Dark matter models with (pseudo)scalar mediators

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Contents

• Higgs portal singlet fermion/vector DM models :
  - EFT vs. renormalizable, gauge invariant, unitary models
  - GC gamma ray excess, Collider Signatures

• Pseudoscalar portal DM models

Related talks by M. Kakizaki, Jinsu Kim, Toshinori Matsui on Gravitational waves, Higgs inflation
Comparison with the EFT approach

• SFDM scenario is ruled out in the EFT
• We may lose information in DM phenomenology.

Djouadi, et al. 2011

Higgs portal DM models

\[ \mathcal{L}_{\text{scalar}} = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4 \]

\[ \mathcal{L}_{\text{fermion}} = \bar{\psi} \left( i \gamma \cdot \partial - m_\psi \right) \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \bar{\psi} \psi \]

\[ \mathcal{L}_{\text{vector}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} \lambda_V (V_\mu V^\mu)^2 + \frac{1}{2} \lambda_{HV} H^\dagger H V_\mu V^\mu. \]

arXiv:1112.3299, … 1402.6287, etc.
Higgs portal DM models

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- Scalar CDM: looks OK, renorm... BUT ..... 
- Fermion CDM: nonrenormalizable 
- Vector CDM: looks OK, but it has a number of problems (in fact, it is not renormalizable)
Usual story within EFT

• Strong bounds from direct detection exp’s put stringent bounds on the Higgs coupling to the dark matters

• So, the invisible Higgs decay is suppressed

• There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored

• All these conclusions are not reproduced in the full theories (renormalizable) however
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

This simple model has not been studied properly!!
• Mixing and Eigenstates of Higgs-like bosons

\[ \mu_H^2 = \lambda_H v_H^2 + \mu_H s v_s + \frac{1}{2} \lambda_H s v_s^2, \]
\[ m_s^2 = -\frac{\mu_H^3}{v_s} - \mu_s v_s - \lambda_s v_s^2 - \frac{\mu_H s v_s^2}{2v_s} - \frac{1}{2} \lambda_H s v_s^2. \]

\[ M_{\text{Higgs}}^2 \equiv \begin{pmatrix} m_{hh}^2 & m_{hs}^2 \\ m_{hs}^2 & m_{ss}^2 \end{pmatrix} \equiv \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \]

\[ H_1 = h \cos \alpha - s \sin \alpha, \]
\[ H_2 = h \sin \alpha + s \cos \alpha. \]
Ratiocination

- Signal strength (reduction factor)

\[
\begin{align*}
  r_i &= \frac{\sigma_i \text{ Br}(H_i \rightarrow \text{SM})}{\sigma_h \text{ Br}(h \rightarrow \text{SM})} \\
  r_1 &= \frac{\cos^4 \alpha \, \Gamma_{H_1}^{\text{SM}}}{\cos^2 \alpha \, \Gamma_{H_1}^{\text{SM}} + \sin^2 \alpha \, \Gamma_{H_1}^{\text{hid}}} \\
  r_2 &= \frac{\sin^4 \alpha \, \Gamma_{H_2}^{\text{SM}}}{\sin^2 \alpha \, \Gamma_{H_2}^{\text{SM}} + \cos^2 \alpha \, \Gamma_{H_2}^{\text{hid}} + \Gamma_{H_2 \rightarrow H_1 H_1}}
\end{align*}
\]

\[0 < \alpha < \pi/2 \Rightarrow r_1(r_2) < 1\]

Invisible decay mode is not necessary!

If \( r_i > 1 \) for any single channel, this model will be excluded!!
Constraints

- Dark matter to nucleon cross section (constraint)

\[ \sigma_p \approx \frac{1}{\pi} \mu^2 \Lambda_p^2 \approx 2.7 \times 10^{-2} \frac{m_p^2}{\pi} \left( \frac{m_p}{v} \right) \lambda \sin \alpha \cos \alpha \left( \frac{1}{m_1^2} - \frac{1}{m_2^2} \right)^2 \]

Excluded!

destructive!

[Diagram showing the process of dark matter to nucleon interaction with specific values for mass and cross section constraints.]
• We don’t use the effective lagrangian approach (nonrenormalizable interactions), since we don’t know the mass scale related with the CDM

\[ \mathcal{L}_{\text{eff}} = \bar{\psi} \left( m_0 + \frac{H^\dagger H}{\Lambda} \right) \psi. \]

or \[ \lambda h \bar{\psi} \psi \]

- Only one Higgs boson \((\alpha = 0)\)

- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Breaks SM gauge sym
Low energy pheno.

