Complementary Constraints on LDM
from Heavy Meson Decays

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[arXiv:1404.6599]
with Nicolas Fernandez, Jason Kumar and Ilsoo Seong

Quarkonium Decays to Light Dark Matter (LDM)

bilinear	C	P	J	state
$\bar{\psi}\psi$	+	+	0	$S=1,\ L=1$
$\imath\bar{\psi}\gamma^5\psi$	+	-	0	$S=0,\ L=0$
$\bar{\psi}\gamma^0\psi$	-	+	0	none
$\bar{\psi}\gamma^i\psi$	-	-	1	$S=1,\ L=0,2$
$\bar{\psi}\gamma^0\gamma^5\psi$	+	-	0	$S=0,\ L=0$
$\bar{\psi}\gamma^i\gamma^5\psi$	+	+	1	$S=1,\ L=1$
$\bar{\psi}\sigma^{0i}\psi$	-	-	1	$S=1,\ L=0,2$
$\bar{\psi}\sigma^{ij}\psi$	-	+	1	$S=0,\ L=1$
$\phi^\dagger\phi$	+	+	0	$S=0,\ L=0$
$\imath Im(\phi^\dagger\partial^0\phi)$	-	+	0	none
$\imath Im(\phi^\dagger\partial^i\phi)$	-	-	1	$S=0,\ L=1$
$B_\mu^\dagger B^\mu$	+	+	0	$S=0,\ L=0;\ S=2,\ L=2$
$\imath Im(B_\nu^\dagger\partial^0 B^\nu)$	-	+	0	none
$\imath Im(B_\nu^\dagger\partial^i B^\nu)$	-	-	1	$S=0,\ L=1;\ S=2,\ L=1,3$
$\imath(B_i^\dagger B_j - B_j^\dagger B_i)$	-	+	1	$S=1,\ L=0,2$
$\imath(B_i^\dagger B_0 - B_0^\dagger B_i)$	-	-	1	$S=0,\ L=1;\ S=2,\ L=1,3$
$\epsilon^{0ijk}B_i\partial_j B_k$	+	-	0	$S=1,\ L=1$
$-\epsilon^{0ijk}B_0\partial_j B_k$	+	+	1	$S=2,\ L=2$
$B^\nu\partial_\nu B_0$	+	+	0	$S=0,\ L=0;\ S=2,\ L=2$
$B^\nu\partial_\nu B_i$	+	-	1	$S=1,\ L=1$

$\Upsilon(1S)$ and J/Ψ Bilinears

Need $J^{PC} = 1^{--}$ $q\bar{q}$ bound states:
Either $\bar{q}\gamma^i q$ or $\bar{q}\sigma^{0i}q$ couples to DM

Invisible Decays

- Can constrain SM-DM interactions for $2m_X < M$
- e^+/e^- colliders provide novel probe for nonWIMP DM with $10\,\mathrm{MeV} < m_X < 10\,\mathrm{GeV}$

Previous Work

arXiv: 0910.2587, 0712.0016, 1305.6609, 1005.1277, 0909.4919

Use $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ to Detect $\Upsilon(1S)$ Peak

$$M_{rec}^2 = s + M_{\pi\pi}^2 - 2\sqrt{s}E_{\pi\pi}^*$$

- M_{rec} recoil mass distribution
- $M_{\pi\pi}$ invariant mass of dipion
- $E_{\pi\pi}^*$ dipion energy $\Upsilon(3S)$ frame
- $\sqrt{s} \sim 10\,\mathrm{GeV}$ $\Upsilon(3S)$ resonance

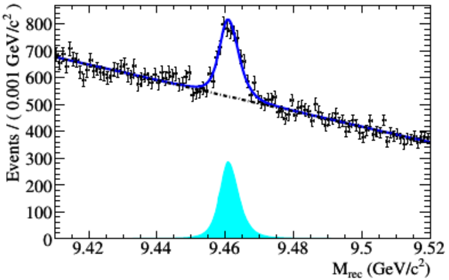


Figure: Maximum likelihood fit for M_{rec} at BaBar [arXiv:0908.2840]. The total fit (solid line) is composed of nonpeaking background (dashed line) and peaking component (solid filled). Invisible width calculated by subtracting background peak contribution.

$$\mathcal{B}(\Upsilon(1S) \to invisible) < 3.0 \times 10^{-4}$$
$$\mathcal{B}(J/\Psi \to invisible) < 7.2 \times 10^{-4}$$

$$\mathcal{B}(\Upsilon(1S) \to \nu\bar{\nu}) = 9.85 \times 10^{-6}$$
$$\mathcal{B}(J/\Psi \to \nu\bar{\nu}) = 2.70 \times 10^{-8}$$

