices as in Fig. 2. These graphs indicate that the darkon effect can suppress the Higgs branching ratios into SM particles by up to 3 orders of magnitude. More precisely, the values of \( \mathcal{R} \) in the viable regions of \( m_D \) are collected in Table I. One notices that the two allowed regions of \( m_D \) lead to two distinct ranges of \( \mathcal{R} \) in each \( m_h \) case, the gap between them narrowing as \( m_h \) increases. Moreover, \( \mathcal{R} \) at a particular \( m_D \) rises drastically right after \( m_h \) exceeds \( 2m_W \) and the channel \( h \to WW \) is fully open, which quickly builds up \( \Gamma_h^{SM} \). It is worth remarking, in addition, that the upper limits of \( \mathcal{R} \) in the viable low-\( m_D \) region would not change much if its maximum value were increased from 15 GeV to 20 GeV (or even 30 GeV).

FIG. 2: Branching ratio of \( h \to DD \) as a function of \( m_D \) in (a) SM3+D and (b) SM4+D for \( m_h = 115, 150, 200, 450 \) GeV.
FIG. 3: Reduction factor $R$ as a function $m_D$ in (a) SM3+D and (b) SM4+D for $m_h = 115, 150, 200, 450$ GeV.

TABLE I: Ranges of $R$ corresponding to the allowed $m_D$ regions (I) from 2.5 to 15 GeV and (II) not far from, but less than, $m_h/2$, for $m_h = 115, 150, 200, 450$ GeV in (a) SM3+D and (b) SM4+D.

|       | 115        | 150        | 200        | 450        |
|-------|------------|------------|------------|------------|
| I a   | [0.0007,0.009] | [0.0018,0.020] | [0.058,0.41] | [0.15,0.65] |
| II a  | [0.56,1]   | [0.48,1]   | [0.95,1]   | [0.97,1]   |
| I b   | [0.0014,0.018] | [0.0025,0.029] | [0.065,0.44] | [0.16,0.68] |
| II b  | [0.79,1]   | [0.72,1]   | [0.98,1]   | [0.99,1]   |

With our $R$ examples, we can explore how the darkon effect may alter the LHC limits on $m_h$. Since the determination of the $m_h$ exclusion zones is based on the measured upper-limit on the Higgs production cross-section at the $pp$ collider divided by its SM expectation, $\sigma/\sigma_{SM}$, where $\sigma_{SM} = \sigma(pp \to h + \text{anything})B(h \to XX)_{SM}$, any change in $\sigma_{SM}$ would also change the limit and hence the disallowed regions. The presence of the darkon with $m_D < m_h/2$ implies that $B(h \to XX)_{SM}$ needs to be replaced by $B(h \to XX) = R B(h \to XX)_{SM}$ and hence $\sigma/\sigma_{SM}$ by $\sigma/(\sigma_{SM}R)$. This would amount to the weakening of the bounds by a factor $1/R$. 
Specifically, the latest 95%-CL upper-limits on $\sigma/\sigma_{SM}$ in the SM3, and their median expected limits, reported by ATLAS and CMS [2, 3] have minima of around 0.3 to 0.4. From Fig.3 and Table 4 we can then infer that the $m_h$ exclusion zone in the SM3, from 145 to 466 GeV [2, 3], can be entirely recovered in the SM3+D if $m_D \lesssim 5$ GeV. Furthermore, the recovered region may become slightly smaller as $m_D$ rises to 15 GeV. For $m_D \sim m_h/2$, with $R \gtrsim 0.5$, only some of the disallowed Higgs masses can be made viable again.

On a related note, it is intriguing that the modest ($\sim 2$ standard deviation) excess at $m_h \sim 140$ GeV observed by both ATLAS and CMS [2, 3] can be explained as a Higgs having $B_{inv} \sim 0.5$ at $m_D \sim 60$ GeV in the SM3+D according to Fig.3(a). A similar interpretation was previously offered in Ref. [32].

In the SM4 case, the 95%-CL upper-limits on $\sigma/\sigma_{SM}$ and their median expected limits lie mainly between 0.1 and 0.2, whereas their minima are roughly 0.06-0.08 and 0.03, respectively [2, 7]. Based on Fig.3 and Table 4 we then conclude that not all, but a sizable fraction, of the $m_h$ exclusion zone, 120-600 GeV, can be recovered in the SM4+D if $m_D \lesssim 5$ GeV. As $m_D$ goes up to 15 GeV, only $m_h \lesssim 2m_W$ can be saved. If $m_D \sim m_h/2$, the viable zone is limited to $m_h \sim 120$ GeV. As LHC luminosity grows, the recovered region in the SM4+D may shrink fast, unless its Higgs is detected.

