Charming Dark Matter

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Outline

Background

- Most dark matter analyses done with simplified models
- Very easy to work with – but this simplicity hides all the interesting effects
- If there is a complex flavour structure, then typically Minimal Flavour Violation is invoked

What is Minimal Flavour Violation?

- In the SM, without quark masses, there is a global flavour symmetry $\mathrm{SU(3)}_{Q_L} \times \mathrm{SU(3)}_{\mathrm{u}_R} \times \mathrm{SU(3)}_{\mathrm{d}_R}$
- Broken by $m_q \neq 0$
- Get unitary coupling matrix V_{CKM}

Minimal Flavour Violation (MFV)

- FCNC $\propto$ off-diagonal elements of $V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger}$
- If your model obeys MFV $\Rightarrow$ can't get large new contributions to flavour measurement

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- Bad if you want to do some flavour physics

Beyond MFV

- If we want new physics effects, we have to go beyond MFV
- A relatively simple extension is Dark Minimal Flavour Violation (DMFV)

Dark Minimal Flavour Violation[1]

- Add dark matter that transforms under a new flavour symmetry $SU(3)_\chi$
- In the simplest case – three DM particles
- $SU(3)_\chi$ is broken by coupling matrix λ

[1] Agrawal, Blanke, Gemmler – arXiv:1405.6709

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- We have DM coupling to right handed up-type quarks
  - Right handed because then our model is $SU(2)_L$ invariant
  - Up-type to allow for NP in the charm sector
- Charm bounds have not been looked at before

Charm bounds

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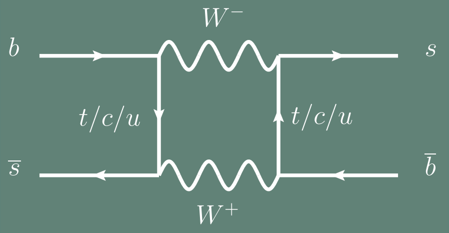
Charm bounds

- What charm processes can bound new physics?
- D mixing?
- Situation is unclear . . .

Neutral Meson Mixing

- In the SM, neutral mesons can turn into their antiparticles through box diagrams like the one below



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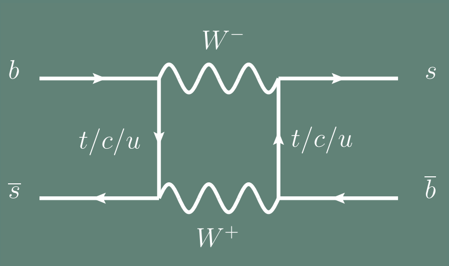

- This diagram represents a contribution to an off-diagonal Hamiltonian element $\langle \mathsf{B}|\mathcal{H}|\overline{\mathsf{B}}\rangle$

Neutral Meson Mixing

- Because of mixing, meson/anti-meson are not mass eigenstates – find new eigenstates with mass difference ΔM, width difference $\Delta\Gamma$
- Measurements of $\Delta M, \Delta\Gamma$ generally provide strong constraints on new physics

Neutral Meson Mixing

- As an example, for B_s^0 mesons we have:

$$\Delta\Gamma^{\text{theory}} = (5.8 \pm 1.3) \times 10^{-14}\ \text{GeV}$$
$$\Delta\Gamma^{\text{exp}} = (5.5 \pm 0.4) \times 10^{-14}\ \text{GeV}$$

Charm vs Heavy Quark Expansion

- HQE is an expansion in $\frac{1}{m_Q}$ where Q is a heavy quark
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- HQE is used to predict $\Delta\Gamma_\mathrm{D}$ (and then ΔM_D)
- 3-4 orders of magnitude difference!
- Because $m_\mathrm{c} < m_\mathrm{b}$?

Charm vs Heavy Quark Expansion

- But certain HQE predictions are much better, e.g.[1]:

$$\frac{\tau(D^+)}{\tau(D^0)}_{\text{exp}} \approx 2.54 \pm 0.02, \quad \frac{\tau(D^+)}{\tau(D^0)}_{\text{HQE}} \approx 2.8 \pm 1.5$$

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- Maybe GIM suppression lifts at higher orders?

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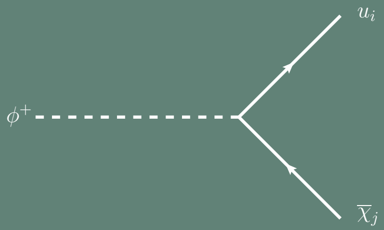
- D mixing?
- Not a straightforward bound to apply

Charming dark matter model

- Our model has 4 new particles:
  - 3 DM particles χ_i – singlets under the SM gauge group
  - A mediator ϕ, with electric and colour charge
- The interaction part of the Lagrangian is:

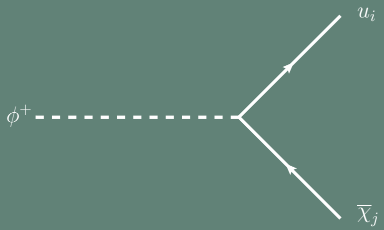
$$\mathcal{L}_{\text{int}}^{\text{NP}} = -\lambda_{ij}\overline{\text{u}}_i(1-\gamma^5)\chi_j\phi^+ - \lambda_{ij}^*\overline{\chi}_j(1+\gamma^5)\text{u}_i\phi^- + \frac{g_{\phi\phi}}{4}(\phi^+\phi^-)^2 + g_{H\phi}\phi^+\phi^-\text{H}^\dagger\text{H}$$



