Flavored Dark Matter

Jennifer Kile

Northwestern University

May 10, 2011

Pheno 2011

Based on 1104.5239, JK, Amarjit Soni

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.
  BSM physics to the rescue?

→ *Could DM & flavor involve same BSM physics?*

So, take the hypothesis that:

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

Assumptions

Want to be model-independent, but must make 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 f or f, f' mixture.
- Consider wide range (0-TeV) of DM masses.

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.

Assumptions, Cont'd

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→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):

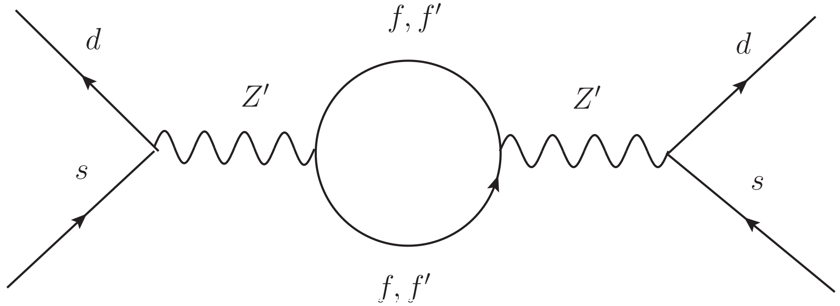
- $\mathcal{O}^g_{mnsd} = (\bar{f}_m \Gamma^\mu f_n)(\bar{s}\Gamma_\mu d)$ give $K^+ \to \pi^+ f^{(\prime)} \bar{f}^{(\prime)}$.
- Take $\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.7 \pm 1.1 \times 10^{-10}$ as limit on $K^+ \to \pi^+ f \bar{f}$.
- Limits on NP scale (depending on f, f' masses):
  RH: $42 - 47$ 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 $C^g_{f_2f_1ds}/\Lambda^2$, 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.
- If f comprises all of DM (elastic scattering):

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? Can f' be long-lived?
  - Consider tiny mass splitting δ; only loop-suppressed decays allowed: $f' \to f\nu\bar{\nu}$, $f' \to f + n\gamma$, $f' \to f e^+ e^-$.
  - RH case: For NP scale of 1 TeV, f' can be long-lived if $\delta \lesssim (1200\text{ keV}) \left(\frac{\text{GeV}}{m_f}\right)^{1/3}$.
  - Vector case: long-lived if $\delta < 2m_e$.
  - Direct detection: dramatic $O(\text{MeV})$ E_{rec}, but current exp'ts only sensitive below ~ 100 keV.

Signatures at LHC

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

Look for flavor gauge bosons Z', decay products.

Built RH toy model with $SU(2)_F$ flavor symmetry:

- 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.
- Corresponds to effective scales:

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

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

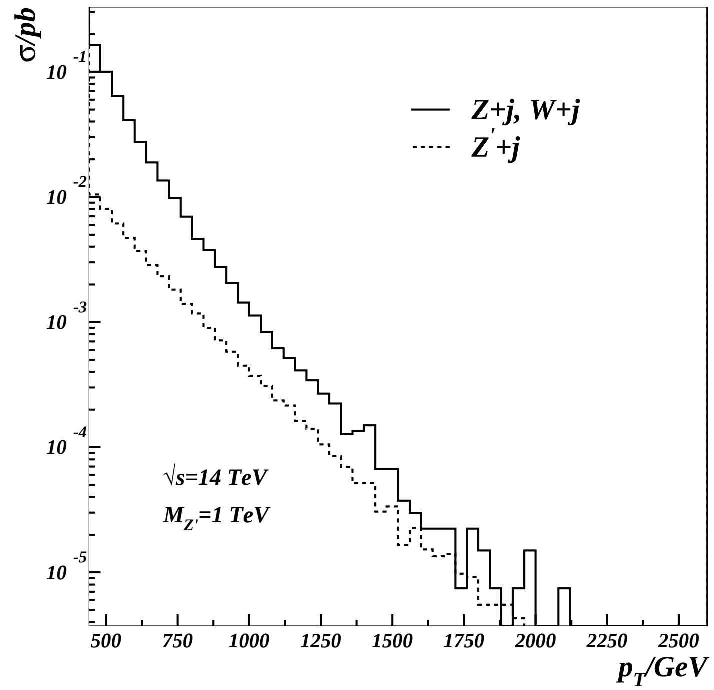
with all other coeff's linking the two sectors 0.

Signatures at LHC cont'd

Possible signature at LHC: monojet.

Signal:

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



SM backgrounds:

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

$pp \longrightarrow W^{\pm}j$, $W^{\pm} \longrightarrow \ell^{\pm}\nu$,
$\ell^{\pm}$ 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 $S/\sqrt{B} \approx 22$).
$p_t > 625$ GeV: $S/B = 20\%$.

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...
    - 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!