INVISIBLE WIDTHS OF HEAVY MESONS

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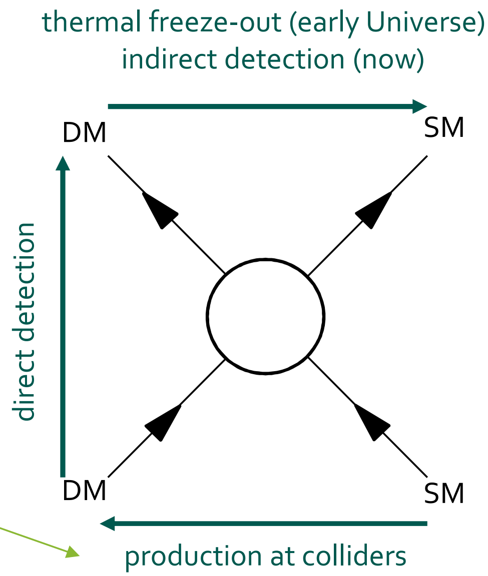
Motivation – light Dark Matter

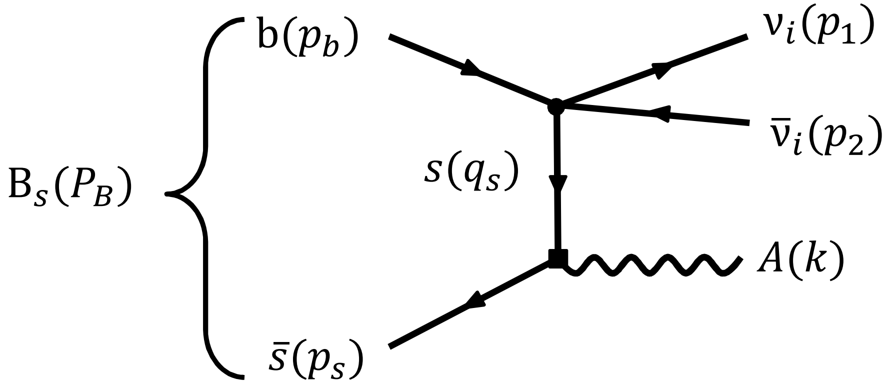
- Only gravitational evidence of Dark Matter
  - Can we see it elsewhere?

- If DM couples to quarks, can find:
  - Final states with other particles
  - Final states by itself: i.e. "Invisible widths"

- Light DM: $M_{DM} < 5\ \mathrm{GeV}$
  - Can use heavy meson decays to probe for it



Motivation – invisible background



- Main background in SM for invisible width is neutrinos
  - Lowest order in G_F is $M \to \nu\bar{\nu}$

- Experimental M → Invisible:
  - $\mathcal{B}(B_d \to inv) < 1.3 \times 10^{-4}$ Belle (2012)
  - $\mathcal{B}(B_d \to inv) < 2.4 \times 10^{-5}$ BaBar (2012)
  - $\mathcal{B}(D^0 \to inv) < 9.4 \times 10^{-5}$ Belle (2017)

Two body decay: $M \to \nu\bar{\nu}$

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

where $\begin{cases} \text{for B-decays: } J^\mu_{Qq} = \bar{q}_L \gamma^\mu b_L \\ \text{for D-decays: } J^\mu_{Qq} = \bar{u}_L \gamma^\mu c_L \end{cases}$

also for B-decays: $\lambda_k X^l(x_k) = \left|V^*_{tq} V_{tb}\right| \cdot \frac{x_t}{8}\left[\frac{x_t+2}{x_t-1} + \frac{3(x_t-2)}{(x_t-1)^2}\ln x_t\right]$

Branching ratio are tiny:

$$\mathcal{B}(B_s \to \nu\bar{\nu}) = \frac{G_F^2\, \alpha^2\, f_B^2\, M_B^3}{16\pi^3 \sin^4\theta_\omega\, \Gamma_{B_s}} \left|V^*_{tq} V_{tb}\right|^2 X^2(x_t)\, x_\nu^2$$

$$\mathcal{B}(B_s \to \nu\bar{\nu}) = 3.07 \times 10^{-2} \left(\frac{m_\nu}{0.1\ eV}\right)^2$$

$$\mathcal{B}(B_d \to \nu\bar{\nu}) = 1.24 \times 10^{-25} \left(\frac{m_\nu}{0.1\ eV}\right)^2$$

$$\mathcal{B}(D^0 \to \nu\bar{\nu}) = 1.1 \times 10^{-30} \left(\frac{m_\nu}{0.1\ eV}\right)^2$$

