Andriy Badin, Wayne State University

Dark Matter production in heavy meson decays

Based on work done in collaboration with Alexey Petrov [arXiv:1005.1277]

Outline

- General idea
- Formalism
- SM background
- Scalar Dark Matter production
- Fermion Dark Matter production
- Conclusion

General Idea

- Missing energy decays of heavy mesons. Are they due to neutrino or DM?
- Some data for missing energy decays is not available. Our results provide motivation for these studies.
- Compare results for DM production with current experimental bounds and try to rule-out the light DM

SM prediction and experimental data

- Theory
- Experiment

SM prediction and experimental data

- Theory

$$\mathcal{B}(B_s \to \nu\overline{\nu}) \simeq \ 3.07 \times 10^{-24}$$

$$\mathcal{B}(B_d \to \nu\overline{\nu}) \simeq \ 1.24 \times 10^{-25}$$

$$\mathcal{B}(D^0 \to \nu\overline{\nu}) \simeq \ 1.1 \times 10^{-30}$$

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- Experiment

$\mathrm{NO\ DATA}$

$< \; 2.2 \times 10^{-4}[1]$

$\mathrm{NO\ DATA}$

[1] B. Aubert et al., Phys.Rev.Lett.93:091802,2004. [arXiv: hep-ex/0405071]

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$< 4.7 \times 10^{-5}$[1]

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[1] B. Aubert et al., Phys.Rev.Lett.93:091802,2004. [arXiv: hep-ex/0405071]

Formalism

$B_q \to \chi\chi$ decays

$$\begin{aligned}
\langle 0|\,\bar{b}\gamma^{\mu}q\,|B_q\rangle &= \langle 0|\,\bar{b}q\,|B_q\rangle = 0, \\
\langle 0|\,\bar{b}\gamma^{\mu}\gamma_5 q\,|B_q\rangle &= i f_{B_q} P^{\mu} \\
\langle 0|\,\bar{b}\gamma_5 q\,|B_q\rangle &= -i\frac{f_{B_q} M_{B_q}^2}{m_b + m_q}.
\end{aligned}$$

$B_q \to \chi\,\chi\,\gamma$ decays

$$
\begin{aligned}
\langle\gamma(k)|\bar{b}\gamma_\mu q|B_q(k+q)\rangle &= e\;\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}q^\rho k^\sigma\,\frac{f_V^B(q^2)}{M}, \\
\langle\gamma(k)|\bar{b}\gamma_\mu\gamma_5 q|B_q(k+q)\rangle &= -ie\left[\epsilon^*_\mu\,(kq)-(\epsilon^* q)\,k_\mu\right]\,\frac{f_A^B(q^2)}{M}
\end{aligned}
$$

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

$B_q \to \chi\,\chi\,\gamma$ decays

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

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

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

$$f_V^B(E_\gamma) = f_A^B(E_\gamma) = \frac{f_{B_q}M_{B_q}}{2E_\gamma}\left(-Q_q R_q + \frac{Q_b}{m_b}\right) + \mathcal{O}\left(\frac{\Lambda^2_{QCD}}{E^2_\gamma}\right) \equiv \frac{f_{B_q}M_{B_q}}{2E_\gamma}F_{B_q},$$

where $R_q^{-1} \sim M_{B_q} - m_b$, and $F_{B_q} = -Q_q R_q + \frac{Q_b}{m_b} \sim \frac{M_{B_q}Q_b - m_b(Q_b+Q_q)}{m_b(M_{B_q}-m_b)}$.

$B_q \to \chi\, \chi\, \gamma$ decays

$$\begin{aligned}
\langle\gamma(k)|\bar{b}\gamma_\mu q|B_q(k+q)\rangle &= e\ \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}q^\rho k^\sigma \frac{f_V^B(q^2)}{M},\\
\langle\gamma(k)|\bar{b}\gamma_\mu\gamma_5 q|B_q(k+q)\rangle &= -ie\left[\epsilon^*_\mu\,(kq)-(\epsilon^* q)\,k_\mu\right]\frac{f_A^B(q^2)}{M}
\end{aligned}$$

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

$$\begin{aligned}
G &= 4g_1; \qquad N = \frac{-4}{q^2}(f_1+g_1)\\
H &= \frac{-4(qk)}{q^2}(f_1+g_1); \qquad f_1(g_1) = \frac{f_0(g_0)}{(1-q^2/\mu^2_{f(g)})^2}
\end{aligned}$$

Various DM scenario

$$\mathcal{H}_{eff}^{(s)} = 2\sum_i \frac{C_i^{(s)}}{\Lambda^2} O_i$$

- Scalar DM - allows to avoid Lee-Weinberg bound.
- Fermion DM (Dirac or Majorana)
- Vector DM. Don't know about any model with spin=1 DM but provide results for generality

Scalar DM

$$
\begin{aligned}
O_1 &= m_b(\bar{b}_R q_L)(\chi_0^* \chi_0), \\
O_2 &= m_b(\bar{b}_L q_R)(\chi_0^* \chi_0), \\
O_3 &= (\bar{b}_L \gamma^\mu q_L)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0), \\
O_4 &= (\bar{b}_R \gamma^\mu q_R)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0),
\end{aligned}
$$

Scalar DM

$$\begin{aligned} O_1 &= m_b(\bar{b}_R q_L)(\chi_0^* \chi_0), \\ O_2 &= m_b(\bar{b}_L q_R)(\chi_0^* \chi_0), \\ O_3 &= (\bar{b}_L \gamma^\mu q_L)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0), \\ O_4 &= (\bar{b}_R \gamma^\mu q_R)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0), \end{aligned}$$

Most likely there is NO radiative decay.

Scalar DM

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 2.03 \times 10^{-16}\ GeV^{-4} \text{ for } m_\chi = 0$$

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

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 2.22 \times 10^{-16}\ GeV^{-4} \text{ for } m_\chi = 0.2 \times M_{B_d}$$

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 2.54 \times 10^{-16}\ GeV^{-4} \text{ for } m_\chi = 0.3 \times M_{B_d}$$

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 3.39 \times 10^{-16}\ GeV^{-4} \text{ for } m_\chi = 0.4 \times M_{B_d}$$

Scalar DM

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 1.70 \times 10^{-11}\ GeV^{-4} \text{ for } m = 0$$

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 2.03 \times 10^{-11}\ GeV^{-4} \text{ for } m = 0.1 \times M_{B_d}$$

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 3.49 \times 10^{-11}\ GeV^{-4} \text{ for } m = 0.2 \times M_{B_d}$$

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 9.88 \times 10^{-11}\ GeV^{-4} \text{ for } m = 0.3 \times M_{B_d}$$

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 8.11 \times 10^{-10}\ GeV^{-4} \text{ for } m = 0.3 \times M_{B_d}$$

