Flavored Dark Matter

Jennifer Kile
Northwestern University

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Motivation: DM & Flavor

Lots of stuff we don't know about DM:

- Number of DM species? Dark sector?
- Mass(es)?
- Interactions with SM? DM-DM interactions?

Meanwhile, back in the SM....

- Origin of 3 fermion families unknown. Presumably, BSM physics will come to the rescue.
- Many models of "horizontal" symmetries to address flavor issues.

In both cases, more questions than answers.

Could BSM physics that describes DM and BSM physics that describes SM flavor be related?

Assumptions

So, we take the hypothesis that:

- DM belongs to hidden, “dark” sector which contains at least 2 species (flavors) &
- DM & SM share a common flavor interaction.

Want to be as model-independent as possible.

But, space of possibilities to explore utterly huge; must make some assumptions:

On the dark side:

- Take dark sector to contain 2 particles, f, f'. Take both f, f' fermionic.
- $m_f < m_{f'}$; DM composed of either f or mixture of f and f'.
- Consider wide range (0-TeV) of DM masses.

Assumptions, Cont'd

On the SM side:

- For simplicity, consider only interactions with s, d (and u, c, t when required by gauge invariance). But, not excluding other interactions.
- Analyses w/ t's or ℓ's very different.

And, about the mediator(s):

- Assume heavy ($\sim$ TeV), neutral (Z'-like) flavor gauge boson(s) coupled to dark and SM sectors.
- Both flavor-changing, flavor-conserving vertices.
- Will consider two scenarios:
  1) purely right-handed interactions and
  2) purely vector interactions.
- Low-scale flavor physics$\rightarrow$analysis only useful for models with no tree-level $K - \bar{K}$ mixing.

Analysis Strategy

- Put it all together, get effective 4-fermion op's:

$$\frac{C^g_{ijab}}{\Lambda^2}\mathcal{O}^g_{ijab} = \frac{C^g_{ijab}}{\Lambda^2}(\bar{f}_i\Gamma^{g\mu}f_j)(\bar{q}_a\Gamma^g_\mu q_b)$$

$i, j = f, f' \quad a, b = s, d$ (and sometimes u, c, t)
$g = V, R$: $\Gamma^{V\mu} = \gamma^\mu$, $\Gamma^{R\mu} = \gamma^\mu\frac{(1+\gamma_5)}{2}$, $\frac{C^g_{ijab}}{\Lambda^2}$ TBD.

- Also get 4-f op's and 4-quark op's like

$$\frac{C^g_{sdds}}{\Lambda^2}\mathcal{O}^g_{sdds} = \frac{C^g_{sdds}}{\Lambda^2}(\bar{s}\Gamma^{g\mu}d)(\bar{d}\Gamma^g_\mu s).$$

- Arise from same physics, expect all op's in each scenario (RH or V) have similar $|C^g_{ijab}|/\Lambda^2$, *but*
- Interaction & mass eigenstates need not be same; SM implies eff. scales can easily vary 1-2 o.o.m.

Very Low-Mass DM

Kaon decays ($m_{f^{(\prime)}} \lesssim 180$ MeV):

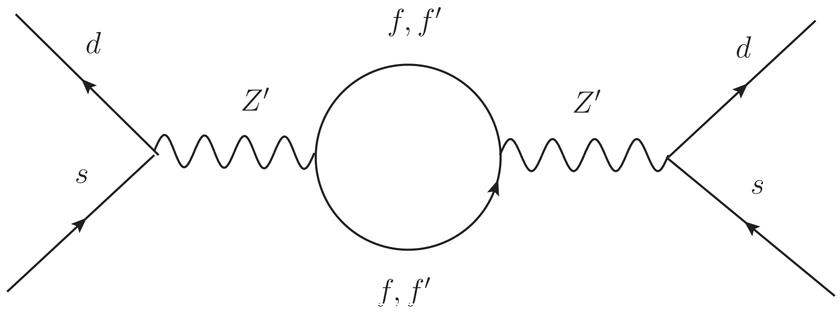
- $\mathcal{O}^g_{mnsd} = (\bar{f}_m \Gamma^\mu f_n)(\bar{s}\Gamma_\mu d)$ give $K^+ \to \pi^+ f^{(\prime)} \bar{f}^{(\prime)}$.
- Take $\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.7 \pm 1.1 \times 10^{-10}$ as limit on $K^+ \to \pi^+ f \bar{f}$.
- Consider two cases:
  1)$f\bar{f}$ final state, f nearly massless
  2)$f\bar{f}'$ final state, $m_f \sim 0$, $m_{f'} \sim 100$ MeV.
- Limits on NP scale:
  RH: $42 - 47$ TeV
  V: $70 - 80$ TeV

Supernova cooling:

- Constrains coupling of $\bar{f}^{(\prime)} f^{(\prime)}$ to pions ($\bar{d}d$).
- Limits on NP scale for $\mathcal{O}^R_{mndd}$ of order $\sim$TeV.

