The Simplest Higgs Portal
Dark Matter Model and Its Extensions

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Higgs Portal Workshop
Umass, 05/01/2014
Dark Matter Properties

- Neutral (electric charge = 0 and colorless)
- Very weakly interacting, no EM interaction
- Very long lived or absolutely stable
- Hot or warm or cold, prefer cold dark matter (CMD)
- Mass, spin not known

This talk will concentrate on WIMP CMD
Standard Model of Particles
SU(3) x SU(2) x U(1)

None of the SM particles can play the role of DM
The discovery of Higgs in 2012 mass is about 126 GeV
The Higgs fit SM very well

The LHC Higgs cannot have invisible branching ratio larger than 20 ~ 30%!
Constrain Higgs portal Dark Matter models.
DM Candidates in Particle Physics

- Many many candidates in fact
- Wide ranges of mass and coupling strengths
- If one tries to solve hierarchy problem, weak scale DM is well motivated
- Strong CP motivated axion

The simplest: SM + a real scalar!
The Darkon Model

Thermal production of DM

- Boltzmann Equation:
  \[ \frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right] \]

  - Dilution from expansion
  - $X + X \rightarrow SM + SM$
  - $SM + SM \rightarrow X + X$

\[ \Omega_X \approx \frac{6 \times 10^{27} \ cm^3 \ s^{-1}}{\langle \sigma_{ann} v \rangle} \]

- $X$ (CDM) is initially in thermal equilibrium

- As universe cools down, $X$ only decreases by pair annihilation

- As universe expands, $X$ eventually decouples from the SM
DM relic density, detection and DM production at colliders

Efficient scattering now (Direct detection)

Efficient annihilation now (Indirect detection)

Efficient production now (Particle colliders)
Status of Direct DM detection
There are several indications of light DM of order $10\,\text{GeV}$, DAMA, CoGENT, CRESST, CDSMII…

It is often claimed that Xenon and Lux experiments rule out these possibilities.

But, the detection is target dependent. If interaction of DM with proton and neutron are different, Isopin Violating DM, it may happen that the nuclei-DM cross section for Xenon is small, but not for other nuclei.

Low mass DM of order $10\,\text{GeV}$ mass is not completely ruled out!
The Darkon Model SM+D, the simplest Higgs portal model, as a realistic realization

SM+D: SM3 + a real SM singlet D darkon field (plays the role of dark matter).

Sileira&Zee, PLB (1985)

Beyond the SM part, the Lagrangian of the model

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

where \( \lambda_D, m_0, \) and \( \lambda \) are free parameters and \( H \) is the Higgs doublet containing the physical Higgs field \( h \). Only two of its free parameters besides \( m_h \) are:

\( \lambda \) and the darkon mass \( m_D = (m_0^2 + \lambda v^2)^{1/2} \)

D is stable due to a \( D \to -D \) Z2 symmetry.

After \( H \) develops VEV, there is a term: \( v DD h \).
This term is important for annihilation of \( D D \to h \to \) SM particle
This term also induce \( h \to DD \) if DM mass is less than half of the Higgs mass
increasing the invisible decay width and make the LHC detection harder!
D is stable, but can annihilate through h exchange

\[ \sigma_{\text{ann}} v_{\text{rel}} = \frac{8\lambda^2 v^2}{(4m_D^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \sum_i \Gamma(\tilde{h} \to X_i) \frac{2m_D}{2m_D}, \]

\( v_{\text{rel}} = 2|\mathbf{p}_D^{\text{cm}}|/m_D \) is the relative speed of the DD pair in their cm frame, \( \tilde{h} \) is a virtual having the same couplings to other states as \( h \) of mass \( m_h \), an invariant mass \( \sqrt{s} = 2m_D \),

\[ \Omega_D h^2 \simeq \frac{1.07 \times 10^9 x_f}{\sqrt{g_*} m_{\text{Pl}} \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \text{GeV}}, \quad x_f \simeq \ln \frac{0.038 m_{\text{Pl}} m_D \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle}{\sqrt{g_*} x_f}, \]

\( h \) is the Hubble constant in units of 100 km/(s·Mpc), \( m_{\text{Pl}} = 1.22 \times 10^{19} \) GeV