Examples of Scalar DM

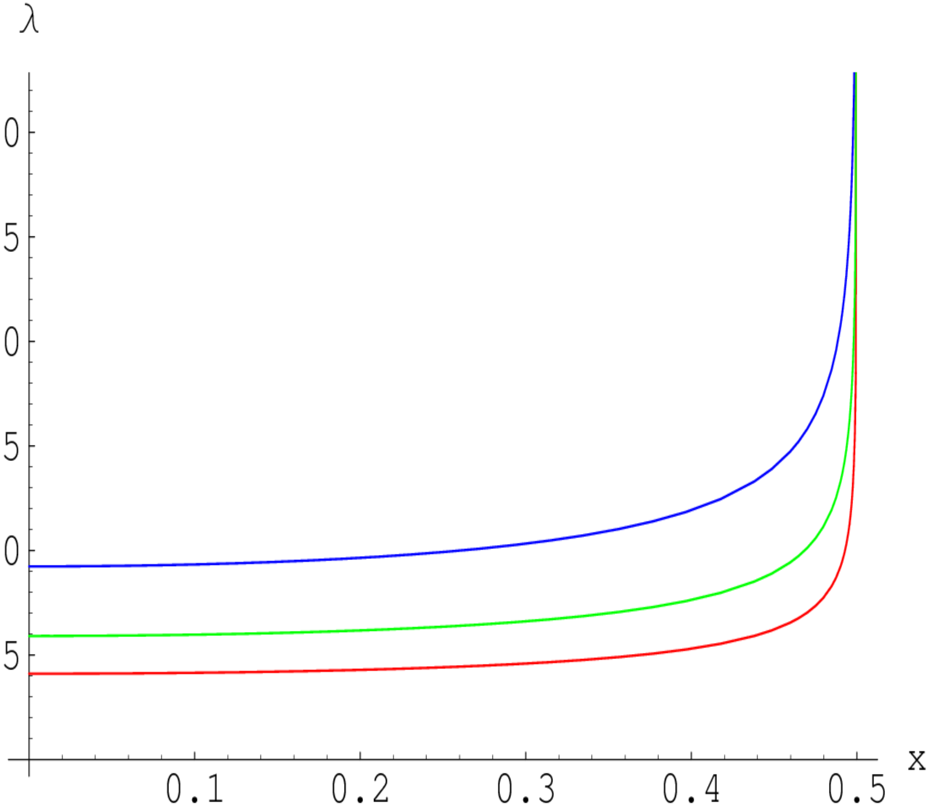
Minimal Scalar DM model [1]

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

$$C_{1,3,4}^{(s)} = 0,\ C_2^{(s)} = 3\lambda g_w^2 V_{ts} V_{tb}^* x_t / 256\pi^2, \text{ and } \Lambda = M_H$$

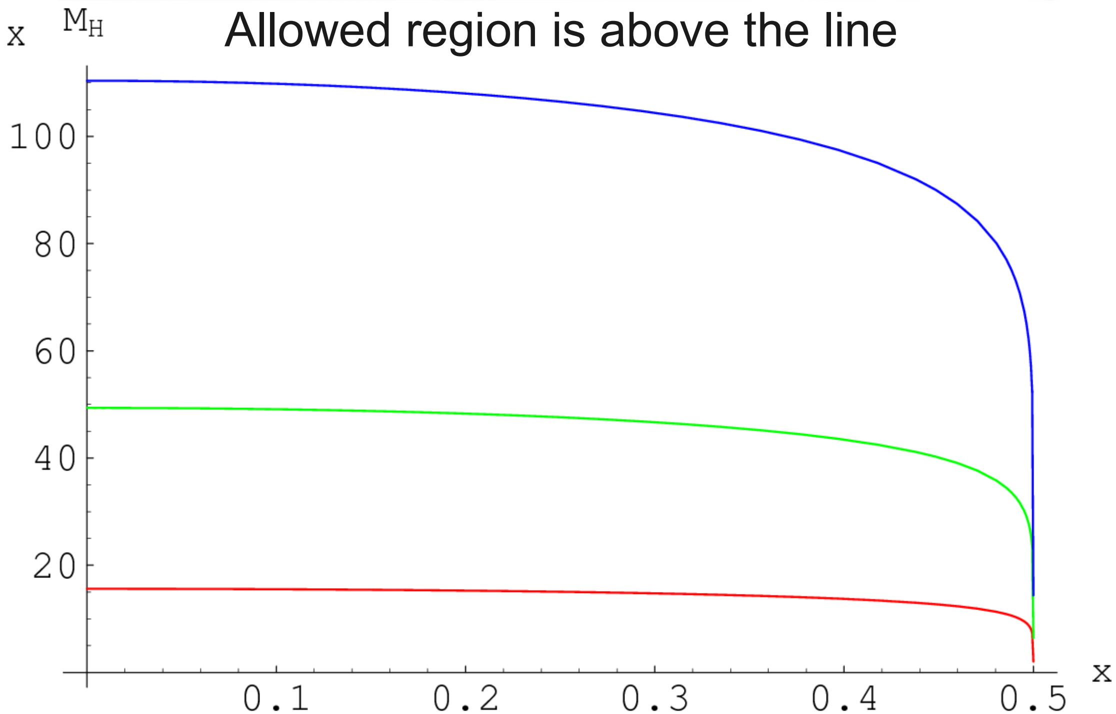
$$5.94 \times 10^6 \left(\frac{\lambda}{M_H^2}\right)^2 \sqrt{1 - 4x_S^2} \leq 1$$

[1] C.P. Burges, M. Pospelov and T. ter Veldhuis, Nucl.Phys. B619, 709 (2001);