- Universal suppression of collider SM signals
  [See 1112.1847, Seungwon Baek, P. Ko & WIP]
- If “$m_h > 2 m_\phi$”, non-SM Higgs decay!
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)
  
  $$\lambda_{PH} \Rightarrow \lambda_H = \left[ 1 + \left( \frac{m_\phi^2}{m_h^2} - 1 \right) \sin^2 \alpha \right] \lambda_{H}^{SM}$$

  If “$m_\phi > m_h$”, vacuum instability can be cured.
Vacuum Stability Improved by the singlet scalar $S$

A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)
Similar for Higgs portal Vector DM

\[ \mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4} (V_\mu V^\mu)^2 \]

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- A complete model should be something like this:
There appear a new singlet scalar $h_X$ from $\phi_X$, which mixes with the SM Higgs boson through Higgs portal.

The effects must be similar to the singlet scalar in the fermion CDM model, and generically true in the DM with dark gauge sym.

Important to consider a minimal renormalizable and unitary model to discuss physics correctly [Baek, Ko, Park and Senaha, arXiv: 1212.2131 (JHEP)].

Can accommodate GeV scale gamma ray excess from GC.
Figure 6. The scattered plot of $\sigma_p$ as a function of $M_X$. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 $\sigma$, while the red-(black-)colored points gives $r_1 > 0.7$($r_1 < 0.7$). The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity of the next XENON experiment, XENON1T.

Figure 8. The vacuum stability and perturbativity constraints in the $\alpha$-$m_2$ plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\phi = M_X/(g_X Q_\phi)$.

New scalar improves EW vacuum stability
Higgs portal DM as examples

\[
L_{\text{scalar}} = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4
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\[
L_{\text{fermion}} = \bar{\psi} [i \gamma \cdot \partial - m_\psi] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \bar{\psi} \psi
\]

\[
L_{\text{vector}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} \lambda_V (V_\mu V^\mu)^2 + \frac{1}{2} \lambda_{HV} H^\dagger H V_\mu V^\mu.
\]

arXiv:1112.3299, ... 1402.6287, etc.
Is this any useful in phenomenology?

YES!
Fermi-LAT $\gamma$-ray excess

- Gamma-ray excess in the direction of GC

$\GC : \ b \sim l \lesssim 0.1^\circ$

[1402.6703, T. Daylan et.al.]
• A DM interpretation

\[ DM + DM \rightarrow bb \text{ with } \sigma v = 1.7 \times 10^{-26} \text{ cm}^3/\text{s} \]

\[ m_{DM} = 35.25 \text{ GeV} \]

* See “1402.6703, T. Daylan et.al.” for other possible channels

• Millisecond Pulsars (astrophysical alternative)

It may or may not be the main source, depending on
- luminosity func.
- bulge population
- distribution of bulge population

* See “1404.2318, Q. Yuan & B. Zhang” and “1407.5625, I. Cholis, D. Hooper & T. Linden”
The observed GeV scale $\gamma$-ray spectrum may be explained if DM annihilates mainly into $b\bar{b}$ with a velocity-averaged annihilation cross section close to the canonical value of thermal relic dark matter. This implies that $30 \text{ GeV} \lesssim m_{V} \lesssim 40 \text{ GeV}$ in case of the $s$-channel annihilation (Fig. 2) scenario. It is also possible to produce $b\bar{b}$ with the nearly same energy from the decay of highly non-relativistic $\phi$ which is produced from the annihilation of DM having mass of $60 \text{ GeV} \lesssim m_{V} \lesssim 80 \text{ GeV}$ (Fig. 3). In both cases, it is expected to have $\tau\bar{\tau}$ and $c\bar{c}$ productions too in the final states, because $H_1$ will decay into them with branching ratios about 7% and 3%.

In the process of Fig. 2, the thermal-averaged annihilation cross section of VDM is given by

$$\langle \sigma v_{\text{rel}} \rangle_f\bar{f} = \frac{\sum f \left( \frac{g_X}{s_\alpha c_\alpha} \right)^2}{3\pi m_X^2 |\sum i \left( -m_i^2 + i m_i \Gamma_i \right) |^2} \left( \frac{m_f v_{\text{H}}}{1 - 4 m_f^2 v_{\text{H}}^2} \right)^3/2$$

(3.11)

where $m_f$ is the mass of a SM fermion $f$. Note that Eq. (3.11) is suppressed by a factor $s_\alpha^2 m_f^2$.

Hence a large enough annihilation cross section for the right amount to relic density can be achieved only around the resonance region. However in the resonance region the annihilation cross section varies a lot, as the Mandelstam $s$-variable varies from the value at freeze-out to the value in a dark matter halo at present. Therefore, this process can not be used for the GeV scale $\gamma$-ray spectrum from the galactic center.