\( x_f = m_D/T_f \quad g_* \), number of relativistic degrees of freedom with masses less than \( T_f \)
Direct Search

\[
\sigma_{\text{el}} \approx \frac{\lambda^2 g_{NNh}^2 v^2 m_N^2}{\pi (m_D + m_N)^2 m_h^4} \cdot \sigma_{\pi N} = 45 \text{ MeV}
\]

\[
g_{NNh}, \quad \mathcal{L}_{qqh} = -\sum_q m_q \bar{q} q h/v, \quad g_{NNh}^{SM^3} = 1.71 \times 10^{-3}
\]

\[
\sigma_{\pi N} \quad 35 \text{ MeV to } 80 \text{ MeV}
\]

\[
1.3 \times 10^{-3} \lesssim g_{NNh}^{SM^3} \lesssim 3.2 \times 10^{-3}
\]

If dark matter mass is heavy $m_D > 300$ GeV or around $m_h/2$ no problem for both relic density and direct detection. But is small than $m_h/2$, there are problems with direct detection and also invisible Higgs decay!
Dark matter relic density and direct detection allow solutions with dark matter mass less than half of Higgs mass. H → DD allowed.

\[ \Gamma(h \rightarrow DD) = \frac{1}{8\pi} \frac{\lambda^2 v^2}{m_h} \sqrt{1 - \left( \frac{2m_D}{m_h} \right)^2}. \]

Too large an invisible branching ratio. This model is out!

If the DM mass is indeed small, the model has to be extended!!
To have low DM mass ($m_D < m_h/2$), one must overcome two problems:

1. Reconcile various DM direct search constraints? Xeno and Lux exclude all indications of low DM mass from Dama, CoGENT, CRESST and CDMSII: Isospin Violating DM. (Fegn etal, PLB2011)

2. Avoid too large an invisible decay of Higgs boson.

    More than one Higgs boson. (Cai, Ren & He PRD2011, Tandean & He, 2011, 2012)
The WIMP-nucleon cross-section $\sigma_{el}^N$ in the isospin-symmetric limit is related to the WIMP-proton elastic cross-section $\sigma_{el}^p$ in the presence of isospin violation by

$$\sigma_{el}^N f_p^2 \sum_i \eta_i \mu_{A_i}^2 A_i^2 = \sigma_{el}^p \sum_i \eta_i \mu_{A_i}^2 \left[ Z f_p + (A_i - Z) f_n \right]^2$$

the sum is over isotopes of the element in the detector material with which the WIMP interacts dominantly. $Z$ is proton number of the element, $A_i$ $(\eta_i)$ each denote the nucleon number (fractional abundance) of its isotopes, $\mu_{A_i} = m_{A_i} m_{\text{WIMP}}/(m_{A_i} + m_{\text{WIMP}})$ involving the isotope and WIMP masses.

If isospin is conserved, $f_n = f_p$, the measurement of event rates of WIMP-nucleus scattering will translate into the usual $\sigma_{el}^N = \sigma_{el}^p$.

For $f_n = -0.7 f_p$, accounting for the $A_i$ and $Z$ numbers for the different detector materials, one can transform some of the contradictory data on WIMP-nucleon cross-sections into $\sigma_{el}^p$ numbers which overlap with each other.

But this also makes the extracted $\sigma_{el}^p$ enhanced relative to the current measured values of $\sigma_{el}^N$ by up to 4 orders of magnitude, depending on $A_i$ and $Z$. 
Feng et al arxiv:1307.1758
Isospin symmetric

\[ f_n/f_p = -0.7 \]
NLO corrections for nucleon couplings

Vincenzo Cirigliano\textsuperscript{a}, Michael L. Graesser\textsuperscript{a}, Grigory Ovanesyan\textsuperscript{a,b}, Ian M. Shoemaker\textsuperscript{a,c}

arXiv:1311.5886

\[
\frac{dR^{\text{NLO}}}{dE_R} = \frac{\sigma_p \rho_0}{2\mu^2m_X} \left[ Z(1 + s_pE_R) + (A - Z)(r + s_nE_R) \right] F(E_R) + A_2(E_R)^2 \times \eta(E_R, m_X, m_A),
\]

