Lepton-Flavored Dark Matter

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May 5, 2015
Pheno 2015

Based on Phys.Lett. B744 330-338, JK, Andrew Kobach & Amarjit Soni.

Motivation

Wanted to address two paradoxes:

- Dark matter relic density vs. direct-detection experiments:
  - If DM is a thermal relic, new physics scale favored by relic density calculation is $\mathcal{O}(100 \text{ GeV} - 1 \text{ TeV})$.
  - Direct-detection constraints imply NP contributions to DM-nucleon interactions have scale $\gtrsim 10$ TeV.
- Muon $g-2$ vs. other leptonic processes:
  - Muon $g-2$ is currently 3.6σ above the SM expectation; NP explanations favor scale $< \mathcal{O}(1 \text{ TeV})$.
  - NP contributions to flavor-violating interactions $\mu \to 3e$, $\tau \to e\mu\mu$, $\tau \to ee\mu$, $\tau \to 3e$, $\mu \to e\gamma$ constrained to scales $> \mathcal{O}(10{-}100 \text{ TeV})$.
  - Contributions to flavor-conserving processes $e^+e^- \to \ell^+\ell^-(\ell = e, \mu, \tau)$ constrained to have NP scale $> 4 - 5$ TeV.

Could these paradoxes have a common resolution?

Lepton-Flavored DM

Enter lepton-flavored DM (LFDM):

- Taking SM leptons, DM charged under gauged flavor interaction.
- Do not assume a specific flavor model; instead attempt to be model-independent.
- Assuming dark sector particles to be Dirac fermions. DM denoted χ.
- Assume e, ν_e not charged under flavor symmetry.
- Take purely vector interactions; gives correct sign for $g-2$ contribution.
- Take mass, flavor interaction bases in charged-lepton sector to be closely aligned; allow rotations between bases in dark sector.
- Do allow flavor-changing vertices.
- Call gauge bosons which couple to flavor-diagonal charged-lepton vertices $X_{i\alpha}$ and those which change flavor Y_α.

Lepton-Flavored DM

- We take there to be 2 $X_{i\alpha}$ and 1 Y_α.
- We thus arrive at a Lagrangian:

$$\begin{aligned}\mathcal{L} \supset & \sum_{i=1,2} X_{i\alpha}\Big[k_{i\mu\mu}J^\alpha_\mu + k_{i\tau\tau}J^\alpha_\tau + k'_{iL}\overline{\chi}_L\gamma^\alpha\chi_L + k'_{iR}\overline{\chi}_R\gamma^\alpha\chi_R\Big] \\ & + Y_\alpha\Big[h_{\mu\tau}K^\alpha + h'_L\overline{\chi}_L\gamma^\alpha\chi_L + h'_R\overline{\chi}_R\gamma^\alpha\chi_R\Big] \\ & + Y^\dagger_\alpha\Big[h_{\mu\tau}(K^\alpha)^\dagger + h'_L\overline{\chi}_L\gamma^\alpha\chi_L + h'_R\overline{\chi}_R\gamma^\alpha\chi_R\Big]\end{aligned}$$

where

$$\begin{aligned} J^\alpha_\mu &= \overline{\mu}_L\gamma^\alpha\mu_L + \overline{\mu}_R\gamma^\alpha\mu_R + \overline{\nu}_{L\mu}\gamma^\alpha\nu_{L\mu} + \overline{\nu}_{R\mu}\gamma^\alpha\nu_{R\mu} \\ J^\alpha_\tau &= \overline{\tau}_L\gamma^\alpha\tau_L + \overline{\tau}_R\gamma^\alpha\tau_R + \overline{\nu}_{L\tau}\gamma^\alpha\nu_{L\tau} + \overline{\nu}_{R\tau}\gamma^\alpha\nu_{R\tau} \\ K^\alpha &= \overline{\mu}_L\gamma^\alpha\tau_L + \overline{\mu}_R\gamma^\alpha\tau_R + \overline{\nu}_{L\mu}\gamma^\alpha\nu_{L\tau} + \overline{\nu}_{R\mu}\gamma^\alpha\nu_{R\tau}\end{aligned}$$

- k's, h's coefficients which we will vary.

