Searching for super-WIMPs in leptonic meson decays

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Introduction

- Evidence for DM points to its gravitational properties, nature of DM is still under study
- Experimental measurements of relic abundance provides constraints on the masses and interaction strengths
  - *D. N. Spergel et al. [WMAP Collaboration]*
- Recent interest in light DM particles (masses down to the keV range)
  - Motivated by difficulties in understanding of small-scale gravitational clustering in numerical simulations with WIMPs
- Models with light mass O(keV-MeV) imply weaker than weak (superweak) interaction between DM and SM sector, super-WIMPs
  - *M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Rev. D 78, 115012 (2008) [arXiv:0807.3279 [hep-ph]];*
  - *M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B 662, 53 (2008) [arXiv:0711.4866 [hep-ph]];*

Introduction

- Super-WIMPs can be emitted and absorbed by SM particles.
  - Need not be stable against decays to lighter SM particles, no need to impose an ad-hoc Z_2 symmetry
- Due to small couplings, experimental search requires large statistics and ability to resolve missing energy
  - Super-B factories fit this bill
- We focus on Bosonic super-WIMPs and attempt to constrain their couplings with the SM through leptonic B decays
  - Axion-like dark matter, spin 0 (may also couple through CP odd Higgs)

    M. Pospelov, A. Ritz, M. Voloshin. , Physical review D 78, 115012 (2008)
  - Massive vector DM, spin 1 (appears as mediators in models of 'secluded' WIMP DM)

    M.Pospelov et al. , Phys. lett. B 662 (2008) 53-61

Leptonic B decay

- Leptonic B decay is helicity suppressed

$$\Gamma(B \to \ell\bar{\nu}) = \frac{G_f^2}{8\pi^2} V_{ub}^2 f_B^2 m_B^3 \frac{m_\ell^2}{m_B^2}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2$$

- Arises from the helicity flip needed on the outgoing lepton to conserve angular momentum, since initial meson is spinless

- Can be overcome by adding third particle – DM
  - Vector DM is similar to adding a photon
  - Axion DM involves derivative coupling, and hence can carry orbital angular momentum

$$B \to \ell\bar{\nu}_\ell X$$

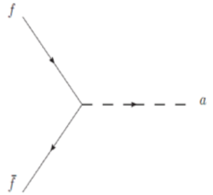
- The charged lepton spectrum of the 3-body decay will differ from the 2-body spectrum, the branching ratio can be used to constrain DM properties

Axion-like Dark Matter

$$B^- \to \ell^- \bar{\nu}_\ell a$$

- Tree level interaction with SM involves derivative operators

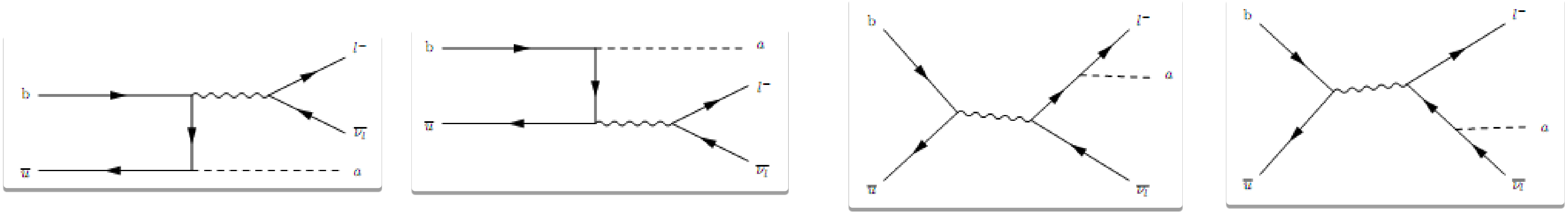
$$\mathcal{L}_a = -\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma_5\psi + \frac{C_\gamma}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$= \left(\frac{1}{f_a} + \frac{4\pi C_\gamma}{f_a \alpha}\right) k_\mu \gamma^\mu \gamma_5 + \left(\frac{8\pi C_\gamma}{f_a \alpha}\right) m_\psi \gamma_5$$