Kaon Mixing

- Assume no tree-level $\mathcal{O}^g_{sdsd}$ ($\Lambda \sim 10^3 - 10^4$ TeV).
- Interactions w/DM give $K - \bar{K}$ mixing at 1 loop:



- Take op's which change flavor in both sectors, ie:

$$\frac{C^R_{f'fds}}{\Lambda^2}\mathcal{O}^R_{f'fds} = \frac{C^R_{f'fds}}{\Lambda^2}(\bar{f}'_R\gamma^\mu f_R)(\bar{d}_R\gamma_\mu s_R)$$

- Only contribute if mass eigenstates f, f' not same as interaction eigenstates.
- Place limits on combinations of $C^g_{f_2 f_1 ds}/\Lambda^2$, mixing angle α, and $\delta = m_{f'} - m_f$.

Kaon Mixing, cont'd

- Loop diag gives $K_L - K_S$ mass difference.
  RH case (vector similar):

$$\Delta^R_{m_K} = \left| A f_K^2 m_K \alpha^{*2} \beta^2 \left(\frac{C^R_{f_2 f_1 ds}}{\Lambda^2} \right)^2 \frac{\delta^2}{(4\pi)^2} \right|$$

  where $A \sim 1$, $f_K = K$ decay const.

- Taking $\Delta_{m_K} = 3.48 \times 10^{-15}$ GeV and $\Lambda = 1$ TeV,
  $|C^R_{f_2 f_1 ds} \alpha^* \beta \delta| \lesssim 7 - 8$ GeV
  $|C^V_{f_2 f_1 ds} \alpha^* \beta \delta| \lesssim 1$ GeV

- Δ_{m_K} depends only on magnitude $|C^R_{f_2 f_1 ds} \alpha^* \beta \delta|$.
  ϵ_K may improve limit on δ by up to o.o.m.

Small splittings may be interesting....

DM Direct Detection

- Operators $\mathcal{O}^g_{ffdd}$ give interactions with nucleons.
- For RH case, the spin-ind't DM-nucleon x-sect is

$$\sigma_{SI} = \frac{|C^R_{ffdd}|^2}{\Lambda^4} \frac{M^2_{red}}{16\pi} \frac{(Z + 2(A - Z))^2}{A^2}$$

- For vector interactions,

$$\sigma_{SI} = \frac{|C^V_{ffdd}|^2}{\Lambda^4} \frac{9}{\pi} M^2_{red}$$

- Results, assuming that f comprises all of DM:

m_f	$(\lvert C^R_{ffdd}\rvert/\Lambda^2)^{-1/2}$/TeV	$(\lvert C^V_{ffdd}\rvert/\Lambda^2)^{-1/2}$/TeV
$\sim$ 10 GeV (CoGeNT)	~ 0.7	~ 2
few$\times$10 GeV (XENON100)	$\gtrsim 7$	$\gtrsim 19$
$\sim$ 1 TeV (XENON100)	$\gtrsim 4$	$\gtrsim 11$

Multicomponent DM?

Do $\mathcal{O}^g_{f'fdd}, \mathcal{O}^g_{f'fss}$ allow f' to be component of DM?

- Tree level decays $f' \to f\pi^0$ or $f' \to f$+jets much too rapid unless NP scale very high.
- Consider tiny δ; only loop-suppressed decays allowed: $f' \to f\nu\bar{\nu}$, $f' \to f + n\gamma$, $f' \to fe^+e^-$.
- RH case: Strongest constraint on δ from 2-loop diagram for $f' \to f\gamma$. f' can be long-lived if
$$\delta \lesssim (1200\text{ keV}) \left(\frac{\text{GeV}}{m_f}\right)^{1/3}$$
- Vector case:
  $\delta > 2m_e$: fast $f' \to fe^+e^-$.
  $\delta < 2m_e$: f' long-lived for interesting NP scale.
- Direct detection: dramatic $O(\text{MeV})$ E_{rec}, but current exp'ts only sensitive below ~ 100 keV.

Toy Models

Constructed toy models (one RH, one V) which

- Do not contribute to $K - \bar{K}$ mixing at tree level.
- Are anomaly-free.

For both models

- DM transforms as doublet under gauged $SU(2)_F$:

$$F = \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$$

- Ops $\mathcal{O}^g_{sdsd} = (\bar{s}\Gamma^\mu d)(\bar{s}\Gamma_\mu d)$ do not obey $SU(2)_F$, not generated at tree level.
- 3 $SU(2)_F$ Z' gauge bosons which get mass from some $SU(2)_F$ doublet scalar φ.