Badin, Petrov (2010)

- Helicity suppression factor of $x_\nu^2 = \left(\frac{m_\nu}{M_B}\right)^2$
- Can it be used to measure neutrino mass?
  - PDG

However, SM Invisible decay has more terms!!

$$\mathcal{B}(M \to \not{E}) = \mathcal{B}(M \to \nu\bar{\nu}) + \boxed{\mathcal{B}(M \to \nu\bar{\nu}\nu\bar{\nu})} + \cdots$$

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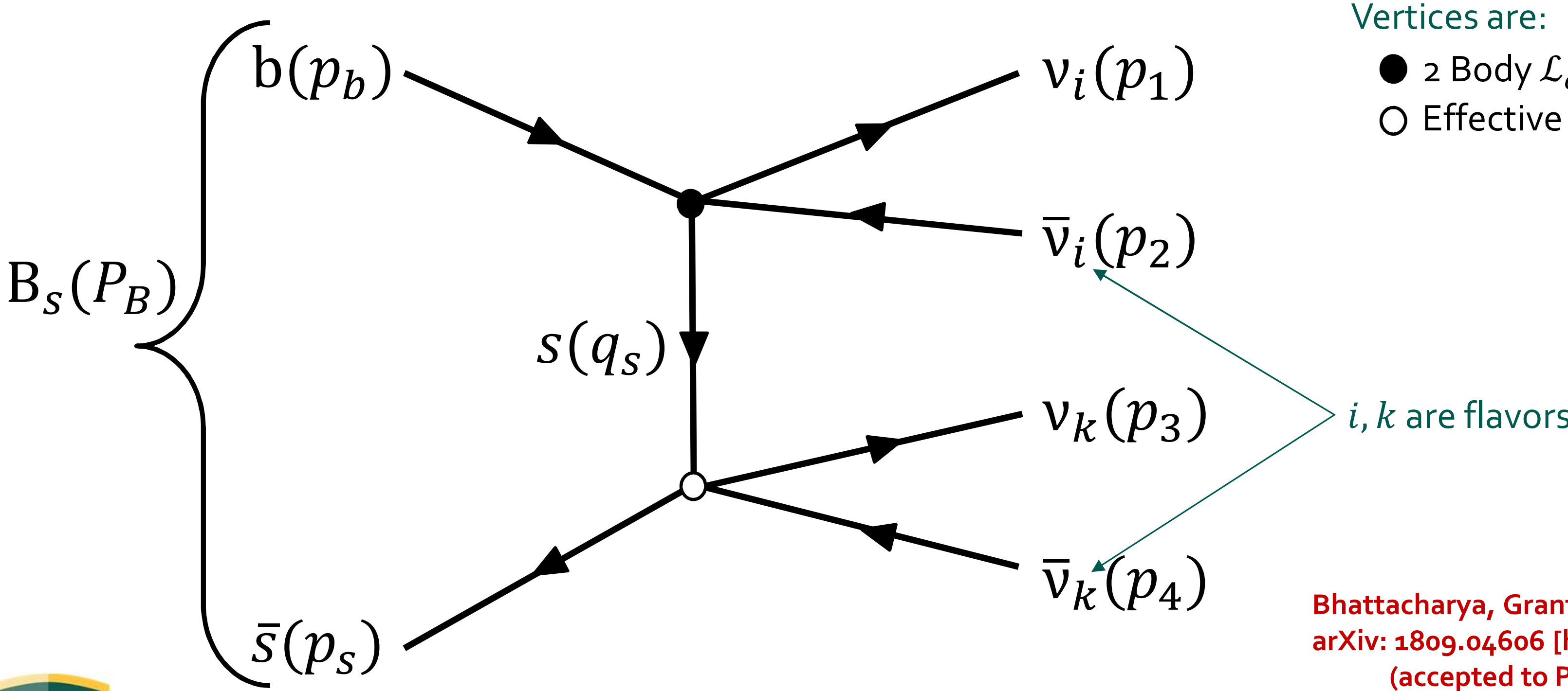
$$\frac{\mathcal{B}(M\to\nu\bar{\nu}\nu\bar{\nu})}{\mathcal{B}(M\to\nu\bar{\nu})} \sim \frac{G_F^2 M_M^4}{16\pi^2 x_\nu^2} \gg 1$$

