Dark Matter, Flavor, and Connections to LHC

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Motivation

- Explanation of Dark Matter (DM) requires physics beyond the Standard Model.
- Little known of nature of DM; may have complicated interactions.
- Number of species of DM unknown.
- Origin of 3 fermion families unexplained in SM.

So, hypothesize that:

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

Note: Results preliminary.

Dark Matter and Flavor

- Take dark sector to contain 2 particles, f_1, f_2.
- $m_{f_1} < m_{f_2}$; f_1 comprises dark matter.
- Assume interaction mediated by heavy, neutral (Z'-like) flavor gauge boson(s) coupling to dark sector and to quarks.
- Generically, expect both flavor-changing and flavor-conserving interactions.
- For simplicity, for this talk, consider only interactions with s, d quarks.
  One can also consider interactions with t, c, etc.
- Assume purely right-handed interaction.
- Take DM to be fermionic.
- Consider wide range (keV-TeV) of DM masses.

Analysis Strategy

- Do not choose specific flavor model; instead use effective four-fermion operators:

$$\frac{C_{ijab}}{\Lambda^2}\mathcal{O}_{ijab} = \frac{C_{ijab}}{\Lambda^2}(\bar{f}_{iR}\gamma^\mu f_{jR})(\bar{q}_{aR}\gamma_\mu q_{bR})$$

  with $i, j = 1, 2$, $q_a, q_b = s, d$ and $\frac{C_{ijab}}{\Lambda^2}$ TBD.

- Will assume all op's have not-too-different $\frac{|C_{ijab}|}{\Lambda^2}$.
- As SM flavor governed by same physics, expect operator $\mathcal{O}_{sdds} = \bar{s}_R\gamma^\mu d_R\bar{d}_R\gamma_\mu s_R$ as well as $\mathcal{O}_{dddd}$ and $\mathcal{O}_{ssss}$ generated at similar scales.
- In general, interaction & mass eigenstates related by rotation angles; taking SM as guide, reasonable for effective scales to differ by 1-2 orders of magnitude.

Laboratory Constraints

- $\mathcal{O}_{sdsd} = \bar{s}_R\gamma^\mu d_R\bar{s}_R\gamma_\mu d_R$ constrained by $K^0 - \bar{K}^0$ mixing to have $\frac{|C_{sdsd}|}{\Lambda^2} < \frac{1}{\mathcal{O}(10^3\ \text{TeV})^2}$.
  $\longrightarrow$ Assume interaction comes from model with no tree-level contributions to $K^0 - \bar{K}^0$ mixing.
- If $f_{1,2}$ very light (< 180 MeV), $K^+ \rightarrow \pi^+ f_i f_j$.
  $Br(K^+ \rightarrow \pi^+ \text{ invisible}) = 1.7 \pm 1.1 \times 10^{-10}$

$$\rightarrow \frac{|C_{ijsd}|}{\Lambda^2} < \frac{1}{\mathcal{O}(40\ \text{TeV})^2}$$

- Search for dijet resonance from CDF excludes Z' mass range of $320 - 740$ GeV, if quark couplings are same as SM Z.

DM Direct Detection

- Generically expect op of form $\bar{f}_{iR}\gamma^{\mu}f_{jR}\bar{d}_R\gamma_{\mu}d_R$.
  $\longrightarrow$ DM direct detection experiments.
- Assuming that f_1 comprises all of DM,
  Limits on the spin-independent cross-section σ_{SI} from CDMS & XENON10 in mass range $m_f \approx 10$'s of GeV,

$$\sigma_{SI} < \text{few} \times 10^{-44}\ \text{cm}^2$$

correspond to $\frac{|C_{11dd}|}{\Lambda^2} \lesssim \frac{1}{(4\ \text{TeV})^2}$.
For $m_f = 1$ TeV, gives limit of $\lesssim \frac{1}{(3\ \text{TeV})^2}$.

Relic Density

- If DM consists of only one species, relic density requires velocity-averaged annihilation cross-section at freezeout $< \sigma v >$ of $\approx 3 \times 10^{-26} \text{cm}^3/\text{s}$.
- Each operator will contribute to the cross-section

$$< \sigma v >_{ijab} = \frac{|C_{ijab}|^2}{\Lambda^4} \frac{3 m_f^2}{8\pi}$$

- For $m_f = 1$ TeV, this gives upper bound on the new physics scale, $\sum \frac{|C_{ijab}|^2}{\Lambda^4} \gtrsim \frac{1}{(2.5 \text{ TeV})^2}$, with tighter bounds for smaller m_f.
- To agree with direct detection limits, must have terms other than C_{11dd}.