Limits on Diffuse Gamma Ray Flux

$$\mu(\Phi_{PP}, J) = (A_{eff} T_{obs}) \times \frac{\langle \sigma_A v \rangle}{8\pi m_X^2} \int_{E_{thr}}^{m_X} \frac{dN_\gamma}{dE_\gamma} dE_\gamma \times \int_{\Delta\Omega} \int_l \rho_X^2 \, dl \, d\Omega$$

Expected number of signal events factorizes nicely into particle physics and DM astrophysics, with annihilation cross section $\langle \sigma_A v \rangle$ and associated photon spectrum dN_γ / dE_γ along l over solid angle $\Delta\Omega$ [arXiv:1108.2914].

Dwarf Spheroidal Galaxies

- Large DM content inferred by observation of baryons
- Lack of SM astrophysical production mechanisms
- Correlate with DM annihilation signals at Galactic center

Navarro-Frenk-White DM Density Profile

$$\rho_X(r) = \frac{\rho_{X0} r_s^3}{r(r_s + r)^2}$$

Particle Physics Constraint from Stacked Analysis of Dwarf Spheroidal Galaxies

$$\Phi_{PP} < 5.0^{+4.3}_{-4.5} \times 10^{-30} \, \mathrm{cm}^3 \, \mathrm{s}^{-1} \, \mathrm{GeV}^{-2}$$

Relevant Effective Contact Operators

Name	Interaction Structure	Annihilation	Scattering
F5	$(1/\Lambda^2)\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$	Yes	SI
F6	$(1/\Lambda^2)\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	No	No
F9	$(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q$	Yes	SD
F10	$(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu}q$	Yes	No
S3	$(1/\Lambda^2)\imath Im(\phi^\dagger\partial_\mu\phi)\bar{q}\gamma^\mu q$	No	SI
V3	$(1/\Lambda^2)\imath Im(B^\dagger_\nu\partial_\mu B^\nu)\bar{q}\gamma^\mu q$	No	SI
V5	$(1/\Lambda)(B^\dagger_\mu B_\nu - B^\dagger_\nu B_\mu)\bar{q}\sigma^{\mu\nu}q$	No	SD
V7	$(1/\Lambda^2)B^{(\dagger)}_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu q$	No	No
V9	$(1/\Lambda^2)\epsilon^{\mu\nu\rho\sigma}B^{(\dagger)}_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu q$	No	No

Table: EFT operators which can mediate the decay of a $J^{PC} = 1^{--}$ quarkonium bound state. We also indicate if the operator can permit an s-wave dark matter initial state to annihilate to $q\bar{q}$; if so, then a bound can also be set by indirect observations of photons originating from dwarf spheroidals. Lastly, we indicate if the operator can mediate velocity-independent scattering [arXiv:1305.1611].

Relevant Bilinears for Our Matrix Elements

Bilinear	C	P	J	State
$\bar{\psi}\gamma^i\psi$	$-$	$-$	1	$S=1, L=0,2$
$\bar{\psi}\gamma^i\gamma^5\psi$	$+$	$+$	1	$S=1, L=1$
$\bar{\psi}\sigma^{0i}\psi$	$-$	$-$	1	$S=1, L=0,2$
$\imath Im(\phi^\dagger\partial^i\phi)$	$-$	$-$	1	$S=0, L=1$
$\imath Im(B_\nu^\dagger\partial^i B^\nu)$	$-$	$-$	1	$S=0, L=1; S=2, L=1,3$
$\imath(B_i^\dagger B_0 - B_0^\dagger B_i)$	$-$	$-$	1	$S=0, L=1; S=2, L=1,3$
$-\epsilon^{0ijk}B_0\partial_j B_k$	$+$	$+$	1	$S=2, L=2$
$B_\nu\partial^\nu B_i$	$+$	$-$	1	$S=1, L=1$

Table: Bilinears for either bound state quarkonium or dark matter.

Branching Fractions to Scalar and Fermionic Dark Matter

$$\mathcal{B}_{F5}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{16\pi^2\alpha^2 Q^2\Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{1/2}\left(1+\frac{2m_X^2}{M^2}\right)$$

$$\mathcal{B}_{F6}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{16\pi^2\alpha^2 Q^2\Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}$$

$$\mathcal{B}_{F9}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{8\pi^2\alpha^2 Q^2\Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{1/2}\left(1+\frac{8m_X^2}{M^2}\right)$$

$$\mathcal{B}_{F10}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{8\pi^2\alpha^2 Q^2\Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}$$

$$\mathcal{B}_{S3}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{256\pi^2\alpha^2 Q^2\Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}$$

We have written the decay rates in terms of $\mathcal{B}(e^+e^-)$ instead of $\psi(0)$. Note $q = b$ for $\Upsilon(1S)$ or $q = c$ for J/ψ. F6, F10 and S3 are p-wave suppressed because the DM bilinears can't annihilate an $L = 0$ state.

