Invisible widths of heavy mesons

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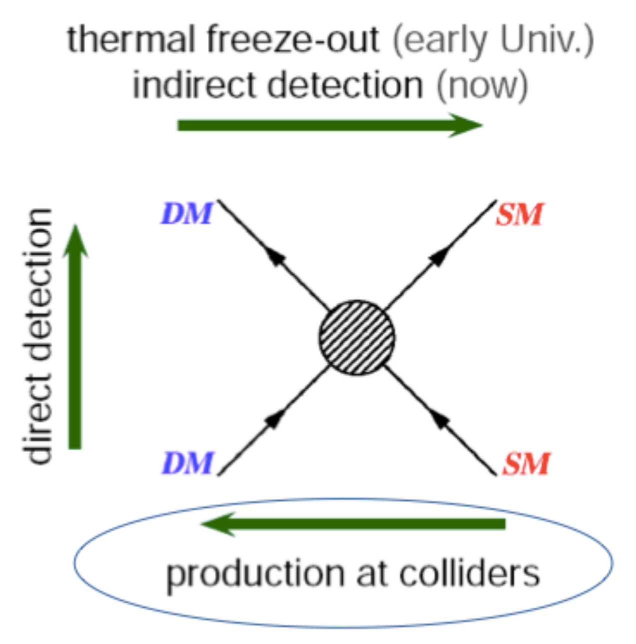
Table of Contents:

- There is compelling evidence for Dark Matter (DM) from its gravitational influence on stars in galaxies, etc.
  - … but DM does not have to have EW-scale mass (WIMP miracle)

Pospelov, Ritz, Voloshin;
Feng, Rajaraman, Takayava;
Dolgov, Hansen,; etc.

$$\Omega_{DM} h^2 \sim \langle \sigma_{ann} v_{rel} \rangle^{-1} \propto \frac{M^2}{g^4}$$

  - If DM is light ($M_{DM} < 5$ GeV), we can use heavy flavored particle decays to probe its properties
  - EFT description: lots of effective operators! Selecting quantum numbers of the decaying meson may help in determining spin and other quantum numbers of the Dark Matter states



Light DM states in meson decays

- If DM couples to quarks, it can appear
  - in the final states with other hadronic/leptonic/… states
    - … which might reduce available phase space (mass effects)
  - as "invisible" final states (M → nothing)
    - … which can be studied at e^+e^- machines
- Meson decays can be advantageous if DM couplings to quarks depend on quark mass
- Consider decays of "designer states" (M: spin-1 and spin-0)
  - kinematics: possibility to constrain Wilson coefficients of effective operators without invoking "single operator dominance" (SOD)
  - can be used to study DM with or w/out Z_2 symmetry
  - have different (irreducible) SM background (M → neutrinos)

Experimental constraints on invisible widths

- Experimental constraints on invisible widths
  - for 1^{--} quarkonium states

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

BaBar (2009),
BES (2008)

  - for 0^{-} heavy pseudoscalar states

$$\mathcal{B}(B_d^0 \to \text{invisible}) < 1.3 \times 10^{-4}$$
$$\mathcal{B}(B_d^0 \to \text{invisible}) < 2.4 \times 10^{-5}$$
$$\mathcal{B}(D^0 \to \text{invisible}) < 9.4 \times 10^{-5}$$

Belle (2012),
BaBar (2012)
Belle (2017)

  - new data will be available from BES III and Belle II

2. Invisible decays of vector quarkonium states

- Any studies of [bb]([cc]) → missing energy + X would have SM background
  - Invisible decays of heavy quarkonium (BR): two neutrino states

$$B(\Upsilon(1S) \to \nu\bar{\nu}) = \frac{\Gamma(\Upsilon(1S) \to \nu\bar{\nu})}{\Gamma_{\Upsilon(1S)}} = \frac{N_\nu G_F^2}{48\pi}\left(1 - \frac{4}{3}\sin^2\theta_W\right)^2 \frac{f^2_{\Upsilon(1S)} M^3_{\Upsilon(1S)}}{\Gamma_{\Upsilon(1S)}}$$

Chang, Lebedev, Ng (1998); Yeghiyan (2009)

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

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

BaBar (2009), BES (2008)

  - Decays with photons and missing energy (BR & γ-spectrum)

$$B(\Upsilon(3S) \to \nu\bar{\nu}\gamma) = \frac{N_\nu G_F^2}{243\pi} \frac{\alpha}{4\pi} \frac{f^2_{\Upsilon(3S)} M^3_{\Upsilon(3S)}}{\Gamma_{\Upsilon(3S)}}$$

Theory: $B(\Upsilon(3S) \to \nu\bar{\nu}\gamma) = (3.14^{+0.38}_{-0.32}) \times 10^{-9}$

Experiment: $B(\Upsilon(3S) \to \gamma + \text{invisible}) < (0.7\text{–}31) \times 10^{-6}$,

Currently, SM "physics" background in not an issue.