  - Dim 5 operators, f_a has dimension, C_γ is dimensionless

- 4 diagrams contribute to the amplitude



$$\mathcal{A}_{M\to\ell\bar{\nu}a} = \mathcal{A}_\ell + \mathcal{A}_q,$$

Quark model

- Since the meson is a bound state of quarks, we must employ a model to describe the effective quark-antiquark distribution
  - *A. Szczepaniak, E. M. Henley and S. J. Brodsky, Phys. Lett. B 243, 287 (1990) ;*
  - *G. P. Lepage and S. J. Brodsky, Phys. Rev. D 22, 2157 (1980)*
- The wave function for a meson M can be written as

$$\psi_M = \frac{I_c}{\sqrt{6}} \phi_M(x) \gamma_5 (\not{P}_M + M_M g_M(x))$$

x - momentum fraction carried by the heavy quark

g_M - 1 for heavy mesons, 0 for light mesons

the decay constant is related to the normalization

$$\int_0^1 \phi_M(x) dx = \frac{f_M}{2\sqrt{6}}$$

- The matrix element can be calculated by integrating over the momentum fraction

$$\langle 0 | \bar{q} \Gamma^\mu Q | M \rangle = \int_0^1 dx \; \mathrm{Tr} \left[\Gamma^\mu \psi_M \right]$$

Decay width and spectrum

- We obtain the decay width in the light DM mass limit with $\rho \equiv m_\ell / m_B$

$$\Gamma_{B\to\ell\nu_\ell a} = \frac{G_F^2 f_B^2 |V_{ub}|^2 M_B^5}{64\pi^3 f_a^2}\Big[\tfrac{1}{6}(2\rho^2 + 3\rho^4 + 12\rho^4 \log\rho - 6\rho^6 + \rho^8)$$
$$+ g_B^2 \left(\frac{m_b\phi_0 - M_B\phi_1}{f_B M_B}\right)^2 (1 - 6\rho^2 - 12\rho^4 \log\rho + 3\rho^4 + 2\rho^6)\Big]$$

- Note: $g_B \to 0$ give the same expression as the one obtained in a non-relativistic constituent quark model (NRCQM)

