Heavy Quark Flavored Scalar Dark Matter

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Outline

• Motivation
• Model
• DM couples to three flavors
  • Direct detection
    • interplay between H.P. and VLP
    • RGE, threshold matching
• DM couples to heavy flavors
  • Thermal relic
  • Direct/Indirect detection
  • Top FCNC
  • Collider Signals
• Summary
Why Flavored DM?

• Main components in \((p, n)\): **gluons** & **light quarks**

• No confirmed DM direct detection signal
  • constrained coupling of DM to **gluons** & **light quarks**
  • blind spot: cancellations in scattering amplitude

• Favored channels when fitting astro- anomalies
  • \(b\bar{b}, \tau\tau\) are favored, up to astro-uncertainties  [Hooper et al]

• Theoretical model building  [Agrawal, Kilic et al]
  • flavor symmetry in dark sector, MFV…

In this work

• we consider a real scalar DM, coupling to \( \{U_i = u_R, c_R, t_R\} \) via a vector-like fermion portal \( \psi \)

• three DM-\( U_i-\psi \) couplings \( \{y_1, y_2, y_3\} \) reflecting flavor structure, receiving DD constraints with different strengths.

• vector-like fermion portal \( \psi \) (VLP) can radiatively generate Higgs portal (HP)

• both twist-0 (scalar-type) and twist-2 operators are considered

• RGE effects and heavy quark threshold matching are addressed
The model

• DM: real scalar $S$

• Vector-like (VL) fermion $\psi$, $m_\psi > m_S$
  • $(\psi, U_i)$ same quantum number
  • no chiral anomaly

• $Z_2$ parity to stabilize DM: $S, \psi$ are odd
  • no mass mixing $(S, H), (\psi, U_i)$
  • $Br \left( \psi \rightarrow SU_i^{(*)} \right) = 100\%$
  • LHC searches for VL $(T, B)$ do not apply

\[
L_{\text{new}} = L_{\text{fermion}} + L_{\text{scalar}} + L_{\text{Yukawa}},
\]
\[
L_{\text{fermion}} = \bar{\psi} (i \gamma^\mu D_\mu - m_\psi) \psi,
\]
\[
L_{\text{scalar}} = \frac{1}{2} \partial^\mu S \partial_\mu S - \frac{1}{2} m_S^2 S^2 - \frac{1}{4!} \lambda_S S^4 - \frac{1}{2} \lambda_{SH} S^2 H^2,
\]
\[
L_{\text{Yukawa}} = -y_1 S \bar{\psi}_L u_R - y_2 S \bar{\psi}_L c_R - y_3 S \bar{\psi}_L t_R + h.c.,
\]
DM-nucleon scattering: General

- $\mu_{EFT} \sim m_Z$
  $$\mathcal{L}_{\text{eff}} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p, \quad \mathcal{O}_S^q = \phi^2 m_q \bar{q} q,$$
  $$\mathcal{O}_S^g = \frac{\alpha_s}{\pi} \phi^2 G_A^{\mu\nu} G_{\mu\nu}^A.$$

- RGE
  $$C_S^q(\mu) = C_S^q(\mu_0) - 4C_S^G(\mu_0) \frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))} (\gamma_m(\mu) - \gamma_m(\mu_0)),$$
  $$C_S^G(\mu) = \frac{\beta(\alpha_s(\mu))}{\alpha_s^2(\mu)} C_S^G(\mu_0).$$

- Quark thresholds
  $$C_S^q(\mu_b)|_{N_f=4} = C_S^q(\mu_b)|_{N_f=5},$$
  $$C_S^G(\mu_b)|_{N_f=4} = -\frac{1}{12} \left[ 1 + \frac{11}{4\pi} \alpha_s(\mu_b) \right] C_S^b(\mu_b)|_{N_f=5} + C_S^G(\mu_b)|_{N_f=5}.$$