Light Dark Matter in vector quarkonium decays

- Effective Lagrangian analysis of low-mass Dark Matter
  - Leading-order operators for DM relevant for the 1^{--} quarkonium decays for the spin-1/2 (X), spin-0 (ϕ), and spin-1 (B_μ) DM states

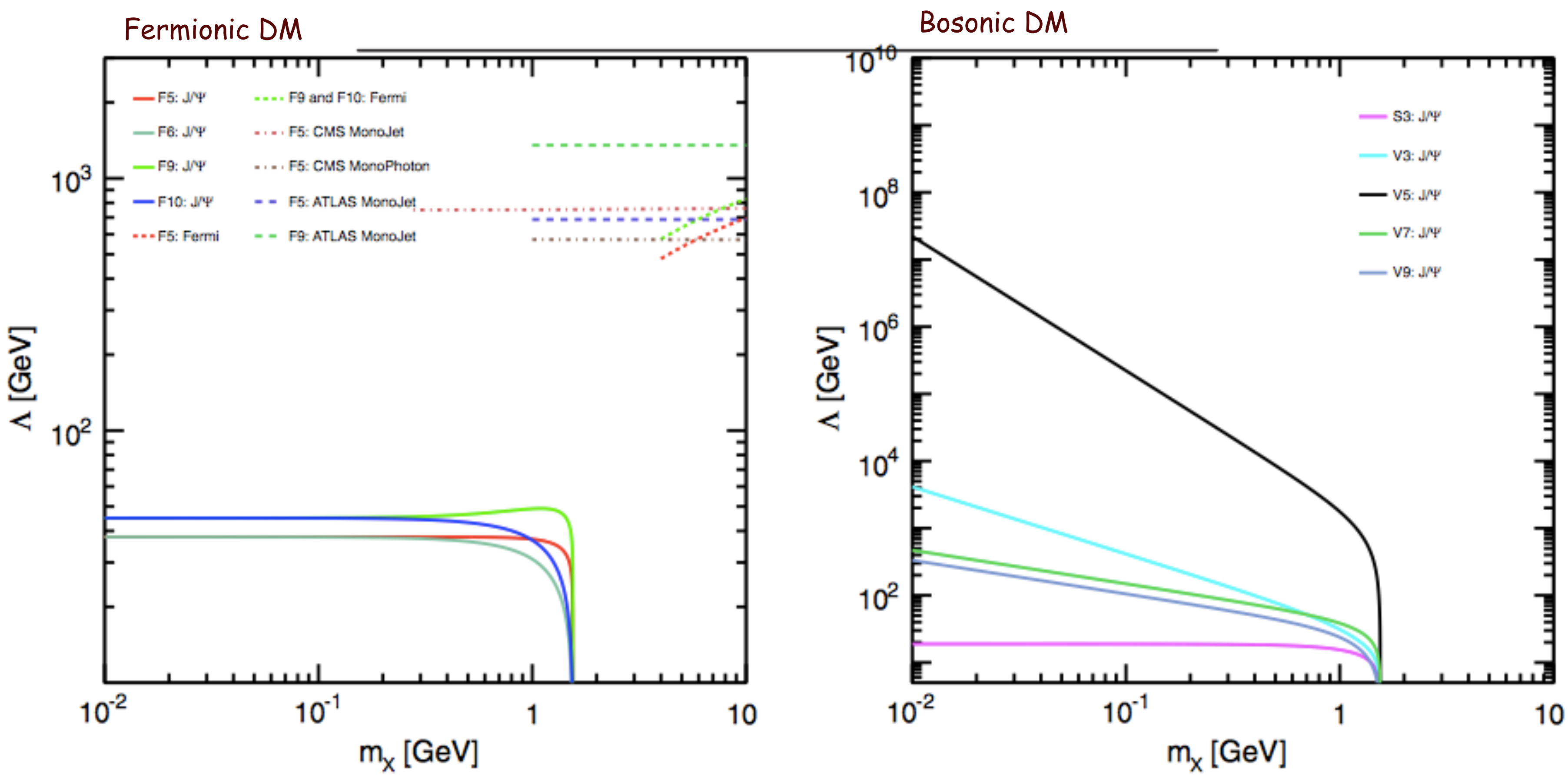
Fernandez, Kumar, Seong, Stengel (2014)