Xe, \(m_X=10\) GeV; \(\bar{\lambda}_3=0\)

\[
\frac{dR^{\text{NLO}}}{dE_R} = \frac{\sigma_p \rho_0}{2\mu^2m_X} \left[ \frac{Z(1 + s_pE_R) + (A - Z)(r + s_nE_R) }{F(E_R) + A_2(E_R)^2} \right] \times \eta(E_R, m_X, m_A),
\]

1. Introduction

At present, the field of DM direct detection is in an uncertain and exciting state with a number of experiments Origins and the Danish Institute for Advanced Study, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark

1.5

-Origins and the Danish Institute for Advanced Study, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark

\[
\begin{align*}
\text{Benchmark D: } f_d/f_p=0.15, \bar{\lambda}_3=0, \bar{\lambda}_0=-0.025 \\
\text{Benchmark E: } f_d/f_p=-1.45, \bar{\lambda}_3=0, \bar{\lambda}_0=-0.1 \\
\text{Benchmark F: } f_d/f_p=-1, \bar{\lambda}_3=0, \bar{\lambda}_0=0.1 \\
\text{Benchmark G: } f_d/f_p=-1, \bar{\lambda}_3=\bar{\lambda}_0=1 \\
\sigma_{\text{NN}} = 60\text{ MeV}
\end{align*}
\]

\[
\frac{dR^{\text{NLO}}}{dE_R} = \frac{\sigma_p \rho_0}{2\mu^2m_X} \left[ Z(1 + s_pE_R) + (A - Z)(r + s_nE_R) \right] F(E_R) + A_2(E_R)^2 \times \eta(E_R, m_X, m_A),
\]

Xe, \(m_X=10\) GeV; \(\bar{\lambda}_3=0\)
Benchmark A: \(f_n/f_p=-0.7, \, \bar{\lambda}_s=\bar{\lambda}_\theta=0\)

Benchmark B: \(f_n/f_p=-0.7, \, \bar{\lambda}_s=0, \, \bar{\lambda}_\theta=-0.1\)

Benchmark C: \(f_n/f_p=-0.7, \, \bar{\lambda}_s=0, \, \bar{\lambda}_\theta=0.1\)
Two Higgs doublets + Darkon Model

The Higgs sector is the THDM of type III
- Both Higgs doublets couple to the fermions.
- Neutral physical scalar Higgs fields $h$ & $H$

\[
\begin{pmatrix}
    h^0_1 \\
    h^0_2
\end{pmatrix} =
\begin{pmatrix}
    \cos \alpha & -\sin \alpha \\
    \sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
    H_1 \\
    h
\end{pmatrix}
\]

Darkon Lagrangian
\[
\mathcal{L}_D = \frac{1}{2} \partial^\mu D \partial_\mu D - \frac{1}{4} \lambda_D D^4 - \frac{1}{2} m_0^2 D^2 - \left[ \lambda_1 H_1^\dagger H_1 + \lambda_2 H_2^\dagger H_2 + \lambda_3 (H_1^\dagger H_2 + H_2^\dagger H_1) \right] D^2
\]

Darkon mass & darkon-Higgs couplings
\[
m_D^2 = m_0^2 + \left[ \lambda_1 \cos^2 \beta + \lambda_2 \sin^2 \beta + \lambda_3 \sin(2\beta) \right] v^2
\]
\[
\lambda_h = -\lambda_1 \sin \alpha \cos \beta + \lambda_2 \cos \alpha \sin \beta + \lambda_3 \cos(\alpha + \beta)
\]
\[
\lambda_H = \lambda_1 \cos \alpha \cos \beta + \lambda_2 \sin \alpha \sin \beta + \lambda_3 \sin(\alpha + \beta)
\]