- $\mu_{\text{had}} \sim 1$ GeV

$$\mathcal{L}_{\text{SI}}^{(N)} = f_N \phi^2 \bar{N} N, \quad \sigma = \frac{1}{\pi} \left( \frac{M_T}{M + M_T} \right)^2 |n_p f_p + n_n f_n|^2.$$
DM-nucleon scattering: This model

- Both HP and VLP contribute, we consider amplitudes up to $O(y_i^2)$
- active $d.o.f$s depend on $\mu_{EFT}$, we compare $\mu_{EFT} \sim m_Z$ with $\mu_{EFT} \sim \mu_{had}$
DM-nucleon scattering: This model

- We include both twist-0 (scalar-type) and twist-2 operators
  - destructive interferences between twist-2 up quark with twist-0 gluon
  - twist-2 gluon Wilson at $O(y_i^2)$ coefficient suppressed by additional $\alpha_s/\pi$

\[
\mathcal{L}_{\text{eff}} = \sum_{p=q,g} C_{S}^{p} \mathcal{O}_{S}^{p} + \sum_{p=q,g} C_{T_2}^{p} \mathcal{O}_{T_2}^{p},
\]

\[
f_N/m_N = \sum_{q=u,d,s} C_{S}^{q} (\mu_{\text{had}}) f_{T_q}^{(N)} - \frac{8}{9} C_{S}^{g} (\mu_{\text{had}}) f_{T_G}^{(N)} + \frac{3}{4} \sum_{q} C_{T_2}^{q} (\mu) [q(2; \mu) + \bar{q}(\bar{q}(2; \mu)] - \frac{3}{4} C_{T_2}^{g} (\mu) g(2; \mu),
\]

\[
f_{T_q}^{(N)} \equiv \langle N|m_q \bar{q}q|N\rangle/m_N,
\]

\[q(2; \mu) = \int_{0}^{1} dx \, x \, q(x, \mu), \quad \bar{q}(2; \mu) = \int_{0}^{1} dx \, \bar{q}(x, \mu), \quad g(2; \mu) = \int_{0}^{1} dx \, x \, g(x, \mu)\]
Higgs Portal at $O(y_i^2)$: only generate twist-0

- radiative corrections from vector-like $\psi$ portal, mainly top quark $y_3^2 y_t$

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

\[ \mathcal{L}_{\text{Yukawa}} = -y_1 S \overline{\psi} u_R - y_2 S \overline{\psi} c_R - y_3 S \overline{\psi} t_R + h.c., \]

\[ \lambda_{\text{SH}}^{\text{PI}} = \sum_{k=1,2,3} (-8) y_3^2 N_c \left( \frac{m_{U_k}}{v} \right)^2 \frac{1}{16\pi^2} \left( 4C_{00} + m_S^2 (C_{11} + C_{22}) - 2m_S^2 C_{12} \right), \]

\[ C_{ij} \equiv C_{ij}(m_S^2, 0, m_{\psi}^2, m_{U_k}^2, m_{U_k}^2), \]

After proper renormalization

\[ \lambda_{\text{SH}}^{\text{ren.}} = \lambda_{\text{SH}} + \delta \lambda_{\text{SH}} + \lambda_{\text{SH}}^{\text{PI}} + \lambda_{\text{SH}} \left( \frac{1}{2} \delta Z_h + \delta Z_S + \delta v \right) \]
Higgs Portal at $O(y_i^2)$: only generate twist-0

