Charming Dark Matter

Matthew Kirk[1]

IPPP, Durham University

30 November 2015

[1]Supervisor: Alexander Lenz, DM calculations by Tom Jubb

Outline

- Background
- Model Description
  - Neutral Meson Mixing
  - Heavy Quark Expansion
- A First Look
  - Experimental Constraints
  - What is allowed?
- Summary

Background

- Most dark matter models are very simple – they include a single new dark matter candidate that couples to a single SM particle, via some mediator
- Very easy to work with – but this simplicity hides all the interesting effects
- It also doesn't look like the SM as we know it so far

Background

- Next step up is to include multiple DM particles that can couple to multiple SM particles
- But (e.g if you have interactions with multiple quark generations) then you have to worry about effects in flavour physics
- Lots of rare processes that might be affected

Minimal Flavour Violation (MFV)

- The normal response in DM models is to invoke Minimal Flavour Violation

What is Minimal Flavour Violation?

- In the SM, without quark masses, there is a global flavour symmetry $SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$
- Simple version – all the quark generations behave the same
- This is broken by the introduction of quarks masses via the Yukawa couplings

What is Minimal Flavour Violation?

- After moving to the mass eigenbasis for quarks, we are left with a non-diagonal unitary coupling matrix V_{CKM}
- Unitarity leads to GIM suppression – in the approximation of massless (or just equal mass) quarks, many flavour changing neutral current processes vanish
- E.g. mixing is $\propto \left(V_{\mathrm{CKM}} V^{\dagger}_{\mathrm{CKM}}\right)_{12} = 0$

Minimal Flavour Violation (MFV)

- The normal response in DM models is to invoke Minimal Flavour Violation
- If your model obeys MFV, then all interactions that could break the flavour symmetry have coupling matrices that are diagonal or unitary
- In both cases – can't get large new contributions to flavour measurements

Minimal Flavour Violation (MFV)

- Good if you are just looking at dark matter - just say MFV and all flavour problems vanish

Minimal Flavour Violation (MFV)

- Good if you are just looking at dark matter - just say MFV and all flavour problems vanish
- 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)
- Keeps the number of parameters down, and guarantees stability of the DM

Dark Minimal Flavour Violation

- 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

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)

Model

- Now we have a theoretical basis, we have to think about what kind of interaction we want

Model

- Now we have a theoretical basis, we have to think about what kind of interaction we want
- Our choice is DM coupling to right handed up-type quarks

Model

- Now we have a theoretical basis, we have to think about what kind of interaction we want
- Our choice is 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
  - Also, never been done before [1]

Model

- Now we have a theoretical basis, we have to think about what kind of interaction we want
- Our choice is 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
  - Also, never been done before [1]

[1] Not strictly true – but only looking at top forward-backward asymmetry

New particles

- 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:

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

New Physics with Charm Quarks

- Is there any new physics to be found with charm quarks?

New Physics with Charm Quarks

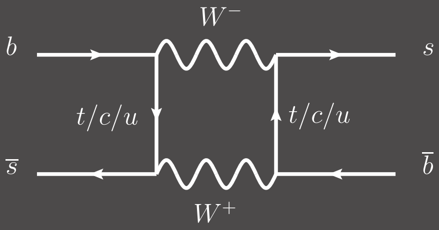
- Is there any new physics to be found with charm quarks?
- Maybe . . .

New Physics with Charm Quarks

- Is there any new physics to be found with charm quarks?
- Maybe . . .
- Small detour into neutral meson mixing

Neutral Meson Mixing

- In the SM, neutral mesons (D^0, B^0_s, B^0_d, K^0) can turn into their antiparticles through box diagrams, like the one below (representing $\overline{B^0_s} \to B^0_s$)



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

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

Neutral Meson Mixing

- Because of mixing, meson/anti-meson are not mass eigenstates – find new eigenstates with mass difference $\Delta M \propto |M_{12}|$
- Measurements of ΔM generally provide strong constraints on new physics

Neutral Meson Mixing

- Because of mixing, meson/anti-meson are not mass eigenstates – find new eigenstates with mass difference $\Delta M \propto |M_{12}|$
- Measurements of ΔM generally provide strong constraints on new physics
- As an example, for B_s^0 mesons we have:

$$\Delta M^{\text{theory}} = (1.20 \pm 0.18) \times 10^{-11}\ \text{GeV}$$
$$\Delta M^{\text{exp}} = (1.1688 \pm 0.0014) \times 10^{-11}\ \text{GeV}$$

