Flavored Dark Matter

Direct detection and Colliders

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arXiv: 1109.3516
PA, S. Blanchet, Z. Chacko, C. Kilic

Evidence for WIMP dark matter

Why dark matter (at the weak scale)?

The astrophysical evidence for dark matter is very strong.

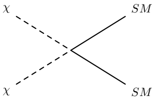
- Galactic rotation curves
- Cosmic Microwave Background
- Big Bang Nucleosynthesis
- Gravitational lensing observations

Weakly interacting massive particles naturally yield observed relic abundance.

- New weak scale physics motivated by the hierarchy problem in the standard model

The WIMP miracle

Miracle up to orders of magnitude



$$\sim \frac{\lambda^2}{m_\phi^2}$$

$$\langle \sigma_A v \rangle \sim \frac{\lambda^4 m_\chi^2}{32\pi m_\phi^4} \sim \frac{(0.45)^4 (100\ \text{GeV})^2}{32\pi (200\ \text{GeV})^4} \sim 3 \times 10^{-26}\ \text{cm}^3/\text{s}$$

$$\sigma^{(n)} \sim \frac{\lambda^4 m_n^2}{64\pi m_\phi^4} \sim \frac{(0.45)^4 (1\ \text{GeV})^2}{64\pi (200\ \text{GeV})^4} \sim 5 \times 10^{-41}\ \text{cm}^2$$

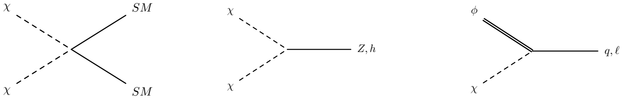
Current limits from Xenon100 experiment: $10^{-44}\ \text{cm}^2$

(for $m_\chi \sim 100$ GeV)

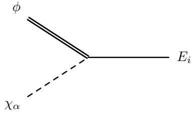
Flavored dark matter

Who ordered that?

- Renormalizable interactions



- Focus on the case where dark matter
  - is a Dirac fermion.
  - is a SM singlet.
  - transforms under $U(3)_E$.



$$\lambda_j{}^i E^j \chi_i \phi + h.c.$$

Flavor structure

- Lepton sector of SM has $U(3)_L \times U(3)_E$ global symmetry
  - Broken to $U(1)^3$ by Yukawa couplings of the SM

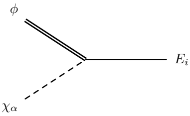
$$y_A{}^i L^A E_i^c H + h.c.$$

$$y_A{}^i : (3, \bar{3}) \text{ under } SU(3)_L \times SU(3)_E$$

- Minimal flavor violating interactions

$$\lambda_j{}^i = \left(\alpha I + \beta\, y^\dagger y\right)_j^{\ i}$$

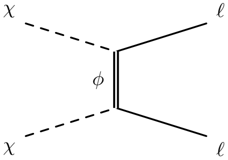
$$[m_\chi]_i{}^j = \left(m_0 I + \Delta m\, y^\dagger y\right)_i^{\ j}$$



  - dark matter flavors have small splittings
  - equal coupling for different flavors

Relic abundance

- Annihilation via t-channel ϕ



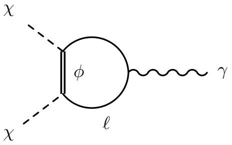
$$\langle \sigma v \rangle \approx \frac{\lambda^4 m_\chi^2}{32\pi (m_\chi^2 + m_\phi^2)^2}$$

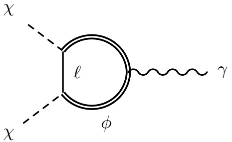
- With additional couplings more channels open up, allowing smaller λ values.