Toy Models, cont'd

RH model:

- Place RH down-type quarks in $SU(2)_F$ doublet:

$$D_R = \begin{pmatrix} d_{R1} \\ d_{R2} \end{pmatrix}$$

- DM diag only 1-loop cont'n to $K - \bar{K}$ mixing.
- Anomalies! Must add new fermions or charge other SM particles under $SU(2)_F$.

Vector model:

- Also need LH quark doublets, RH up-type quarks

$$\mathcal{Q}_L = \begin{pmatrix} Q_{L1} \\ Q_{L2} \end{pmatrix}, \quad U_R = \begin{pmatrix} u_{R1} \\ u_{R2} \end{pmatrix}$$

- No anomalies this time!
- 1-loop cont'n to $K - \bar{K}$ mix. NP scale $\gtrsim$ 1TeV.

Signatures at LHC

At LHC, $\sqrt{s} \sim 14$ TeV–eff. op. formalism not valid.

Look for flavor gauge bosons Z', decay products.

Take right-handed toy model as example:

- 3 Z' gauge bosons; take all to have mass 1 TeV.
- Take f, f' to have negligible mass.
- $SU(2)_F$ coupling same as SM $SU(2)$ coupling g.
- Fermions added to cancel anomalies very heavy.
- Gives effective scales:

$$\frac{|C^R_{iiaa}|}{\Lambda^2} = \frac{g^2}{4\ \text{TeV}^2} \approx \frac{1}{(3\ \text{TeV})^2}$$

$$\frac{|C^R_{ff'sd}|}{\Lambda^2} = \frac{|C^R_{f'fds}|}{\Lambda^2} = \frac{g^2}{2\ \text{TeV}^2} \approx \frac{1}{(2\ \text{TeV})^2}$$

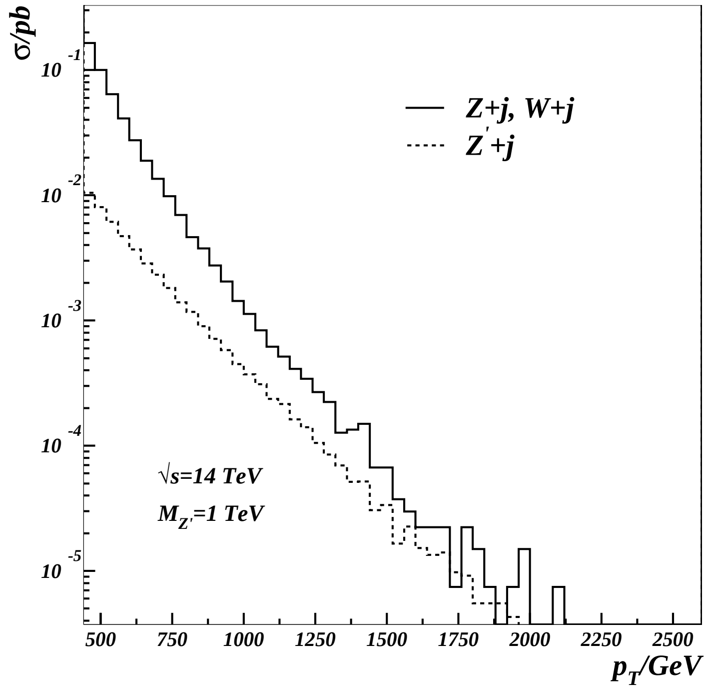
with all other coeff's linking the two sectors 0.

Signatures at LHC cont'd

Possible signature at LHC: monojet.

Signal:

$pp \to Z'j$ ($j = q, g$ jet),
$Z' \to$ invisible.



SM backgrounds:

$pp \to Zj$, $Z \to \nu\bar{\nu}$

$pp \to W^{\pm}j$, $W^{\pm} \to \ell^{\pm}\nu$,
$\ell^{\pm}$ lost in beampipe, $\eta > 2.5$.

Reduce bkg by very tight cut on monojet p_T.

$\sqrt{s} = 14$ TeV

For $\mathcal{L} \sim 100$ fb^{-1}, expect search systematics-limited.

$p_t > 440$ GeV: $S/B = 10\%$ (with $S/\sqrt{B} \approx 22$).

Other signatures possible: dijets, monophoton, ZZ' with $Z \to$ leptons, $Z' \to f'\bar{f}' \to f\bar{f}jjjj$.

Conclusions

- Flavor, DM both require BSM physics. Possibly related?
- Investigated constraints on flavor interactions that involve DM and s, d quarks.
- Extremely rich subject.
    - Constraints from low energy measurements, direct detection, colliders, relic density.
    - Implications for direct detection, LHC.
    - Could investigate interactions with tops or leptons: *very* different analyses!
    - Also: left-handed interactions, scalar DM, specific models...
- Lots to do!