D^0-$\overline{D}^0$ Mixing

- But for D mesons, it is a bit more complicated

D^0-$\overline{D}^0$ Mixing

- But for D mesons, it is a bit more complicated
- Experimental measurement is fine:
  - $\Delta M^{\text{exp}} = (7.0 \pm 2.2) \times 10^{-15}$ GeV

D^0-$\overline{D}^0$ Mixing

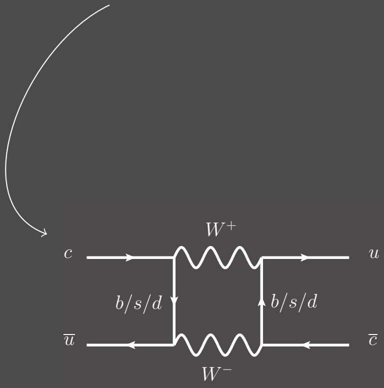
- But for D mesons, it is a bit more complicated
- Experimental measurement is fine:
  - $\Delta M^{\text{exp}} = (7.0 \pm 2.2) \times 10^{-15}$ GeV
- But hard to calculate theoretically – charm quarks are relatively light

Charm vs Heavy Quark Expansion

- HQE is an expansion in $\frac{1}{m_Q}$ where Q is a heavy quark
- Works very well for b quarks ($m_\mathrm{b} \approx 4.6$ GeV)
- But for charm, $m_\mathrm{c} \approx 1.3$ GeV

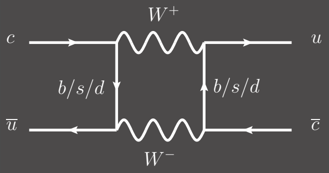
Charm HQE predictions

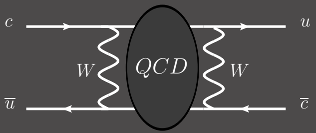
- Short distance contributions give $\Delta M \approx 5 \times 10^{-19}$ GeV



Charm HQE predictions

- Short distance contributions give $\Delta M \approx 5 \times 10^{-19}$ GeV
- Long distance (i.e. non-perturbative) estimate is $\Delta M \sim 10^{-15}$ GeV





Charm vs Heavy Quark Expansion

- It looks like HQE is worse with charm quarks
- This has traditionally been the explanation of the poor SM prediction

Charm vs Heavy Quark Expansion

- It looks like HQE is worse with charm quarks
- This has traditionally been the explanation of the poor SM prediction
- But certain HQE predictions for e.g the ratio of D meson lifetimes are much better
- And some higher order corrections are estimated to be only around 30%

New Physics with Charm Quarks

- Is there any new physics to be found with charm quarks?
- Maybe . . .

New Physics with Charm Quarks

- Is there any new physics to be found with charm quarks?
- Maybe . . .
- It is certainly worth thinking about

Initial Investigation

- In order to see if a flavoured dark matter model can contribute to mixing, we take a slightly simplifed version
- Effectively decouple two of the dark matter particles

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

Initial Investigation

- In order to see if a flavoured dark matter model can contribute to mixing, we take a slightly simplifed version
- Effectively decouple two of the dark matter particles

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

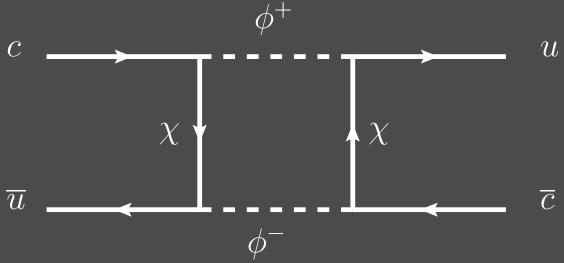
Initial Investigation

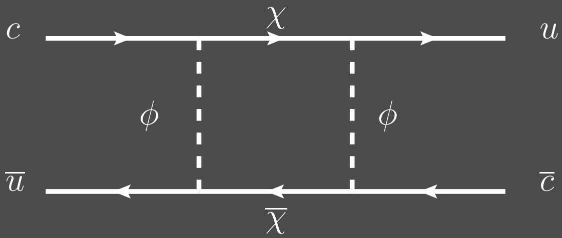
- In order to see if a flavoured dark matter model can contribute to mixing, we take a slightly simplifed version
- Effectively decouple two of the dark matter particles

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

- Reduces the number of free parameters from 10 to 4 - $m_\phi, m_\chi, \lambda_{\mathsf{u}}, \lambda_{\mathsf{c}}$