On the other hand, in the process of Fig. 3 for $m_{\phi} < m_V \lesssim 80 \text{ GeV}$, the thermal-averaged annihilation cross section of VDM is given by

$$\langle \sigma v_{\text{rel}} \rangle_{\text{tot}} = \langle \sigma v_{\text{rel}} \rangle_f\bar{f} + \langle \sigma v_{\text{rel}} \rangle_{\phi\phi}$$

(3.12)
Importance of VDM with Dark Higgs Boson

This mass range of VDM would have been impossible in the VDM model (EFT)

And No 2nd neutral scalar (Dark Higgs) in EFT
FIG. 3: The regions inside solid(black), dashed(blue) and long-dashed(red) contours correspond to $1\sigma$, $2\sigma$ and $3\sigma$, respectively. The red dots inside $1\sigma$ contours are the best-fit points. In the left panel, we vary freely $M_X$, $M_{H_2}$ and $\langle \sigma v \rangle$. While in the right panel, we fix the mass of $H_2$, $M_{H_2} \simeq M_X$. 
FIG. 2: Three illustrative cases for gamma-ray spectra in contrast with CCW data points [11]. All masses are in GeV unit and $\sigma v$ with cm$^3$/s. Line shape around $E \approx M_{H_2}/2$ is due to decay modes, $H_2 \rightarrow \gamma \gamma; Z\gamma$.  

$E^2dN/dE$ (GeV $cm^2$ str s$^{-1}$) vs $E$ (GeV)

As we can see, different parameter sets can give different spectrum shape, especially in the high energy regime. When the branching ratios of $H_2 \rightarrow \gamma \gamma; Z\gamma$ are increasing, we can see the gamma lines more easily around $E \approx M_{H_2}/2$. Since the annihilation cross section is at order of $10^{-26}$ cm$^3$/s and the branching ratios of $H_2 \rightarrow \gamma \gamma; Z\gamma$ are around 0.2% at most, the considered parameters are still consistent with constraint from gamma-line searches.

We now use the 2 function and find its minimum to find out the best fit:

$$\chi^2(M_X, M_{H_2}, h) = \sum_{i,j} (\mu_i f_i) \nabla_{1ij} (\mu_j f_j), (3.2)$$

where $\mu_i$ and $f_i$ are the predicted and measured fluxes in the $i$-th energy bin respectively, and $\nabla$ is the 24 $\times$ 24 covariance matrix. We take the numerical values for $f_i$ and $\nabla$ from CCW [11]. Minimizing the $\chi^2$ against $f_i$ with respect to $M_X$, $M_{H_2}$ and $h$ gives the best-fit points, and then two-dimensional 1, 2, 3 contours are defined at $\chi^2_{min}=2$.

Fig. 3 is our main result. In the left panel, $M_X$, $M_{H_2}$ and $h$ are freely varied, so that the total degree of freedom (d.o.f.) is 21. The red dot represents the best-fit point with $M_X'=95.0$ GeV, $M_{H_2}=86.7$ GeV, $h'v=4.0 \times 10^{-26}$ cm$^3$/s, (3.3) gives $\chi^2_{min}=22.0$, with the corresponding p-value equal to 0.40. We also notice that there are two separate regimes, one in the low mass region and the other in high mass region. The higher mass region is basically aligned with $M_{H_2} \approx M_X$ since otherwise a highly-boosted $H_2$ would give a harder gamma-ray spectrum. In this region, $\sigma v=1.0 \times 10^{-26}$.
This would have never been possible within the DM EFT

<table>
<thead>
<tr>
<th>Channels</th>
<th>Best-fit parameters</th>
<th>$\chi^2_{\text{min}}$/d.o.f.</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$XX \rightarrow H_2H_2$</td>
<td>$M_X \simeq 95.0\text{GeV}$, $M_{H_2} \simeq 86.7\text{GeV}$ \quad $\langle \sigma v \rangle \simeq 4.0 \times 10^{-26}\text{cm}^3/\text{s}$</td>
<td>22.0/21</td>
<td>0.40</td>
</tr>
<tr>
<td>(with $M_{H_2} \neq M_X$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$XX \rightarrow H_2H_2$</td>
<td>$M_X \simeq 97.1\text{GeV}$ \quad $\langle \sigma v \rangle \simeq 4.2 \times 10^{-26}\text{cm}^3/\text{s}$</td>
<td>22.5/22</td>
<td>0.43</td>
</tr>
<tr>
<td>(with $M_{H_2} = M_X$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$XX \rightarrow H_1H_1$</td>
<td>$M_X \simeq 125\text{GeV}$ \quad $\langle \sigma v \rangle \simeq 5.5 \times 10^{-26}\text{cm}^3/\text{s}$</td>
<td>24.8/22</td>
<td>0.30</td>
</tr>
<tr>
<td>(with $M_{H_1} = 125\text{GeV}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$XX \rightarrow b\bar{b}$</td>
<td>$M_X \simeq 49.4\text{GeV}$ \quad $\langle \sigma v \rangle \simeq 1.75 \times 10^{-26}\text{cm}^3/\text{s}$</td>
<td>24.4/22</td>
<td>0.34</td>
</tr>
</tbody>
</table>

TABLE I: Summary table for the best fits with three different assumptions.
Collider Implications