Allowed region is below the line

Allowed region is above the line



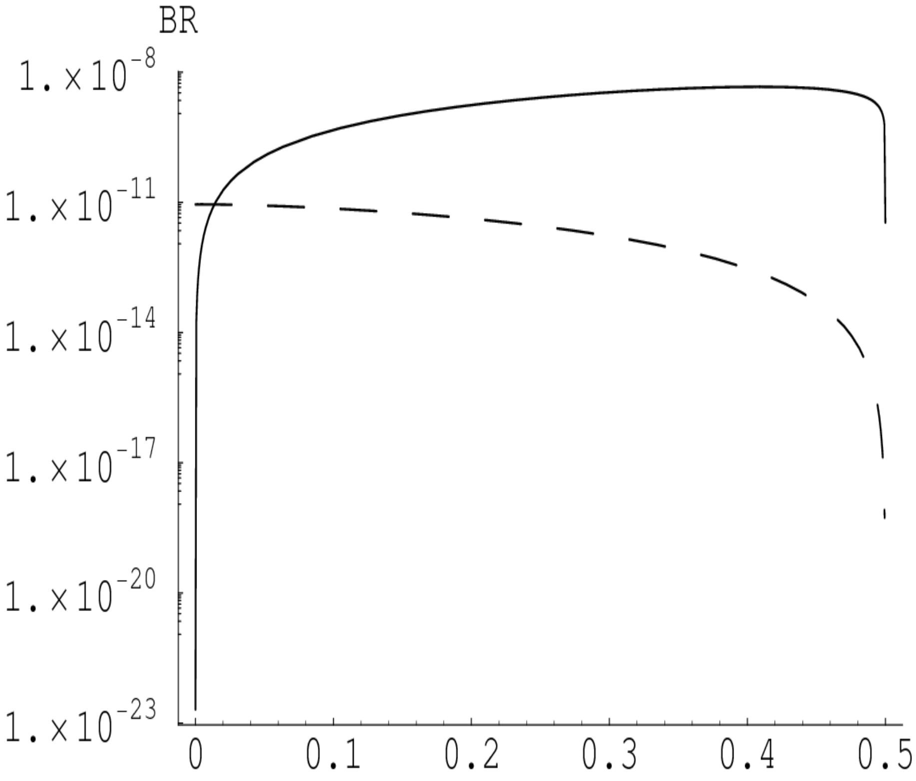
Fermionic DM

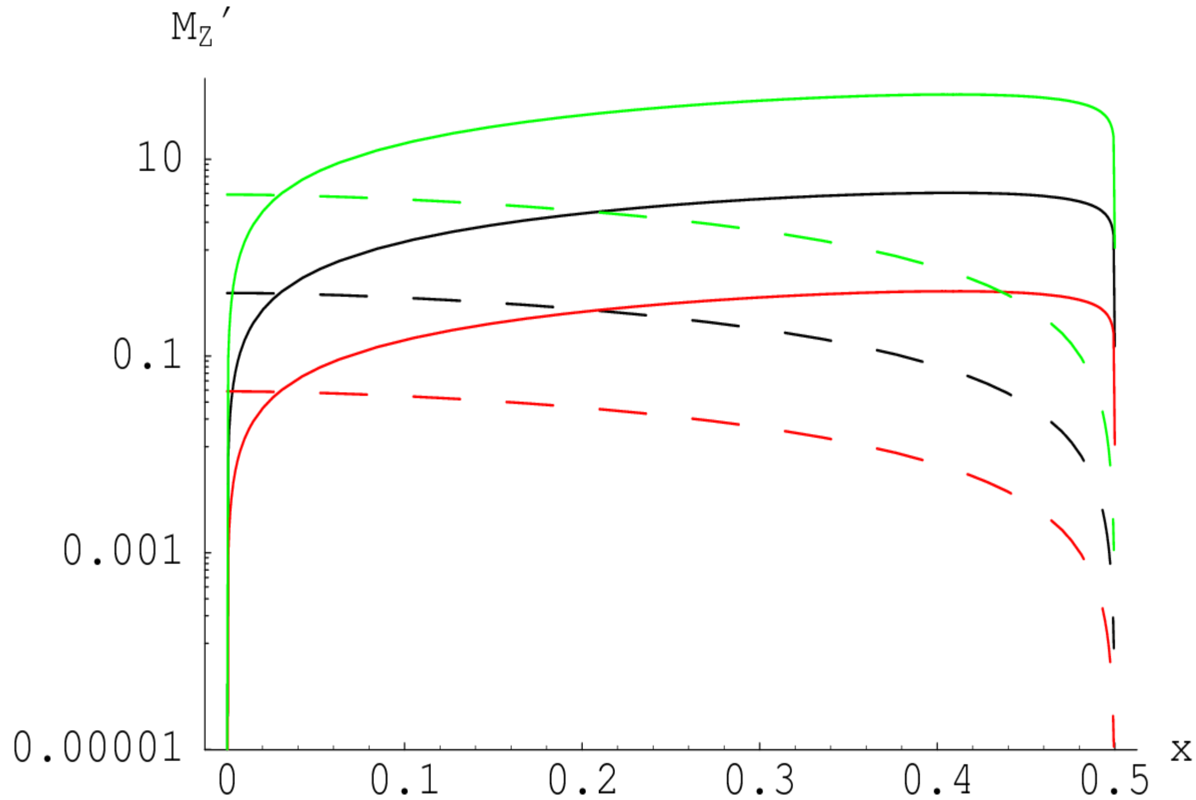
$$\mathcal{H}_{eff}^{(\chi_{1/2})} = \frac{4}{\Lambda^2}\sum_i C_i Q_i$$

$$\begin{aligned}
Q_1 &= (\bar{b}_L\gamma_\mu s_L)(\overline{\chi}_{1/2_L}\gamma^\mu\chi_{1/2_L}) & Q_2 &= (\bar{b}_L\gamma_\mu s_L)\overline{\chi}_{1/2_R}\gamma^\mu\chi_{1/2_R}) \\
Q_3 &= (\bar{b}_R\gamma_\mu s_R)(\overline{\chi}_{1/2_L}\gamma^\mu\chi_{1/2_L}) & Q_4 &= (\bar{b}_R\gamma_\mu s_R)(\overline{\chi}_{1/2_R}\gamma^\mu\chi_{1/2_R}) \\
Q_5 &= (\bar{b}_L s_R)(\overline{\chi}_{1/2_L}\chi_{1/2_R}) & Q_6 &= (\bar{b}_L s_R)(\overline{\chi}_{1/2_R}\chi_{1/2_L}) \\
Q_7 &= (\bar{b}_R s_L)(\overline{\chi}_{1/2_L}\chi_{1/2_R}) & Q_8 &= (\bar{b}_R s_L)(\overline{\chi}_{1/2_R}\chi_{1/2_L}) \\
Q_9 &= (\bar{b}_L\sigma_{\mu\nu}s_R)(\overline{\chi}_{1/2_L}\sigma^{\mu\nu}\chi_{1/2_R}) & Q_{10} &= (\bar{b}_L\sigma_{\mu\nu}s_R)(\overline{\chi}_{1/2_R}\sigma^{\mu\nu}\chi_{1/2_L}) \\
Q_{11} &= (\bar{b}_R\sigma_{\mu\nu}s_L)(\overline{\chi}_{1/2_L}\sigma^{\mu\nu}\chi_{1/2_R}) & Q_{12} &= (\bar{b}_R\sigma_{\mu\nu}s_L)(\overline{\chi}_{1/2_R}\sigma^{\mu\nu}\chi_{1/2_L})
\end{aligned}$$

Hidden Valleys[1]

$$C_1 = \frac{G_F k g' \alpha M_Z M_{Z'}}{2g\sqrt{2}\sin^2\theta_W} V_{tb} V_{ts}^* X(x) \text{ and } \Lambda = M_{Z'}$$



