Flavored dark matter and its laboratory tests

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The matter fields of the Standard Model \((Q, U^c, D^c, L, E^c)\) come in three copies, or flavors, that differ only in their masses.

An interesting possibility is that the dark matter field, \(\chi\), also carries flavor quantum numbers, and is the lightest of three copies that differ only in their masses. We focus on renormalizable contact interactions between DM and SM.

What kind of quantum number?

If SM = \(L, E^c\): "lepton flavored DM"

If SM = \(Q, U^c, D^c\): "quark flavored DM"

Reminds of sneutrino DM in the MSSM, which, in its simplest form, has long been excluded by direct detection bounds!
Here no such bound applies as we are assuming that our DM particle is a singlet, and the only portal to the SM is the mediator $\phi$!

The collider signatures of our framework are decay chains due to the mass hierarchy in the new "dark" family with many final state leptons.

We also want to study a DM scenario that goes beyond the extensively studied neutralino in the MSSM, which does not carry any flavor charge. One expects the collider signatures to be very different.

Flavor correlations among final-state leptons should allow for a discrimination of flavored DM models vs unflavored ones!
Outline

★ Lepton flavored DM
  □ Flavor structure
  □ Relic abundance
  □ Direct detection
  □ Collider signals

★ Quark flavored DM
  □ Flavor structure
  □ ...

★ Collider signals of tau-flavored DM
  □ Representative choice of model
  □ Signal topologies
  □ Backgrounds

★ Distinguishing tau-flavored DM from other unflavored DM models

★ Conclusions
Lepton-flavored DM
Lepton-flavored DM

- The lepton sector has a $U(3)^L \times U(3)^E$ flavor symmetry which is explicitly broken to $U(1)^3$ by the Yukawa interactions that give mass to the leptons. [We neglect here small neutrino masses.]

- The characteristic vertex of lepton flavored DM involves contact interactions of the form:

  ![Diagram](image)

  The mediator $φ$ is necessarily electrically charged and the symmetry that keeps DM stable implies that $φ$ cannot decay entirely to SM states, and that lepton-flavor violating processes arise at loop level.

- For concreteness, we assume here that $χ$ is a Dirac fermion that interacts with the SU(2) singlet $E^c$, and $φ$ is a complex scalar.

$\chi$ transforms under the $SU(3)^F$ flavor symmetry, where $U(3)^F$ is a U(3) flavor, such as neutralino dark matter in the MSSM.
In general, the matrix $\lambda$ will contain both diagonal and off-diagonal elements, giving rise to lepton flavor violation. The experimental bounds are satisfied if all elements are $<10^{-3}$ for $m_\phi \sim 200$ GeV.

These couplings are by themselves too small to generate the correct thermal relic abundance for $\chi$. One needs $O(1)$ couplings!

For couplings of order one to be compatible with lepton flavor violation bounds, the matrix $\lambda$ must be aligned with the Yukawa coupling matrix.

A natural framework where this occurs is Minimal Flavor Violation, where it is assumed that the only source of flavor violation in the theory is the Yukawa matrix.

In this scenario, the dark matter flavor symmetry $U(3)_\chi$ is identified with $U(3)_E$ or $U(3)_L$. 
Lepton-flavored DM

★ Writing the lepton Yukawa matrix as \( y_A^i L^A E_i^c H + \text{h.c.} \), if we identify the \( U(3)_X \) with \( U(3)_E \), then MFV restricts \( \lambda \) to the form:

\[
\lambda_j^i = (\alpha \mathbb{1} + \beta y^\dagger y)_j^i
\]

For the DM mass matrix, it is restricted to

\[
[m_\chi]_{ij} = (m_0 \mathbb{1} + \Delta m y^\dagger y)_i^j
\]

Since the Yukawa couplings are small, the various DM flavors have small splittings and couple in a flavor diagonal way to leptons.

Depending on the sign of \( \Delta m \), the lightest state can be either electron or tau flavored.

★ If we identify the \( U(3)_X \) with \( U(3)_L \), then MFV restricts \( \lambda \) to the form:

\[
\lambda_A^i = \alpha y_A^i \quad \text{and the mass matrix to} \quad [m_\chi]_{AB} = (m_0 \mathbb{1} + \Delta m yy^\dagger)_A^B
\]

The couplings to leptons are now hierarchical, though still flavor diagonal.