$m_h = 125\text{GeV}$, $\text{Br}(H \rightarrow \text{inv}) < 0.51$ at 90\% CL

Based on EFTs

$m_h = 125.5\text{GeV}$, $\text{Br}(H \rightarrow \text{inv}) < 0.52$ at 90\% CL
• However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

\[ \mathcal{L}_{\text{SFDM}} = \bar{\psi} (i\partial - m_\psi - \lambda_\psi S) - \mu_H S H^+ H - \frac{\lambda_{HS}}{2} S^2 H^+ H + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_3^2 S^2 - \mu_3 S^3 - \frac{\mu_5}{3} S^3 - \frac{\lambda_5}{4} S^4. \]

\[ \mathcal{L}_{\text{VDM}} = -\frac{1}{4} V_{\mu\nu} V_{\mu\nu} + D_\mu \Phi^+ D^\mu \Phi - \lambda_\Phi \left( \Phi^+ \Phi - \frac{v_3^2}{2} \right)^2 - \lambda_{\Phi H} \left( \Phi^+ \Phi - \frac{v_3^2}{2} \right) \left( H^+ H - \frac{v_2^2}{2} \right). \]
• However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

$$\mathcal{L}_{\text{SFDM}} = \bar{\psi} (i\partial - m_\psi - \lambda_\psi S) - \mu_H S H^+ H - \frac{\lambda_H}{2} S^2 H^+ H$$

$$+ \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

$$\mathcal{L}_{\text{VDM}} = \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^+ D^\mu \Phi - \lambda_\Phi \left( \Phi^+ \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_H \left( \Phi^+ \Phi - \frac{v_\Phi^2}{2} \right) \left( H^+ H - \frac{v_H^2}{2} \right)$$

Interpretation of collider data is quite model-dependent in Higgs portal DMs and in general
Invisible H decay into a pair of VDM


\[
\begin{align*}
(\Gamma_{h}^{\text{inv}})_{\text{EFT}} &= \frac{\lambda_{VH}^2 v_H^2 m_h^3}{128\pi m_V^4} \times \\
& \quad \left(1 - \frac{4m_V^2}{m_h^2} + 12 \frac{m_V^4}{m_i^4} \right) \left(1 - \frac{4m_V^2}{m_h^2} \right)^{1/2} \\
\Gamma_{i}^{\text{inv}} &= \frac{g_X^2}{32\pi} \frac{m_i^3}{m_V^2} \left(1 - \frac{4m_V^2}{m_i^2} + 12 \frac{m_V^4}{m_i^4} \right) \left(1 - \frac{4m_V^2}{m_i^2} \right)^{1/2} \sin^2 \alpha
\end{align*}
\]

Invisible H decay width : finite for small mV in unitary/renormalizable model
DD vs. Monojet : Why complementarity breaks down in EFT ?

- S. Baek, P. Ko, M. Park, WIPark, C.Yu, arXiv:1506.06556
Why is it broken down in DM EFT?

The most nontrivial example is the \((\text{scalar}) \times (\text{scalar})\) operator for DM-N scattering:

\[
\mathcal{L}_{SS} \equiv \frac{1}{\Lambda_{dd}^2} \bar{q}q\bar{\chi}\chi \quad \text{or} \quad \frac{m_q}{\Lambda_{dd}^3} \bar{q}q\bar{\chi}\chi
\]

This operator clearly violates the SM gauge symmetry, and we have to fix this problem.
Crossing & WIMP detection

Correct relic density $\rightarrow$ Efficient annihilation then

Efficient annihilation now
(Indirect detection)

Efficient scattering now
(Direct detection)

Efficient production now
(Particle colliders)
Crossing & WIMP detection

Correct relic density $\rightarrow$ Efficient annihilation then

However, this crossing relation could lead to incorrect physics quite often!
Better to be careful, and work in more complete models for ID or CS.

Efficient scattering now
(Direct detection)
### Effective operators: LHC & direct detection