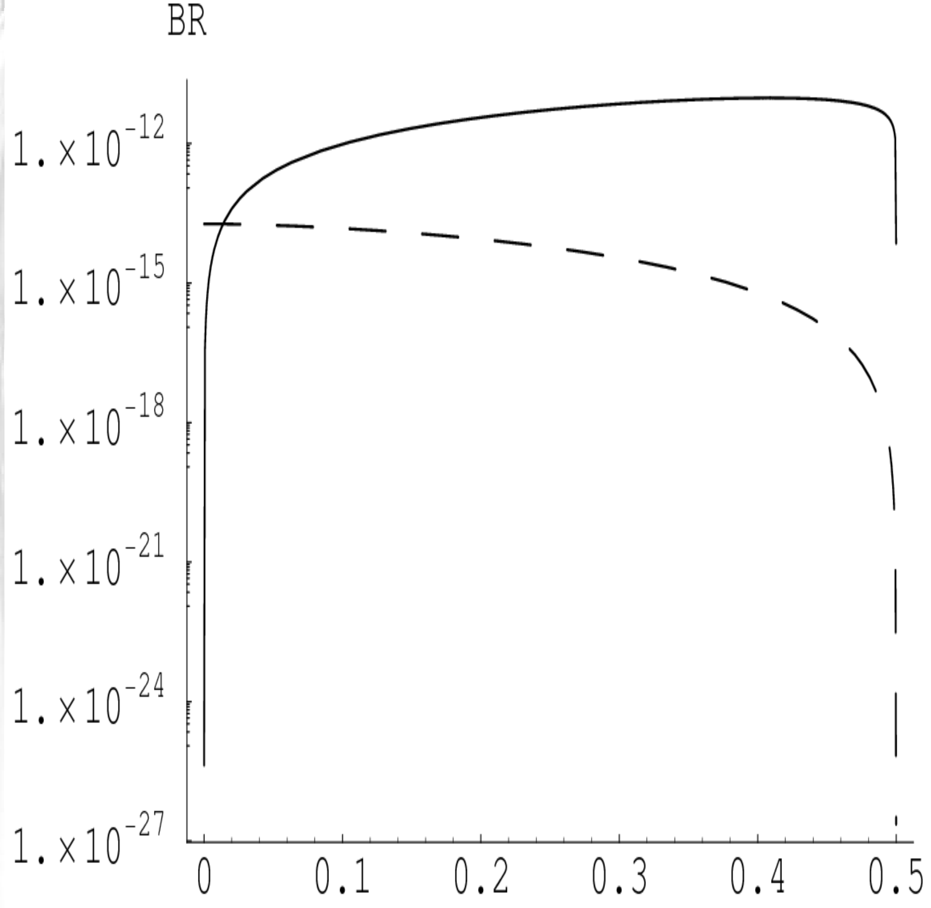


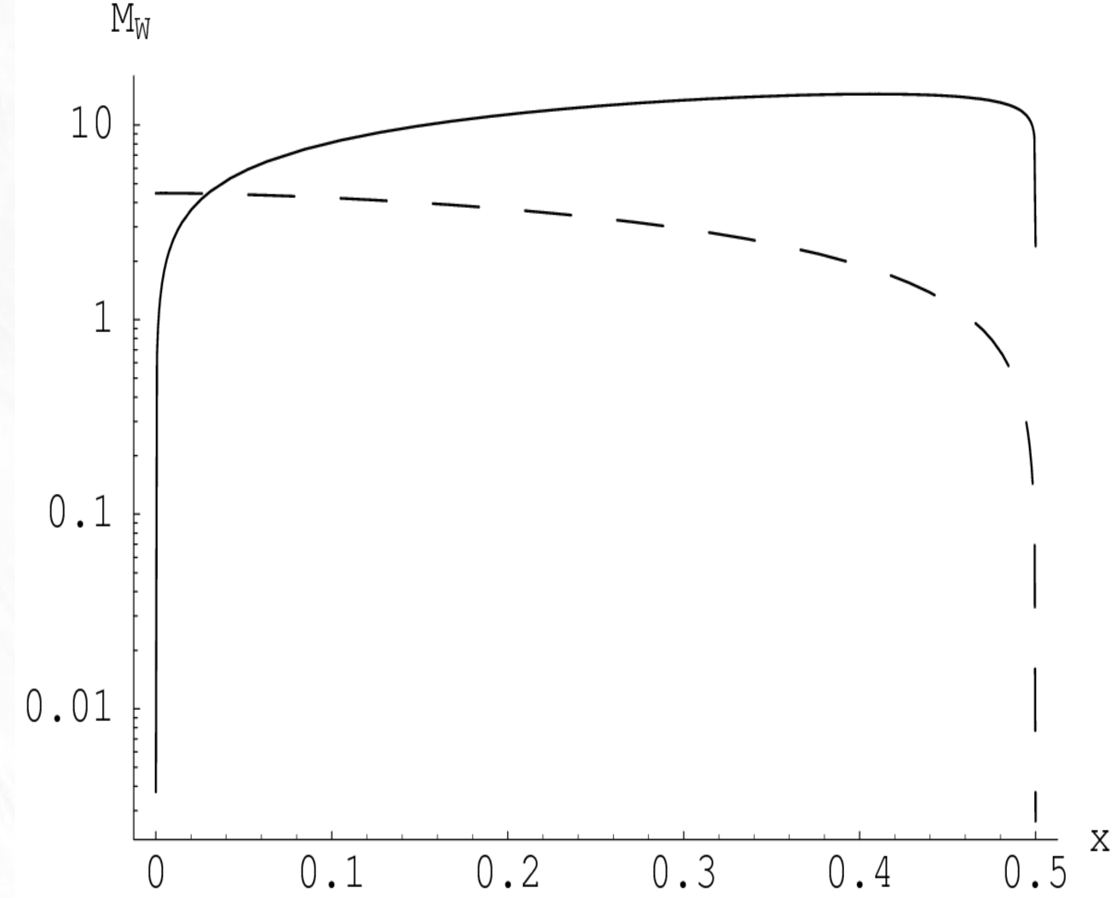
Black, red and green correspond to $g_1 k = 1,\ 0.1$ and 10 respectively

[1] M. J. Strassler and K. M. Zurek, Phys. Lett. B **651**, 374 (2007)

Right-Handed neutrino[1]

$$C_4 = \frac{g^2}{8}\frac{\alpha}{2\pi\sin^2\theta_W} \qquad \Lambda = M_{W^R}$$





J.-M. Frére et al.[arxiv:hep-ph/0610240v2]

Majorana Fermions DM [1]

$$\bar{\chi}\gamma_\mu\chi = 0 \qquad \bar{\chi}\sigma^{\mu\nu}\chi = 0$$

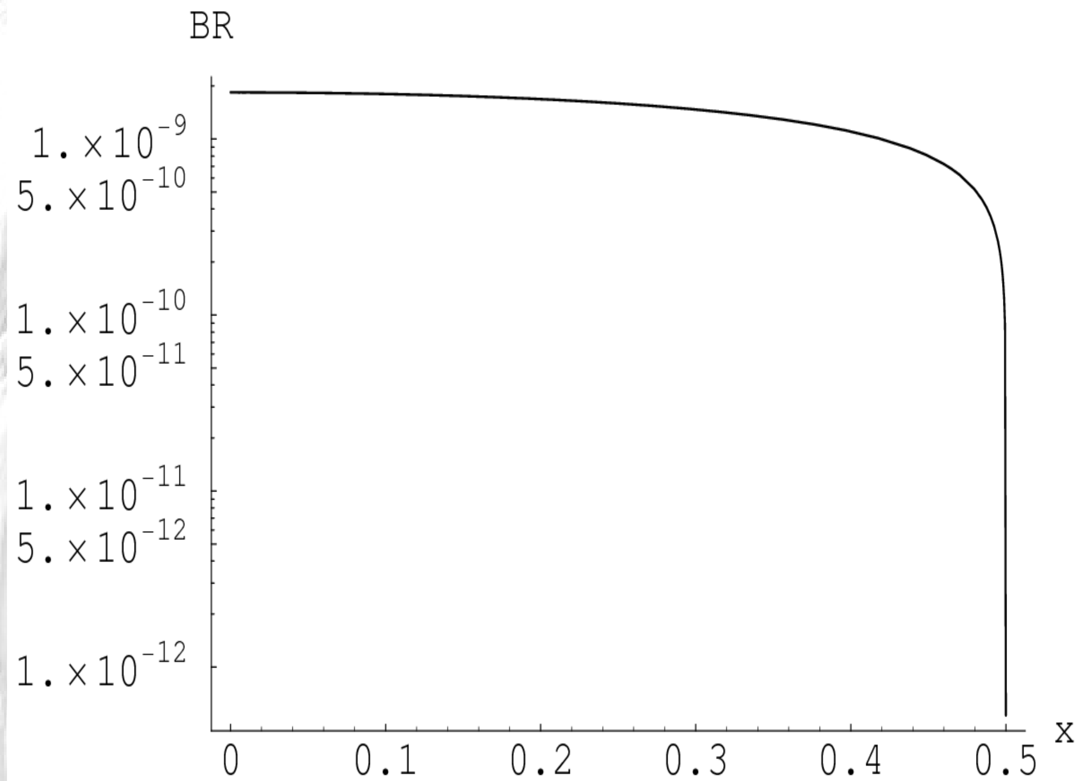
$$-\mathcal{L}_f = \frac{M}{2}\bar{\psi}\psi + \mu\bar{\tilde{H}}_d\tilde{H}_u + \lambda_d\bar{\psi}\tilde{H}_d H_d + \lambda_u\bar{\psi}\tilde{H}_u H_u$$

$$\chi = -\psi\cos\theta + \tilde{H}_d\sin\theta \qquad \sin^2\theta = \frac{\lambda_u^2 v_u^2}{\lambda_u^2 v_u^2 + \mu^2}$$