Branching Fractions to Vector Dark Matter

$$\mathcal{B}_{V3}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{128\pi^2\alpha^2 Q^2\Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}\left(1+\frac{M^4}{8m_X^4}\left(1-\frac{2m_X^2}{M^2}\right)^2\right)$$

$$\mathcal{B}_{V5}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^2}{16\pi^2\alpha^2 Q^2\Lambda^2}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}\frac{M^2}{m_X^2}\left(1+\frac{M^2}{4m_X^2}\right)$$

$$\mathcal{B}_{V7}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{64\pi^2\alpha^2 Q^2\Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}\frac{M^2}{m_X^2}$$

$$\mathcal{B}_{V9}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{256\pi^2\alpha^2 Q^2\Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{5/2}\frac{M^2}{m_X^2}$$

Terms in which scale as m_X^{-2} (m_X^{-4}) have one (two) longitudinally polarized vector boson in a final state with total spin $S = 1$ ($S = 0, 2$). Note the constraints from unitarity are trivial in the non-relativistic limit, because the elastic scattering cross section is at threshold [eg arXiv:1403.6610].

$\Upsilon(1S)$ Mediator Scale

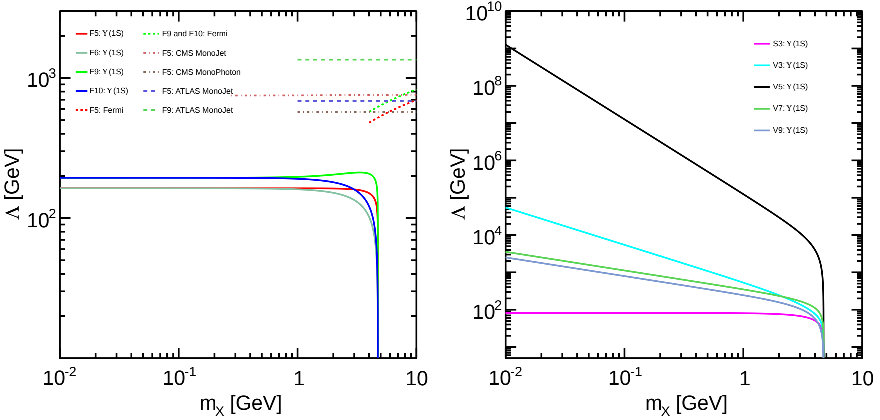


Figure: Bounds on the mediator scale, Λ, for fermionic and scalar DM (left panel) and vector DM (right panel) of mass m_X arising from constraints on $\Upsilon(1S) \to$ *nothing* decays, from constraints on DM annihilation to light quarks in dwarf spheroidal galaxies, and from monojet/photon searches at LHC.

Scattering Cross Sections

We are looking for velocity independent scattering off of protons

$$\sigma^p_{SI} \sim \mu_p^2 \left| \sum_q \frac{B^p_q}{m_X m_q} \mathcal{M}_{Xq\to Xq} \right|^2 , \quad \sigma^p_{SD} \sim \mu_p^2 \left| \sum_q \frac{\delta^p_q}{m_X m_q} \mathcal{M}_{Xq\to Xq} \right|^2$$

$$\sigma^{F5}_{SI} = \frac{\mu_p^2}{\pi\Lambda^4}\left(B^p_u + B^p_d\right)^2$$

$$\sigma^{S3}_{SI} = \sigma^{V3}_{SI} = \frac{\mu_p^2}{4\pi\Lambda^4}\left(B^p_u + B^p_d\right)^2$$

$$\sigma^{F9}_{SD} = \frac{12\mu_p^2}{\pi\Lambda^4}\left(\delta^p_u + \delta^p_d\right)^2$$

$$\sigma^{V5}_{SD} = \frac{2\mu_p^2}{\pi\Lambda^2 m_X^2}\left(\delta^p_u + \delta^p_d\right)^2$$

Form Factors and Comments

- $B^p_u = B^n_d = 2, \ B^n_u = B^p_d = 1$
- $\delta^p_u = 0.54^{+0.09}_{-0.22}, \ \delta^p_d = -0.23^{+0.09}_{-0.16}$
- Need universal coupling to u, d
- Enhancement from longitudinal polarization of vector LDM
- Enhancement from dimension 5

