Vector dark matter annihilation with internal bremsstrahlung

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Candles of Darkness, ICTS

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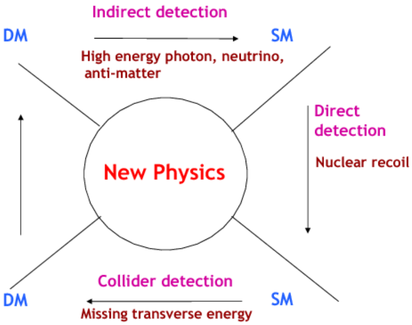
Overview

Introduction

Search of Dark Matter

Dark matter can be searched by many ways:



Status of Dark Matter Detection: 1409.4590

Direct, Indirect and Collider Detection.

- Important to understand DM nature and confirm or ruled out its existence.
- Recent results of XENON1T (1705.06655), LUX (1608.07648) and PandaX (1607.07400) put very stringent bounds on DM scattering cross-section.
- Effective operator description breaks down at LHC energies.

We will focus on Indirect detection of dark matter.

Indirect Detection

Possibility of detection

Dark matter annihilates into SM particles or messengers and contribute to the cosmic flux of particles.

- Large uncertainties in the flux.
- Energy distribution of messenger is featureless.

- Smoking gun signatures like $\gamma\gamma$ and $Z\gamma$ escape from these uncertainties.

We will focus on Internal Bremsstrahlung signature.

Internal Bremsstrahlung

Fermion Dark Matter

- Annihilation cross-section of DM into $\bar{f}f$:

$$\sigma v(\chi\chi \to \bar{f}f) = a + bv^2$$

where $a = \frac{y^4}{32\pi M_\chi^2}\frac{m_f^2}{M_\chi^2}\frac{1}{(1+r^2)^2}$ and $b = \frac{y^4}{48\pi}\frac{1}{M_\chi^2}\frac{1+r^4}{(1+r^2)^4}$

with $r = M_\Psi/M_\chi$ (1203.1312).

- Annihilation cross-section of DM into $\bar{f}f$:

$$\sigma v(SS \to \bar{f}f) = \frac{y^4}{60\pi}\frac{v^4}{M_S^2}\frac{1}{(1+r^2)^4}$$

with $r = M_\Phi/M_\chi$ (1307.6480).

Idea and Importance

- The annihilation cross-section:

$$\sigma_{\bar{f}f} v \propto m_f^2 \text{ or } v^2$$

Dark matter (scalar+fermion) annihilation into SM fermions is chirality suppressed.

bilinear	C	P	J	state
$\bar{\psi}\psi$	+	+	0	$S = 1, L = 1$
$\imath\bar{\psi}\gamma^5\psi$	+	-	0	$S = 0, L = 0$
$\bar{\psi}\gamma^0\gamma^5\psi$	+	-	0	$S = 0, L = 0$
$\bar{\psi}\gamma^i\gamma^5\psi$	+	+	1	$S = 1, L = 1$
$\phi^\dagger\phi$	+	+	0	$S = 0, L = 0$
$\imath Im(\phi^\dagger\partial^i\phi)$	-	-	1	$S = 0, L = 1$

Bilinears transformations: 1305.1611

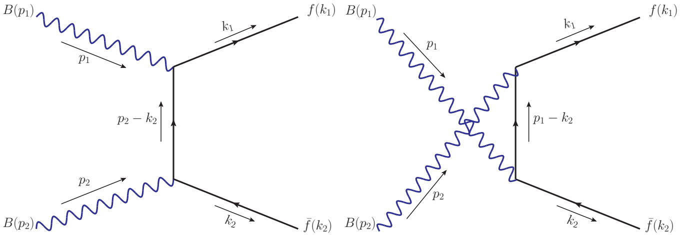
Points

- This m_f^2 suppression disappears if the final state contains an additional photon.
- The emission of additional photon is known as internal bremsstrahlung (IB).
- Internal bremsstrahlung = final state radiation + virtual IB

Vector dark matter

- Interaction Lagrangian,

$$\mathscr{L} = \lambda_L \bar{\Psi}\gamma^\mu P_L f B_\mu + \lambda_L^* \bar{f}\gamma^\mu P_L \Psi B_\mu$$



The different possible amplitudes which give rise to $S = 0$ state.

