Dark matter, Flavor, and LHC physics in DM models with bottom partner

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Based on 1601.07396 with J. Kawamura (Waseda) and 1612.01643 with J.Kawamura, T. Abe and S. Okawa (Nagoya)
Introduction
WIMP dark matter scenario is very interesting, because DM can be related to TeV-scale new physics, which could be discovered near future.
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There are many possibilities of setups and many motivations.
But almost all experimental results are consistent with the SM predictions.

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There are many possibilities for the BSMs, but BSM may be very SM-like at TeV scale.

“Let’s consider possible and simple setups with DM, that do not break the SM predictions so much.”

In particular, we discuss “Fermion portal DM”.

( with J.Kawamura, T. Abe and S. Okawa )
Interaction between SM particle ($f_i$) and DM ($X$) in Fermion Portal Dark Matter Model

(Bai, Berger. 1308.0612; Wise, Perez 1303.1452; etc.)

\[ \lambda_j f_i \overline{f}_j X^\dagger \] flavor-dependent

Extra particle with SM charges and dark charge
Interesting and good points of this model

\[ \lambda_b \overline{F_L} \overline{X} X^\dagger b_R + \lambda_s \overline{F_L} \overline{X} X^\dagger s_R + \lambda_d \overline{F_L} \overline{X} X^\dagger d_R + h.c. \]

I. simple!
Interesting and good points of this model

\[ \lambda_b \overline{F}_L X^\dagger b_R + \lambda_s \overline{F}_L X^\dagger s_R + \lambda_d \overline{F}_L X^\dagger d_R + h.c. \]

2. No tree-level FCNCs
Interesting and good points of this model

\[ \lambda_b \overline{F_L} X^\dagger b_R + \lambda_s \overline{F_L} X^\dagger s_R + \lambda_d \overline{F_L} X^\dagger d_R + h.c. \]

2. No tree-level FCNCs

3. safe for EWPOs because F is vector-like
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2. No tree-level FCNCs

3. safe for EWPOs because F is vector-like

4. There are candidates for the underlying theory:

flavor symmetric model (E. Ma, 1311.3213; Okawa, YO, work in progress)

GUT (P. Ko, C. Yu, YO, 1601.00586)
Interesting and good points of this model

\[ \lambda_b \overline{F_L} X^\dagger b_R + \lambda_s \overline{F_L} X^\dagger s_R + \lambda_d \overline{F_L} X^\dagger d_R + h.c. \]

5. Many observables relate each other!

Dark Matter Physics
**Interesting and good points of this model**

\[
\lambda_b \overline{F_L X}^\dagger b_R + \lambda_s \overline{F_L X}^\dagger s_R + \lambda_d \overline{F_L X}^\dagger d_R + \text{h.c.}
\]

5. many observables relate each other!
Interesting and good points of this model

$$\lambda_b \overline{F}_L X^\dagger b_R + \lambda_s \overline{F}_L X^\dagger s_R + \lambda_d \overline{F}_L X^\dagger d_R + h.c.$$  

5. many observables relate each other!

LHC Physics
We can find correlations!

\[ \lambda_b \overline{F}_L X^\dagger b_R + \lambda_s \overline{F}_L X^\dagger s_R + \lambda_d \overline{F}_L X^\dagger d_R + h.c. \]
Recently, DM constraints getting very strong!

Indirect detection

\[ \langle \sigma v \rangle \text{ [cm}^3/\text{s}] \]

$\langle \sigma v \rangle \sim 10^{-27}$ cm$^3$/s

$3 \cdot 10^{-29}$ cm$^3$/s

Direct detection

WIMP–nucleon cross section [zd]

We consider complex scalar DM and fermionic F, which mainly couples to bottom quark.

