# 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 $V_{\mathrm{CKM}}$

# Minimal Flavour Violation (MFV)

- FCNC $\propto$ off-diagonal elements of $V_{\text{CKM}} V_{\text{CKM}}^{\dagger}$
- 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 $\lambda$

[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

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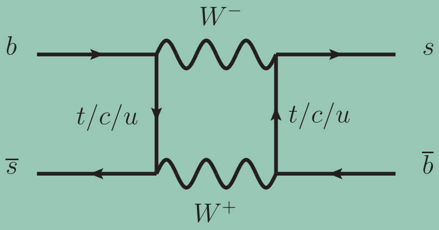
- D mixing?
- Situation is unclear . . .

# Neutral Meson Mixing

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



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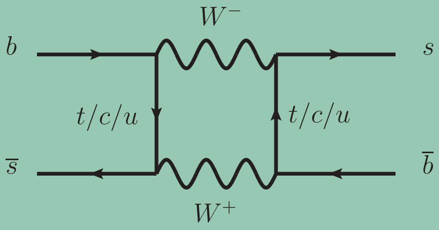


- This diagram represents a contribution to an off-diagonal Hamiltonian element $\langle \mathrm{B}|\mathcal{H}|\overline{\mathrm{B}}\rangle$

# Neutral Meson Mixing

- Because of mixing, meson/anti-meson are not mass eigenstates – find new eigenstates with mass difference $\Delta M$, 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
- HQE is used to predict $\Delta\Gamma_{\mathrm{D}}$ (and then $\Delta M_{\mathrm{D}}$)

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- 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]:

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

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- Maybe GIM suppression lifts at higher orders?

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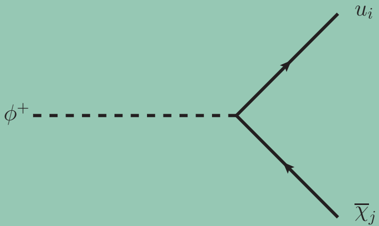
- D mixing?
- Not a straightforward bound to apply

# Charming dark matter model

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

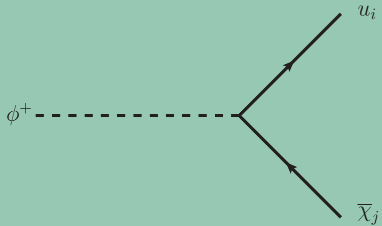
$$\mathcal{L}_{\text{int}}^{\text{NP}} = -\lambda_{ij}\overline{\text{u}}_i(1-\gamma^5)\chi_j\phi^+ - \lambda_{ij}^*\overline{\chi}_j(1+\gamma^5)\text{u}_i\phi^- + \frac{g_{\phi\phi}}{4}(\phi^+\phi^-)^2 + g_{H\phi}\phi^+\phi^-\text{H}^\dagger\text{H}$$



# 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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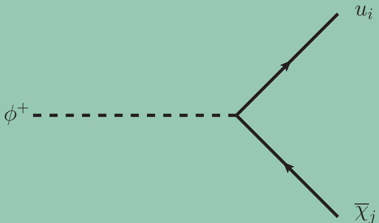
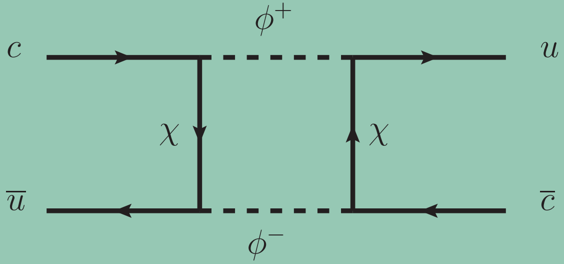
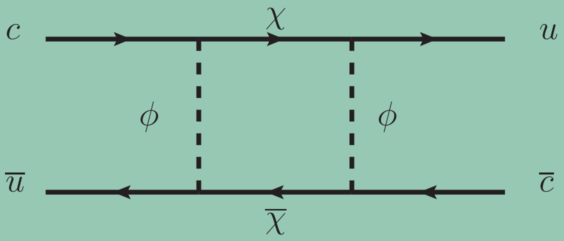
- Parameter space is 11 dimensional
  - $m_\phi, m_{\chi_0}$
  - $\lambda$ can be parameterised by:
    - 3 mixing angles
    - 3 CP violating phases
    - 3 non-negative elements



# New Box Diagrams

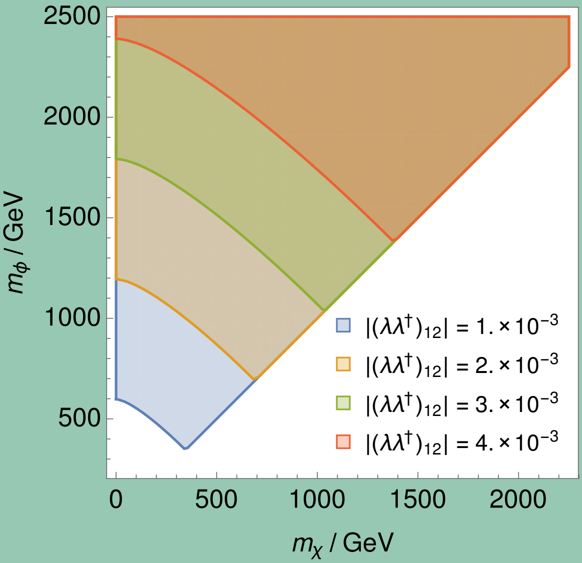


# Constraints

- The flavour constraint we have imposed upon our model is $|M_{12}|^{\mathrm{NP}} \leqslant |M_{12}|^{\mathrm{exp}}$, i.e. we are allowing for the uncertainty in the SM prediction