If the relic abundance is determined by \( \lambda \) then only the tau flavor can constitute DM.
The relic abundance of the DM particle (a singlet!) is set by its annihilation rate to leptons. The primary mode is the $t$-channel $\phi$ exchange to two leptons. The thermally averaged cross-section, to first order, is given by

$$\langle \sigma v \rangle = \frac{\lambda^4 m_\chi^2}{32\pi (m_\chi^2 + m_\phi^2)^2}$$

Direct detection signals proceed through the following loop diagrams:

The main interaction between $\chi$ and the nucleus is given by the charge-charge coupling. This term leads to the following cross-section:

$$\frac{d\sigma_{\text{ZZ}}}{dE_r} = \frac{2m_N}{4\pi v^2} Z^2 b_p^2 F^2(E_r)$$

with

$$b_p = \frac{\lambda^2 e^2}{64\pi^2 m_\phi^2} \left[ 1 + \frac{2}{3} \log \left( \frac{m_\phi^2}{m_\chi^2} \right) \right]$$

which is a spin-independent interaction, and therefore enhanced by $Z$, the total charge of the nucleus.
We now plot the ratio $\lambda / m_\phi$ corresponding to a thermal WIMP with the right relic abundance, and contrast it with direct detection bounds, both for the case where DM is electron and tau flavored:
Lepton-flavored DM

★ Collider signatures?

1) $\phi$ can be pair-produced through the $Z$ or the photon:

![Diagram showing $\phi$ pair-produced through $Z$ or photon]

2) The decay chain can be either long or short:

![Diagram showing decay chains]

We will focus on this signal which we consider the most promising:

At least 4 isolated leptons and missing energy.
Quark-flavored DM
We now consider the case where DM carries quark flavor. The quark sector of the SM has a $U(3)_Q \times U(3)_U \times U(3)_D$ flavor symmetry, broken down to $U(1)$ baryon number by the Yukawas.

The characteristic vertex of quark flavored DM can be

![Diagram showing the interaction between SM, dark matter, and quarks]

Either

$$\lambda_A A^A \chi^\alpha \phi + \text{h.c.}$$

or

$$\lambda_i \chi^\alpha U_i^c \phi + \text{h.c.}$$

or

$$\lambda_a \chi^\alpha D_a^c \phi + \text{h.c.}$$

where $\alpha$ is the $U(3)_\chi$ flavor index.

There are contributions to flavor violating processes, such as $K - \bar{K}$ mixing. The experimental bounds are satisfied if all elements are $<10^{-2}$ for $m_\phi \sim 500$ GeV.
Just like in the lepton case, these couplings are too small to generate the right relic abundance. So we will again rely on the MFV framework to have large couplings.

We write the Yukawa couplings as
\[ \hat{y}_A^a Q^A D^c_a H + y_A^i Q^A U^c_i H^\dagger + \text{h.c.} \]

1) DM couples to \( U^c \)

- If \( U(3)_\chi \) is identified with \( U(3)_U \), MFV restricts the matrix \( \lambda \) to be of the form
  \[ \lambda_i^j = (\alpha \mathbb{1} + \beta y^\dagger y)_i^j \]
  while the mass term for \( \chi \) becomes
  \[ [m_\chi]^j_i = (m_0 \mathbb{1} + \Delta m y^\dagger y)_i^j \]
  The DM states that couple to the first two generations are nearly degenerate in mass, and the mixing with the top flavor is small. Depending on the sign of \( \Delta m \), the lightest state can be either up or top flavored.

- If \( U(3)_\chi \) is identified with \( U(3)_D \), MFV restricts the matrix \( \lambda \) to be of the form
  \[ \lambda_a^i = \alpha (\hat{y}^\dagger y)_a^i \]
  while the mass term for \( \chi \) becomes
  \[ [m_\chi]^b_a = (m_0 \mathbb{1} + \Delta m \hat{y}^\dagger \hat{y})_a^b \]
  The couplings to SM are here hierarchical, and the DM state is expected to be bottom flavored.
Similar arguments hold for the case $U(3)_\chi \sim U(3)_Q$.

2) DM couples to $D^c$

The argument to derive the flavor structure from MFV is basically identical to what I have just shown. For instance, if $U(3)_\chi$ is identified with $U(3)_U$, the matrix $\lambda$ is restricted to be of the form $\lambda^a_i = \alpha (y^\dagger \hat{y})^a_i$ while the mass term for $\chi$ becomes

$$ [m_\chi]_i^j = (m_0 1 + \Delta m y^\dagger y)^i_j $$

The first two flavors are quasi-degenerate in mass, the couplings to SM are hierarchical, and the DM state is expected to be top flavored.