Amp	$\epsilon(p_1)$	$\epsilon(p_2)$	s_1	s_2
1	0	0	+1/2	-1/2
2	+1	-1	+1/2	-1/2
3	-1	+1	+1/2	-1/2
4	0	0	-1/2	+1/2
5	+1	-1	-1/2	+1/2
6	-1	+1	-1/2	+1/2

- Matrix element:

$$\mathcal{M}_a \equiv \mathcal{M}_{L=0,S=0\rightarrow s_1=+1/2 s_2=-1/2} = \frac{1}{\sqrt{3}}\left[\mathcal{M}_2 + \mathcal{M}_3 - \mathcal{M}_1\right],$$

$$\mathcal{M}_b \equiv \mathcal{M}_{L=0,S=0\rightarrow s_1=-1/2 s_2=+1/2} = \frac{1}{\sqrt{3}}\left[\mathcal{M}_5 + \mathcal{M}_6 - \mathcal{M}_4\right].$$

$$\sum_{spin} |\mathcal{M}|^2 = |\mathcal{M}_a|^2 + |\mathcal{M}_b|^2 = 0$$

But

- The annihilation cross-section for $B(p_1)B(p_2) \to \bar{f}(k_1)f(k_2)$ is not suppressed.

- Reason: Dark matter can be in a $L = 0, S = 2, J = 2$ state. Final state does not mix different Weyl spinors.

No chirality suppression. Two body final state is dominant.

Continue

- For spin-0 and spin-1/2 DM, no operator of dimension ≤ 8, having non-trivial matrix element.
- For spin-1 DM,

$$\mathcal{O} = \frac{1}{2\Lambda^2} B_{\{\mu} B_{\nu\}} \left(\bar{f} \gamma^{\{\mu} \partial^{\nu\}} f - \partial^{\{\nu} \bar{f} \gamma^{\mu\}} f \right)$$
$$\mathcal{O}' = \frac{1}{2\Lambda^2} B_{\{\mu} B_{\nu\}} \left(\bar{f} \gamma^{\{\mu} \gamma^5 \partial^{\nu\}} f - \partial^{\{\nu} \bar{f} \gamma^{\mu\}} \gamma^5 f \right)$$

- CP-even and respect SM flavor symmetry. CAN NOT BE PROJECTED OUT.

No chirality suppression. Two body final state is dominant.

Solution

- Dark matter initial state is polarized.
- $J = 2$ initial state is projected out.

- REALIZATION: Dark matter form a BB bound state. Decay to ground state before its constituents annihilate.

Chirality suppression in cs. Internal bremsstrahlung becomes important.

The different possible amplitudes which give rise to $S = 0$ state.

Amp	$\epsilon(p_1)$	$\epsilon(p_2)$	s_1	s_2	$\epsilon^*(l_1)$
1	0	0	$-1/2$	$-1/2$	$+1$
2	$+1$	-1	$-1/2$	$-1/2$	$+1$
3	-1	$+1$	$-1/2$	$-1/2$	$+1$
4	0	0	$+1/2$	$+1/2$	-1
5	$+1$	-1	$+1/2$	$+1/2$	-1
6	-1	$+1$	$+1/2$	$+1/2$	-1

- Matrix element:

$$\mathcal{M}_c \equiv \mathcal{M}_{L=0,S=0\to s_1=-1/2,s_2=-1/2,\epsilon^*=+1} = \frac{1}{\sqrt{3}}\left[\mathcal{M}_2 + \mathcal{M}_3 - \mathcal{M}_1\right]$$

$$\mathcal{M}_d \equiv \mathcal{M}_{L=0,S=0\to s_1=+1/2,s_2=+1/2,\epsilon^*=-1} = \frac{1}{\sqrt{3}}\left[\mathcal{M}_5 + \mathcal{M}_6 - \mathcal{M}_4\right] \ldots$$

- Matrix element of DM annihilation into $\bar{f} f \gamma$ for $J = 0$ initial state:

$$\sum |\mathcal{M}|^2 = \frac{32\pi\alpha\lambda_L^4 (2+r^2)^2}{3M_B^2} \frac{4(1-y)}{(1-r^2-2x)^2(3+r^2-2x-2y)^2} \times (2+2x^2+2x(y-2)-2y+y^2)$$

with $r = M_\Psi / M_B$, $x = 2E_f/\sqrt{s}$ and $y = 2E_\gamma/\sqrt{s}$.

Note: Extra factor $(2+r^2)^2$. Important from LHC prospective.