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$\bar{\chi}\chi\bar{q}q$</td>
<td>$m_q/M^3_*$</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{\chi}\gamma^5\chi\bar{q}q$</td>
<td>$i m_q/M^3_*$</td>
</tr>
<tr>
<td>D3</td>
<td>$\bar{\chi}\chi\bar{q}\gamma^5 q$</td>
<td>$i m_q/M^3_*$</td>
</tr>
<tr>
<td>D4</td>
<td>$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$</td>
<td>$m_q/M^3_*$</td>
</tr>
<tr>
<td>D5</td>
<td>$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$</td>
<td>$1/M^2_*$</td>
</tr>
<tr>
<td>D6</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$</td>
<td>$1/M^2_*$</td>
</tr>
<tr>
<td>D7</td>
<td>$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$</td>
<td>$1/M^2_*$</td>
</tr>
<tr>
<td>D8</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$</td>
<td>$1/M^2_*$</td>
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<tr>
<td>D9</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$</td>
<td>$1/M^2_*$</td>
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<tr>
<td>D10</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$</td>
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<tr>
<td>D11</td>
<td>$\bar{\chi}\chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\alpha_s/4 M^3_*$</td>
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<td>D12</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$i\alpha_s/4 M^3_*$</td>
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<td>D13</td>
<td>$\bar{\chi}\chi G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>$i\alpha_s/4 M^3_*$</td>
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<td>D14</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>$\alpha_s/4 M^3_*$</td>
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</tr>
<tr>
<td>C2</td>
<td>$\chi\dagger\chi\bar{q}\gamma^5 q$</td>
<td>$i m_q/M^2_*$</td>
</tr>
<tr>
<td>C3</td>
<td>$\chi\dagger\partial_{\mu}\chi\bar{q}\gamma^\mu q$</td>
<td>$1/M^2_*$</td>
</tr>
<tr>
<td>C4</td>
<td>$\chi\dagger\partial_{\mu}\chi\bar{q}\gamma^\mu\gamma^5 q$</td>
<td>$1/M^2_*$</td>
</tr>
<tr>
<td>C5</td>
<td>$\chi\dagger\chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\alpha_s/4 M^2_*$</td>
</tr>
<tr>
<td>C6</td>
<td>$\chi\dagger\chi G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>$i\alpha_s/4 M^2_*$</td>
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<tr>
<td>R1</td>
<td>$\chi^2\bar{q}q$</td>
<td>$m_q/2 M^2_*$</td>
</tr>
<tr>
<td>R2</td>
<td>$\chi^2\bar{q}\gamma^5 q$</td>
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</tr>
<tr>
<td>R3</td>
<td>$\chi^2 G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\alpha_s/8 M^2_*$</td>
</tr>
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<td>R4</td>
<td>$\chi^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>$i\alpha_s/8 M^2_*$</td>
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</tbody>
</table>

Table of effective operators relevant for the collider/direct detection connection

*Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2010*
Effective operators: LHC & direct detection

LHC limits on WIMP-quark and WIMP-gluon interactions are competitive with direct searches

Beltran et al, Agrawal et al., Goodman et al., Bai et al., 2010; Goodman et al., Rajaraman et al. Fox et al., 2011; Cheung et al., Fitzpatrick et al., March-Russel et al., Fox et al., 2012......

These bounds do not apply to SUSY, etc.

Complete theories contain sums of operators (interference) and not-so-heavy mediators (Higgs)

From Paolo Gondolo’s talk
Limitation and Proposal

• EFT is good for direct detection, but not for indirect or collider searches as well as thermal relic density calculations in general.

• Issues: Violation of Unitarity and SM gauge invariance, Identifying the relevant dynamical fields at energy scale we are interested in, Symmetry stabilizing DM etc.
Usually effective operator is replaced by a single propagator in simplified DM models

This is not good enough, since we have to respect the full SM gauge symmetry (Bell et al for $W^+\text{missing } ET$)

In general we need two propagators, not one propagator, because there are two independent chiral fermions in 4-dim spacetime

$$\frac{1}{\Lambda^2_i} \bar{q} \Gamma_i q \bar{\chi} \Gamma_i \chi \rightarrow \frac{g_q g_\chi}{m^2_\phi - s} \bar{q} \Gamma_i q \bar{\chi} \Gamma_i \chi$$
Our Model: a ‘simplified model’ of colored $t$-channel, spin-0, mediators which produce various mono-$x + missing$ energy signatures (mono-Jet, mono-$W$, mono-$Z$, etc.):

W+missing ET : special
\[
\frac{1}{\Lambda_i^2} \bar{q} \Gamma_i q \bar{\chi} \Gamma_i \chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s} \bar{q} \Gamma_i q \bar{\chi} \Gamma_i \chi
\]

- This is good only for W+missing ET, and not for other singatures
- The same is also true for (scalar)x(scalar) operator, and lots of confusion on this operator in literature
- Therefore let me concentrate on this case in detail in this talk
\(\overline{Q}_L H d_R\) or \(\overline{Q}_L \tilde{H} u_R\), \(\text{OK}\)

\[ h\bar{\chi}\chi, \quad s\bar{q}q \]

Both break SM gauge

\[
\mathcal{L} = \frac{1}{2} m_s^2 S^2 - \lambda_{s\chi} s\bar{\chi}\chi - \lambda_{sq} s\bar{q}q \\
\mathcal{L} = -\lambda_{h\chi} h\bar{\chi}\chi - \lambda_{hq} h\bar{q}q
\]

Therefore these Lagragians are not good enough

\[ s\bar{\chi}\chi \times h\bar{q}q \rightarrow \frac{1}{m_s^2} \bar{\chi}\chi\bar{q}q \]