The relic abundance is set by the major annihilation mode, the $t$-channel annihilation to a pair of quarks. The calculation follows in a similar way as for the lepton case, and we find

$$ \langle \sigma v \rangle = \frac{3\lambda^4 m_\chi^2}{32\pi (m_\chi^2 + m_\phi^2)^2} $$
MFV suggests that the lightest state in the DM multiplet carries either the flavor of a first generation quark, or a third generation quark. Direct detection signals are VERY different in the two cases. If DM carries up or down flavor, the following very dangerous tree-level diagram is allowed:

More precisely, the DM-nucleus cross-sections in this case are given by:

\[
\sigma_0 = \frac{\mu^2 \lambda^4}{64\pi m_\phi^4} [A + Z]^2 \quad \text{for } \chi_u
\]

\[
\sigma_0 = \frac{\mu^2 \lambda^4}{64\pi m_\phi^4} [2A - Z]^2 \quad \text{for } \chi_d
\]

… Which is HUGE, and clearly excluded by direct detection experiments:

Xenon100 excluded.
★ The more interesting case would be when DM carries flavor of the third generation.

★ The dominant diagram is given by

and the dominant term in this diagram is the charge-charge interaction, which gives rise to the cross-section:

★ The thermal WIMP is here within reach of current direct detection experiments:

\[ \sigma_{ZZ}^0 = \frac{\mu^2 Z^2}{\pi} \left[ \frac{3\lambda^2 e^2 Q}{64\pi^2 m_\phi^2} \left[ 1 + \frac{2}{3} \log \left( \frac{m^2}{m_\phi^2} \right) \right] \right]^2 \]
Collider signatures?

1) $\phi$ can be pair-produced through an off-shell gluon:

2) The decay chain can be either long or short:

Most promising: 6 jets, two of which are $b$-jets, and missing energy

Relies heavily on $b$-tagging efficiency. Main backgrounds: $tt$+jets, and $bb$+jets
Collider signals of \( \tau \) flavored DM
Motivated by the MFV analysis, we will consider here the case where the lightest state in the DM multiplet is a Dirac particle carrying tau flavor.

MFV also implies that the couplings of all the DM states to SM are basically equal.

For concreteness, we consider two benchmark scenarios:

\[ \mathcal{L} = \sum_{i=e,\mu,\tau} [\chi_i^E E_i^c \phi + \text{h.c.}] \]

\( \tau \text{FDM1} \)
- \( m_{\chi,e} = 110 \) GeV
- \( m_{\chi,\mu} = 110 \) GeV
- \( m_{\chi,\tau} = 90 \) GeV
- \( m_\phi = 160 \) GeV

\( \tau \text{FDM2} \)
- \( m_{\chi,e} = 90 \) GeV
- \( m_{\chi,\mu} = 90 \) GeV
- \( m_{\chi,\tau} = 70 \) GeV
- \( m_\phi = 150 \) GeV

The \( \phi \phi \) production cross-section through Drell-Yan is \( p \)-wave suppressed since \( \phi \) is a scalar.

LHC with tens of fb\(^{-1}\) needed!
★ We are looking for these signal events:

\[ \phi^+ \rightarrow \ell^+ \ell^- \rightarrow \tau^+ \]

\[ \phi^- \rightarrow \ell^- \ell^+ \rightarrow \tau^- \]

★ What are the main backgrounds?

1. \((Z/\gamma)^(*) (Z/\gamma)^(*)\)

   A. \(Z \rightarrow \ell^+ \ell^-\) 

      the on-shell decay is dominant, but it can be reduced by a suitable \(Z\) veto.

   B. \(Z \rightarrow \tau^+ \tau^- \rightarrow \ell^+ \ell^-\) 

      this can potentially by-pass the \(Z\) veto, but the branching is small and the leptons from tau are softer.

   C. \(Z^*/\gamma^* \rightarrow \ell^+ \ell^-\) 

      the off-shell production is suppressed, but it can by-pass both \(Z\) veto and energy cut. We apply a missing energy cut to reduce it.
2. \( t\bar{t}(Z/\gamma)^{(\ast)} \)

Although this is a three-body production, the cross-section is similar to the previous background. When both tops decay leptonically, and the \( Z \) goes to leptons, this can fake our signal. However, this process will typically be accompanied by energetic jets, which we cut on.

3. \( WW(Z/\gamma)^{(\ast)} \)

The cross-section is here much smaller than the previous one, since it is purely electroweak. However, this process is not accompanied by energetic jets.