Relic Density

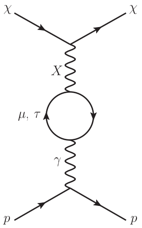
- Assuming a thermal relic, so want $\langle \sigma v \rangle \sim 4.4 \times 10^{-26}\ \text{cm}^3/\text{s}$ (Steigman, et al, 2012).
- Given above Lagrangian, obtain

$$\langle \sigma v \rangle = \frac{m_\chi^2}{2\pi} \left\{ \frac{2h_{\mu\tau}^2 (h_L' + h_R')^2}{M_Y^4} + \left[\left(\sum_{i=1,2} \frac{k_{i\mu\mu}(k_{iL}' + k_{iR}')}{M_{X_i}^2} \right)^2 + \left(\sum_{i=1,2} \frac{k_{i\tau\tau}(k_{iL}' + k_{iR}')}{M_{X_i}^2} \right)^2 \right] \right\}$$

- If take $\langle \sigma v \rangle = m_\chi^2/\Lambda^4$, then $\Lambda \sim (130\ \text{GeV})\sqrt{m_\chi/\text{GeV}}$.

Direct Detection

- Flavor gauge bosons do not couple at tree level to nucleons; direct detection arises first at 1 loop:



- Estimate diagram as running from $\mu \sim M_X$ to m_ℓ:

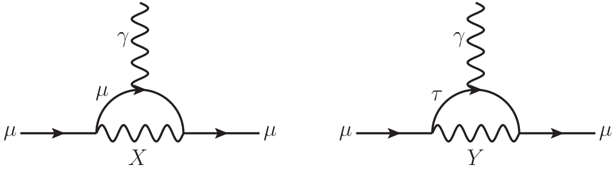
$$\sigma_{\chi p} = \frac{\alpha^2 \mu_N^2}{36\pi^3} \left[\sum_{i=1,2} \frac{k_{i\mu\mu}(k'_{iR} + k'_{iL})}{M_{X_i}^2} \ln \frac{\mu^2}{m_\mu^2} + \frac{k_{i\tau\tau}(k'_{iR} + k'_{iL})}{M_{X_i}^2} \ln \frac{\mu^2}{m_\tau^2} \right]^2$$

where $\mu_N = m_\chi m_p / (m_\chi + m_p)$.

- If $\sigma_{\chi p} \sim \alpha^2 m_p^2 / (36\pi^3 \Lambda^4)$, LUX limit of 10^{-45} cm^2 gives $\Lambda \gtrsim 400$ GeV.
- Loop suppression $\rightarrow$ electroweak-scale LFDM gauge boson masses.

Muon $g-2$

- Measured value of μ $g-2$ currently 3.6σ above SM expectation, $\delta_{a_\mu} = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.8 \pm 8.0) \times 10^{-10}$.
- Contribution from loops containing X, μ and Y, τ:



$$a_\mu = a_\mu^{SM} + \frac{h_{\mu\tau}^2}{4\pi^2}\frac{m_\mu^2}{M_Y^2}\left(\frac{m_\tau}{m_\mu} - \frac{2}{3}\right) + \sum_{i=1,2}\frac{k_{i\mu\mu}^2}{12\pi^2}\frac{m_\mu^2}{M_{X_i}^2}$$

- If only X, μ diagram contributes to $g-2$,

$$\frac{1}{(270\ \text{GeV})^2} < \sum_i \frac{k_{i\mu\mu}^2}{M_{X_i}^2} < \frac{1}{(140\ \text{GeV})^2}$$

  would bring theoretical prediction into experimental 95% CL range.
- Only Y, τ diagram $\rightarrow \frac{1}{(1.9\ \text{TeV})^2} < \frac{h_{\mu\tau}^2}{M_Y^2} < \frac{1}{(1.0\ \text{TeV})^2}$

τ Decays

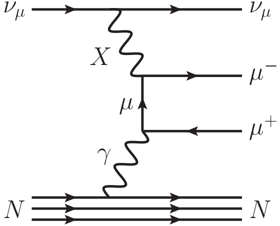
- Y boson can give new contribution to τ decay, $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$. Interferes constructively with SM diagram.

$$\Gamma(\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu) \simeq \frac{m_\tau^5}{\pi^3} \left(\frac{G_F^2}{192} + \frac{\sqrt{2} G_F h_{\mu\tau}^2}{384 \; M_Y^2} \right) \left(1 - \frac{8 m_\mu^2}{m_\tau^2} \right)$$

- SM expectation for $\Gamma(\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu)/\Gamma(\tau^- \to e^- \nu_\tau \overline{\nu}_e)$: 0.9726. Observed: 0.979 ± 0.004.
- Gives $h_{\mu\tau}^2 / M_Y^2 < 1/(2.0 \text{ TeV})^2$ at 95% CL.
- Mild tension with $g-2$ if only Y boson contributes to $g-2$.