Need the mixing between \(s\) and \(h\)
\[
\chi(p) + q(k) \rightarrow \chi(p') + q(k')
\]

\[
\mathcal{M} = \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{v} \lambda_s \sin \alpha \cos \alpha \left[ \frac{1}{t - m_{125}^2 + im_{125} \Gamma_{125}} - \frac{1}{t - m_2^2 + im_2 \Gamma_2} \right] \\
\rightarrow \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{2v} \lambda_s \sin 2\alpha \left[ \frac{1}{m_{125}^2} - \frac{1}{m_2^2} \right] \\
\rightarrow \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{2v} \lambda_s \sin 2\alpha \frac{1}{m_{125}^2} \equiv \frac{m_q}{\Lambda_{dd}^3} \overline{u(p')}u(p)\overline{u(q')}u(q)
\]

\[
\Lambda_{dd}^3 = \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha} \left( 1 - \frac{m_{125}^2}{m_2^2} \right)^{-1}
\]

\[
\tilde{\Lambda}_{dd}^3 = \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha}
\]
Monojet+missing ET

Can be obtained by crossing : $s \leftrightarrow t$

$$\frac{1}{\Lambda^3_{dd}} \rightarrow \frac{1}{\Lambda^3_{dd}} \left[ \frac{m^2_{125}}{s - m^2_{125} + im_{125}\Gamma_{125}} - \frac{m^2_{125}}{s - m^2_{2} + im_{2}\Gamma_{2}} \right] \equiv \frac{1}{\Lambda^3_{col}(s)}$$

There is no single scale you can define for collider search for missing ET
Figure 1: The dominant DM production processes at LHC.

Interference between 2 scalar bosons could be important in certain parameter regions

\[
\left. \frac{d\sigma_i}{dm_{\chi\chi}} \right|_m \propto \left| \frac{\sin 2\alpha \, g_\chi}{m_{\chi\chi}^2 - m_{H_1}^2 + i m_{H_1} \Gamma_{H_1}} - \frac{\sin 2\alpha \, g_\chi}{m_{\chi\chi}^2 - m_{H_2}^2 + i m_{H_2} \Gamma_{H_2}} \right|^2
\]

\[
\text{sin } \alpha = 0.2, g_\chi = 1, m_\chi = 80 \text{GeV}
\]
Interference effects

**Figure 2:** The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.
Parton level distrib.

Figure 3: The parton level distributions of $m_{\chi\chi}$ for gluon-gluon fusion process at 13 TeV LHC.
Exclusion limits with interference effects

Figure 8: The CMS exclusion limits on our simplified models. Left: upper limit from mono-jet search. Right: upper limit from mono-V search.

- P. Ko and Jinmian Li, 1610.03997, PLB (2017)
- S. Baek, P. Ko and Jinmian Li, 1701.04131
FIG. 1: In ATLAS 8TeV mono-jet+$\not{E}_T$ search [6] we plot $M_{\chi\chi}$ and the $P_T$ of a hardest jet in a reconstruction level (after a detector simulation). Upper panels are with $m_\chi = 50$ GeV and lower panels are of $m_\chi = 400$ GeV.
- EFT: Effective operator \( \mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}} \bar{q} q \tilde{\chi} \chi \)

- S.M.: Simple scalar mediator \( S \) of
  \( \mathcal{L}_{int} = \left( \frac{m_q}{v_H} \sin \alpha \right) S \bar{q} q - \lambda_s \cos \alpha S \tilde{\chi} \chi \)

- H.M.: A case where a Higgs is a mediator
  \( \mathcal{L}_{int} = - \left( \frac{m_q}{v_H} \cos \alpha \right) H \bar{q} q - \lambda_s \sin \alpha H \tilde{\chi} \chi \)

- H.P.: Higgs portal model as in eq. (2).

FIG. 1: We follow ATLAS 8TeV mono-jet+\( E_T \) searches [2]. For (a) we simulated various models for the
direct detection, while H.P. case, it is a mixing angle
In S.M. and H.M. cases, we can regard
tors, we consider following four cases between a standard
operator for the direct detection,

The 1

The applied cuts are as follows:

Finally let us discuss the indirect detection signatures
-\( \Lambda_{dd} \)

\( E_{\text{ann}}^{H,M} = \Lambda_{dd} \)

\( m_\chi \) has nothing to do with the scale in the e
\( H \to \gamma \gamma \) is a \( gg \) or a \( H \to h \gamma \) signal

\( M_{\ast} \) in the e
effective operator case.