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	$(1/\Lambda^2)\imath\,\mathrm{Im}(\phi^\dagger\partial_\mu\phi)\bar{q}\gamma^\mu q$	No	SI
V3	$(1/\Lambda^2)\imath\,\mathrm{Im}(B^\dagger_\nu\partial_\mu B^\nu)\bar{q}\gamma^\mu q$	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	$(1/\Lambda^2)\varepsilon^{\mu\nu\rho\sigma}B^{(\dagger)}_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu q$	No	No

  - note that only three operators will contribute to invisible decays
  - there is no need to assume that other Wilson coefficients are small (SOD)

Light Dark Matter in vector quarkonium decays

- Constraints on NP scale Λ from J/ψ decays (use dipion decays of ψ'')



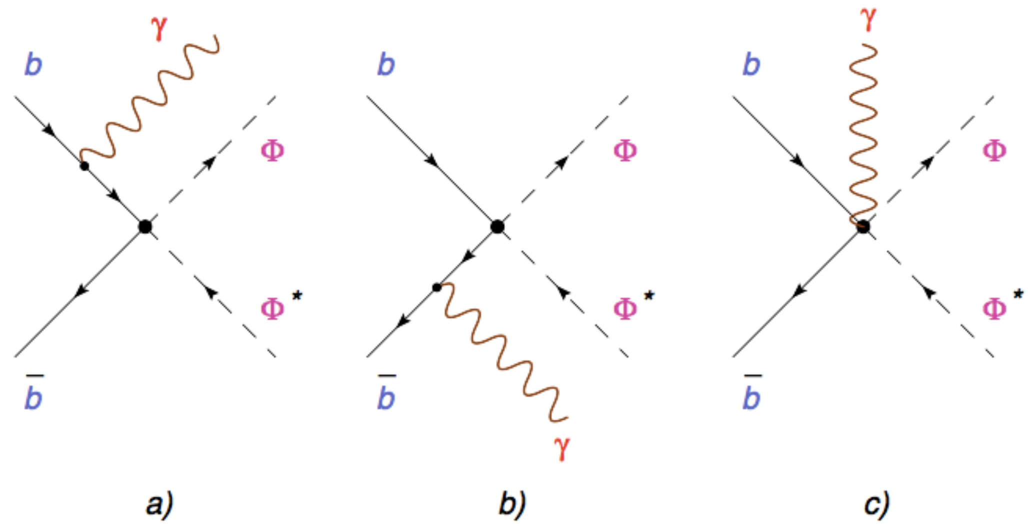
  – Higher luminosities will provide more stringent constraints

Fernandez, Kumar, Seong, Stengel (2014)

Light Dark Matter in vector quarkonium decays

- Effective Lagrangian analysis of low-mass Dark Matter
  - New operators would appear for **Υ**(nS) → γ + missing energy

Yeghiyan (2009)
Fayet (2009)