IB for fermion dark matter

- Matrix element for fermion dark matter:

$$\frac{1}{4}\sum|\mathcal{M}|^2 = \frac{4\pi\alpha y^4}{M_\chi^2}\frac{4(1-y)}{(1-r^2-2x)^2(3+r^2-2x-2y)^2} \times (2+2x^2+2x(y-2)-2y+y^2)$$

with $r = M_\Phi/M_\chi$.

Note: factor $(2+r^2)^2$ is not present.

IB for scalar dark matter

- Matrix element of DM annihilation into $\bar{f} f \gamma$:

$$
\begin{aligned}
|\mathcal{M}|^2 &= \frac{32\pi\alpha y^4}{M_S^2} \frac{4(1-y)}{(1-r^2-2x)^2(3+r^2-2x-2y)^2} \\
&\times \quad (2+2x^2+2x(y-2)-2y+y^2)
\end{aligned}
$$

Note: factor $(2+r^2)^2$ is not present.

Name	Operator	CP
$\mathcal{O}_{\rm R1}$	$i\phi^2\left[\overline{f}_L\overrightarrow{\not{D}}\overrightarrow{D}^\nu(\overrightarrow{D}_\nu f_L)-(\overline{f}_L\overleftarrow{D}_\nu)\overleftarrow{D}^\nu\overleftarrow{\not{D}}f_L\right]$	+
$\mathcal{O}_{\rm R2}$	$i\phi^2\left[\overline{f}_L\overrightarrow{D}^\nu\overrightarrow{\not{D}}(\overrightarrow{D}_\nu f_L)-(\overline{f}_L\overleftarrow{D}_\nu)\overleftarrow{\not{D}}\overleftarrow{D}^\nu f_L\right]$	+
$\mathcal{O}_{\rm R3}$	$\phi^2\epsilon_{\mu\nu\rho\sigma}\left[\overline{f}_L\gamma^\mu\overrightarrow{D}^\nu\overrightarrow{D}^\rho(\overrightarrow{D}^\sigma f_L)+(\overline{f}_L\overleftarrow{D}^\sigma)\overleftarrow{D}^\rho\overleftarrow{D}^\nu\gamma^\mu f_L\right]$	+
$\mathcal{O}_{\rm R4}$	$i(\partial_\mu\phi\partial_\nu\phi)\left[\bar{f}_L\gamma^\mu\overrightarrow{D}^\nu f_L-\bar{f}_L\overleftarrow{D}^\nu\gamma^\mu f_L\right]$	+
$\mathcal{O}_{\rm R5}$	$\phi^2\left[(\overline{f}_L\overleftarrow{D}^\nu)\overrightarrow{\not{D}}(\overrightarrow{D}_\nu f_L)+(\overline{f}_L\overleftarrow{D}_\nu)\overleftarrow{\not{D}}(\overrightarrow{D}^\nu f_L)\right]$	−
$\mathcal{O}_{\rm R6}$	$i\phi^2\epsilon_{\mu\nu\rho\sigma}\left[\overline{f}_L\gamma^\mu\overrightarrow{D}^\nu\overrightarrow{D}^\rho(\overrightarrow{D}^\sigma f_L)-(\overline{f}_L\overleftarrow{D}^\sigma)\overleftarrow{D}^\rho\overleftarrow{D}^\nu\gamma^\mu f_L\right]$	−
$\mathcal{O}_{\rm R7}$	$i\phi^2\epsilon_{\mu\nu\rho\sigma}\left[(\overline{f}_L\overleftarrow{D}^\nu)\gamma^\mu\overrightarrow{D}^\rho(\overrightarrow{D}^\sigma f_L)-(\overline{f}_L\overleftarrow{D}^\sigma)\overleftarrow{D}^\rho\gamma^\mu(\overrightarrow{D}^\nu f_L)\right]$	−

Dim-8 operators contributing to the s-wave cross-section for scalar DM: 1301.1486

Replacement of $\partial_\mu\phi\partial_\nu\phi \longrightarrow B_\mu B_\nu$ gives a Dim-6 operator.

Importance

- In heavy mediator limit:
  - For spin-0 and spin-1/2 dark matter, the squared matrix element scales as r^{-8}.
  - For spin-1 dark matter, the squared matrix element scales as r^{-4}.

Internal bremsstrahlung cross-section is less suppressed for spin-1 dark matter.