\( \text{EFT} : E \equiv \frac{1}{\sqrt{2}} (\bar{q} q + H \bar{q} q) \)

\( \text{S.M.} \)

\( \text{H.M.} \)

\( \text{H.P.} \)

\( H \to (\bar{q} q + H \bar{q} q) \)

G(\bar{q} q + H \bar{q} q) \)

\( \text{EFT} \)

\( \text{S.M.} \)

\( \text{H.M.} \)

\( \text{H.P.} \)

\( \text{EFT} \)

\( \text{S.M.} \)

\( \text{H.M.} \)

\( \text{H.P.} \)

\( \text{EFT} \)

\( \text{S.M.} \)

\( \text{H.M.} \)

\( \text{H.P.} \)

\( \text{EFT} \)

\( \text{S.M.} \)

\( \text{H.M.} \)

\( \text{H.P.} \)
FIG. 1: We follow ATLAS 8TeV mono-jet + missing ET searches [2]. For (a) we simulated various models for the $\sqrt{s}$ distribution / $E_T$ distribution / $E_T$ [GeV]

\begin{align*}
\sqrt{s} \text{ distribution} & \\
\text{unit normalized} & \\
0 & 1000 & 2000 & 3000 & 4000 & \text{unit normalized} \\
\sqrt{s} \text{ [GeV]} & 
\end{align*}

\begin{align*}
E_T \text{ distribution} & \\
\text{unit normalized} & \\
0 & 200 & 400 & 600 & 800 & 1000 & \text{unit normalized} \\
E_T \text{ [GeV]} & 
\end{align*}

FIG. 2: Parton level distributions of various variables in a ($t\bar{t}\chi\bar{\chi}$) channel for a dark matter’s mass $m_\chi = 10$ GeV (above) and $m_\chi = 100$ GeV (below) for LHC 8TeV. As we can see here, due to a higgs propagator, even when $m_2 \to \infty$ case, a missing transverse energy $E_T$ of a higgs portal model shall be different from an effective operator operator case.
FIG. 4: With CMS 8TeV $t\bar{t} + \not{E}_T$ search [6], we plot $M_{\chi\chi}$ and the $\not{E}_T$ in a reconstruction level. Upper panels are with $M_\chi = 50$ GeV and lower panels are of $M_\chi = 400$ GeV.
• EFT: Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}} \bar{q}q \bar{\chi}\chi$

• S.M.: Simple scalar mediator $S$ of
$\mathcal{L}_{int} = \left( \frac{m_q}{v_H} \sin\alpha \right) S \bar{q}q - \lambda_S \cos\alpha S \bar{\chi}\chi$

• H.M.: A case where a Higgs is a mediator
$\mathcal{L}_{int} = -\left( \frac{m_q}{v_H} \cos\alpha \right) H \bar{q}q - \lambda_S \sin\alpha H \bar{\chi}\chi$

• H.P.: Higgs portal model as in eq. (2).

\[
\begin{align*}
\text{H.P.} & \quad \rightarrow \quad \text{H.M.}, \quad m_{H_2}^2 \gg \hat{s} \\
\text{S.M.} & \quad \rightarrow \quad \text{EFT}, \quad m_S^2 \gg \hat{s} \\
\text{H.M.} & \neq \text{EFT}.
\end{align*}
\]

**FIG. 2:** Rescaled cross sections for the monojet+$p_T$ in the signal region SR7 ($E_T > 500$ GeV) at ATLAS [11]. Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The solid and dashed lines correspond to $m_\chi = 50$ GeV and 400 GeV in each model, respectively.
• EFT: Effective operator \( \mathcal{L}_{\text{int}} = \frac{m_q}{\Lambda_{dd}^2} \bar{q}q \bar{\chi} \chi \)

• S.M.: Simple scalar mediator \( S \) of \( \mathcal{L}_{\text{int}} = (\frac{m_q}{v_H} \sin \alpha) S \bar{q}q - \lambda_s \cos \alpha S \bar{\chi} \chi \)

• H.M.: A case where a Higgs is a mediator \( \mathcal{L}_{\text{int}} = -(\frac{m_q}{v_H} \cos \alpha) H \bar{q}q - \lambda_s \sin \alpha H \bar{\chi} \chi \)

• H.P.: Higgs portal model as in eq. (2).

H.P. \( \rightarrow \) H.M., \( m_H^2 \gg \hat{s} \)

S.M. \( \rightarrow \) EFT, \( m_S^2 \gg \hat{s} \)

H.M. \( \neq \) EFT.

![Graph](image)

**FIG. 3:** The experimental bounds on \( M_s \) at 90% C.L. as a function of \( m_{H_2} \) (\( m_S \) in S.M. case) in the monojet+\( E_T \) search (upper) and \( t\bar{t} + \not{E}_T \) search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of S.M., H.M., and H.P., are expressed in terms of the effective mass \( M_s \) through the Eq.(16)-(20). The solid and dashed lines correspond to \( m_\chi = 50 \text{ GeV} \) and 400 GeV in each model, respectively.
A General Comment

assume: \(2m_\chi \ll m_{125} \ll m_2 \ll \sqrt{s}\)

\[
\sigma(\sqrt{s}) = \int_0^1 d\tau \sum_{a,b} \frac{dL_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s)
\]

\[
= \left[ \int_0^{m_{125}^2/s} d\tau + \int_{m_{125}^2/s}^{m_2^2/s} d\tau + \int_{m_2^2/s}^1 d\tau \right] \sum_{a,b} \frac{dL_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s)
\]