(1612.01643 with J.Kawamura, T.Abe, S. Okawa, YO)
SETUP
a simple DM model with a down-type partner

**Extra down-type quark and DM**

<table>
<thead>
<tr>
<th>Fields</th>
<th>spin</th>
<th>SU(3)$_c$</th>
<th>SU(2)$_L$</th>
<th>U(1)$_Y$</th>
<th>U(1)$_X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_L$</td>
<td>1/2</td>
<td>3</td>
<td>1</td>
<td>$-1/3$</td>
<td>1</td>
</tr>
<tr>
<td>$F_R$</td>
<td>1/2</td>
<td>3</td>
<td>1</td>
<td>$-1/3$</td>
<td>1</td>
</tr>
<tr>
<td>$X$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$-1$</td>
</tr>
</tbody>
</table>

**Yukawa couplings**

\[
y^{u}_{ij} \overline{Q}_L \tilde{H} u^j_R + y^{d}_{ij} \overline{Q}_L H d^i_R + h.c. \]

\[
+ m_{F} \overline{F}_L F_R + \lambda_i \overline{F}_L X^\dagger d^i_R + h.c. \]

**Scalar potential**

\[
V_{\text{scalar}} = m_X^2 |X|^2 + \lambda_H |X|^2 |H|^2 + \lambda_X |X|^4 - m_H^2 |H|^2 + \lambda |H|^4
\]
DM(X) interactions with SM particles through

**Higgs exchanging**

$$\lambda_H |X|^2 |H|^2$$

**extra quark exchanging**

$$\lambda_i F_L X^\dagger d^i_R$$

(i = d, s, b)
Phenomenology
8 parameters are fixed by observables.

F mass: \( m_F \)

DM mass: \( m_X \)

\[
\lambda_b \quad \lambda_b
\]

\[
\text{Re}(\lambda_s) \quad \text{Re}(\lambda_s)
\]

\[
\text{Im}(\lambda_s) \quad \text{Im}(\lambda_s)
\]

\[
\text{Re}(\lambda_d) \quad \text{Re}(\lambda_d)
\]

\[
\text{Im}(\lambda_d) \quad \text{Im}(\lambda_d)
\]

\[
\lambda_H |X|^2 |H|^2 \quad \lambda_H
\]
8 parameters are fixed by observables.

F mass:

\[ m_F \]

relevant to direct search@LHC

DM mass:

\[ m_X \]

\[ \lambda_b \]

\[ \text{Re}(\lambda_s) \]

\[ \text{Im}(\lambda_s) \]

\[ \text{Re}(\lambda_d) \]

\[ \text{Im}(\lambda_d) \]

\[ \lambda_H |X|^2 |H|^2 \]

\[ \lambda_H \]
8 parameters are fixed by observables.

F mass: $m_F$

DM mass: $m_X$

$\lambda_i F_L X^\dagger d_R^i$ (i = d, s, b)

$\text{Re}(\lambda_s)$

$\text{Im}(\lambda_s)$

$\text{Re}(\lambda_d)$

$\text{Im}(\lambda_d)$

$\lambda_H |X|^2 |H|^2$ $\lambda_H$

relevant to direct search@LHC

DM physics fix $\lambda_b$ and $\lambda_X$

See difference with Higgs portal DM
8 parameters are fixed by observables.

F mass:
\[ m_F \]

DM mass:
\[ m_X \]

\[ \lambda_i \mathcal{F}_L X^\dagger d_R^i \]

\[ \lambda_b \]

\[ \text{Re}(\lambda_s) \]
\[ \text{Im}(\lambda_s) \]
\[ \text{Re}(\lambda_d) \]
\[ \text{Im}(\lambda_d) \]

\[ \lambda_H |X|^2 |H|^2 \]

relevant to direct search@LHC

DM physics fix \( \lambda_b \) and \( \lambda_X \)

Even if \( \lambda_s \) and \( \lambda_d \) are small, flavor physics is sensitive to new physics!

See difference with Higgs portal DM
8 parameters are fixed by observables.

F mass: $m_F$

DM mass: $m_X$

$\lambda_i \tilde{F}_L X^\dagger d_R^i$ (i = d, s, b)

DM physics fix $\lambda_b$ and $\lambda_X$

Bs-Bs mixing

K-K mixing

Bd-Bd mixing

See difference with Higgs portal DM
8 parameters are fixed by observables.