Importance

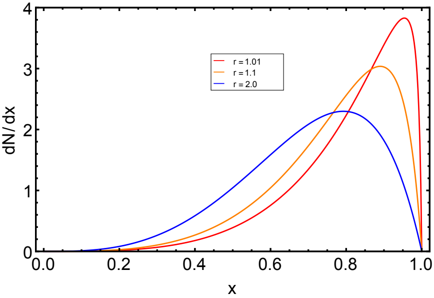
- Internal bremsstrahung is possible through charged mediator m_Ψ.
- Charged particles are tightly constrained from collider experiments.
- If m_Ψ increase then IB cross-section gets suppressed.
- In Vector DM, r can be made much larger, but less suppressed cs.

Open a new window in existing parameter space.

Photon Spectrum: Vector DM

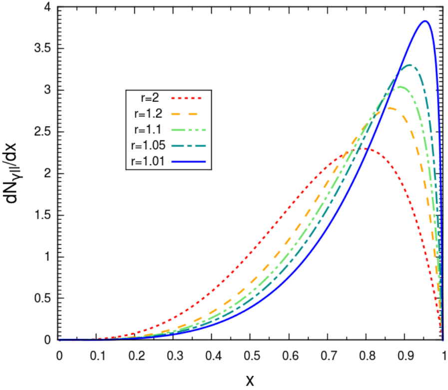
- The photon spectrum is defined as,

$$\frac{dN}{dx} = \frac{1}{v\sigma}\frac{vd\sigma}{dx}$$



Vector dark matter photon spectrum

Photon Spectrum: Scalar DM



Both the photon spectra are identical. Same result with spin-1/2 dark matter.

Summary

Summary

- Annihilation of self-conjugate spin-1 dark matter is considered.
- $BB \longrightarrow \bar{f}f$ annihilation cross-section can be chirality suppressed only if initial state is $J = 0$.
- $J = 2$ initial state has an unsuppressed $2 \longrightarrow 2$ annihilation cross-section.

- Vector dark matter should be polarized.

Summary

- Shape of the photon spectrum for spin-1 dark matter is same as for spin-0 and spin-1/2 dark matter.
- Matrix element is m_Ψ^{-2} suppressed.
- Even heavy mediator can give large annihilation cross-section.
- This open a new window in parameter space.

Thank You!

Back Up

- The matrix element for $B(p_1)B(p_2) \to f(k_1)\bar{f}(k_2)$ process:

$$
\begin{aligned}
i\mathcal{M} &= \lambda_L^* \lambda_L \epsilon_\mu(p_1)\epsilon_\alpha(p_2) \\
&\times \bar{u}(k_1)[\gamma^\mu P_L \times \frac{i(\not{q} + m_\Psi)}{q^2 - m_\Psi^2} \times \gamma^\alpha P_L \\
&+ \gamma^\alpha P_L \times \frac{i(\not{q}' + m_\Psi)}{q'^2 - m_\Psi^2} \times \gamma^\mu P_L]v(k_2)
\end{aligned}
$$

- The polarization vectors are:

$$
\epsilon^\mu_{\lambda=\pm 1} = \mp(0, 1, \pm i, 0)/\sqrt{2}, \qquad \epsilon^\mu_{\lambda=0} = (0, 0, 0, 1)
$$

Back Up

- The Dirac spinors for considered fermions:

$$u(k_1) = \left(\frac{k_1.\sigma + m_f}{\sqrt{2(E_f + m_f)}} \xi_1 \quad \frac{k_1.\bar{\sigma} + m_f}{\sqrt{2(E_f + m_f)}} \xi_1 \right)^T$$

$$v(k_2) = \left(\frac{k_2.\sigma + m_f}{\sqrt{2(E_{\bar{f}} + m_f)}} \xi_2 \quad - \frac{k_2.\bar{\sigma} + m_f}{\sqrt{2(E_{\bar{f}} + m_f)}} \xi_2 \right)^T$$

Back Up

- The three body annihilation cross-section:

$$v d\sigma = \frac{|\mathcal{M}|^2}{256\pi^3} dx dy$$

- The coordinate considered (two body):

$$k_1^\mu = (m_B, 0, 0, m_B), \qquad k_2^\mu = (m_B, 0, 0, -m_B)$$

- The coordinate considered (three body):

$$l_1 = \Big(E_\gamma, 0, 0, E_\gamma\Big), \qquad k_1 = \Big(E_f, E_f \sin\theta_1, 0, E_f \cos\theta_1\Big)$$

$$k_2 = \Big(E_{\bar{f}}, E_{\bar{f}} \sin\theta_2, 0, E_{\bar{f}} \cos\theta_2\Big)$$