Dark Matter and Vector-like Leptons From Gauged Lepton Number

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Overview

- Introduction
- The Model
- Dark Matter
- LHC Phenemenology
- Conclusions

Introduction

- With the recent discovery of a Higgs the final piece of the SM appears to be in place
- Nature of DM and stabilization mechanism still a mystery
- Also know overall lepton number is a global symmetry of renormalizable SM Lagrangian
- Allowing higher dimensional operators, lepton violating interactions can occur at dimension five

$$\mathcal{L} \sim \frac{1}{\Lambda} |HL|^2$$

- Absence of processes such as neutrino-less double beta decay indicate lepton number is preserved to very high scales
- Could also indicate perhaps more fundamental symmetry

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- We consider promoting the global lepton number to an abelian gauge symmetry $U(1)_L$ Foot, et. al. (1989); Dong, et. al. (2010); Perez, Wise, et. al. (2010), (2011), (2013)

Introduction

- Could this symmetry be related to DM stabilization mechanism?
- We consider promoting the global lepton number to an abelian gauge symmetry $U(1)_L$

  Foot, et. al. (1989); Dong, et. al. (2010); Perez, Wise, et. al. (2010), (2011), (2013)
- Since $U(1)_L$ is anomalous in SM, requires addition of new leptons including RH neutrinos as part of SM
- Must break spontaneously to avoid massless gauge boson
- Can use v.e.v. of a SM singlet scalar (Φ) carrying lepton number
- As a byproduct we also obtain vector-like leptons which been shown recently to have interesting phenomenology

  Joglekar, et. al. (2012), (2013); Arkani-Hamed, et. al. (2013), Batell, et. al. (2012); Feng, et. al. (2013); + others
- DM is the lightest of these leptons and is a (mostly) SM singlet Dirac neutrino

The Model: Anomaly Cancellation

- Extend SM gauge group to $SM \otimes U(1)_L$ with L=1 to SM leptons
- Restrict to minimal particle content and only $D \leq 4$ operators
- Requires addition of RH neutrinos as part of SM + exotic leptons
- A simple choice for the leptons which cancels all anomalies is to add one sequential family with quantum numbers

$$\ell'_L \equiv (\nu'_L \; e'_L) \equiv (2, -1/2, L'),$$
$$e'_R \equiv (1, -1, L'), \;\; \nu'_R \equiv (1, 0, L').$$

- Plus one 'mirror' family with quantum numbers

$$\ell''_R \equiv (\nu''_R \; e''_R) \equiv (2, -1/2, L''),$$
$$e''_L \equiv (1, -1, L''), \;\; \nu''_L \equiv (1, 0, L'').$$

- Anomaly cancellation requires: $L' - L'' = -3$

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- By adding two sets which together are vector-like under SM assures anomaly cancellation in SM gauge factors is preserved

The Model: Global Symmetries and Breaking L

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- DM can not receive mass solely from SM Higgs
- Need to generate contribution to DM mass apart from EWSB
- Majorana masses can be generated by choosing the lepton breaking scalar to carry $L_\Phi = 2L'$ or $L_\Phi = 2L''$
- But this leaves either L' or L'' unbroken meaning lightest lepton of the corresponding sector will be stable and only receive mass from its couplings to the Higgs
- To avoid a heavy stable lepton with unacceptably large couplings to the Z or Higgs boson one must choose L_Φ to generate an interaction between the L' and L'' sectors

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- Anomaly condition ensures that the only possibility is $L_\Phi = 3$

The Model: Yukawa Sector

- Given $L_\Phi = 3$, the Yukawa sector for new leptons can be written,

$$\mathcal{L} \supset -c_\ell \Phi \bar{\ell}''_R \ell'_L - c_e \Phi \bar{e}''_L e'_R - c_\nu \Phi \bar{\nu}''_L \nu'_R - y'_e H \bar{\ell}'_L e'_R$$
$$-y''_e H \bar{\ell}''_R e''_L - y'_\nu \tilde{H} \bar{\ell}'_L \nu'_R - y''_\nu \tilde{H} \bar{\ell}''_R \nu''_L + h.c..$$

- Once Φ obtains a *vev* the couplings c_ℓ, c_e, and c_ν will lead to vector-like masses for the exotic leptons
- Will also receive mass contributions from EWSB via $y'_{\nu,e}, y''_{\nu,e}$
- To avoid mixing with SM leptons: $(L', L'') \neq (1,4), (-4,-1), (-2,1)$
- To avoid Majorana masse we take: $(L', L'') \neq (0,3), (-\frac{3}{2}, \frac{3}{2}), (-3,0)$
- Otherwise L' can otherwise be any real number that satisfies $L' - L'' = -3$