F mass:

\( m_F \)

DM mass:

\( m_X \)

\( \lambda_b \)

\( \text{Re}(\lambda_s) \)

\( \text{Im}(\lambda_s) \)

\( \text{Re}(\lambda_d) \)

\( \text{Im}(\lambda_d) \)

\( \lambda_H |X|^2 |H|^2 \)

relevant to direct search@LHC

DM physics fix \( \lambda_b \) and \( \lambda_X \)

Bs-Bs mixing

K-K mixing

Bd-Bd mixing

We will find predictions!

See difference with Higgs portal DM
Dark Matter Physics
Relic density (DM annihilation)

s-wave in t-channel ($XX \to bb$) is suppressed by b-quark mass

$$\langle \sigma v \rangle \approx \lambda_b^4 \left( a_0 \frac{m_b^2}{m_F^2} + bv^2 \right)$$

Large Yukawa required

Coannihilation is also important in compressed regions: $m_F \approx m_X$
\( \lambda_b \) for the relic density wo “Higgs portal”

\[
\lambda_b \text{ with } \lambda_H = 0
\]

\[
\Lambda = 1000 \text{TeV}
\]

\[
\Lambda = 100 \text{TeV}
\]

\[
\Lambda = 10 \text{TeV}
\]

\( O(1) \lambda_b \) is required!

Yukawa diverges below 1000TeV

\( m_X \text{[GeV]} \quad m_F \text{[GeV]} \)
Direct Detection of X

DM interacts with $b$ quarks at the tree-level.

\[
\begin{array}{c}
\text{b}^\text{R} \\
F \\
\bar{\text{b}}^\text{R}
\end{array}
\]

But large $\lambda b$ predicts enough large cross section even at the one-loop level.

\[
\begin{array}{c}
q \\
\gamma \\
\bar{q}
\end{array}
\]

almost on the border!
Direct Detection of X

- t-channel is dominant as far as $\lambda_H \lesssim 0.1$

- $\Lambda = 1000\,\text{TeV}$
- $\Lambda = 100\,\text{TeV}$
- $\Lambda = 10\,\text{TeV}$

- LUX2015
- LUX2016
- PandaX-II2016

XENON1T covers this region.
Flavor Physics
The most important processes are $\Delta F=2$ processes

$B_d - \bar{B}_d$ mixing  \hspace{2cm} $B_s - \bar{B}_s$ mixing

\[
\begin{align*}
\text{Diagram:} & \\
& b_R \quad X \quad q_R \\
& \bar{q}_R \quad X \quad \bar{b}_{Rp}
\end{align*}
\]
Observables in the $\Delta F=2$ processes

- $B_d - \overline{B_d}$ mixing
  - $\Delta M_d$  
  - $S_{\psi K}$

- $B_s - \overline{B_s}$ mixing
  - $\Delta M_s$  
  - $S_{\psi \phi}$

- $K_0 - \overline{K_0}$ mixing
  - $\Delta M_K$  
  - $\epsilon_K$

If DM and F are observed, there are only 4 parameters in our scenario.

- $\text{Re}(\lambda_d)$  
  - $\text{Im}(\lambda_d)$

- $\text{Re}(\lambda_s)$  
  - $\text{Im}(\lambda_s)$

I expect that this model can be tested by flavor physics.
Let’s see a sample point!

\[ \lambda_b \text{ with } \lambda_H = 0 \]

\[ m_X \text{[GeV]} \]

\[ m_F \text{[GeV]} \]

LUX2015, LUX2016, PandaX-II2016
$\Delta F=2$ processes in the compressed region: $(m_X, m_F, \lambda_b) = (900\text{GeV}, 964\text{GeV}, 0.66)$

$B_d - \bar{B}_d$ mixing

$S_{\psi K}$ and $\Delta M_{Bd}/(\Delta M_{Bd})_{\text{SM}}$ with $\Omega h^2 \geq 0.11$ ($\lambda_H=0$)

$LUX$ exclusion

$S_{\psi K}$ within 1$\sigma$

$0.95(0.9) \leq \Delta M_{Bd}/(\Delta M_{Bd})_{\text{SM}} \leq 1.05(1.1)$

$B_s - \bar{B}_s$ mixing

$S_{\psi \phi}$ and $\Delta M_{Bs}/(\Delta M_{Bs})_{\text{SM}}$ with $\Omega h^2 \geq 0.11$ ($\lambda_H=0$)