Trident Production

- X bosons can contribute to neutrino trident production (Altmannshofer, et al, 2014):



- Interferes constructively with SM diagrams.
- CHARM-II, CCFR give $\sigma_{data}/\sigma_{SM}$ of 1.58 ± 0.57, 0.82 ± 0.28.
- Gives (95% CL)

$$\sum_i \frac{k_{i\mu\mu}^2}{M_{X_i}^2} < \frac{1}{(490 \text{ GeV})^2}$$

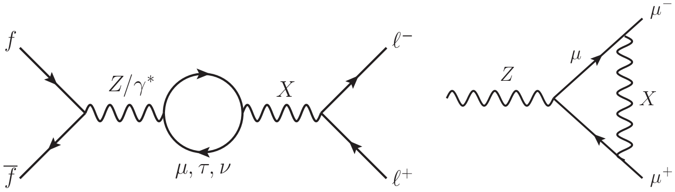
- Conflicts with $g-2$ if only X boson loop contributes to $g-2$.
- Will need both X and Y bosons to fulfill all constraints.

Indirect Detection

- Assumed thermal relic annihilation cross-section; LFDM not relevant for AMS, Pamela, Fermi-LAT excesses.
- Indirect detection bounds not stringent enough to rule out thermal x-sect for $m_\chi \gtrsim 100$ GeV.
- For $m_\chi \lesssim 10$ GeV, thermal relics disfavored by energy injection on CMB. Thermal annihilation cross-sections to $\mu^+\mu^-$, $\tau^+\tau^-$ disfavored by Fermi-LAT, AMS.
- For 10 GeV $\lesssim m_\chi \lesssim 100$ GeV, indirect detection may be important, but uncertainties significant.

LEP

- Loops containing X, Y bosons contribute to $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$:



- Constraints from effective operators, resonance searches, couplings of Z to $\mu^+\mu^-, \tau^+\tau^-$. Obtain approximate limits (95% CL):

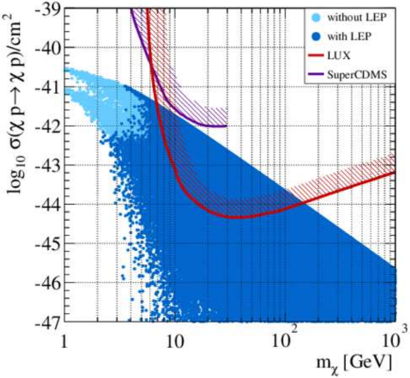
$$\frac{-1}{(300\ \text{GeV})^2} < \sum_i \frac{k_{i\mu\mu}(k_{i\mu\mu} + k_{i\tau\tau})}{M_{X_i}^2} < \frac{1}{(340\ \text{GeV})^2}$$

$$\sum_i \frac{k_{i\mu\mu}^2}{M_{X_i}^2} < \frac{1}{(200\ \text{GeV})^2}$$

$$\left| \sum_i \frac{k_{i\tau\tau}(k_{i\mu\mu} + k_{i\tau\tau})}{M_{X_i}^2} \right| < \frac{1}{(330\ \text{GeV})^2}$$

Allowed Direct-Detection Cross-Section

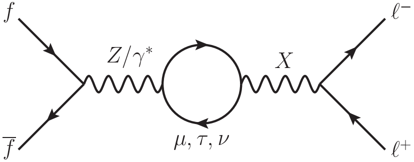
- Now, put all constraints ($g-2$, τ decays, ν tridents, LEP) together.
- Randomly scan over all k's and h's between -1 and 1, M_{X_i}, M_Y between 100 GeV and 10 TeV.
- m_χ set by requiring relic density to have observed value.
- Plot values of direct-detection x-sect allowed by above constraints:



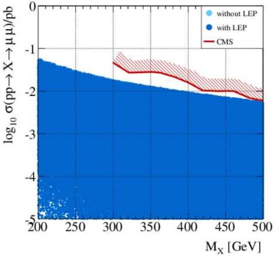
- Indirect detection would affect lower m_χ values.

LHC

- X bosons could be produced at LHC at 1 loop, decay to $\mu^+\mu^-$:



- Size of diagram very dependent on running from renormalization scale μ to M_X. Cross-section approximate. For $\mu = 1$ TeV,



- If a $\mu^+\mu^-$ resonance seen at LHC, LFDM is a candidate explanation!

Conclusions

- LFDM can simultaneously address relic density vs. direct detection and $g-2$ paradoxes.
- Relevant for relic density, direct detection, indirect detection, $g-2$, τ decays, trident production, LEP & LHC.
- Can accomodate each observable at 95% CL.
- Some remaining tension between $g-2$ and trident production/τ decays; suggests we may expect $g-2$ experiment and SM expectation to come into closer agreement in future.
- LFDM may show up at LHC or in direct-detection experiments!