For each integration region for tau, we have to use different EFT

No single EFT applicable to the entire tau regions
Indirect Detection

• Again, no definite correlations between two scales in DD and ID

• Also one has to include other channels depending on the DM mass
Pseudoscalar portal DM

(S. Baek, P. Ko, Jinmian Li, arXiv:1701.04131)

\[ \frac{1}{\Lambda^2} \overline{f} f \bar{\chi} \gamma_5 \chi \]

- Highly suppressed for SI/SD x-section
- DM pair annihilation in the S-wave

Its simplest UV completion:
(different from 2HDM portal)

\[
L = \bar{\chi} (i \partial \cdot \gamma - m_\chi - ig_\chi a \gamma^5) \chi + \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 \\
- (\mu_a a + \lambda_H a^2) \left( H^\dagger H - \frac{v_h^2}{2} \right) - \frac{\mu'_a}{3!} a^3 - \frac{\lambda_a}{4!} a^4 \\
- \lambda_H \left( H^\dagger H - \frac{v_h^2}{2} \right)^2 . \tag{1}
\]

see also Karim Ghorbani, arXiv:1408.4929 [hep-ph]
Interaction Lagrangians

\[ \mathcal{L}_{\text{int}} = -ig_\chi (H_0 \sin \alpha + A \cos \alpha) \bar{\chi}\gamma^5 \chi - (H_0 \cos \alpha - A \sin \alpha) \]
\times \left[ \sum_f \frac{m_f}{v_h} \bar{f}f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right] \quad (7) \]

For comparison, let us define 2 other cases

\[ \mathcal{L}_{\text{int}}^{\text{SS}} = -g_\chi (H_1 \sin \alpha + H_2 \cos \alpha) \bar{\chi}\chi - (H_1 \cos \alpha - H_2 \sin \alpha) \]
\times \left[ \sum_f \frac{m_f}{v_h} \bar{f}f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right] \quad (12) \]

(Higgs portal)

\[ \mathcal{L}_{\text{int}}^{\text{AA}} = -ig_\chi (a \sin \alpha + A \cos \alpha) \bar{\chi}\gamma^5 \chi\]
\quad - i(a \cos \alpha - A \sin \alpha) \sum_f \frac{m_f}{v_h} \bar{f}\gamma^5 f \quad (13) \]

(2HDM+a portal)
FIG. 1. Relic density with varying DM mass, for \( m_A = 400 \) GeV, \( g_X = 1 \) and \( \alpha = 0.3 \). Color code indicates the value of \( \lambda_{H_a} \).

FIG. 2. The cross sections for different DM annihilation (at rest) channels. The dashed black curve correspond to the 95% CL exclusion limit on \( b\bar{b} \) channel obtained from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi-LAT Data [55].
Collider Searches

FIG. 5. The 95% CL exclusion limits from the ATLAS mono-jet search at 13 TeV with integrated luminosity of 3.2 fb$^{-1}$. The dashed curves correspond to models with ten times larger total width of $A$ than $\Gamma_{\text{min}}$ due to the opening of new decay channels.

FIG. 6. Bounds correspond to the LHC searches for two vector boson resonance. The production cross sections of $ZZ$ ($WW$) at 13 TeV in our model are shown by red (blue) points.

FIG. 7. Bounds correspond to the LHC searches for light boson pair from the SM Higgs decay. The shaded region is excluded by the Higgs precision measurement. Our models are shown by dark green points.

FIG. 8. Bounds correspond to the LHC di-Higgs searches in different final states. The production cross section of our models at 13 TeV are shown by dark green points.
Conclusion

• Renormalizable and unitary model (with some caveat) is important for DM phenomenology (EFT can fail completely)

• Imposing the full SM gauge symmetry is crucial for collider searches for DM

• Usually two propagators necessary for UV completion of the effective operators >> Important interference effects to be included in the data analysis
Conclusion

• Renormalizable and unitary model (with some caveat) is important for DM phenomenology (EFT can fail completely)

• Hidden sector DM with Dark Gauge Sym is well motivated, can guarantee DM stability/longevity, solves some puzzles in CDM paradigm, open a new window in DM models including DM-DR interaction

• Especially a wider region of DM mass is allowed due to new open channels
• DM Dynamics dictated by local gauge symmetry

• Non Standard Higgs decays into a pair of DM, light dark Higgs bosons, or dark gauge bosons, etc.

• Additional singlet-like scalar “S” (Dark Higgs) : generic, can play important roles in DM phenomenology, improves EW vac stability, helps Higgs inflation with larger tensor/scalar ratio (also strong 1st order ph tr. in the dark sector, GW, etc. ?) >> Should be actively searched for

• Searches @ LHC & other future colliders