Signatures at LHC

At LHC, $\sqrt{s} = 7 - 14$ TeV.

$\rightarrow$ Eff. op. formalism not valid.
$\rightarrow$ Look for flavor gauge bosons Z' and their decay products.

Note: $\frac{|C_{ijab}|}{\Lambda^2}$ contains both couplings and Z' mass.

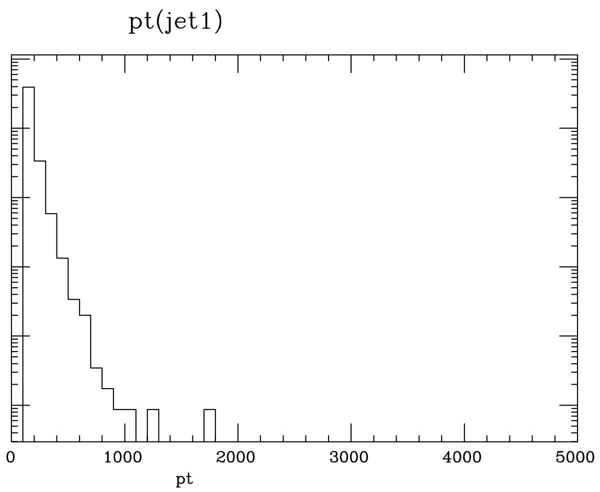
SM left-handed $SU(2)$ Z coupling (i.e. $\theta_W = 0$) corresponds to $\frac{|C_{SM}|}{\Lambda^2} = \frac{g^2}{4M_Z^2} = \frac{1}{v^2}$ with $v \approx 246$ GeV.

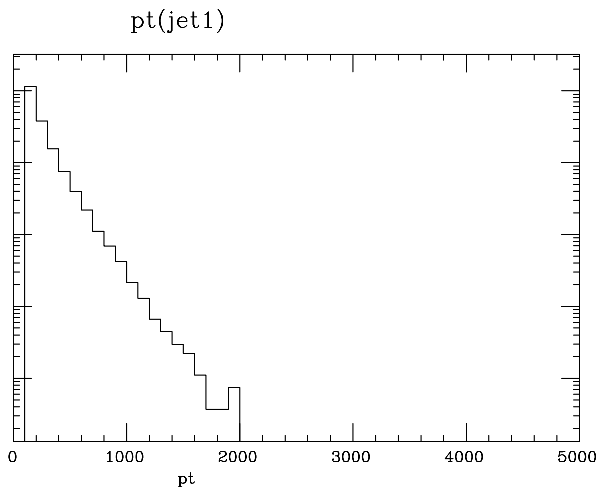
$\rightarrow$ Example: $\frac{|C_{ijab}|}{\Lambda^2} \approx \frac{1}{(3\ \text{TeV})^2}$ could easily imply looking for a 1-TeV Z' resonance.

Signatures at LHC

- Produce Z' via $\bar{q}q \to Z'j$ ($j = q, g$ jet) and $\bar{q}q \to Z'Z$.
- Z' decay channels: $Z' \to \bar{q}^a q^b$, $Z' \to f_i f_j$.
- Monojet signature, $\bar{q}q \to Z'j$, $Z' \to f_1 f_1$: p_T for signal & SM bkg:

$\bar{q}q \to Zj, Z \to \bar{\nu}\nu$: $\bar{q}q \to Z'j, Z' \to f_1 f_1$:





- $\bar{q}q \to Z' \to f_2 f_2$:
If $f_2 \to f_1 \bar{q}q$ in detector, 4 jets + missing p_T.

...Work in progress...

Conclusions

- Flavor, DM both require physics beyond SM.
- Possible that SM and dark sector could share flavor interaction.
- Investigated constraints on flavor interactions that involve DM and s, d quarks.
- Considered constraints from low energy measurements, direct detection, collider searches.
- Investigating to see what ranges of allowed DM masses and interaction scales possibly accessible by LHC!