Direct detection

"Leptophilic dark matter"

Dark matter can interact with nuclei via photon exchange





$$\frac{d\sigma_{DD}}{dE_r} = \frac{1}{v^2} m_N\, \mu_{nuc}^2\, \mu_\chi^2 \left(\frac{S_{nuc}+1}{3S_{nuc}}\right) F_D^2(E_r)$$

$$\frac{d\sigma_{DZ}}{dE_r} = \frac{1}{E_r} Z^2 \frac{e^2\mu_\chi^2}{4\pi} \left[1 - \frac{E_r}{v^2}\frac{m_\chi + 2m_N}{2m_N m_\chi}\right] F^2(E_r)$$

$$\frac{d\sigma_{ZZ}}{dE_r} = \frac{1}{v^2} Z^2 \frac{2m_N}{4\pi} b_p^2\, F^2(E_r)$$

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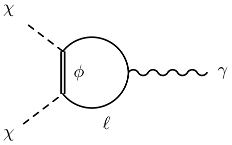

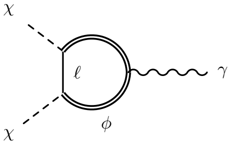

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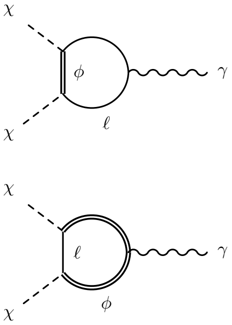

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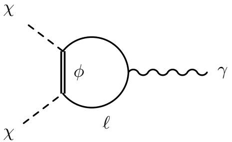

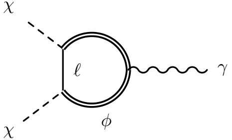

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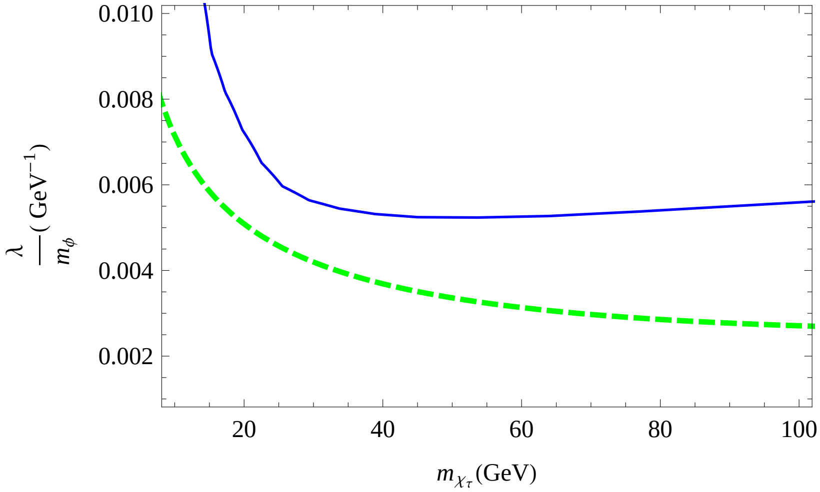
Direct detection bounds

"Leptophilic dark matter"



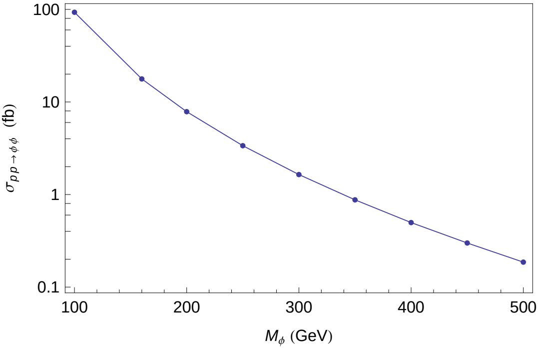
The spectrum

- Spectrum

$$m_{\chi,e} = 90 \text{ GeV}$$
$$m_{\chi,\mu} = 90 \text{ GeV}$$
$$m_{\chi,\tau} = 70 \text{ GeV}$$
$$m_{\phi} = 150 \text{ GeV}$$

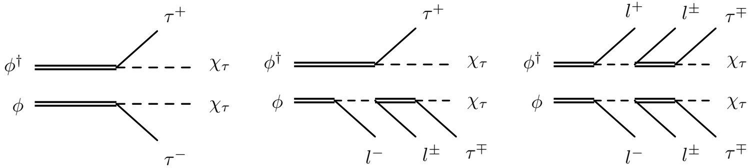
- Weak production $\Rightarrow$ few events
- Lots of leptons $\Rightarrow$ clean signal
- Not early discovery at LHC

Pair production of ϕ at 14 TeV LHC



Signal topologies

- Since coupling is universal, ϕ decays to all three flavors
- Three event topologies