$\Upsilon(1S)$ Complementary Bounds on Dark Matter Scattering

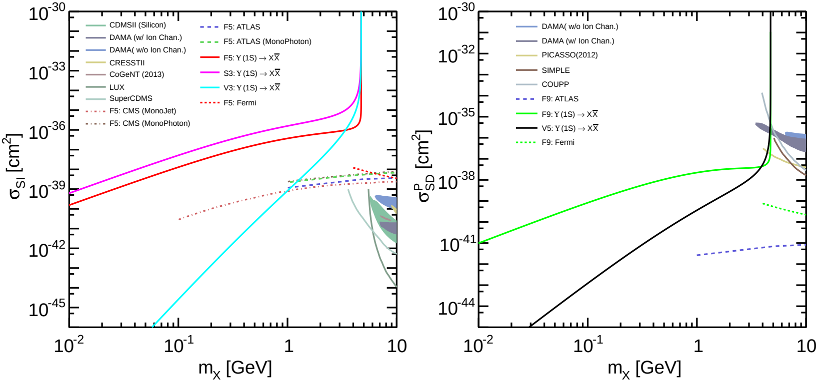


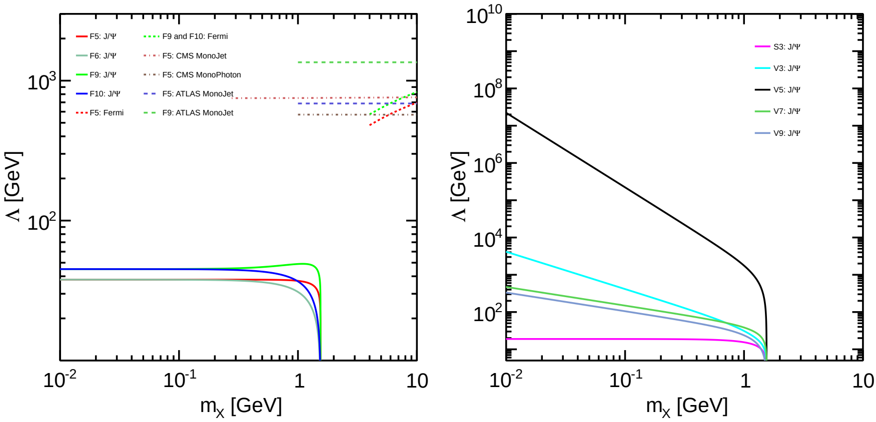
Figure: DM-p SI (left panel) and SD (right panel) scattering for DM coupling universally to quarks through the indicated effective contact operator. The labeled exclusion contours indicate 90 % CL from limits on invisible decays of $\Upsilon(1S)$, 95 % CL from Fermi constraints, and 90 % CL from monojet searches. Signal regions are also shown, as are the 90 % CL exclusion contours from direct detection.

Summary and Outlook

- LDM bounds from Fermi for $m_X \gtrsim 1\,\mathrm{GeV}$ compliment $\Upsilon(1S)$ decay bounds at lower m_X
- Bounds from LHC stronger, constrained by unitarity
- $\Upsilon(1S)$ EFT valid for mediator mass $\sim 10\,\mathrm{GeV} - 1\,\mathrm{TeV}$
- LDM mass better resolved by $\sqrt{s} \sim 10\,\mathrm{GeV}$ beam energy
- Complements LHC searches by distinguishing operators which vanish in nonrelativistic limit
- J/Ψ bounds are weaker, allow larger range of mediator masses

- UV completions with dark $U(1)$
- Better constraints on decays to *nothing* $+\gamma$ through dark A'
- Improved sensitivity to invisible decays at BELLEII and BESIII

J/Ψ Mediator Scale



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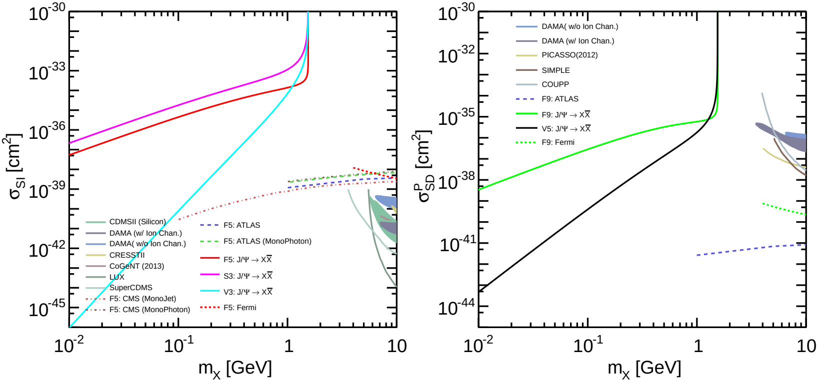
J/Ψ Complementary Bounds on Dark Matter Scattering



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