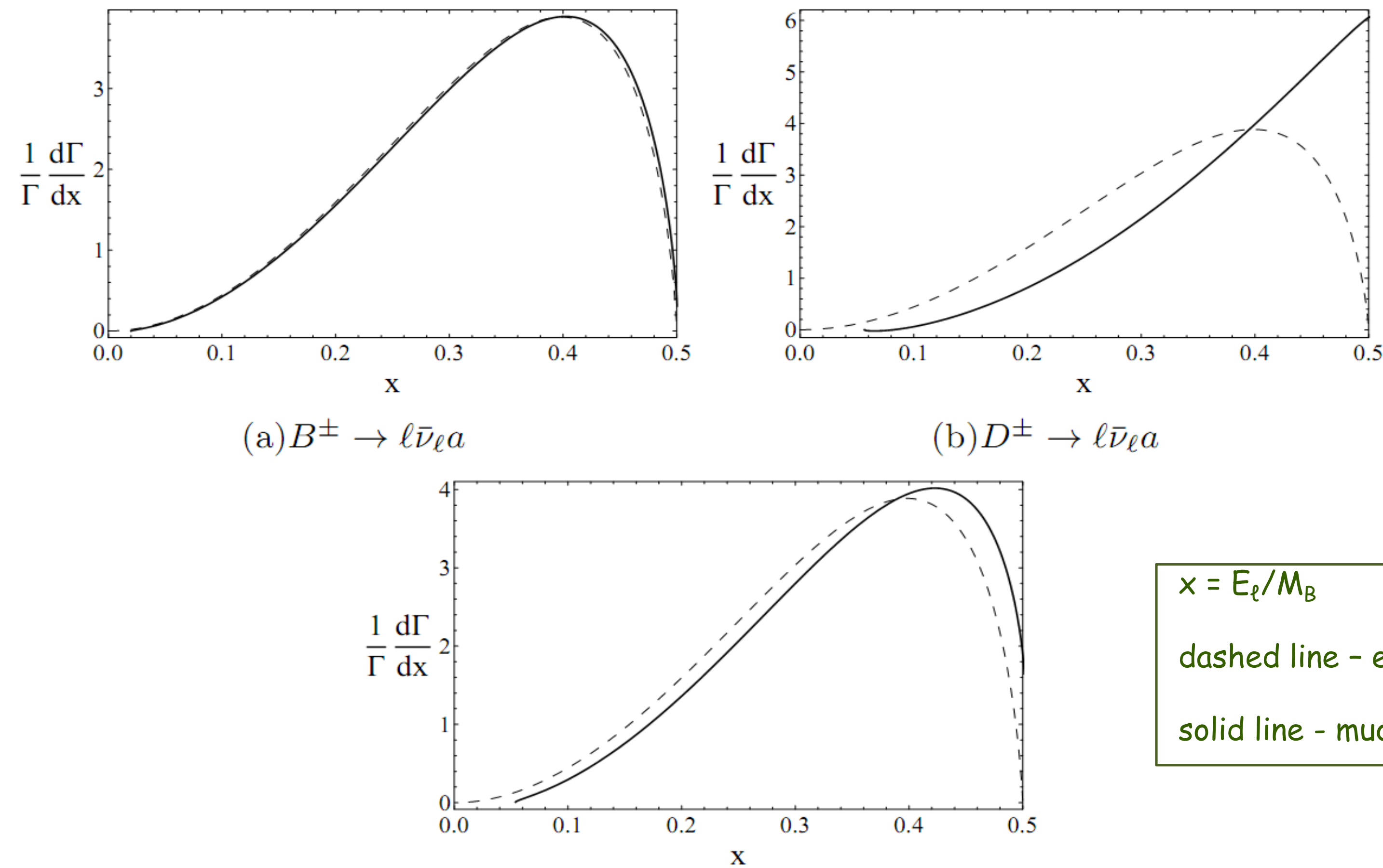
  (C. D. Lu and G. L. Song, Phys. Lett. B 562, 75 (2003) [arXiv:hep-ph/0212363])

  the structure dependent term vanishes and the width is proportional to lepton mass

- Similar results for D^+, D_s^+ are obtained by obvious substitution of relevant parameters such as masses, decay constants and CKM matrix elements.

Decay width and spectrum

- The normalized lepton energy spectrum is shown



(a) $B^{\pm} \to \ell \bar{\nu}_{\ell} a$ (b) $D^{\pm} \to \ell \bar{\nu}_{\ell} a$ (c) $D_s^{\pm} \to \ell \bar{\nu}_{\ell} a$

$x = E_{\ell}/M_B$

dashed line – electron energy spectrum

solid line - muon energy spectrum

Constraints on f_a

- The SM predictions for the $M \to \ell\nu$ process is significantly less than the current experimental bounds and/or measurements.
- At flavor factories, studies of the lepton spectrum in $M \to \ell$ + missing energy can be done to constrain the dark matter parameters
- So experimentally what is detected is

$$\Gamma_{\rm exp}(M \to \ell\bar{\nu}_\ell) = \Gamma_{\rm SM}(M \to \ell\bar{\nu}_\ell) + \int_{E<E_0} dE_a \frac{d\Gamma(M \to a\ell\bar{\nu}_\ell)}{dE_a}$$

(E_0 – Energy cut specific to experiment)