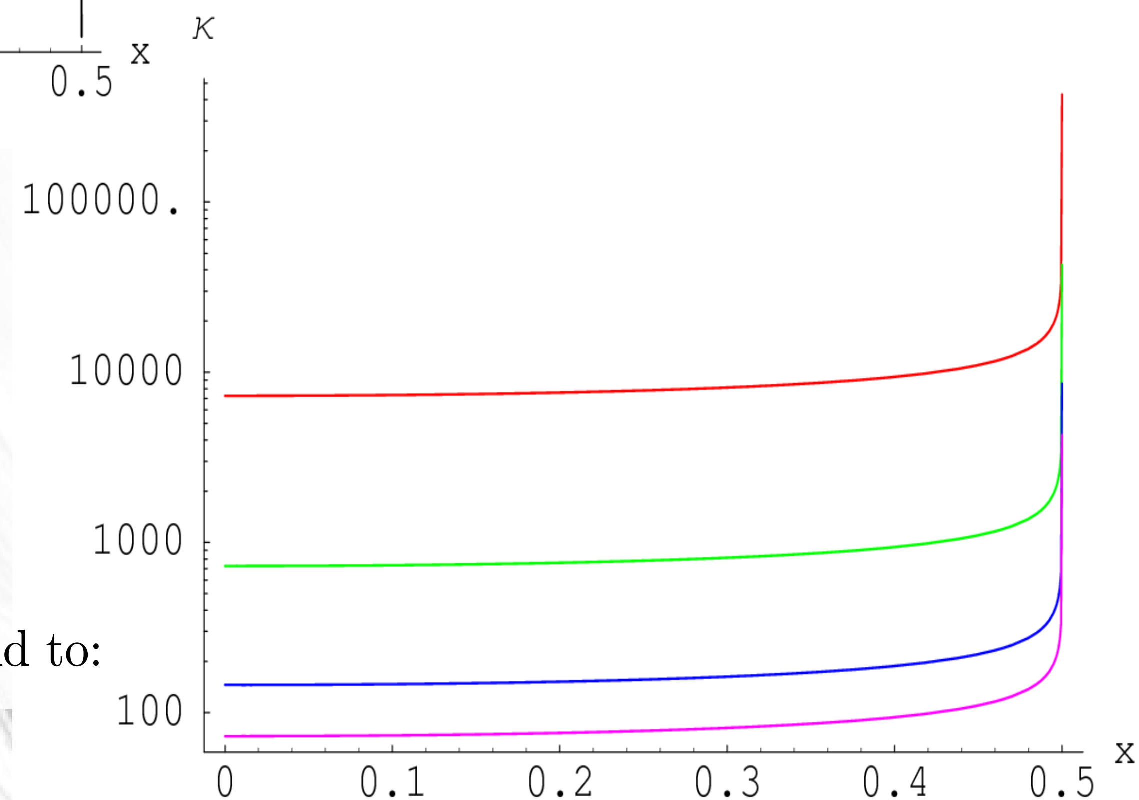
$$m_1 = M\left(1 - \frac{\lambda_u^2 v_u^2}{\lambda_u^2 v_u^2 + \mu^2}\right)$$

$$C_5 = C_6 = \frac{V_{ts}V_{tb}^*\tan b}{(16\pi)^2 v_{sm}^3}\left(\frac{\lambda_d\lambda_u v_u\mu}{\lambda_u^2 v_u^2 + \mu^2}\right)\frac{m_b m_t^2 \ln a_t}{(1-a_t)} \text{ and } \Lambda = M_h$$

[1] C. Bird, R. Kowalewski and M. Pospelov, Mod. Phys. Lett. A 21, 457 (2006)



$$\kappa \equiv \frac{\lambda_d \lambda_u v_u \mu}{\lambda_u^2 v_u^2 + \mu^2}$$



Red, Green, Blue and Purple correspond to: $\tan\beta = v_u/v_d = 1, 10, 100$ and 1000

Vector DM

$$O_1 = m_b(\bar{b}_L q_R)V_\mu V^\mu, \qquad O_4 = (\bar{b}_R \gamma_\mu q_R)V^{\mu\nu}V_\nu,$$
$$O_2 = m_b(\bar{b}_R q_L)V_\mu V^\mu, \qquad O_5 = (\bar{b}_L \gamma_\mu q_L)\widetilde{V}^{\mu\nu}V_\nu,$$
$$O_3 = (\bar{b}_L \gamma_\mu q_L)V^{\mu\nu}V_\nu, \qquad O_6 = (\bar{b}_R \gamma_\mu q_R)\widetilde{V}^{\mu\nu}V_\nu,$$

where $\widetilde{V}^{\mu\nu} = (1/2)\epsilon^{\mu\nu\alpha\beta}V_{\alpha\beta}$ and $q = s, d$

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}
0	0	0	1.4×10^{-8}	1.4×10^{-8}	8.9×10^{-9}	8.9×10^{-9}
0.1	1.2×10^{-9}	1.2×10^{-9}	1.5×10^{-8}	1.5×10^{-8}	9.1×10^{-9}	9.1×10^{-9}
0.2	5.1×10^{-9}	5.1×10^{-9}	1.5×10^{-8}	1.5×10^{-8}	1.0×10^{-8}	1.0×10^{-8}
0.3	1.3×10^{-8}	1.3×10^{-8}	1.6×10^{-8}	1.6×10^{-8}	1.2×10^{-8}	1.2×10^{-8}
0.4	2.9×10^{-8}	2.9×10^{-8}	1.9×10^{-8}	1.9×10^{-8}	1.9×10^{-8}	1.9×10^{-8}

Table 1: Constraints (upper limits) on the Wilson coefficients of operators from the $B_q \to \chi_1 \chi_1$ transition.

Summary

- Considered possibility of DM production in heavy meson decays
- Demonstrated that it is possible to constrain DM properties
- Motivation for experimental studies of missing energy decays
- Light Dark Matter can be potentially ruled out

BACKUP

Fermionic DM general limits

$$
\begin{aligned}
C_{57}^2 + C_{68}^2 &\leq 5.15\times 10^{-16} \\
0.02(C_{13}+C_{24})^2 - 0.23\tilde{C}_{1-8} + 1.32(C_{57}^2 + C_{68}^2) + 0.05C_{57}C_{68} &\leq 7.09\times 10^{-16} \\
0.08(C_{13}+C_{24})^2 - 0.46\tilde{C}_{1-8} + 1.24(C_{57}^2 + C_{68}^2) + 0.22C_{57}C_{68} &\leq 7.58\times 10^{-16} \\
0.18(C_{13}+C_{24})^2 - 0.69\tilde{C}_{1-8} + 1.10(C_{57}^2 + C_{68}^2) + 0.48C_{57}C_{68} &\leq 8.66\times 10^{-16} \\
0.32(C_{13}+C_{24})^2 - 0.93\tilde{C}_{1-8} + 0.92(C_{57}^2 + C_{68}^2) + 0.86C_{57}C_{68} &\leq 1.15\times 10^{-15}
\end{aligned}
$$

$$C_{ij} \equiv C_i - C_j$$

$$\tilde{C}_{1-8} \equiv C_{13}C_{57} + C_{24}C_{57} + C_{13}C_{68} + C_{24}C_{68}$$

Fermionic DM upper bounds on Wilson coefficients

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 GeV
0	–	–	–	–	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}	$2.3 \times$
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}	$2.3 \times$
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}	$2.5 \times$
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}	$2.8 \times$
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}	$3.6 \times$

Table 1: Constraints (upper limits) on the Wilson coefficients of operators the $B_q \to \chi_{1/2}\overline{\chi}_{1/2}$ 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}
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}

Table 2: Constraints (upper limits) on the Wilson coefficients of operators from the $B_q \to \chi_{1/2}\overline{\chi}_{1/2}\gamma$ transition. Note that operators $Q_5 - Q_8$ give no contribution to this decay.