Four body decay to neutrinos



Vertices are:

- ● 2 Body $\mathcal{L}_{eff}$
- ○ Effective Z propagator

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Details of the calculation

Amplitude:

$$\mathcal{A}_s = -\frac{G_F^2\, \alpha\, V_{ts}^*\, V_{tb}\, X(x_t)}{4\pi \sin^2 \theta_\omega} \sum_{i,k} L_{l_i}^{\mu}\, L_{l_k}^{\nu}\, \langle 0|\bar{s}\Gamma^{\mu\nu} b|B_s\rangle$$

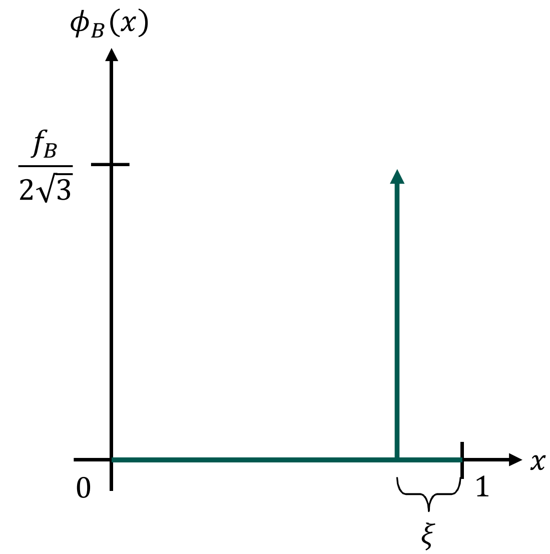
Simple quark model:

$$\langle 0|\bar{s}\Gamma^{\mu\nu} b|B_s\rangle = \int_0^1 dx\, \mathrm{Tr}\left[\Gamma^{\mu\nu}\psi_{B_s}\right] \quad \text{where } x = \frac{p_b}{P_B}$$

Bound state wave function:

$$\psi_B = \frac{I_c}{\sqrt{6}} \phi_B(x) \gamma^5 \left(\gamma^\mu P_{B\mu} + M_B g_B(x)\right)$$

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



Results: Branching Ratios

$$\mathcal{B}(M \to \not{E}) = \mathcal{B}(M \to \nu\bar{\nu}) + \mathcal{B}(M \to \nu\bar{\nu}\nu\bar{\nu}) + \cdots$$

$B_s: 3.07 \times 10^{-24}$

$B_d: 1.24 \times 10^{-25}$

$D^0: 1.1 \times 10^{-30}$

Badin, Petrov (2010)

$B_s: (5.48 \pm 0.89) \times 10^{-15}$

$B_d: (1.51 \pm 0.28) \times 10^{-16}$

$D^0: (2.96 \pm 0.39) \times 10^{-27}$

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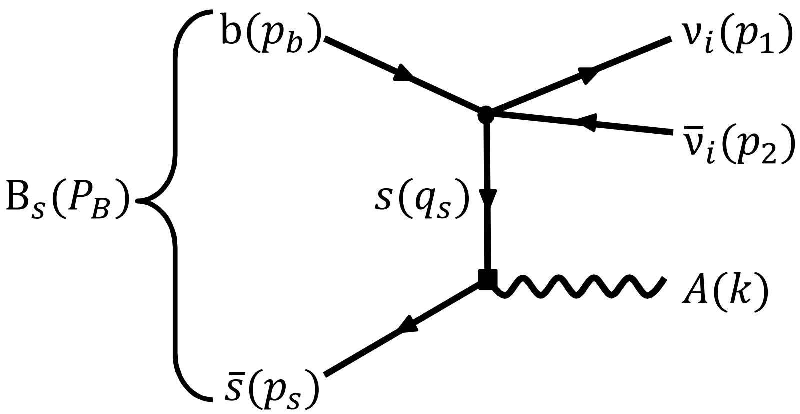
That's 9 Orders Of Magnitude!