Model parameters

- For looking at D mixing constraints, the relevant Lagrangian terms are

$$\mathcal{L} = -\lambda_{ij}\overline{\mathsf{u}}_i(1-\gamma^5)\chi_j\phi^+ - \lambda_{ij}^*\overline{\chi}_j(1+\gamma^5)\mathsf{u}_i\phi^-$$



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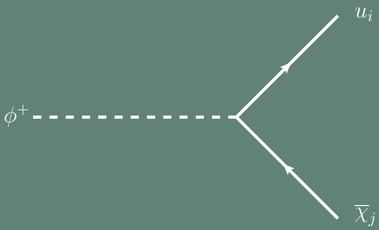
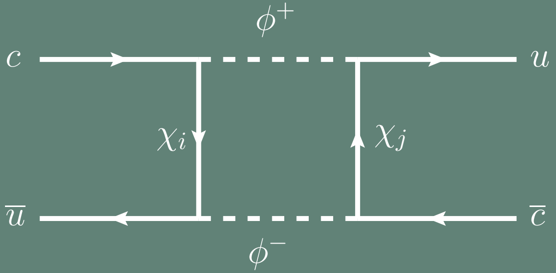
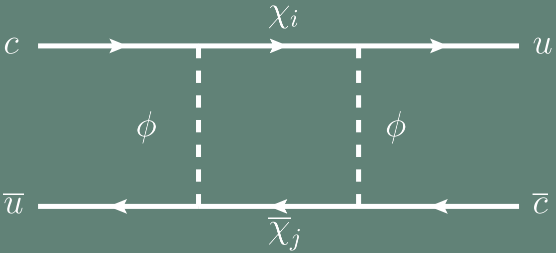
- Parameter space is 11 dimensional
  - m_ϕ, m_{χ_0}
  - λ can be parameterised by:
    - 3 mixing angles
    - 3 CP violating phases
    - 3 non-negative elements



New Box Diagrams

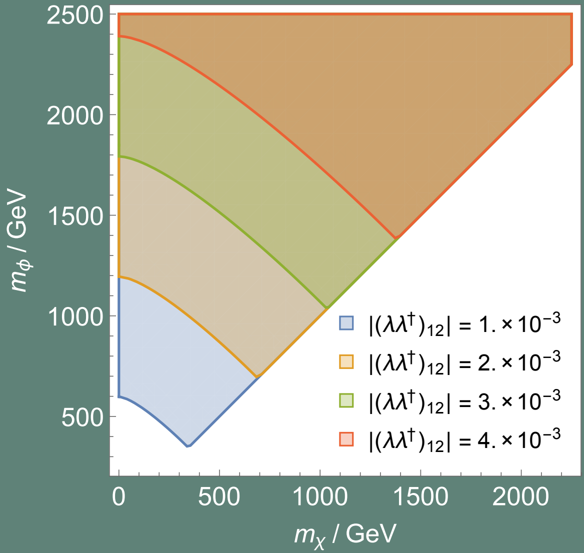




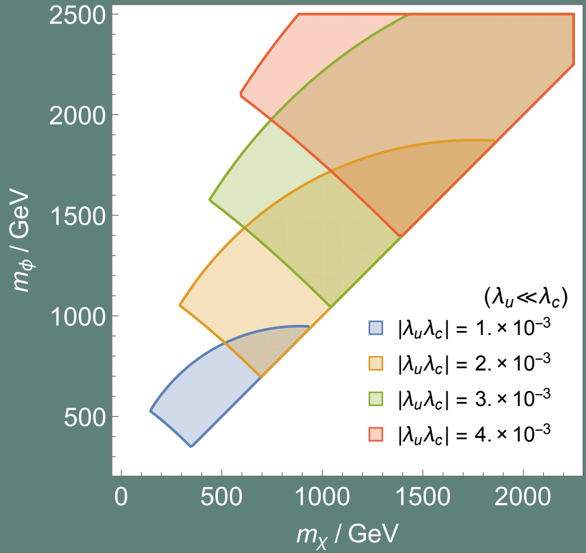
Constraints

- The constraints we impose upon our model are:
  - $|M_{12}|^{\text{NP}} \leqslant |M_{12}|^{\text{exp}}$, i.e. we are allowing for the uncertainty in the SM prediction
  - Dark matter relic density is $\leq \Omega_{\text{DM}} h^2 \approx 0.11$

Allowed Regions



Allowed regions – simplified model



Rare decays

- We also estimated the contributions our model gives to the rare decays $D^0 \to \mu\mu$ and $D^0 \to \gamma\gamma$
- The NP enhancement is $\ll$ the SM prediction

Summary and what next?

- We have shown that a model obeying Dark Minimal Flavour Violation can contribute to D^0 mixing over a reasonable amount of parameter space
- Next steps: constraints from relic density, direct and indirect detection, and collider searches

Backup

Benefits of DMVF

- At lowest order, all the DM particles have equal mass
- As long as one DM flavour is the lightest new particle, even non-renormalisable terms leading to decay are forbidden[1]

[1] Batell, Pradler, Spannowsky (arXiv:1105.1781)
Agrawal, Blanke, Gemmler (arXiv:1405.6709)

Neutral Meson Mixing

- This diagram represents a contribution to an off-diagonal Hamiltonian element $\langle \mathrm{B}|\mathcal{H}|\overline{\mathrm{B}}\rangle$
- The quantity we are interested in is

$$
\begin{aligned}
M_{12} &= \frac{\langle \mathrm{B}|\mathcal{H}|\overline{\mathrm{B}}\rangle}{2M_{\mathrm{B}}} \\
&\propto \sum_{i,j} F(m_i, m_j) V_{ib} V_{is}^* V_{jb} V_{js}^*
\end{aligned}
$$