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- Experiment

NO DATA

$< 2.2 \times 10^{-4}$[1]

NO DATA

[1] B. Aubert et al., Phys.Rev.Lett.93:091802,2004. [arXiv: hep-ex/0405071]

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$< \ 2.2 \times 10^{-4}$[1]

NO DATA

[1] B. Aubert et al., Phys.Rev.Lett.93:091802,2004. [arXiv: hep-ex/0405071]

SM prediction and experimental data

• Theory	• Experiment
$\mathcal{B}(B_s \to \nu\overline{\nu}) \simeq 3.07 \times 10^{-24}$	NO DATA
$\mathcal{B}(B_d \to \nu\overline{\nu}) \simeq 1.24 \times 10^{-25}$	$< 2.2 \times 10^{-4}$[1]
$\mathcal{B}(D^0 \to \nu\overline{\nu}) \simeq 1.1 \times 10^{-30}$	NO DATA
$\mathcal{B}(B_s \to \nu\bar{\nu}\gamma) \simeq 3.7 \times 10^{-8}$	NO DATA
$\mathcal{B}(B_d \to \nu\bar{\nu}\gamma) \simeq 1.9 \times 10^{-9}$	$< 4.7 \times 10^{-5}$[1]
$\mathcal{B}(D^0 \to \nu\bar{\nu}\gamma) \simeq 3.9 \times 10^{-14}$	NO DATA

[1] B. Aubert et al., Phys.Rev.Lett.93:091802,2004. [arXiv: hep-ex/0405071]

Formalism

$B_q \to \chi\chi$ decays

$$\begin{aligned}
\langle 0|\, \bar{b}\gamma^{\mu} q \,|B_q\rangle &= \langle 0|\, \bar{b} q \,|B_q\rangle = 0, \\
\langle 0|\, \bar{b}\gamma^{\mu}\gamma_5 q \,|B_q\rangle &= i f_{B_q} P^{\mu} \\
\langle 0|\, \bar{b}\gamma_5 q \,|B_q\rangle &= -i \frac{f_{B_q} M_{B_q}^2}{m_b + m_q}.
\end{aligned}$$

$B_q \to \chi\, \chi\, \gamma$ decays

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

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

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

$B_q \to \chi\,\chi\,\gamma$ decays

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

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

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

$$f_V^B(E_\gamma) = f_A^B(E_\gamma) = \frac{f_{B_q}M_{B_q}}{2E_\gamma}\left(-Q_qR_q+\frac{Q_b}{m_b}\right)+\mathcal{O}\left(\frac{\Lambda^2_{QCD}}{E_\gamma^2}\right) \equiv \frac{f_{B_q}M_{B_q}}{2E_\gamma}F_{B_q},$$

where $R_q^{-1} \sim M_{B_q}-m_b$, and $F_{B_q} = -Q_qR_q+\frac{Q_b}{m_b} \sim \frac{M_{B_q}Q_b-m_b(Q_b+Q_q)}{m_b(M_{B_q}-m_b)}$.

$B_q \to \chi\,\chi\,\gamma$ decays

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

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

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

$$G = 4g_1; \qquad N = \frac{-4}{q^2}(f_1+g_1)$$

$$H = \frac{-4(qk)}{q^2}(f_1+g_1); \qquad f_1(g_1) = \frac{f_0(g_0)}{(1-q^2/\mu^2_{f(g)})^2}$$

Various DM scenario

$$\mathcal{H}_{eff}^{(s)} = 2\sum_i \frac{C_i^{(s)}}{\Lambda^2} O_i$$

- Scalar DM - allows to avoid Lee-Weinberg bound.
- Fermion DM (Dirac or Majorana)
- Vector DM. Don't know about any model with spin=1 DM but provide results for generality

Scalar DM

$$
\begin{aligned}
O_1 &= m_b(\overline{b}_R q_L)(\chi_0^* \chi_0), \\
O_2 &= m_b(\overline{b}_L q_R)(\chi_0^* \chi_0), \\
O_3 &= (\overline{b}_L \gamma^\mu q_L)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0), \\
O_4 &= (\overline{b}_R \gamma^\mu q_R)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0),
\end{aligned}
$$

Scalar DM

$$
\begin{aligned}
O_1 &= m_b(\overline{b}_R q_L)(\chi_0^* \chi_0), \\
O_2 &= m_b(\overline{b}_L q_R)(\chi_0^* \chi_0), \\
O_3 &= (\overline{b}_L \gamma^\mu q_L)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0), \\
O_4 &= (\overline{b}_R \gamma^\mu q_R)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0),
\end{aligned}
$$

Most likely there is NO radiative decay.

Scalar DM

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 2.03 \times 10^{-16}\ GeV^{-4} \text{ for } m_\chi = 0$$

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

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 2.22 \times 10^{-16}\ GeV^{-4} \text{ for } m_\chi = 0.2 \times M_{B_d}$$

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 2.54 \times 10^{-16}\ GeV^{-4} \text{ for } m_\chi = 0.3 \times M_{B_d}$$

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 3.39 \times 10^{-16}\ GeV^{-4} \text{ for } m_\chi = 0.4 \times M_{B_d}$$

Scalar DM

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 1.70 \times 10^{-11}\ GeV^{-4} \text{ for } m = 0$$

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 2.03 \times 10^{-11}\ GeV^{-4} \text{ for } m = 0.1 \times M_{B_d}$$

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 3.49 \times 10^{-11}\ GeV^{-4} \text{ for } m = 0.2 \times M_{B_d}$$

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 9.88 \times 10^{-11}\ GeV^{-4} \text{ for } m = 0.3 \times M_{B_d}$$

$$\frac{C_3^{(s)}}{\Lambda^2}\frac{C_4^{(s)}}{\Lambda^2} \leq 8.11 \times 10^{-10}\ GeV^{-4} \text{ for } m = 0.3 \times M_{B_d}$$

Examples of Scalar DM

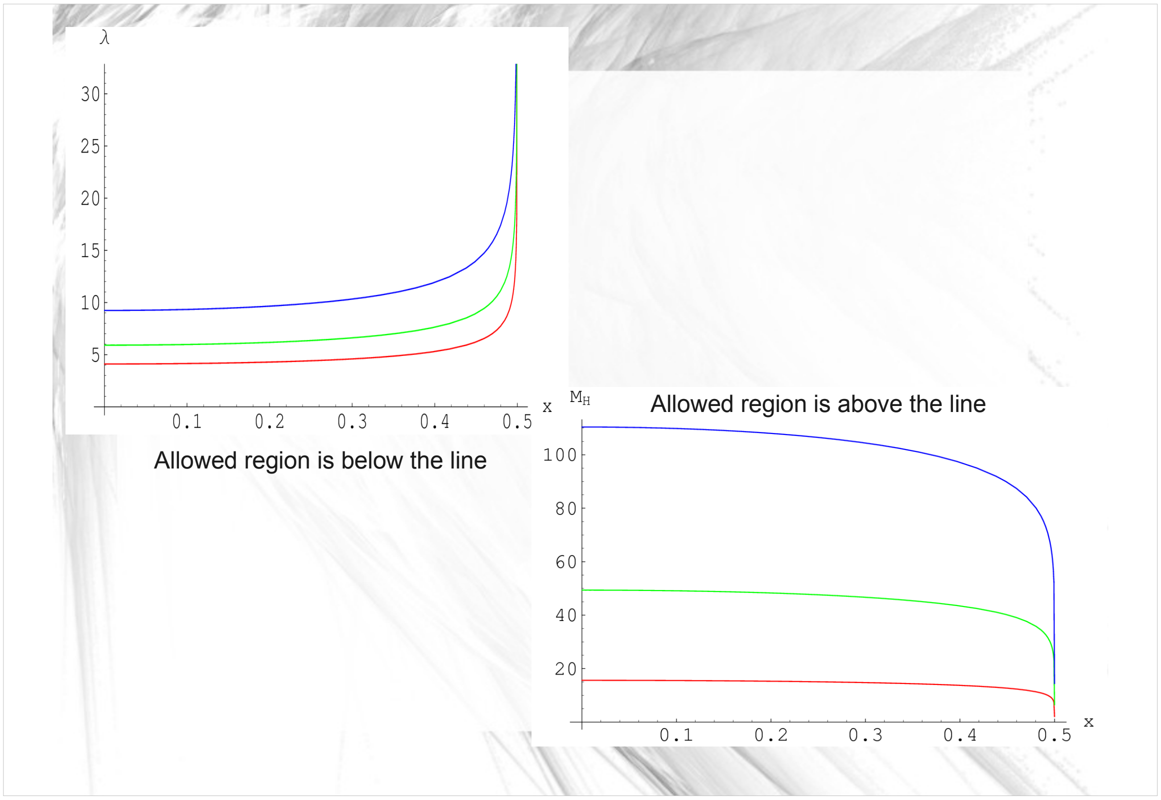
Minimal Scalar DM model [1]

