Cancellation in Dark Matter-Nucleon Interactions: the Role of Non-Standard-Model-like Yukawa Couplings (Phenomenology 2021 Symposium)

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Null results from the DM-search experiments.

Detector sensitivity is gradually approaching the neutrino floor.

WIMP paradigm is losing its miracle!

LUX-ZEPLIN Collaboration: 1802.06039
Several simple extensions of SM (e.g. $Z$-portal, $H$-portal, $Z'$-portal etc.) have been proposed to explain the DM phenomenology.

The Higgs portal models ⇒ most relevant in SI DD for many favoured BSM scenarios (e.g. SUSY).

But the continuous null results have put strong constraints on these simple extensions, threatening them to be ruled out.

Are we missing something?
Some Attempts

• In some parts of the parameter space the DM couplings to $Z$ or $h$ may be highly suppressed or even zero ⇒ Blind spots. [Phys. Rev. D 79 (2009) 023521, J. High Energy Phys. 05 (2013) 100]

• A much suppressed $\sigma_{SI}$ can be obtained if the DD proceeds only through the loops. [Eur.Phys.J.C 78 (2018) 6, 471]

• In a simple H-portal DM model with a complex scalar, a softly broken symmetry might ensure $\sigma_{SI} \to 0$. [Phys. Rev. Lett. 119 (2017) 191801, J. Cosmol. Astropart. Phys. 11 (2018) 050]

• Isospin-violating DM is another interesting scenario which assumes non-identical $f_p$ and $f_n$. [Phys. Rev. D 69 (2004) 063503, Phys. Lett. B 703 (2011) 124-127]

More general approach?
Probably, Yes!

\[
\begin{align*}
\mathcal{L}_N^{SI} &= f_N(\phi\phi)(\bar{N}N) \Rightarrow \\
\mathcal{L}_N^{SI} &= \lambda_N \phi \phi (\bar{N}N) \\
\rho &= \frac{\lambda_N}{m_N} = \sum_{q=u,d,s} f_q^{(N)} \frac{y_q}{m_q} + \\
\rho &= \frac{2}{27} f_G \sum_{q=c,b,t} \frac{C_q y_q}{m_q} \\
\end{align*}
\]

where,

- Almost all the earlier attempts tried to tune \( \lambda_\phi \).
- But what happens if \( \lambda_N \to 0 \) irrespective of \( \lambda_\phi \)?
- \( \lambda_N = 0 \Rightarrow Non-SM-like \) negative \( y_q \).
- If \( y_c \) and \( y_s \) are allowed to deviate from SM:

\[
\begin{align*}
y_s &= -\frac{m_s}{f_s^{(N)}} \left( f_u^{(N)} \frac{y_u}{m_u} + f_d^{(N)} \frac{y_d}{m_d} \right) \\
y_c &= -m_c \left( \frac{y_b}{m_b} + \frac{y_t}{m_t} \right) \\
\end{align*}
\]

But wait... in SM, \( y_q \propto m_q / v !!!! \)
Let’s have a particular type of effective \textbf{dim-6} operators at some NP scale $\Lambda$ in the quark Yukawa interaction Lagrangian,

$$\mathcal{L} \supset -Y_u \bar{q}_L \tilde{H} u_R - Y_d \bar{q}_L H d_R + \Delta \mathcal{L}_{eff} + H.c.$$  \hspace{1cm} (1)

where,

$$\Delta \mathcal{L}_{eff} = \frac{H^\dagger H}{\Lambda^2} \left( Y_H^u \bar{q}_L \tilde{H} u_R + Y_H^d \bar{q}_L H d_R \right).$$  \hspace{1cm} (2)

After EWSB,

$$m_q = v \left( Y_q - \epsilon Y_H^q \right),$$  \hspace{1cm} (3)

$$y_q = (Y_q - 3\epsilon Y_H^q) = \frac{m_q}{v} - 2\epsilon Y_H^q$$  \hspace{1cm} (4)

where, $\epsilon \equiv (v/\Lambda)^2$ and $v \simeq 174$ GeV.

\textbf{And that’s it!} $y_q \neq m_q/v$
A Few Comments

\[ \Lambda \sim \text{TeV} \text{ and } Y_H^q \sim \mathcal{O}(1) \]

- The sign of \( y_q \) depends on the sign of the Wilson coefficients \( Y_H^q \).

- For the first two gen. of quarks \((u, d, s, c)\), \( m_q / v < \epsilon Y_H^q \Rightarrow y_q \) may naturally become negative.

- To achieve the correct \( m_q \) with \( y_q < 0 \), the necessary condition is:
  \[ Y_H^q \left( \frac{v}{\Lambda} \right)^2 > \frac{m_q}{2v} \]
  \( \Rightarrow \) sets an upper bound on \( \Lambda \) (e.g. \( \Lambda \leq 2.9 \text{ TeV} \) for \( m_c = m_c^{\text{SM}} \)).