New Box Diagrams





Relic Density Constraints

- Alongside the mixing constraint, we want the correct relic density for our dark matter

Relic Density Constraints

- Alongside the mixing constraint, we want the correct relic density for our dark matter
- Relic density is calculated by assuming our DM was in thermal equilibrium in the early universe
- The density then dilutes as the universe expands, and eventually drops out of equilibrium

Constraints

- The constraints we impose upon our model are:
  - $\Delta M^{\mathrm{NP}} = \Delta M^{\mathrm{exp}}$, i.e. we are taking the short distance prediction

Constraints

- The constraints we impose upon our model are:
  - $\Delta M^{\text{NP}} = \Delta M^{\text{exp}}$, i.e. we are taking the short distance prediction

$$\Delta M \approx 5 \times 10^{-19}\ \text{GeV}$$

Constraints

- The constraints we impose upon our model are:
  - $\Delta M^{\mathrm{NP}} = \Delta M^{\mathrm{exp}}$, i.e. we are taking the short distance prediction seriously

$\Delta M \approx 5 \times 10^{-19}$ GeV

Constraints

- The constraints we impose upon our model are:
  - $\Delta M^{\mathrm{NP}} = \Delta M^{\mathrm{exp}}$, i.e. we are taking the short distance prediction seriously
  - The relic density of our DM candidate has to be less than the experimental value

$\Delta M \approx 5 \times 10^{-19}$ GeV

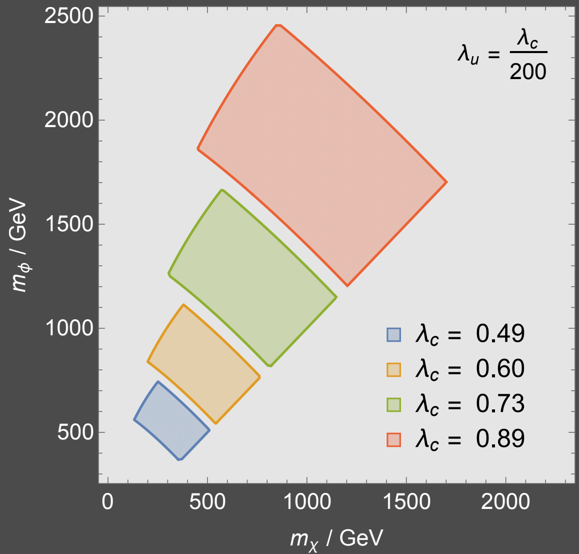
Constraints

- The constraints we impose upon our model are:
  - $\Delta M^{\mathrm{NP}} = \Delta M^{\mathrm{exp}}$, i.e. we are taking the short distance prediction seriously
  - The relic density of our DM candidate has to be less than the experimental value

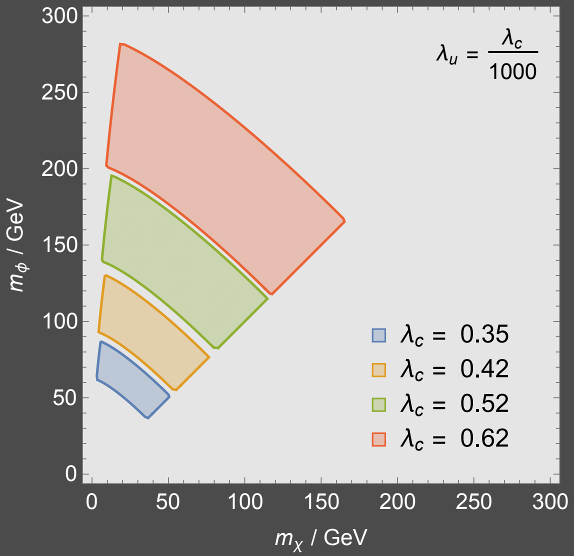
$\Delta M \approx 5 \times 10^{-19}$ GeV

$\Omega_{\mathrm{DM}}\ h^2 = 0.11$

Allowed Regions



Allowed Regions



Rare decays

- We also checked the contributions our model gives to the rare decays $D^0 \to \mu\mu$ and $D^0 \to \gamma\gamma$
- The current experimental limits on these decays are still several orders of magnitude above the SM prediction
- Our model cannot enhance the branching ratios to close to the current limits while still explaining D^0 mixing.

Summary

- We have shown that a simplified Dark Minimal Flavour Violation model can contribute to D^0 mixing over a reasonable amount of parameter space
- The next step is to redo the calculation in the full model
- Also look at constraints from collider searches and direct detection