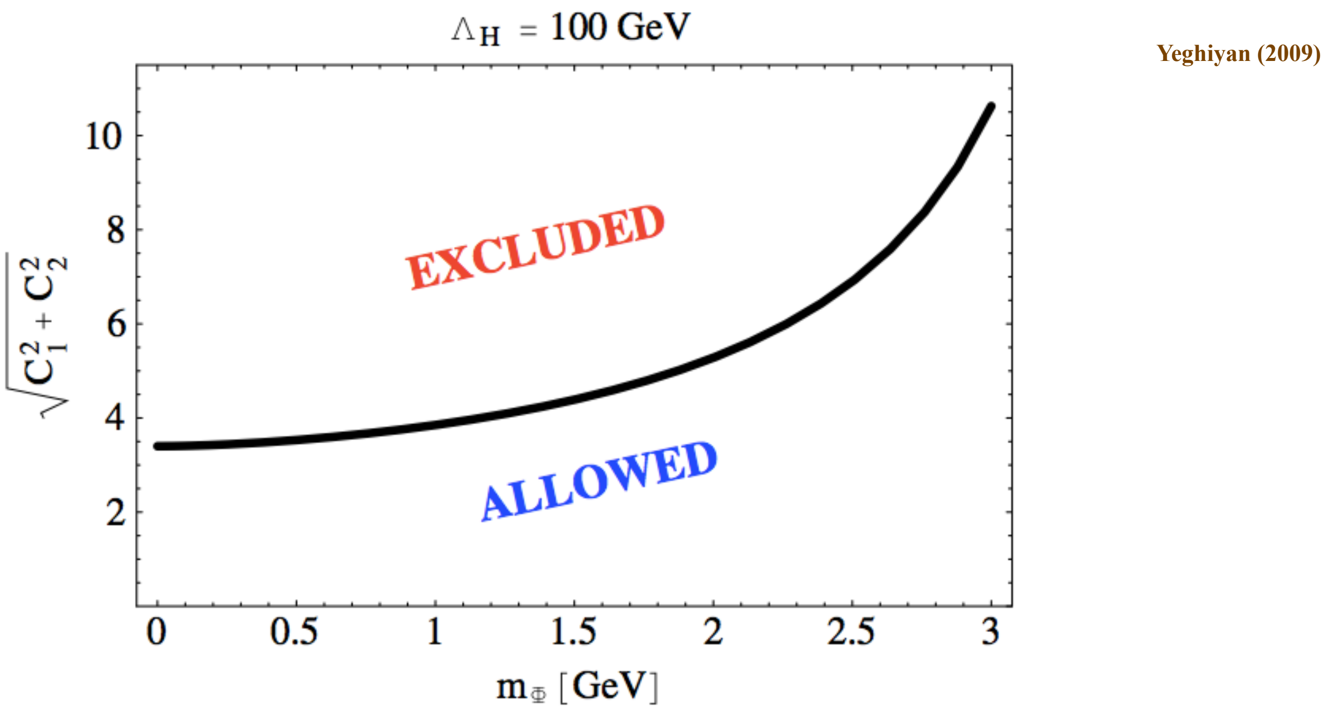


  - For scalar DM only two new operators contribute, $H_{\rm eff} = \frac{2}{\Lambda_H^2}\sum_i C_i O_i,$

$$O_1 = m_b(\bar{b}b)(\Phi^*\Phi), \qquad O_2 = im_b(\bar{b}\gamma_5 b)(\Phi^*\Phi),$$

$$O_3 = (\bar{b}\gamma^\mu b)(\Phi^* i\overleftrightarrow{\partial}_\mu \Phi), \qquad O_4 = (\bar{b}\gamma^\mu\gamma_5 b)(\Phi^* i\overleftrightarrow{\partial}_\mu \Phi),$$

- Constraints on Wilson coefficients from **Υ** (ns) decays



- Higher luminosities will provide more stringent constraints
- Easy to provide specific models for DM, e.g. $-\mathcal{L} = \frac{m_0^2}{2}\Phi^2 + \lambda_1\Phi^2|H_1|^2 + \lambda_2\Phi^2|H_2|^2 + \lambda_3\Phi^2(H_1H_2 + \text{H.c}),$
- … in which case, $|\lambda_3| < \left(\frac{17.4}{\tan\beta}\right)\left(\frac{m_{H^0}}{160\text{ GeV}}\right)^2 f^{-1/2}(x_\Phi).$

2. Invisible decays of pseudoscalar states

- Invisible decays of pseudoscalar B or D states are flavor-violating
  - SM background consists of decays into neutrino final states

★ SM process: B(D) $\rightarrow \nu\nu$

- for B-decays $J^{\mu}_{Qq} = \bar{q}_L \gamma^{\mu} b_L$
- for D-decays $J^{\mu}_{Qq} = \bar{u}_L \gamma^{\mu} c_L$
- and $X(x_t) = \frac{x_t}{8}\left[\frac{x_t+2}{x_t-1} + \frac{3(x_t-2)}{(x_t-1)^2}\ln x_t\right]$

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \times \sum_{l=e,\mu,\tau} \sum_k \lambda_k X^l(x_k) \left(J^{\mu}_{Qq}\right) \left(\overline{\nu}^l_L \gamma_\mu \nu^l_L\right)$$

Badin, AAP
PRD82 (2010) 034005

★ For B(D) $\rightarrow \nu\nu$ decays SM branching ratios are tiny

- SM decay is helicity suppressed, $x_\nu = m_\nu / M_{B_q}$

$$\mathcal{B}(B_s \rightarrow \nu\bar{\nu}) = \frac{G_F^2 \alpha^2 f_B^2 M_B^3}{16\pi^3 \sin^4\theta_W \Gamma_{B_s}} |V_{tb}V_{ts}^*|^2 X(x_t)^2 x_\nu^2$$

- NP: other ways of flipping helicity?

Decay	Branching ratio
$B_s \rightarrow \nu\bar{\nu}$	3.07×10^{-24}
$B_d \rightarrow \nu\bar{\nu}$	1.24×10^{-25}
$D^0 \rightarrow \nu\bar{\nu}$	1.1×10^{-30}

★ More precisely, invisible B(D)-decays in the SM:

Bhattacharya, Grant, AAP
arXiv:1809.04606 [hep-ph]

$$\mathcal{B}\left(B_q \rightarrow \not{E}\right) = \mathcal{B}\left(B_q \rightarrow \nu\bar{\nu}\right) + \mathcal{B}\left(B_q \rightarrow \nu\bar{\nu}\nu\bar{\nu}\right) + \ldots,$$

Invisible widths of pseudoscalar states in the SM

- Invisible widths are dominated by a four-neutrino state in the SM!