- Long-long decay chain is most promising

Signal: Four leptons + missing transverse energy

Backgrounds and cuts

Pre-selection: At least 4 leptons, pT > 7 GeV each

$\ell^+\ell^-\ell^+\ell^-$

- $Z \to \ell^+\ell^-$
- $Z \to \tau^+\tau^- \to \ell^+\ell^-$
- $Z^*, A^* \to \ell^+\ell^-$

$t\bar{t}\ell^+\ell^-$

- $t \to b(W \to l\nu)$

$W^+W^-\ell^+\ell^-$

- $W \to l\nu$

Leptons

- At least 2 leptons, $E > 50$ GeV each

Dijet veto

- Events with ≥ 2 jets, $p_T > 30$ GeV each

Z-veto

- Same-flavor, opposite-charge leptons with $|m_{inv} - m_Z| < 7$ GeV

Missing energy cut: MET > 20 GeV

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57.04 signal + 14.34 SM background @ 14 TeV LHC at 100 fb^{-1}

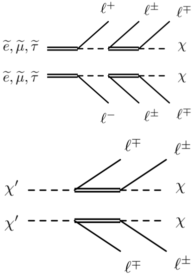
Faking τFDM at the LHC

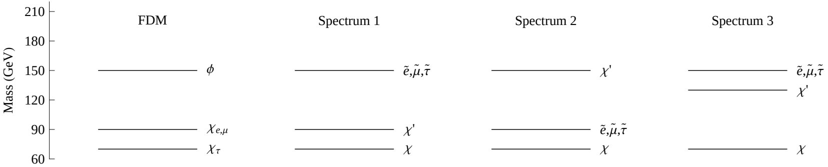
Can we establish that the dark matter signal we observe is τ-fdm?

- Compare with "SUSY"
  - Only light states are

    sleptons: $\widetilde{e}, \widetilde{\mu}, \widetilde{\tau}$
    neutralinos: χ', χ

  - Flavor is carried by the sleptons
  - Dark matter is the LSP, χ
  - Same mass splittings as in FDM

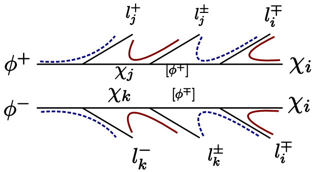




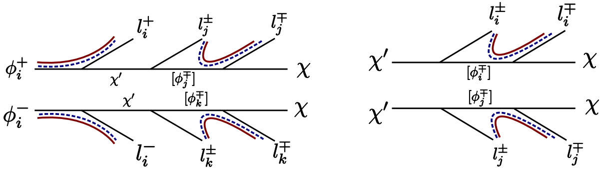
Flavor-charge correlations

Flavor and charge correlation of two most upstream leptons is a good discriminant

- FDM

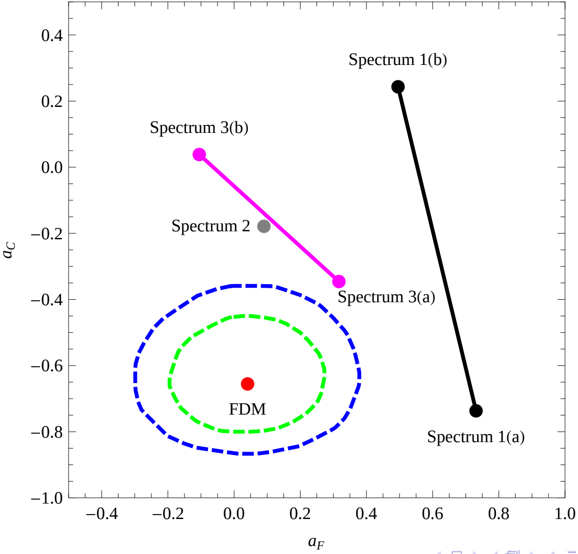


- Fake models



(a) (b)

Flavor-charge correlations



Conclusion

- Flavored dark matter is a simple possibility which has not been explored in a model-independent way.
- It is possible to distinguish a τFDM model from unflavored dark matter at the LHC.
- Our analysis for the τ-FDM can be extended in many ways
  - Kinematic variables to identify particles in decay chains (e.g. Hemisphere method)
  - Kinematic distributions: edges, end-points, mT2
  - Identification of hadronically decaying τs
- Similar conclusions are expected to hold for quark-flavored dark matter at colliders. Stay tuned...

Backup slide: Flavor-charge correlations