Yukawa Lagrangian
\[
\mathcal{L}_Y = -\bar{Q}_{j,L} (\lambda^U_1)_{jl} \tilde{H}_1 U_{l,R} - \bar{Q}_{j,L} (\lambda^P_1)_{jl} H_1 D_{l,R} - \bar{Q}_{j,L} (\lambda^U_2)_{jl} \tilde{H}_2 U_{l,R} - \bar{Q}_{j,L} (\lambda^P_2)_{jl} H_2 D_{l,R}
\]
\[
- \bar{L}_{j,L} (\lambda^E_1)_{jl} H_1 E_{l,R} - \bar{L}_{j,L} (\lambda^E_2)_{jl} H_2 E_{l,R} + \text{H.c.}
\]
If H is the Higgs mediating DM interactions, whose couplings to up and down quarks are different and can lead to IVDM interaction. (the role of H and h can be switched)
The $h$ and $H$ couplings to $W$ and $Z$ may be relevant depending on $m_D$ and are given by

$$\mathcal{L}_{VVH} = \frac{1}{v}(2m_W^2 W^+ W^- + m_Z^2 Z^\mu Z^\mu) [h \sin(\beta - \alpha) + H \cos(\beta - \alpha)]$$

Inspired by the discovery of a 125-GeV SM-like Higgs at the LHC, we adopt

$$\cos(\beta - \alpha) = 0$$

Applying one of its solutions, $\beta - \alpha = \pi/2$, yields

$$k_u^h = k_d^h = k_e^h = 1$$

$$k_u^H = -\cot \beta + \frac{\lambda_1 u}{\sqrt{2} m_u \sin \beta}$$

$$k_d^H = \tan \beta - \frac{\lambda_2^d v}{\sqrt{2} m_d \cos \beta}$$

$$k_e^H = \tan \beta - \frac{\lambda_2^e v}{\sqrt{2} m_e \cos \beta}$$

$$\lambda_h = \lambda_1 \cos^2 \beta + \lambda_2 \sin^2 \beta + \lambda_3 \sin(2\beta)$$

$$\lambda_H = \frac{1}{2}(\lambda_1 - \lambda_2) \sin(2\beta) - \lambda_3 \cos(2\beta)$$

$$\mathcal{L}_{VVH} = (2m_W^2 W^+ W^- + m_Z^2 Z^\mu Z^\mu) \frac{h}{v}$$

Now the couplings of $h$ to SM fermions and gauge bosons are identical to those of SM Higgs.

$h$ is the SM like Higgs. If $\lambda_h = 0$ $h$ does not interacts with DM, no problem with invisible Higgs decay width. $H$ does the job for DM physics!
The observed relic density and $f_n = -0.7 f_p$ requirements lead to limitations on the predicted darkon-proton scattering cross-section.

We find that to enhance $\sigma_{\text{el}}^p$ by a few orders of magnitude under these restrictions implies that $k_{u,d}^H$ have to be big, $k_u^H \sim -2k_d^H$, and the other $k_f^H$ become negligible by comparison.

For example, with $m_H = 200$ (300) GeV we find $0.6 \ (1.4) \times 10^3 \leq \lambda_H k_u^H \leq 0.8 \ (1.8) \times 10^3$ corresponding to $5 \ \text{GeV} \leq m_D \leq 20 \ \text{GeV}$.

Thus in general $k_u^H = \mathcal{O}(10^3)$ if $\lambda_H = \mathcal{O}(1)$ and $m_H$ is a few hundred GeV.

For such large $k_{u,d}^H$, one expects that $k_u^H \sim \lambda_1^u v_1 / m_u$ and $k_d^H \sim \lambda_2^d v_2 / m_d$. Consequently, since $\lambda_1^u v_1 + \lambda_2^u v_2 = \sqrt{2} m_u$ and $\lambda_1^d v_1 + \lambda_2^d v_2 = \sqrt{2} m_d$, some degree of fine cancelations between the $\lambda_a^u d v_a$ terms is needed to reproduce the small $u$ and $d$ masses. This is the price one has to pay for the greatly amplified $\sigma_{\text{el}}^p$. 
IVDM: data & THDM+D
Conclusions

- Dark Matter exists, properties are not known completely.
- There are constraints from direct detections of DM. There are indications that DM has low mass of order 10 GeV, but excluded naively by Xenon experiments. One can reconcile the Xenon data with some of the low mass DM indications, via Isospin Violating DM.
- The properties of the Higgs boson discovered at the LHC can put stringent constraints on DM models.
- Possible to construct model to explain the low mass of DM indicated by the recent CDSMII and consistent with Xenon data, example: TypeIII 2HDM.