- In addition to a missing DM candidate, "soft" photons lift the helicity suppression allowing the amplitude to be of comparable order to the parent process.
- We incorporate soft photons up to an upper photon energy cut in NRCQM

$$\Gamma_{\rm exp}(M \to \ell\bar{\nu}_\ell) \;=\; \Gamma_{\rm SM}(M \to \ell\bar{\nu}_\ell) \;\left[1 + R_a(E_0) + R_{\gamma_s}(E_0')\right]$$

$$R_a(E_0) = \frac{1}{\Gamma_{\rm SM}(M \to \ell\bar{\nu}_\ell)} \int_{E<E_0} dE_a \frac{d\Gamma(M \to a\ell\bar{\nu}_\ell)}{dE_a}$$

Constraints on f_a

- Branching ratios for various leptonic meson decays including experimentally seen channels, and bounds on the unseen channels.
- The best constraints should come from the electron channels

Channel (Seen)	Experiment (Maximum)	Standard Model	$f_a^2 R_a(E_0)$ $E_0 = 100$ MeV	$R_{\gamma_s}(E'_0)$ $E'_0 = 50$ MeV	$R_{\gamma_s}(E'_0)$ $E'_0 = 100$ MeV	$R_{\gamma_s}(E'_0)$ $E'_0 = 300$ MeV
$\mathcal{B}(B^\pm \to \tau^\pm \bar{\nu}_\tau)$	1.7×10^{-4}	7.9×10^{-5}	1.6×10^{2}	4.9×10^{-5}	1.9×10^{-4}	1.9×10^{-3}
$\mathcal{B}(D^\pm \to \mu^\pm \bar{\nu}_\mu)$	3.8×10^{-4}	3.6×10^{-4}	3.1×10^{3}	4.0×10^{-3}	1.8×10^{-2}	1.7×10^{-2}
$\mathcal{B}(D_s^\pm \to \mu^\pm \bar{\nu}_\mu)$	5.9×10^{-3}	5.3×10^{-3}	4.6×10^{2}	2.0×10^{-4}	7.8×10^{-4}	6.0×10^{-3}
$\mathcal{B}(D_s^\pm \to \tau^\pm \bar{\nu}_\tau)$	5.4×10^{-2}	5.1×10^{-2}	6.5×10^{0}	2.1×10^{-5}	8.0×10^{-5}	6.2×10^{-4}
Channel (Unseen)						
$\mathcal{B}(B^\pm \to e^\pm \bar{\nu}_e)$	$< 1.9 \times 10^{-6}$	8.3×10^{-12}	6.6×10^{7}	4.6×10^{2}	1.8×10^{3}	1.6×10^{4} ⇦
$\mathcal{B}(B^\pm \to \mu^\pm \bar{\nu}_\mu)$	$< 1.0 \times 10^{-6}$	3.5×10^{-7}	1.8×10^{3}	1.1×10^{-2}	4.3×10^{-2}	3.6×10^{-1}
$\mathcal{B}(D^\pm \to e^\pm \bar{\nu}_e)$	$< 8.8 \times 10^{-6}$	8.5×10^{-9}	3.1×10^{6}	1.9×10^{2}	7.6×10^{2}	7.1×10^{3} ⇦
$\mathcal{B}(D^\pm \to \tau^\pm \bar{\nu}_\tau)$	$< 1.2 \times 10^{-3}$	9.7×10^{-4}	1.0×10^{1}	1.7×10^{-3}	7.7×10^{-3}	6.2×10^{-2}
$\mathcal{B}(D_s^\pm \to e^\pm \bar{\nu}_e)$	$< 1.2 \times 10^{-4}$	1.2×10^{-7}	9.8×10^{6}	8.6×10^{0}	3.3×10^{1}	2.6×10^{2} ⇦

Constraints on f_a

- Branching ratios for various leptonic meson decays including experimentally seen channels, and bounds on the unseen channels.
- The best constraints should come from the electron channels
- We can then get lower bounds f_a by reconciling the measured experimental branching ratio with the combination of SM, DM and soft photon contributions