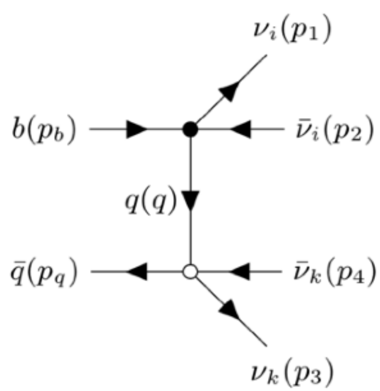
$$\mathcal{B}\left(B_q \to \not{E}\right) = \mathcal{B}\left(B_q \to \nu\bar{\nu}\right) + \mathcal{B}\left(B_q \to \nu\bar{\nu}\nu\bar{\nu}\right) + ...,$$

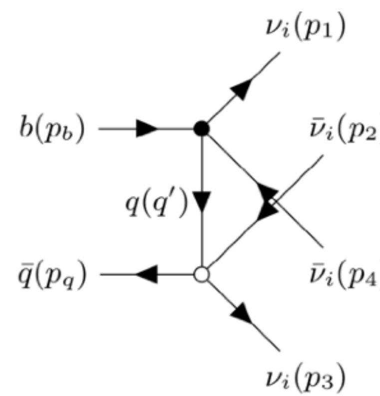
– emission of extra neutrino pair lifts helicity suppression, expect

$$\frac{\mathcal{B}\left(B_q \to \nu\bar{\nu}\nu\bar{\nu}\right)}{\mathcal{B}\left(B_q \to \nu\bar{\nu}\right)} \sim \frac{G_F^2 M_B^4}{16\pi^2 x_\nu^2} \gg 1$$

Bhattacharya, Grant, AAP
arXiv:1809.04606 [hep-ph]

– the calculation is a bit more involved (4-body final state, formfactors, etc.)





– use a simple model to evaluate meson form-factors

Invisible widths of pseudoscalar states in the SM

- Invisible widths are dominated by a four-neutrino state in the SM!
  - decay amplitude involves a form-factor

$$\mathcal{A}_q = -\frac{G_F^2 \alpha V_{tq}^* V_{tb} X(x_t)}{4\pi \sin^2\theta_w} \sum_{i,k} L^{\mu}_{\ell_i} L^{\nu}_{\ell_k} \langle 0|\bar{q}\Gamma_{\mu\nu} b|B_q\rangle$$

  - ... which is calculated within a simple quark model

$$\langle 0|\, \bar{q}\Gamma^{\mu\nu} b\,|B_s\rangle = \int_0^1 dx\ \mathrm{Tr}\left[\Gamma^{\mu\nu}\psi_B\right]$$

... where the wave function is

$$\psi_B = \frac{I_c}{\sqrt{6}}\phi_B(x)\gamma^5\left(\not{P}_B + M_B g_B(x)\right)$$

$$\phi_B(x) = \frac{f_B}{2\sqrt{3}}\delta(1-x-\xi)$$

  - calculating 4-body phase space integrals yield rates consistent with our expectations

Decay	Branching ratio
$B_s^0 \to 4\nu$	5.5×10^{-15}
$B_d^0 \to 4\nu$	1.5×10^{-16}
$D^0 \to 4\nu$	3.0×10^{-27}

Bhattacharya, Grant, AAP
arXiv:1809.04606 [hep-ph]

Invisible decays of pseudoscalar states

- Similarly, for the radiative neutrino modes…

★ For B(D) → $\nu\nu\gamma$ decays SM branching ratios are still tiny

- need form-factors to describe the transition

$$\langle\gamma(k)|\bar{b}\gamma_\mu q|B_q(k+q)\rangle = e\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}q^\rho k^\sigma \frac{f_V^B(q^2)}{M_{B_q}}$$

$$\langle\gamma(k)|\bar{b}\gamma_\mu\gamma_5 q|B_q(k+q)\rangle = -ie[\epsilon_\mu^*(kq) - (\epsilon^* q)k_\mu] \times \frac{f_A^B(q^2)}{M_{B_q}},$$

$$\langle\gamma(k)|\bar{b}\sigma_{\mu\nu} q|B_q(k+q)\rangle = \frac{e}{M_{B_q}^2}\epsilon_{\mu\nu\lambda\sigma}[G\epsilon^{*\lambda}k^\sigma + H\epsilon^{*\lambda}q^\sigma + N(\epsilon^* q)q^\lambda k^\sigma]$$

Decay	Branching ratio
$B_s \to \nu\bar{\nu}\gamma$	3.68×10^{-8}
$B_d \to \nu\bar{\nu}\gamma$	1.96×10^{-9}
$D^0 \to \nu\bar{\nu}\gamma$	3.96×10^{-14}

Can calculate photon energy distributions as well.