- On the contrary, \( y_q > 0 \) can only set a lower bound on \( \Lambda \).

- The choice of negative values for \( y_q \) is more natural and predictive.
A huge room is available for the variation of first two gen. of quark Yukawa couplings.

Projected reach in the absolute $y_q$ values ($q = u, d, s, c$) at the LHC with 3000 fb$^{-1}$ of IL: [J. High Energy Phys. 01 (2020) 139]

$$|y_u| < 560 \, y_u^{SM}, \quad |y_d| < 260 \, y_d^{SM}, \quad |y_s| < 13 \, y_s^{SM}, \quad |y_c| < 1.2 \, y_c^{SM}. $$

Utilizing processes sensitive to the sign of $y_q$, the HL-LHC can restrict,

$$-1550 < y_u/y_u^{SM} < 700 \, \& \, -800 < y_d/y_d^{SM} < 300. $$

[arXiv:1608.04376]

$$y_c/y_c^{SM} \sim [-0.6, 3]. $$

[Phys. Rev. Lett. 118 (2017) 121801]
Singlet Scalar DM and Negative $y_q$

Let’s consider a specific realization of the dim-6 operators through new heavy VL particles at the NP scale $\Lambda$:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{NP}} + \mathcal{L}_{\text{DM}}$$

$\mathcal{L}_{\text{NP}}$: Underlying New Physics

Considering only one gen. of VL quarks,

| $SU(2)$ Doublet      | $SU(2)$ Singlets               |
|----------------------|--------------------------------|
| $Q = (C, S)(3, 2, 1/6)$ | $C(3, 1, 2/3)$ & $S(3, 1, -1/3)$ |

$$-\mathcal{L}_{\text{NP}} = \left( \lambda_{QC} \bar{Q}_L \tilde{H} C_R + \lambda_{QS} \bar{Q}_L H S_R \right)$$
$$+ \left( \lambda_{qC} \bar{q}_L \tilde{H} C_R + \lambda_{qS} \bar{q}_L H S_R \right)$$
$$+ \left( \lambda_{Qc} \bar{Q}_L \tilde{H} c_R + \lambda_{Qs} \bar{Q}_L H s_R \right) + H.c. \quad (5)$$
• The *dim-6* operators in Eq. (2) can be obtained after integrating out the heavy VL quarks.

\[
Y^c_H = \lambda_{qC} \lambda^*_{QC} \lambda_{Qc} \quad , \quad \Lambda = \sqrt{M_C M_Q} ,
\]

\[
Y^s_H = \lambda_{qS} \lambda^*_{QS} \lambda_{Qs} \quad , \quad \Lambda = \sqrt{M_S M_Q} .
\]

• Thus, with \( M_{Q,C,S} \sim 2 \, \text{TeV} \) and all the \( \lambda_{NP} \sim \mathcal{O}(1) \), the \( y_{q=c,s} \) can be considered for modification [Eq. (4)].
For a real singlet scalar $\phi$ as the DM particle,

$$V = \frac{1}{2} \mu_\phi^2 \phi^2 + \lambda H\phi (H^\dagger H)$$

After EWSB, the $\phi$-mass term, $M_\phi = \sqrt{\mu_\phi^2 + 2\lambda H\phi v^2}$.

This variation is generated using micrOMEGAs.

The dependence of $\Omega_\phi h^2$ on the variations of $y_c$ and $y_s$ is negligible.
$\sigma_{SI}$ and the Large Cancellation

- These exact cancellation values (i.e. $y_s = -0.77y_s^{SM}$ & $y_c = -1.875y_c^{SM}$ in 1st fig. and $y_c = -2.91y_c^{SM}$ in the 2nd) have been obtained for a typical set of $f_q^{(N)}$: \[\text{arXiv:1305.0237}\]

\[
\begin{align*}
f_u^p &= 0.0153, & f_d^p &= 0.0191, & f_s^p &= 0.0447, \\
f_u^n &= 0.0110, & f_d^n &= 0.0273, & f_s^n &= 0.0447
\end{align*}
\]
• The above fig. shows that for the same set of $y_c$ and $y_s$ where $\lambda_p \to 0$, $\lambda_n \neq 0 \Rightarrow$ **Isospin Violation**

• In this framework $\lambda_n/\lambda_p \equiv f_n/f_p > 0$ can be easily achieved, but $f_n/f_p < 0$ appears only within a narrow domain of $y_q/y_q^{SM}$. 
• We considered a H-portal DM model and assumed non-SM-like negative values for $y_q \Rightarrow \sigma_{SI} \rightarrow 0$.

• $y_q < 0$ can be realized in presence of a dim-6 effective operator $\Rightarrow$ an upper bound on the NP scale $\Lambda$.

• A model with new particles (VL quarks & $\phi$) has been discussed as a practical realization of this idea.

• The proposed framework is able to accommodate isospin violation.

• Even though the future DM-search experiments are blind to our proposal, it might be tested at the HL-LHC.
Thank you