Channel	$f_a(MeV)$
$\mathcal{BR}\left(B^\pm \to \tau^\pm \bar{\nu}_\tau\right)$	12
$\mathcal{BR}\left(D^\pm \to \mu^\pm \bar{\nu}_\mu\right)$	236
$\mathcal{BR}\left(D_s^\pm \to \mu^\pm \bar{\nu}_\mu\right)$	62
$\mathcal{BR}\left(D_s^\pm \to \tau^\pm \bar{\nu}_\tau\right)$	11

Mixing with CP-odd Higgs

- In particular models of DM such as the axion portal, the axion can mix with the CP-odd Higgs in a two Higgs doublet model
  - *M. Freytsis, Z. Ligeti and J. Thaler, Phys. Rev. D 81, 034001 (2010) [arXiv:0911.5355 [hep-ph]]*

$$a_p = a\cos\theta - A^0\sin\theta$$

$$A_p^0 = a\sin\theta + A^0\cos\theta$$

where $\tan\theta = \frac{v_{EW}}{f_a}\sin 2\beta$

- Then in the new basis $B \to \ell\nu a$ amplitude can be derived from the $B \to \ell\nu A^0$ amplitude

$$\mathcal{M}(B \to \ell\nu a_p) = -\sin\theta\mathcal{M}(B \to \ell\nu A^0) + \cos\theta\mathcal{M}(B \to \ell\nu a)$$

- The yukawa interactions of the CP-odd higgs with the fermions are

$$\mathcal{L}_{A^0 f\bar{f}} = \frac{ig\tan\beta}{2m_W} m_d\bar{d}\gamma_5 dA^0 + \frac{ig\cot\beta}{2m_W} m_u\bar{u}\gamma_5 uA^0$$

Mixing with CP-odd Higgs

- In the axion portal scenario the axion mass is predicted to lie within a specific range of 360 < $m_a \lesssim$ 800 MeV and decay constant fa between 1-3 TeV so as to explain the galactic electron/positron excess
- The decay width is

$$\Gamma\left(B \to \ell \nu_\ell a_{phys}\right) = \frac{G_F^2 |V_{ub}|^2 m_B^3}{256\pi^3 \left(f_a^2 + v_{EW}^2 \sin^2 2\beta\right)} \left[\cos 2\beta \left(m_u \phi_1 + m_b(\phi_0 - \phi_1)\right) + 5(m_b + m_u)\phi_1 - 5 m_b \phi_0\right]^2$$

$$\times \left[12 x_a^4 \log(x_a) - 4x_a^6 + 3x_a^4 + (\rho - 1)^4 (4(\rho - 2)\rho + 1) - 12(\rho - 1)^4 \log(1 - \rho)\right]$$

($x_a = m_a / m_B$)

The lower bounds are given by

Channel	$f_a(MeV)$ $\tan\beta = 1$	$f_a(MeV)$ $\tan\beta = 5$	$f_a(MeV)$ $\tan\beta = 10$	$f_a(MeV)$ $\tan\beta = 20$
$\mathcal{BR}\left(B^\pm \to \tau^\pm \bar{\nu}_\tau\right)$	70	340	357	361
$\mathcal{BR}\left(D^\pm \to \mu^\pm \bar{\nu}_\mu\right)$	416	2874	3078	3131
$\mathcal{BR}\left(D_s^\pm \to \mu^\pm \bar{\nu}_\mu\right)$	532	1380	1499	1529

($f_a >> v_{EW} \sin 2\beta$)

Vector Dark matter

$$B \to \ell\bar{\nu}V_{DM}$$

- Appear in 'Secluded' WIMP models, vector boson acts as mediators that couple the heavier WIMPs to the SM.
- Vector boson couples to the SM via kinetic mixing

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + \mathcal{L}_{h'} + \mathcal{L}_{d>4},$$

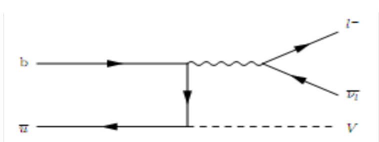
- We can rotate out the mixing term with the redefinitions