Badin, AAP (2010)

- helicity suppression is lifted

$$A(B_q \to \nu\bar{\nu}\gamma) = \frac{2eC_1^{\rm SM}(x_t)}{M_{B_q}}[\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}q^\rho k^\sigma f_V^B(q^2) + i[\epsilon_\mu^*(kq) - (\epsilon^* q)k_\mu]f_A^B(q^2)]\bar{\nu}_L\gamma^\mu\nu_L,$$

★ BUT: missing energy does not always mean neutrinos

- nice constraints on light Dark Matter properties !!!

Standard Model backgrounds

$$\mathcal{B}\left(B_q \to \not{E}\right) = \mathcal{B}\left(B_q \to \nu\bar{\nu}\right) + \mathcal{B}\left(B_q \to \nu\bar{\nu}\nu\bar{\nu}\right) + ...,$$

Decay	Branching ratio
$B_s \to \nu\bar{\nu}$	3.07×10^{-24}
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$D^0 \to \nu\bar{\nu}\gamma$	3.96×10^{-14}

Currently, SM "physics" background in not an issue. But the effect is cute.

Invisible decays of pseudoscalar states: scalar DM

- Consider invisible decays into a pair of scalar light DM states

★ Generic effective Lagrangian: $\mathcal{H}_{eff} = \sum_i \frac{2C_i^{(s)}}{\Lambda^2} O_i$

- respective neutral currents for B-and D-decays

$$O_1 = m_Q \left(J_{Qq}\right)_{RL} \left(\chi_0^* \chi_0\right)$$
$$O_2 = m_Q \left(J_{Qq}\right)_{LR} \left(\chi_0^* \chi_0\right)$$
$$O_3 = \left(J_{Qq}^\mu\right)_{LL} \left(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0\right)$$
$$O_4 = \left(J_{Qq}^\mu\right)_{RR} \left(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0\right)$$

Badin, AAP (2010)

★ Scalar DM does not exhibit helicity suppression

- $B(D) \to E_{mis}$ is more powerful than $B(D) \to E_{mis}\,\gamma$

$$\mathcal{B}(B_q \to \chi_0\chi_0) = \frac{(C_1^{(s)} - C_2^{(s)})^2}{4\pi M_{B_q}\Gamma_{B_q}} \left(\frac{f_{B_q} M_{B_q}^2 m_b}{\Lambda^2(m_b + m_q)}\right)^2 \times \sqrt{1 - 4x_\chi^2},$$

$$\mathcal{B}(B_q \to \chi_0^*\chi_0\gamma) = \frac{f_{B_q}^2 \alpha C_3^{(s)} C_4^{(s)} M_{B_q}^5}{6\Lambda^4 \Gamma_{B_q}} \left(\frac{F_{B_q}}{4\pi}\right)^2 \times \left(\frac{1}{6}\sqrt{1 - 4x_\chi^2}(1 - 16x_\chi^2 - 12x_\chi^4) - 12x_\chi^4 \log\frac{2x_\chi}{1 + \sqrt{1 - 4x_\chi^2}}\right).$$

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 2.07 \times 10^{-16}\ \text{GeV}^{-4}$$
for $m_\chi = 0.1 \times M_{B_d}$,

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 1.55 \times 10^{-12}\ \text{GeV}^{-4} \quad \text{for } m = 0,$$
$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 7.44 \times 10^{-11}\ \text{GeV}^{-4} \quad \text{for } m = 0.4 \times M_{B_d}$$

These general bounds translate into constraints onto constraints for particular models

Example of a particular model of scalar DM

★ Several different models of light scalar DM
- simplest: singlet scalar DM
- more sophisticated - less restrictive

$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$
$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{\rm EW}^2)S^2 + \lambda v_{\rm EW} S^2 h$$
$$+ \frac{\lambda}{2}S^2 h^2,$$