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

$$C_{1,3,4}^{(s)} = 0,\; C_2^{(s)} = 3\lambda g_w^2 V_{ts} V_{tb}^* x_t/256\pi^2, \text{ and } \Lambda = M_H$$

$$5.94 \times 10^6 \left(\frac{\lambda}{M_H^2}\right)^2 \sqrt{1 - 4x_S^2} \leq 1$$

[1] C.P. Burges, M. Pospelov and T. ter Veldhuis, Nucl.Phys. B619, 709 (2001);


λ
30
25
20
15
10
5
0.1
0.2
0.3
0.4
0.5
x
Allowed region is below the line
M_H
Allowed region is above the line
100
80
60
40
20
0.1
0.2
0.3
0.4
0.5
x

Fermionic DM

$$\mathcal{H}_{eff}^{(\chi_{1/2})} = \frac{4}{\Lambda^2}\sum_i C_i Q_i$$

$$Q_1 = (\bar{b}_L\gamma_\mu s_L)(\overline{\chi}_{1/2_L}\gamma^\mu\chi_{1/2_L}) \quad Q_2 = (\bar{b}_L\gamma_\mu s_L)\overline{\chi}_{1/2_R}\gamma^\mu\chi_{1/2_R})$$

$$Q_3 = (\bar{b}_R\gamma_\mu s_R)(\overline{\chi}_{1/2_L}\gamma^\mu\chi_{1/2_L}) \quad Q_4 = (\bar{b}_R\gamma_\mu s_R)(\overline{\chi}_{1/2_R}\gamma^\mu\chi_{1/2_R})$$

$$Q_5 = (\bar{b}_L s_R)(\overline{\chi}_{1/2_L}\chi_{1/2_R}) \quad Q_6 = (\bar{b}_L s_R)(\overline{\chi}_{1/2_R}\chi_{1/2_L})$$

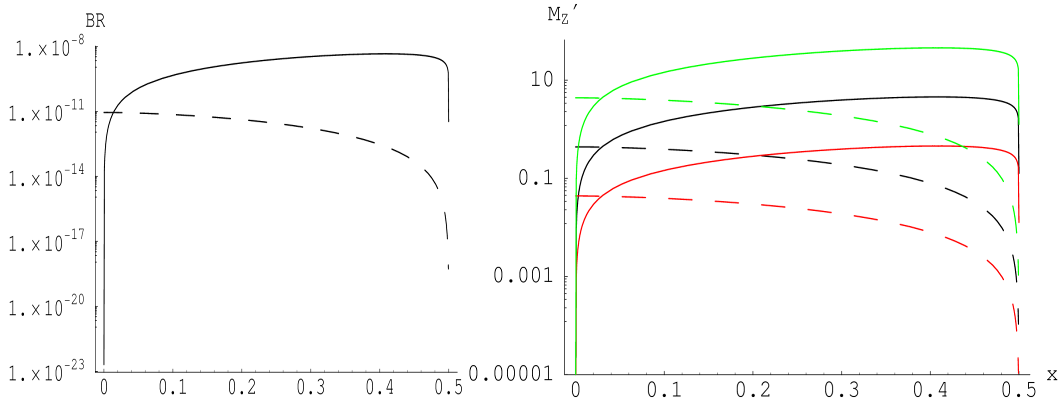
$$Q_7 = (\bar{b}_R s_L)(\overline{\chi}_{1/2_L}\chi_{1/2_R}) \quad Q_8 = (\bar{b}_R s_L)(\overline{\chi}_{1/2_R}\chi_{1/2_L})$$

$$Q_9 = (\bar{b}_L\sigma_{\mu\nu}s_R)(\overline{\chi}_{1/2_L}\sigma^{\mu\nu}\chi_{1/2_R}) \quad Q_{10} = (\bar{b}_L\sigma_{\mu\nu}s_R)(\overline{\chi}_{1/2_R}\sigma^{\mu\nu}\chi_{1/2_L})$$

$$Q_{11} = (\bar{b}_R\sigma_{\mu\nu}s_L)(\overline{\chi}_{1/2_L}\sigma^{\mu\nu}\chi_{1/2_R}) \quad Q_{12} = (\bar{b}_R\sigma_{\mu\nu}s_L)(\overline{\chi}_{1/2_R}\sigma^{\mu\nu}\chi_{1/2_L})$$

Hidden Valleys[1]

$$C_1 = \frac{G_F k g' \alpha M_Z M_{Z'}}{2g\sqrt{2}\sin^2\theta_W} V_{tb} V_{ts}^* X(x) \text{ and } \Lambda = M_{Z'}$$

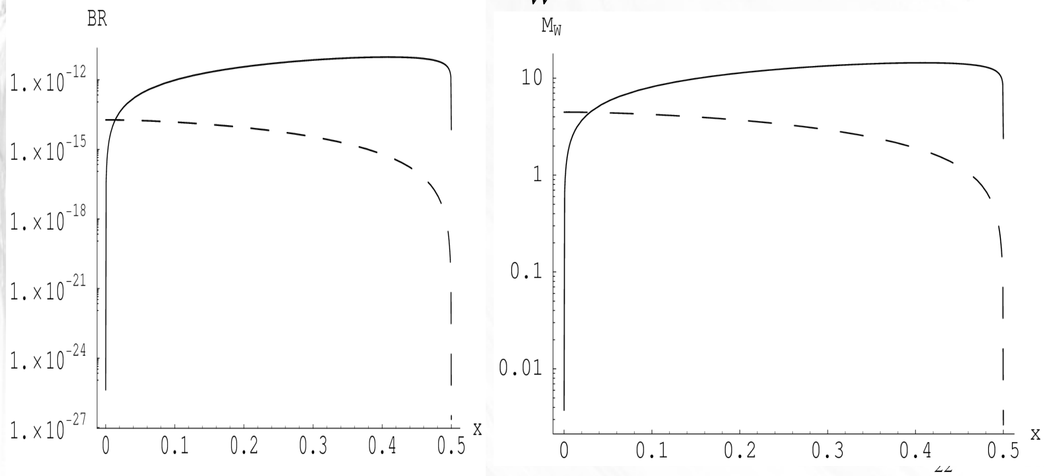


Black, red and green correspond to $g_1 k = 1,\ 0.1$ and 10 respectively

[1] M. J. Strassler and K. M. Zurek, Phys. Lett. B 651, 374 (2007)