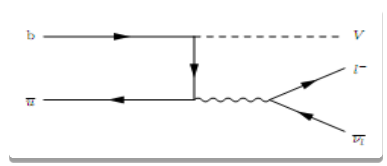
$$A \to A' - \frac{\kappa}{\sqrt{1-\kappa^2}}V', \qquad V \to \frac{1}{\sqrt{1-\kappa^2}}V'.$$

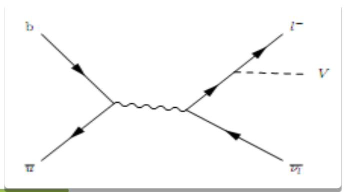
- Shifting the fermionic interaction couplings appropriately

$$\mathcal{L}_f = -eQ_f A'_\mu \bar{\psi}_f \gamma^\mu \psi_f - \frac{\kappa e Q_f}{\sqrt{1-\kappa^2}} V'_\mu \bar{\psi}_f \gamma^\mu \psi_f,$$

$$\frac{\kappa e}{\sqrt{1-\kappa^2}} \approx \kappa e$$

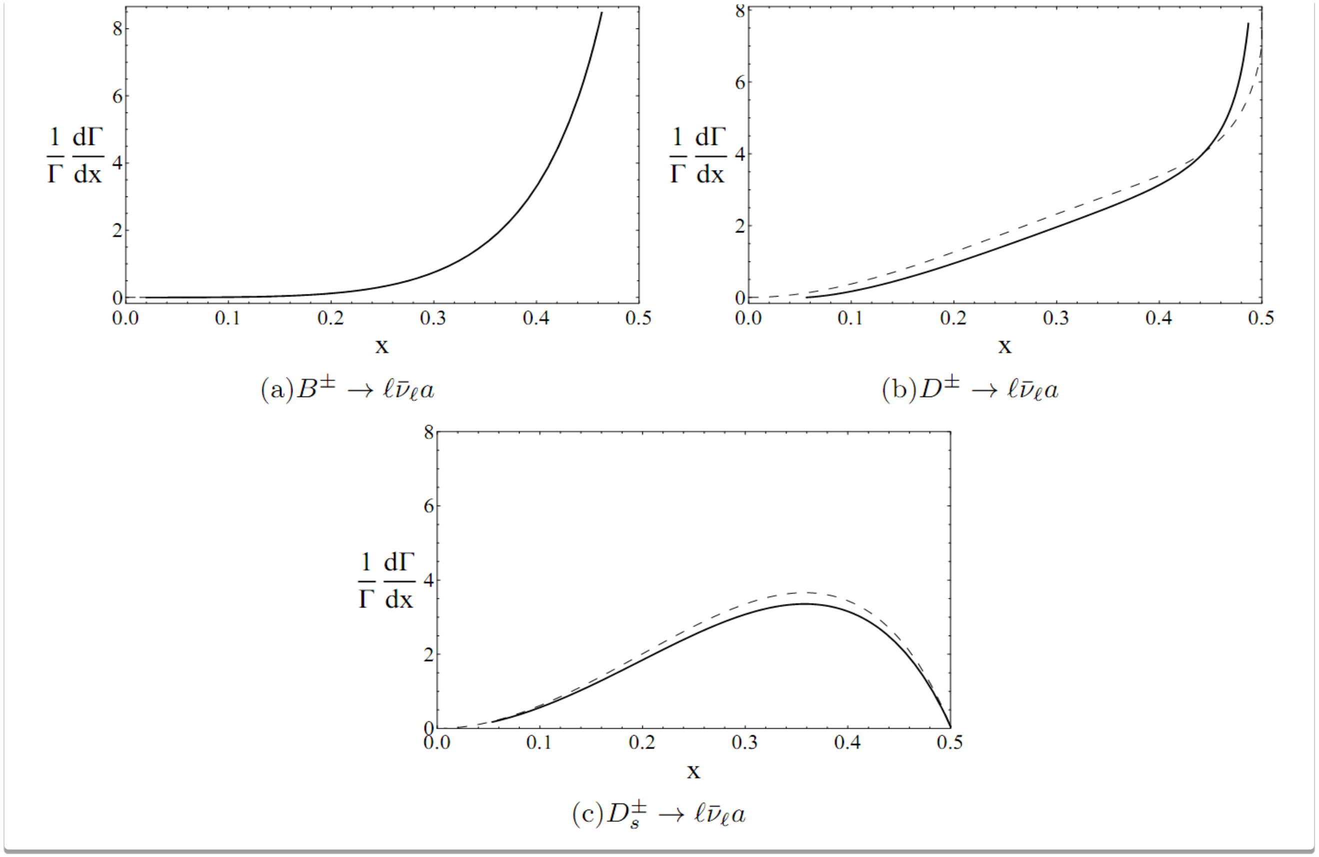






Spectrum and bounds

- We can constrain the parameter κ using the same data as the ALDM case
- The lepton spectrum is shown



Spectrum and bounds

- We can constrain the parameter κ using the same data as the ALDM case
- Upper bounds on kappa

Channel	$\kappa^{-2} R_V(E_0)$ $E_0 = 100$ MeV	κ
$\mathcal{B}\left(B^{\pm} \to \tau^{\pm}\bar{\nu}_{\tau}\right)$	8.8×10^{-3}	≤ 11.6
$\mathcal{B}\left(D^{\pm} \to \mu^{\pm}\bar{\nu}_{\mu}\right)$	5.7×10^{-1}	≤ 0.31
$\mathcal{B}\left(D_s^{\pm} \to \mu^{\pm}\bar{\nu}_{\mu}\right)$	5.4×10^{-2}	≤ 1.49
$\mathcal{B}\left(D_s^{\pm} \to \tau^{\pm}\bar{\nu}_{\tau}\right)$	1.3×10^{-4}	≤ 20.8
$\mathcal{B}\left(B^{\pm} \to e^{\pm}\bar{\nu}_{e}\right)$	1.8×10^{3}	≤ 11.2