- radiative corrections from vector-like $\psi$ portal, mainly top quark $y_3^2 y_t$

$$C_{S,\text{HP}}^{u,c} = \frac{\lambda_{S,H}^{\text{ren.}}}{m_h^2}, \quad C_{S,\text{HP}}^g = -\frac{\lambda_{S,H}^{\text{ren.}}}{12m_h^2},$$

$$\lambda_{S,H}^{1\text{PI}} = \sum_{k=1,2,3} (-8)y_3^2 N_c \left( \frac{m_{U_k}}{v} \right)^2 \frac{1}{16\pi^2} \left( 4C_{00} + m_S^2(C_{11} + C_{22}) - 2m_S^2C_{12} \right),$$

$$C_{ij} \equiv C_{ij}(m_S^2, 0, m_S^2; m_\psi^2, m_{U_k}^2, m_{U_k}^2),$$

**After proper renormalization**

$$\lambda_{S,H}^{\text{ren.}} = \lambda_{S,H} + \delta \lambda_{S,H} + \lambda_{S,H}^{1\text{PI}} + \lambda_{S,H} \left( \frac{1}{2} \delta Z_h + \delta Z_S + \delta v \right)$$
Vector-like $\psi$ portal at $O(y_i^2)$: both twist-0/2

- DM-gluon loop coupling: **Short / Long** Distances are distinguished

$$y_i^2$$
Vector-like $\psi$ portal at $O(y_i^2)$: both twist-0/2

- Assuming $\mu_{EFT} \sim m_Z$
  - top, fully integrated out, generates $\{O_S^g\}$
  - up/charm, active d.o.f, generates $\{O_S^g, O_{S/T_2}^{u,c}\}$

$$C_{S,VLP}^{g} = C_{S,VLP}^{g,LD+SD}_t + C_{S,VLP}^{g,SD}_{u,c},$$

$$C_{S,VLP}^{g,LD+SD}_t = \frac{1}{4} \frac{y_3}{2} \left( f^{(a)}_+ + f^{(b)}_+ + f^{(c)}_+ \right) (m_S; m_t, m_\psi),$$

$$C_{S,VLP}^{g,SD}_{u,c} = \frac{1}{4} \frac{y_{1,2}^2}{2} \left( f^{(b)}_+ + f^{(c)}_+ \right) (m_S; m_{u,c}, m_\psi).$$
XENON1T bounds on separate $\{y_1, y_2, y_3\}$

$m_\psi = 0.1 \text{ TeV}$

$\text{Solid: } \mu_{\text{EFT}} = m_Z$

$\text{Dashed: } \mu_{\text{EFT}} = 1 \text{ GeV}$
XENON1T bounds on separate \( \{y_1, y_2, y_3\} \)

**Equation:**

\[ m_\psi = 0.5 \text{ TeV} \]

**Diagram:**

XENON1T bounds on \( y_i \), with \( y_{j\neq i} = 0 \), \( m_\psi = 0.5 \text{ TeV} \)

Solid: \( \mu_{\text{EFT}} = m_Z \)

Dashed: \( \mu_{\text{EFT}} = 1 \text{ GeV} \)
XENON1T bounds on separate $\{y_1, y_2, y_3\}$

$m_\psi = 1$ TeV

Solid: $\mu_{\text{EFT}} = m_Z$
Dashed: $\mu_{\text{EFT}} = 1$ GeV
Bounds on $\gamma_1$ and H.P. are strong

- Both are well studied and strongly constrained
VLP through heavy quark flavors

• By setting $y_1$ and Higgs portal $\lambda_{SH}^{ren.}$ to be negligibly small, we focus on DM-charm/top interactions $\{y_2, y_3\}$ to explore surviving status.

\[ \mathcal{L} \supset -y_2 S\overline{\psi}_L c_R - y_3 S\overline{\psi}_L t_R + h.c. \]

• This can be realized in the framework of Minimal Flavor Violation.