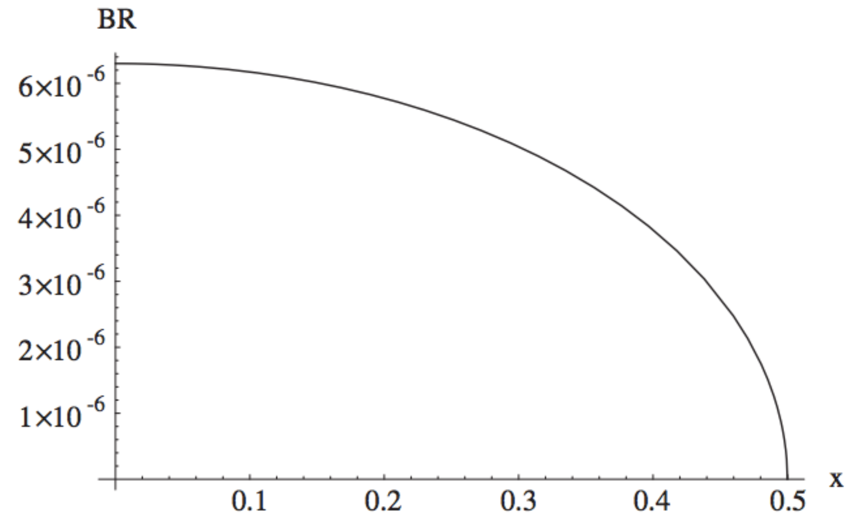
Pospelov, Ritz, Voloshin;

★ B(D) decays rate in this model

$$\mathcal{B}(B_q \to SS) = \left[\frac{3g_w^2 V_{tb}V_{tq}^* x_t m_b}{128\pi^2}\right]^2 \frac{\sqrt{1-4x_S^2}}{16\pi M_B \Gamma_{B_q}}\left(\frac{\lambda^2}{M_H^4}\right) \times \left(\frac{f_{B_q}M_{B_q}^2}{m_b + m_q}\right)^2,$$

- fix λ from relic density

$$\sigma_{\rm ann} v_{\rm rel} = \frac{8 v_{\rm EW}^2 \lambda^2}{M_H^2} \times \lim_{m_{h^*}\to 2m_S} \frac{\Gamma_{h^* X}}{m_h^*}$$



These results are complimentary to constraints from quarkonium decays with missing energy

Invisible decays of pseudoscalar states: fermionic DM

★ Generic effective Lagrangian: $\mathcal{H}_{eff} = \sum_i \frac{4C_i}{\Lambda^2} O_i$

- respective neutral currents for B-and D-decays

$$O_1 = \left(J^{\mu}_{Qq}\right)_{LL} \left(\bar{\chi}_{1/2L}\gamma_\mu \chi_{1/2L}\right)$$
$$O_2 = \left(J^{\mu}_{Qq}\right)_{LL} \left(\bar{\chi}_{1/2R}\gamma_\mu \chi_{1/2R}\right)$$
$$O_3 = O_{1(L\leftrightarrow R)}, \quad O_4 = O_{2(L\leftrightarrow R)}$$
$$O_5 = \left(J_{Qq}\right)_{LR} \left(\bar{\chi}_{1/2L}\ \chi_{1/2R}\right)$$
$$O_6 = \left(J_{Qq}\right)_{LR} \left(\bar{\chi}_{1/2R}\ \chi_{1/2L}\right)$$
$$O_7 = O_{5(L\leftrightarrow R)}, \quad O_8 = O_{6(L\leftrightarrow R)}$$
$$+ \ \text{tensor operators}$$

★ Scalar DM does exhibit helicity suppression

- B(D) → E_{mis} maybe less powerful than B(D) → $E_{mis}\gamma$
- ... but it really depends on the DM mass!

$$\mathcal{B}(B_q \to \bar{\chi}_{1/2}\chi_{1/2}) = \frac{f_{B_q}^2 M_{B_q}^3}{16\pi \Gamma_{B_q} \Lambda^2}\sqrt{1-4x_\chi^2}$$
$$\times \Bigg[C_{57}C_{68}\frac{4M_{B_q}^2 x_\chi^2}{(m_b+m_q)^2} - (C_{57}^2 + C_{68}^2)$$
$$\times \frac{M_{B_q}^2(2x_\chi^2-1)}{(m_b+m_q)^2} - 2\tilde{C}_{1-8}\frac{x_\chi M_{B_q}}{m_b+m_q}$$
$$+ 2(C_{13}+C_{24})^2 x_\chi^2 \Bigg],$$

Badin, AAP (2010)

Lots of operators — less so in particular models

Invisible decays of pseudoscalar states: fermionic DM

Badin, AAP (2010)

★ Constraints from B decays are the best at the moment

TABLE I. Constraints (upper limits) on the Wilson coefficients of operators of Eq. (43) from the $B_q \to \chi_{1/2}\bar{\chi}_{1/2}$ transition. Note that operators Q_9–Q_{12} give no contribution to this decay.