Finally, the fact that the SM Higgs decay rates into SM particles are not modified by the darkon’s presence implies that the relative sizes of these decay rates in the SM3+D (SM4+D) are the same as their counterparts in the SM3 (SM4). It follows that, if the LHC observes an unambiguous signal of a new electrically neutral particle in the mass range from $\sim 115$ GeV to 1 TeV and if its production rate is below that of the SM Higgs, but still within SM3+D (SM4+D) expectations, examining the relative rates of the new particle’s visible decay modes would be a means to help establish whether it is an SM3+D (SM4+D) Higgs or it belongs to some other model. If it seems to be an SM3+D or SM4+D Higgs, future DM direct searches with improved sensitivity can check the model further for consistency.

In conclusion, we have explored the implications of the the SM Higgs mass exclusion zones recently obtained at the LHC for the simplest WIMP DM models, the SM3+D and SM4+D. Current experimental constraints allow $m_D$ values not too far from, but less than, $m_h/2$ and those compatible with the light-WIMP hypothesis. In these two regions, the invisible mode $h \rightarrow DD$ can dominate the Higgs decay, with an enhanced branching ratio. We have demonstrated that, as a consequence, significant portions of the presently excluded ranges of the SM3 and SM4 Higgs mass may be recovered. With increased luminosity, the LHC may even uncover a Higgs having SM-like visible decays still hidden in the currently disallowed regions. We emphasize that the SM3+D and SM4+D predictions overlap well with the parameter space for the possible WIMP evidence in the new CRESST-II measurement, although it is in tension with limits from some other DM experiments. More precise data from future DM direct searches can test the models more stringently.

This work was supported in part by NSC and NCTS of ROC, NNSF and SJTU 985 grants of PRC, and NCU Plan to Develop First-Class Universities and Top-Level Research Centers.

[1] CDF and D0 Collaborations, arXiv:1107.5518 [hep-ex].
[2] ATLAS Collaboration, Report No. ATLAS-CONF-2011-135, 2011, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/AtlasResultsEPS2011.
[3] CMS Collaboration, Report No. CMS PAS HIG-11-022, 2011, http://cms.web.cern.ch/cms/News/2011/LP11
[4] M. Baak et al., arXiv:1107.0975 [hep-ph].
[5] M. Spira, A. Djouadi, D. Graudenz, and P.M. Zerwas, Nucl. Phys. B 453, 17 (1995) arXiv:hep-ph/9504378.
[6] Q. Li, M. Spira, J. Gao, and C.S. Li, Phys. Rev. D 83, 094018 (2011) arXiv:1011.4484 [hep-ph].
[7] CMS Collaboration, Report No. CMS PAS HIG-11-011, 2011, http://cms.web.cern.ch/cms/News/2011/EPS_2011.
[8] CDF and D0 Collaborations, arXiv:1105.3965 [hep-ex]; X.G. He and G. Valencia, arXiv:1108.0222 [hep-ph].
[9] G.H. Brooijmans et al., arXiv:0802.3715 [hep-ph], review some examples of models with no elementary Higgs.
[10] X.G. He, S.Y. Ho, J. Tandean, and H.C. Tsai, Phys. Rev. D 82, 035016 (2010) arXiv:1004.3464 [hep-ph].
[11] W.Y. Keung and P. Schwaller, JHEP 1106, 054 (2011) arXiv:1103.3765 [hep-ph].
[12] V. Silveira and A. Zee, Phys. Lett. B 161, 136 (1985); J. McDonald, Phys. Rev. D 50, 3637 (1994) arXiv:hep-ph/0702143.
[13] C.P. Burgess, M. Pospelov, and T. ter Veldhuis, Nucl. Phys. B 619, 709 (2001) arXiv:hep-ph/0011335.
[14] E. Komatsu et al. [WMAP Collaboration], Astrophys. J. Suppl. 192, 18 (2011) arXiv:1001.4538 [astro-ph.CO].
[15] R. Bernabei et al., Eur. Phys. J. C 67, 39 (2010) arXiv:1002.1028 [astro-ph.GA].
[16] C.E. Aalseth et al. [CoGeNT Collaboration], Phys. Rev. Lett. 106, 131301 (2011) arXiv:1002.4703 [astro-ph.CO].
[17] D.S. Akerib et al. [CDMS Collaboration], Phys. Rev. D 82, 122004 (2010) arXiv:1011.4290 [astro-ph.CO]; Z. Ahmed et al. [CDMS-II Collaboration], Phys. Rev. Lett. 106, 131302 (2011) arXiv:1101.2482 [astro-ph.CO].
[18] J. Angle et al. [XENON10 Collaboration], Phys. Rev. Lett. 107, 051301 (2011) arXiv:1104.3088 [astro-ph.CO].
[19] E. Aprile et al. [XENON100 Collaboration]. arXiv:1104.2549 [astro-ph.CO].
[20] G. Angloher et al. [CRESST Collaboration], arXiv:1109.0702 [astro-ph.CO].
[21] G.B. Gelmini, arXiv:1106.6278 [hep-ph].
[22] J.R. Ellis, K.A. Olive, and C. Savage, Phys. Rev. D 77, 065026 (2008) arXiv:0801.3656 [hep-ph].
[23] J. Gasser, H. Leutwyler, and M.E. Sainio, Phys. Lett. B 253, 252 (1991); M.M. Pavan, I.I. Strakovsky, R.L. Workman, and R.A. Arndt, PiN Newslett. 16, 110 (2002) arXiv:hep-ph/0111066.
[24] S. Gusken et al. [TXL Collaboration], Phys. Rev. D 59, 054504 (1999) arXiv:hep-lat/9809066; K.I. Ishikawa et al. [PACS-CS Collaboration], Phys. Rev. D 80, 054502 (2009) arXiv:0905.0962 [hep-lat]; R.D. Young and A.W. Thomas, Nucl. Phys. A 844, 266C (2010) arXiv:0911.1757 [hep-lat] and references therein.
[25] X.G. He, T. Li, X.Q. Li, J. Tandean, and H.C. Tsai, Phys. Rev. D 79, 023521 (2009) arXiv:0811.0658 [hep-ph]; Phys. Lett. B 688, 332 (2010) arXiv:0912.4722 [hep-ph].
[26] D. Hooper, J.I. Collar, J. Hall, D. McKinsey, and C. Kelso, Phys. Rev. D 82, 123509 (2010)
[28] J.I. Collar, arXiv:1103.3481 [astro-ph.CO]; arXiv:1106.0653 [astro-ph.CO].