$S_{\psi \phi}$ within 1$\sigma$

$0.95(0.9) \leq \Delta M_{Bs}/(\Delta M_{Bs})_{\text{SM}} \leq 1.05(1.1)$

$\sim 10\%$ error still exist. (CKMfitter, 1309.2293, 1501.05013)
\(\Delta F=2\) processes in the compressed region: \((m_X, m_F, \lambda_b) = (900\text{GeV}, 964\text{GeV}, 0.66)\)

\[
\begin{align*}
B_d - \overline{B_d} & \quad \text{mixing} \\
K_0 - \overline{K_0} & \quad \text{mixing} \\
B_s - \overline{B_s} & \quad \text{mixing}
\end{align*}
\]

We find predictions for the deviations of meson mixings.

\(~10\%\) error still exist. (CKMfitter, 1309.2293, 1501.05013)
Summary

- Experimental results are very consistent with SM.
  There are many candidates for BSMs motivated by DM, mysteries of SM, but we need consider SM-like BSM around 1 TeV.
- I’m discussing simple DM models with extra vector-like.

\[ \lambda_i^f F^f_L X^\dagger f_{Ri} + \lambda_i^{f'} F^{f'}_R X^\dagger f'_{Li} \ (f = e, d, u; \ f' = Q, L) \]

These can avoid constraints from EWPOs, tree-level FCNCs and direct detection of DM.
• In particular, we focus on scalar DM model with “bottom partner.”

• This setup can evade the strong bound from the indirect detection, but will be severely constrained by the new results of the direct detections.

    We are looking forward to XENON1T results!

• The constraints and predictions for the $\Delta F=2$ processes are shown. →We can find correlations and prove our model.
Backup
**List of DM (X) models with partners (F)**

<table>
<thead>
<tr>
<th>Dark Matter (X)</th>
<th>DM mainly couples</th>
<th>Structure of Yukawa</th>
<th>Other Refs.</th>
</tr>
</thead>
</table>
| **“Fermion Portal DM”**  
(Bai, Berger. 1308.0612) | Fermion, complex scalar | up quark | \(\lambda_u \overline{F}_L^u X^\dagger u_R\)  
“Effective WIMPS”  
(Chang, et.al. 1307.8120)  
Ko,Baek,Wu,  
1606.00072;  
Toma,1307.6181;  
Giacchino,1307.6480;  
etc. |
| **“Vector-like Portal”**  
(Wise, Perez 1303.1452) | Complex scalar | quarks, leptons | \(\lambda_u \overline{F}_L^f X^\dagger f_R\)  
(f = u, d, e) |
| **“Flavored DM”**  
(Bhattacharya,London,et.al, 1509.04271) | Flavor-charged scalar | all quarks | \(\lambda_{ij} \overline{F}_L^{ij} X^\dagger_i f_R^j\)  
\((i, j = \text{flavor index})\)  
Kile, Soni,1104.5239;  
Batell, et.al,1105.1781;  
Kamenic, et.al,1107.0623;  
Argrawal,et.al,1109.3516;  
etc. |
| **Ibarra, Wild et.al,1511.04452** | Real scalar | light quarks | \(\lambda_q \overline{F}^q X R q_R\) |
| **This talk** | Complex Scalar | bottom quark | \(\lambda_i \overline{F}_L^d X^\dagger d_R^i\)  
\((\lambda_b \gg |\lambda_s|, |\lambda_d|)\) |
Result including “Higgs Portal”

$\lambda_d$ with $\lambda_H=0.1$

$\lambda \ll 1$ with $\lambda_H = 0.1$

\begin{align*}
\Lambda &= 1000 \text{TeV} \\
\Lambda &= 100 \text{TeV} \\
\Lambda &= 10 \text{TeV}
\end{align*}

$PandaX$–$II2016$

$LUX2016$

$3\text{FTVMUJODMVE}JHHT1PSUBMz$