★ To summarize our cuts:

- \textbf{Lepton cut} – We demand events with at least four leptons with \( pT > 7 \) GeV. At least two of these are further required to have \( E > 50 \) GeV.
- \textbf{Dijet veto} – We discard events with two or more jets of \( pT > 30 \) GeV each.
- \textbf{Z veto} – We veto events if the invariant mass of any \( Z \)-candidate (same flavor and opposite charge) falls within 7 GeV of the \( Z \) mass.
- \textbf{Missing energy} – We require at least 20 GeV of missing energy in each signal event.
The results are shown in this table:

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Event rate after cuts at 100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lepton cuts</td>
</tr>
<tr>
<td>$\tau$FDM1</td>
<td>46.73</td>
</tr>
<tr>
<td>$\tau$FDM2</td>
<td>75.39</td>
</tr>
<tr>
<td>$l^+ l^- l^+ l^-$</td>
<td>1617.94</td>
</tr>
<tr>
<td>$t\bar{t} l^+ l^-$</td>
<td>89.57</td>
</tr>
<tr>
<td>WW$l^+ l^-$</td>
<td>14.70</td>
</tr>
</tbody>
</table>

In order to have a 5 $\sigma$ discovery of $\tau$ FDM2 above SM backgrounds, around 20 fb$^{-1}$ of integrated luminosity are needed. For $\tau$ FDM1, an integrated luminosity around 40 fb$^{-1}$ is needed.
Q: Is it possible to distinguish FDM from models with similar signatures but where DM does not carry flavor?

We introduce a strawman model (MSSM inspired)

- 3 right-handed sleptons that are degenerate in mass
- A light neutralino (χ, DM!) and a heavier one (χ’), both with flavor-blind couplings to leptons and sleptons: \( \chi' E_i^c \chi^{(*)} \tilde{E}_i^c + h.c. \)

We want to distinguish the two models based on charge and lepton correlations among final state leptons:

Topology A

Topology B

FDM
The phenomenology of the strawman model will crucially depend on the mass spectrum one chooses. We opt for three benchmark scenarios:

- **Mainly topology A**
- **Only topology B**
- **Mixture!**

After running the Monte Carlo simulation, we find the following charge and flavor correlation for the two hardest $p_T$ leptons:

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Frac. events with same flavor</th>
<th>Frac. events with same charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$FDM1</td>
<td>0.52</td>
<td>0.14</td>
</tr>
<tr>
<td>$\tau$FDM2</td>
<td>0.49</td>
<td>0.14</td>
</tr>
<tr>
<td>Spectrum 1(a)</td>
<td>0.87</td>
<td>0.13</td>
</tr>
<tr>
<td>Spectrum 1(b)</td>
<td>0.61</td>
<td>0.39</td>
</tr>
<tr>
<td>Spectrum 2</td>
<td>0.55</td>
<td>0.41</td>
</tr>
<tr>
<td>Spectrum 3(a)</td>
<td>0.66</td>
<td>0.33</td>
</tr>
<tr>
<td>Spectrum 3(b)</td>
<td>0.60</td>
<td>0.38</td>
</tr>
</tbody>
</table>
We want to understand now how well the 14 TeV LHC can statistically distinguish the two models with 100 fb$^{-1}$. We find:

$\tau$FDM, on the other hand exhibits no flavor correlated leptons in events passing cuts for di-flavor and charge are defined as,

$$a_F, a_C = \frac{n_{\text{same}} - n_{\text{diff.}}}{n_{\text{same}} + n_{\text{diff.}}}$$

Where the charge and lepton asymmetries are defined as:

Discrimination at the 2σ level possible!
Conclusion

★ Theories where DM carries flavor and has renormalizable contact interactions with the SM have a rich phenomenology, in particular in direct detection experiments and colliders.

★ A theoretical framework that can motivate such models, while evading present bounds on flavor violation (both in the quark and lepton sectors), is Minimal Flavor Violation.

★ When DM is a thermal relic, we have shown that many of these models (both with quark-flavored and lepton-flavored DM) can be probed in the near future in direct detection experiment.

★ For the collider phenomenology, we focused on a class of models where dark matter carries tau flavor. The signals include events with four or more isolated leptons and missing energy.

★ We have performed a full simulation of the signal and the main SM backgrounds, including detector effects, and found that these theories can be discovered at the 14 TeV LHC.

★ We have also shown that flavor and charge correlations among final state leptons may allow this type of models to be distinguished from unflavored DM models.