Right-Handed neutrino[1]

$$C_4 = \frac{g^2}{8}\frac{\alpha}{2\pi \sin^2 \theta_W} \qquad \Lambda = M_{W^R}$$



J.-M. Frére et al.[arxiv:hep-ph/0610240v2]

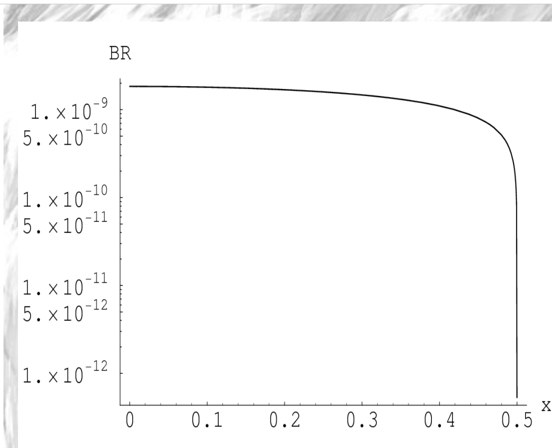
Majorana Fermions DM [1]

$$\bar{\chi}\gamma_\mu\chi = 0 \qquad \bar{\chi}\sigma^{\mu\nu}\chi = 0$$

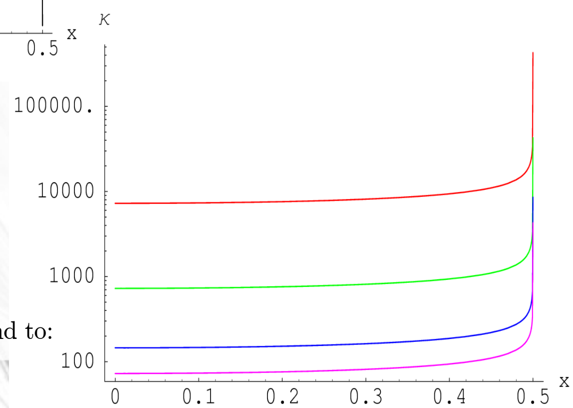
$$\begin{aligned}
-\mathcal{L}_f &= \frac{M}{2}\bar{\psi}\psi + \mu\bar{\tilde{H}}_d\tilde{H}_u + \lambda_d\bar{\psi}\tilde{H}_d H_d + \lambda_u\bar{\psi}\tilde{H}_u H_u \\
\chi &= -\psi\cos\theta + \tilde{H}_d\sin\theta \quad \sin^2\theta = \frac{\lambda_u^2 v_u^2}{\lambda_u^2 v_u^2 + \mu^2} \\
m_1 &= M\left(1 - \frac{\lambda_u^2 v_u^2}{\lambda_u^2 v_u^2 + \mu^2}\right)
\end{aligned}$$

$$C_5 = C_6 = \frac{V_{ts}V_{tb}^*\tan b}{(16\pi)^2 v_{sm}^3}\left(\frac{\lambda_d\lambda_u v_u\mu}{\lambda_u^2 v_u^2 + \mu^2}\right)\frac{m_b m_t^2\ln a_t}{(1-a_t)} \text{ and } \Lambda = M_h$$

[1] C. Bird, R. Kowalewski and M. Pospelov, Mod. Phys. Lett. A 21, 457 (2006)



$$\kappa \equiv \frac{\lambda_d \lambda_u v_u \mu}{\lambda_u^2 v_u^2 + \mu^2}$$



Red, Green, Blue and Purple correspond to:
$\tan\beta = v_u/v_d = 1, 10, 100$ and 1000

Vector DM

$$O_1 = m_b(\bar{b}_L q_R)V_\mu V^\mu, \qquad O_4 = (\bar{b}_R\gamma_\mu q_R)V^{\mu\nu}V_\nu,$$

$$O_2 = m_b(\bar{b}_R q_L)V_\mu V^\mu, \qquad O_5 = (\bar{b}_L\gamma_\mu q_L)\widetilde{V}^{\mu\nu}V_\nu,$$

$$O_3 = (\bar{b}_L\gamma_\mu q_L)V^{\mu\nu}V_\nu, \qquad O_6 = (\bar{b}_R\gamma_\mu q_R)\widetilde{V}^{\mu\nu}V_\nu,$$

where $\widetilde{V}^{\mu\nu} = (1/2)\epsilon^{\mu\nu\alpha\beta}V_{\alpha\beta}$ and $q = s, d$

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}
0	0	0	1.4×10^{-8}	1.4×10^{-8}	8.9×10^{-9}	8.9×10^{-9}
0.1	1.2×10^{-9}	1.2×10^{-9}	1.5×10^{-8}	1.5×10^{-8}	9.1×10^{-9}	9.1×10^{-9}
0.2	5.1×10^{-9}	5.1×10^{-9}	1.5×10^{-8}	1.5×10^{-8}	1.0×10^{-8}	1.0×10^{-8}
0.3	1.3×10^{-8}	1.3×10^{-8}	1.6×10^{-8}	1.6×10^{-8}	1.2×10^{-8}	1.2×10^{-8}
0.4	2.9×10^{-8}	2.9×10^{-8}	1.9×10^{-8}	1.9×10^{-8}	1.9×10^{-8}	1.9×10^{-8}

Table 1: Constraints (upper limits) on the Wilson coefficients of operators from[25] the $B_q \to \chi_1\chi_1$ transition.

Summary

- Considered possibility of DM production in heavy meson decays
- Demonstrated that it is possible to constrain DM properties
- Motivation for experimental studies of missing energy decays
- Light Dark Matter can be potentially ruled out

BACKUP

Fermionic DM general limits

$$
\begin{aligned}
C_{57}^2 + C_{68}^2 &\leq 5.15 \times 10^{-16} \\
0.02(C_{13}+C_{24})^2 - 0.23\tilde{C}_{1-8} + 1.32(C_{57}^2 + C_{68}^2) + 0.05C_{57}C_{68} &\leq 7.09 \times 10^{-16} \\
0.08(C_{13}+C_{24})^2 - 0.46\tilde{C}_{1-8} + 1.24(C_{57}^2 + C_{68}^2) + 0.22C_{57}C_{68} &\leq 7.58 \times 10^{-16} \\
0.18(C_{13}+C_{24})^2 - 0.69\tilde{C}_{1-8} + 1.10(C_{57}^2 + C_{68}^2) + 0.48C_{57}C_{68} &\leq 8.66 \times 10^{-16} \\
0.32(C_{13}+C_{24})^2 - 0.93\tilde{C}_{1-8} + 0.92(C_{57}^2 + C_{68}^2) + 0.86C_{57}C_{68} &\leq 1.15 \times 10^{-15}
\end{aligned}
$$

$$C_{ij} \equiv C_i - C_j$$

$$\tilde{C}_{1-8} \equiv C_{13}C_{57} + C_{24}C_{57} + C_{13}C_{68} + C_{24}C_{68}$$

Fermionic DM upper bounds on Wilson coefficients

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 GeV
0	–	–	–	–	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}	$2.3 \times$
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}	$2.3 \times$
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}	$2.5 \times$
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}	$2.8 \times$
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}	$3.6 \times$

Table 1: Constraints (upper limits) on the Wilson coefficients of operators the $B_q \to \chi_{1/2}\overline{\chi}_{1/2}$ 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}
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}

Table 2: Constraints (upper limits) on the Wilson coefficients of operators from the $B_q \to \chi_{1/2}\overline{\chi}_{1/2}\gamma$ transition. Note that operators $Q_5 - Q_8$ give no contribution to this decay.