$\mathcal{B}\left(B^{\pm} \to \mu^{\pm}\bar{\nu}_{\mu}\right)$	1.0×10^{-1}	≤ 4.17
$\mathcal{B}\left(D^{\pm} \to e^{\pm}\bar{\nu}_{e}\right)$	1.5×10^{3}	≤ 0.83
$\mathcal{B}\left(D^{\pm} \to \tau^{\pm}\bar{\nu}_{\tau}\right)$	1.8×10^{-4}	≤ 36.4
$\mathcal{B}\left(D_s^{\pm} \to e^{\pm}\bar{\nu}_{e}\right)$	5.2×10^{2}	≤ 1.37

Channel	$\mathcal{B}(\kappa = 0.31)$
$\mathcal{B}\left(B^{\pm} \to e^{\pm}\bar{\nu}_{e}\right)$	1.4×10^{-9}
$\mathcal{B}\left(B^{\pm} \to \mu^{\pm}\bar{\nu}_{\mu}\right)$	3.6×10^{-9}
$\mathcal{B}\left(D^{\pm} \to e^{\pm}\bar{\nu}_{e}\right)$	1.2×10^{-6}
$\mathcal{B}\left(D^{\pm} \to \tau^{\pm}\bar{\nu}_{\tau}\right)$	1.7×10^{-8}
$\mathcal{B}\left(D_s^{\pm} \to e^{\pm}\bar{\nu}_{e}\right)$	6.2×10^{-6}

Conclusion

- Considered two models of light dark matter
- Used experimental data along with SM predictions of leptonic B and D decays to constrain the model parameters
- Considered the effect of mixing with the CP-odd Higgs in a 2HDM
- With better measurements and statistics, we expect strong constraints to come from the electron channels

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