# Allowed Regions



# Simplified Model for relic density[1]

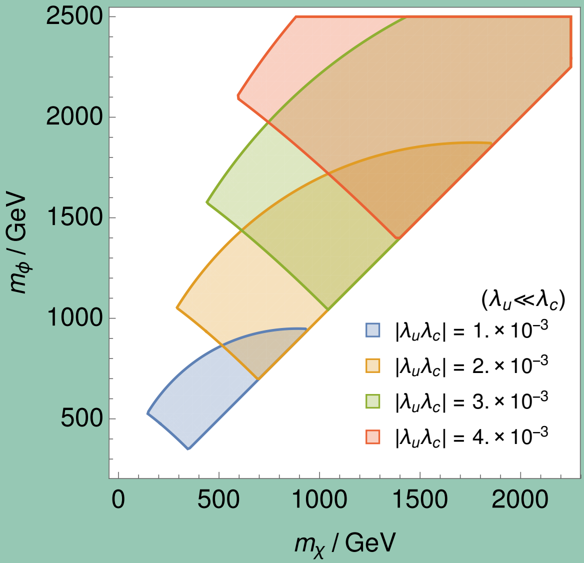
- In order to easily visualise relic density constraint, take a simplified model

$$\mathcal{L}^{\mathsf{simp}} = -\lambda_i \bar{\mathsf{u}}_i (1 - \gamma^5) \chi \phi^+ - \lambda_i \overline{\chi} (1 + \gamma^5) \mathsf{u}_i \phi^-$$

- Effectively decouple two of the dark matter particles – reduces the number of free parameters from 11 to 4

[1] calculations by Tom Jubb

# Allowed regions – simplified model



# Rare decays

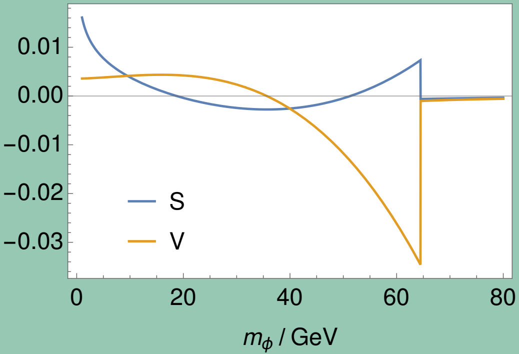
- We also estimated the contributions our model gives to the rare decays $\mathrm{D}^0 \to \mu\mu$ and $\mathrm{D}^0 \to \gamma\gamma$
- The resulting NP enhancement is $\ll$ the SM prediction

# Electroweak Precision Observables

- Heavy new physics contributions to gauge boson propagators can be parameterised by Peskin-Takeuchi $S, T, U$ parameters
- Our mediator contributes $S \sim 10^{-6}$, $T = 0$
- Compare with experimental fit $S \approx 0.05$

# Electroweak Precision Observables

- For lighter NP, i.e. close or below the electroweak scale, $V, W, X$ parameters relevant
- In our model, only $S$ and $V$ independent and non-zero



# What next?

- Constraints from relic density, direct and indirect detection, and collider searches

# Summary

- We have shown that a model obeying Dark Minimal Flavour Violation can contribute to $D^0$ mixing over a reasonable amount of parameter space
- We have looked at rare decay constraints, and corrections to gauge boson masses
- Direct and indirect detection coming soon

# 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

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

# STU parameters

$$\frac{\alpha}{4s_W^2 c_W^2} S \equiv \frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2}$$

$$\alpha V \equiv \left.\frac{\partial \Pi_{ZZ}}{\partial q^2}\right|_{q^2=m_Z^2} - \frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2}$$

# STU for DMFV

- For SU(2) singlet with charge Q, $S$ and $V$ given by [1]

$$S \propto Q^2 \left( -\frac{16}{3} + \frac{16 m_\phi^2}{m_Z^2} + \frac{r}{m_Z^6} f(t,r) \right) \qquad r = m_Z^4 - 4 m_Z^2 m_\phi^2$$

$$V \propto Q^2 \left( 2 - 24 \frac{m_\phi^2}{m_Z^2} + 6 \frac{m_\phi^2}{m_Z^4} f(t,r) \right) \qquad t = 2 m_\phi^2 - m_Z^2$$

$$f(t,r) = \begin{cases} \sqrt{r} \ln \left| \frac{t - \sqrt{r}}{t + \sqrt{r}} \right| & \text{for} \quad r > 0, \\ 0 & \text{for} \quad r = 0, \\ 2\sqrt{-r} \arctan \frac{\sqrt{-r}}{t} & \text{for} \quad r < 0. \end{cases}$$

[1] Grimus, Lavoura, Ogreid, Osland (arXiv:0802.4353)