Example of BSM: Dark Photon

Lowest order diagram: $\mathcal{O}(\epsilon^2)$



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

mixing parameter

Strongest experimental bounds:
$\mathcal{B}(B_d \to inv) < 2.4 \times 10^{-5}$
yields $|\epsilon| < 125$

BaBar (2012)

Strongest SM bounds:
$\mathcal{B}(B_d \to 4\nu) = (1.51 \pm 0.28) \times 10^{-16}$
yields $|\epsilon| \sim 3.1 \times 10^{-4}$

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Still have room for DM, but need more experimental data!

Conclusions

- SM contribution to the invisible width of heavy mesons:
  - Branching ratio is dominated by a four neutrino final state
    - 9 orders of magnitude for B-decays over $\mathcal{B}(B \to v\bar{v})$
    - 3 orders of magnitude for D-decays over $\mathcal{B}(D \to v\bar{v})$
- Can we use invisible widths to constrain neutrino mass?
  - Since $\mathcal{B}(M \to v\bar{v}v\bar{v}) \gg \mathcal{B}(M \to v\bar{v})$

    and $\mathcal{B}(M \to v\bar{v}v\bar{v})$ is <u>**NOT**</u> proportional to m_ν

    $\Rightarrow$ NO!
- Can we use invisible widths to search for light DM?
  - Perhaps, but need more experimental data

Questions?

References

[1] N. Craig, A. Katz, M. Strassler and R. Sundrum, JHEP 1507, 105 (2015)

[2] P. Meade, S. Nussinov, M. Papucci and T. Volansky, JHEP 1006, 029 (2010)

[3] G. Aad et al. [ATLAS Collaboration], Phys. Rev. Lett. 108, 251801 (2012)

[4] G. Aad et al. [ATLAS Collaboration], Phys. Rev. D 92, no. 1, 012010 (2015)

[5] R. Aaij et al. [LHCb Collaboration], Eur. Phys. J. C 77, no. 12, 812 (2017)

[6] R. Essig et al., "Working Group Report: New Light Weakly Coupled Particles," arXiv:1311.0029 [hep-ph].

[7] C. Patrignani et al. [Particle Data Group], Chin. Phys. C 40, no. 10, 100001 (2016).

[8] A. Badin and A. A. Petrov, Phys. Rev. D 82, 034005 (2010)

[9] C. L. Hsu et al. [Belle Collaboration], Phys. Rev. D 86, 032002 (2012)

[10] J. P. Lees et al. [BaBar Collaboration], Phys. Rev. D 86, 051105 (2012)

[11] Y.-T. Lai et al. [Belle Collaboration], Phys. Rev. D 95, no. 1, 011102 (2017)

[12] S. de Boer, arXiv:1807.05845 [hep-ph].

[13] G. Buchalla and A. Buras, Nucl. Phys. B 400, 225 (1993)

[14] T. Inami and C. S. Lim, Prog. Theor. Phys. 65, 297 (1981) [Erratum-ibid. 65, 1772 (1981)]

[15] A. Goobar, S. Hannestad, E. Mortsell and H. Tu, JCAP 0606, 019 (2006)

[16] C. D. Lu and D. X. Zhang, Phys. Lett. B 381, 348 (1996)

[17] Y. G. Aditya, K. J. Healey and A. A. Petrov, Phys. Lett. B 710, 118 (2012)

[18] W. Altmannshofer, P. Ball, A. Bharucha, A. J. Buras, D. M. Straub and M. Wick, JHEP 0901, 019 (2009)

[19] B. Holdom, Phys. Lett. 166B, 196 (1986).

[20] M. Baumgart, C. Cheung, J. T. Ruderman, L. T. Wang and I. Yavin, JHEP 0904, 014 (2009)

[21] T. M. Aliev, A. Ozpineci and M. Savci, Phys. Lett. B 393, 143 (1997) [22] C. D. Lu and D. X. Zhang, Phys. Lett. B 381, 348 (1996)