[1109.3516, Agraval et al; 1501.02202, Kilic et al]
Combined results

$\gamma_3 = 0.5$

$\gamma_2 = 0.5$
\[ y_3 = 0.5 \]

\[ y_2 = 0.5 \]

Combined results, \( y_3 = 0.5, y_2 = 0.5 \)

\[ m_S \sim \frac{m_t}{2} \quad m_S \sim 500 \text{ GeV} \]

FCNC Brs of top quark, \( y_3 = 0.5, y_2 = 0.5 \) with \( \Omega h^2 = 0.12 \)

**Jets + MET**

**1/lep + jets + MET**

**Xenon-1T Dwarf**

**Thermal relic**

\[ m_\gamma \approx 0.5 \]

\[ m_\gamma \approx 0 \]

\[ m_\gamma \approx 500 \text{ GeV} \]

\[ m_\gamma \approx m_\nu \]

\[ m_\gamma \approx 500 \text{ GeV} \]

\[ \text{Br} \approx 10^{-10} \]

\[ \text{Br} \approx 10^{-7} \]
$y_3 = 0.5$

$m_S \sim \frac{m_t}{2}$

$m_S \sim 500$ GeV

\[ y_2 = 1.0 \]

Combined results, $y_3 = 0.5$, $y_2 = 1.0$

FCNC Brs of top quark, $y_3 = 0.5$, $y_2 = 1.0$ with $\Omega h^2 = 0.12$

jets + MET
1lep + jets + MET
Xenon-1T Dwarf
Thermal relic

$\gamma, cZ$

$cS\gamma$

$cS$
$y_3 = 0.5$

$y_2 = 3.0$

Combined results, $y_3 = 0.5$, $y_2 = 3.0$

Thermal relic DM with $m_S < m_t$ is almost excluded

FCNC Brs of top quark, $y_3 = 0.5$, $y_2 = 1.0$ with $\Omega h^2 = 0.12$

$\gamma$, $\gamma$, $c\gamma$, $cZ$

$1\text{lep} + \text{jets} + \text{MET}$

Dwarf

Thermal relic
Summary

• No confirmed DD signal, DM may couple weakly to gluons & light quarks.

• we consider a real scalar DM, coupling to \( \{U_i = u_R, c_R, t_R\} \) via a vector-like fermion portal \( \psi \). XENON1T constraints on \( \{y_1, y_2, y_3\} \) through pure VLP are in descending order, which may imply flavor structure in DM sector.

• RGE effects and heavy quark threshold matching can be significant for \( \{y_1, y_2\} \). Radiative HP constraints on \( \{y_3\} \) can be strong.

• For exclusive DM couplings to heavy quarks \( \{c, t\} \) with \( y_2, y_3 \sim O(1) \), thermal relic DM with \( m_S < m_t \) is almost excluded, surviving top FCNC Brs < \( 10^{-7} \) still allowed in current bounds.
Thank you for your attention
Back up slides
Short / Long distance decomposition (SD / LD)

- Two mass scales in DM-gluon loop: $m_{\text{quark}}$ (LD) and $m_{\tilde{q}}$ (SD)
- Loop momentum integral separated into:

$$f_G|_q = f_G|^{\text{LD}}_q + f_G|^{\text{SD}}_q$$
SUSY case

$$O_S^g \equiv \frac{\alpha_s}{\pi} \bar{\chi}^0 \chi^0 G_{\mu\nu} A^{\mu\nu}$$

$$\mathcal{L} = \bar{q}(a_q + b_q \gamma_5)\tilde{\chi}^i \tilde{q} + \text{h.c.}$$

$$f_G = \sum_{q=\text{all}} f_G^{SD}|_q + \sum_{Q=c,b,t} f_G^{LD}|_Q$$

$$f_G^{SD}|_q = \frac{\alpha_s}{4\pi} \left( \frac{a_q^2 + b_q^2}{4} M f_+^s + \frac{a_q^2 - b_q^2}{4} m_q f_-^s \right)$$

$$f_G^{LD}|_q = \frac{\alpha_s}{4\pi} \left( \frac{a_q^2 + b_q^2}{4} M f_+^l + \frac{a_q^2 - b_q^2}{4} m_q f_-^l \right)$$

SD is characterized by $q_{\text{loop}} \sim m_{\tilde{q}}$

LD is characterized by $q_{\text{loop}} \sim m_q$

higher energy $\rightarrow$ shorter distance