x_χ	C_1/Λ^2, GeV^{-2}	C_2/Λ^2, GeV^{-2}	C_3/Λ^2, GeV^{-2}	C_4/Λ^2, GeV^{-2}	C_5/Λ^2, GeV^{-2}	C_6/Λ^2, GeV^{-2}	C_7/Λ^2, GeV^{-2}	C_8/Λ^2, GeV^{-2}
0	...	...	...	...	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}
0.1	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}
0.2	9.7×10^{-8}	9.7×10^{-8}	9.7×10^{-8}	9.7×10^{-8}	2.5×10^{-8}	2.5×10^{-8}	2.5×10^{-8}	2.5×10^{-8}
0.3	6.9×10^{-8}	6.9×10^{-8}	6.9×10^{-8}	6.9×10^{-8}	2.8×10^{-8}	2.8×10^{-8}	2.8×10^{-8}	2.8×10^{-8}
0.4	6.0×10^{-8}	6.0×10^{-8}	6.0×10^{-8}	6.0×10^{-8}	3.6×10^{-8}	3.6×10^{-8}	3.6×10^{-8}	3.6×10^{-8}

★ … the same is true for the radiative decays with missing energy

TABLE II. Constraints (upper limits) on the Wilson coefficients of operators of Eq. (43) from the $B_q \to \chi_{1/2}\bar{\chi}_{1/2}\gamma$ transition. Note that operators Q_5–Q_8 give no contribution to this decay.

x_χ	C_1/Λ^2, GeV^{-2}	C_2/Λ^2, GeV^{-2}	C_3/Λ^2, GeV^{-2}	C_4/Λ^2, GeV^{-2}
0	6.3×10^{-7}	6.3×10^{-7}	6.3×10^{-7}	6.3×10^{-7}
0.1	7.0×10^{-7}	7.0×10^{-7}	7.0×10^{-7}	7.0×10^{-7}
0.2	9.2×10^{-7}	9.2×10^{-7}	9.2×10^{-7}	9.2×10^{-7}
0.3	1.5×10^{-6}	1.5×10^{-6}	1.5×10^{-6}	1.5×10^{-6}
0.4	3.4×10^{-6}	3.4×10^{-6}	3.4×10^{-6}	3.4×10^{-6}

These general bounds translate into constraints onto constraints for particular models

Extra: dark photons and invisible widths

- Recall that addition of a photon lifted helicity suppression!
  - Assume there is an extra U(1) state V kinetically mixed with weak isospin

$$\mathcal{L} = -\frac{1}{4}W_{3\mu\nu}W^{3\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}V^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu$$

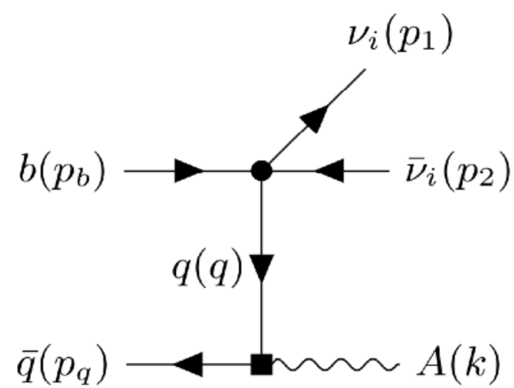
B. Holdom

Note: no direct couplings of V with fermions!

Bhattacharya, Grant, AAP
arXiv:1809.04606 [hep-ph]

  - Eliminating kinetic mixing term (field redefinitions) obtain direct couplings to matter fields $J^\mu_{em} = (2/3)\ \bar{u}\gamma^\mu u - (1/3)\ \bar{d}\gamma^\mu d + \ldots$

$$\mathcal{L} = -e\epsilon\cos\theta_W J^\mu_{em} V'_\mu,$$



  - Lowest order (in ϵ) is then given by two diagrams
  - Current experimental bound on inv. widths gives $\epsilon < 125$ (not competitive)

4. Things to take home

- Light Dark Matter constitutes a viable scenario for DM physics
  - can be searched for in the decays of heavy meson states
- Low energy EFTs for light DM states contain many operators
  - constrained kinematics of the invisible decays may help to determine the quantum numbers of DM states
  - can also help to constrain Wilson coefficients w/out assuming single operator dominance
- Heavy meson decays to neutrino final states constitute irreducible SM physics background to light DM searches
  - proved that invisible decays of pseudoscalar states are dominated by decays into 4-neutrino final state (similarly proved that for kaons)
  - backgrounds are still small enough to not be a problem in the current round of searches
- Looking forward to upcoming improvement of the experimental constraints


EXTRA!