[29] C. Bird, P. Jackson, R. Kowalewski, and M. Pospelov, Phys. Rev. Lett. 93, 201803 (2004) 
arXiv:hep-ph/0401195; C. Bird, R. Kowalewski, and M. Pospelov, Mod. Phys. Lett. A 21, 457 (2006) 
arXiv:hep-ph/0601090; C.S. Kim, S.C. Park, K. Wang, and G. Zhu, Phys. Rev. D 81, 054004 (2010) 
arXiv:0910.4291 [hep-ph].

[30] G.K. Yeghiyan, Phys. Rev. D 80, 115019 (2009) arXiv:0909.4919 [hep-ph]; A. Badin and 
A.A. Petrov, Phys. Rev. D 82, 034005 (2010) arXiv:1005.1277 [hep-ph].

[31] The implications of the invisible Higgs decay in the darkon model or its variants for Higgs searches were discussed before in [14, 26]; M.C. Bento, O. Bertolami, and R. Rosenfeld, Phys. Lett. B 518, 276 (2001) 
arXiv:hep-ph/0103340; X.G. He, T. Li, X.Q. Li, and H.C. Tsai, Mod. Phys. Lett. A 22, 2121 (2007) 
arXiv:hep-ph/0701156; V. Barger, P. Langacker, M. McCaskey, M.J. Ramsey-Musolf, and 
G. Shaughnessy, Phys. Rev. D 77, 035005 (2008) [arXiv:0706.4311 [hep-ph]]; V. Barger, M. McCaskey, and G. Shaughnessy, Phys. Rev. D 82, 035019 (2010) [arXiv:1005.3328 [hep-ph]]; V. Barger, Y. Gao, M. McCaskey, and G. Shaughnessy, Phys. Rev. D 82, 095011 (2010) [arXiv:1008.1796 [hep-ph]]; M. Aoki, S. Kanemura, and O. Seto, Phys. Lett. B 685, 313 (2010) [arXiv:0912.5536 [hep-ph]]; S. Andreas, C. Arina, T. Hambye, F.S. Ling, and M.H.G. Tytgat, Phys. Rev. D 82, 043522 (2010) 
arXiv:1003.2595 [hep-ph]]; W.L. Guo and Y.L. Wu, JHEP 1010, 083 (2010) [arXiv:1006.2518 [hep-ph]]; T. Li and Q. Shafi, Phys. Rev. D 83, 095017 (2011) [arXiv:1101.3576 [hep-ph]]; Y. Cai, X.G. He, and B. Ren, Phys. Rev. D 83, 083524 (2011) [arXiv:1102.1522 [hep-ph]]; K. Ghosh, B. Mukhopadhyaya, and U. Sarkar, Phys. Rev. D 84, 015017 (2011) [arXiv:1105.5837 [hep-ph]]; Y. Mambrini, 
arXiv:1108.0671 [hep-ph].

[32] M. Raidal and A. Strumia, arXiv:1108.4903 [hep-ph].