Dark Matter: Candidate and Stability

- Examining the neutrino sector once Φ and H obtain v.e.v.s

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} c_\ell (v_\phi + \phi_o) \bar{\nu}''_R \nu'_L - \frac{1}{\sqrt{2}} c_\nu (v_\phi + \phi_o) \bar{\nu}''_L \nu'_R$$
$$-\frac{1}{\sqrt{2}} y''_\nu (v_h + h_o) \bar{\nu}''_R \nu''_L - \frac{1}{\sqrt{2}} y'_\nu (v_h + h_o) \bar{\nu}'_L \nu'_R + h.c.$$

- Which give for the mass matrix

$$\mathcal{M}_\nu = \frac{1}{\sqrt{2}} \begin{pmatrix} c_\ell v_\phi & y'_\nu v_h \\ y''_\nu v_h & c_\nu v_\phi \end{pmatrix}$$

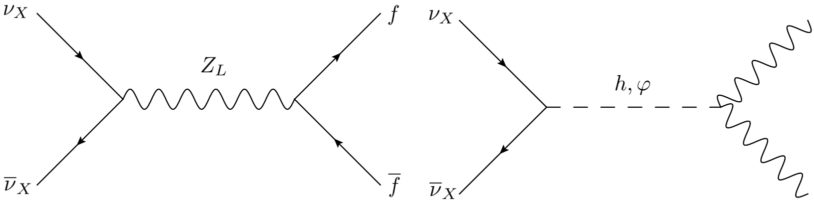
- In the limit where $y'_\nu v_h, y''_\nu v_h \ll c_{\ell,\nu} v_\phi$ masses approximately

$$m_{\nu_X} \approx \frac{1}{\sqrt{2}} c_\nu v_\phi$$
$$m_{\nu_4} \approx \frac{1}{\sqrt{2}} c_\ell v_\phi$$

- We require $c_\nu < c_\ell$, such that ν_X is the DM candidate
- Residual Z_2 symmetry under which all heavy leptons are odd and all SM leptons are even that stabilizes DM

Dark Matter: Annihilation Channels

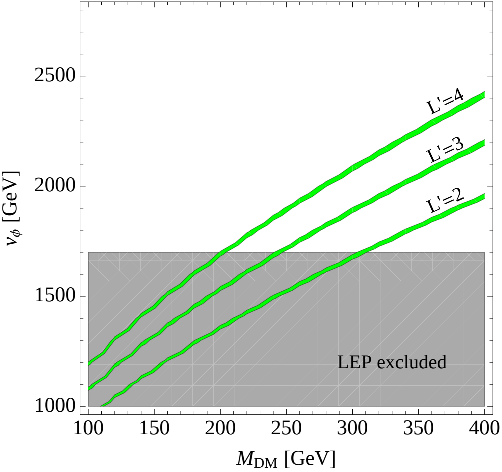
- DM can annihilate via Z_L as well as h and ϕ



- Despite DD requiring $y'_\nu, y''_\nu \ll 1$ the DM can annihilate through h via scalar mixing
- Can also annihilate through Z via neutral vector boson mixing
- Negligible contribution to $\langle \sigma v \rangle$ over most of parameter space
- However will be relevant for DD detection
- Annihilation through ϕ suppressed by small c_ν and small ϕ couplings to SM which only occur at loop level
- Dominant mode is $\bar{\nu}_X \nu_X \to Z_L \to \ell\ell$ over most of p.s.

Dark Matter: Relic Abundance

- Can examine relic density as function of DM mass and v_ϕ for $m_{\nu_X} << M_{Z_L}$ (MICROMEGAS)



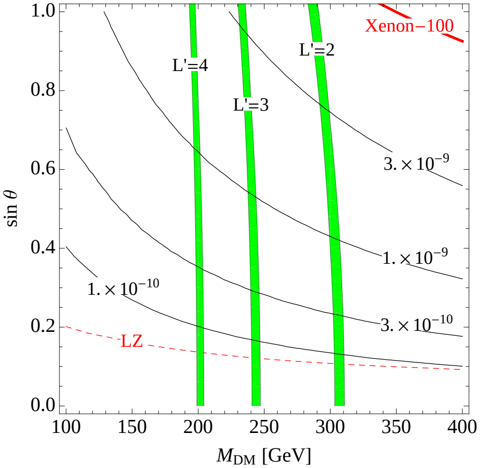
- Since LEP II constraints require $v_\phi \geq 1.7$ TeV implies DM masses $\gtrsim$ 200 GeV or large L', L'' to obtain correct relic density

Dark Matter: Direct Detection

- In limit $y'_\nu, y''_\nu \approx 0$, DM still couples to h and ϕ through

$$\mathcal{L} \supset \frac{c_\nu}{\sqrt{2}}(c_\theta \phi - s_\theta h)\bar{\nu}_X \nu_X$$

- Higgs exchange can lead to SI scattering and DD signal

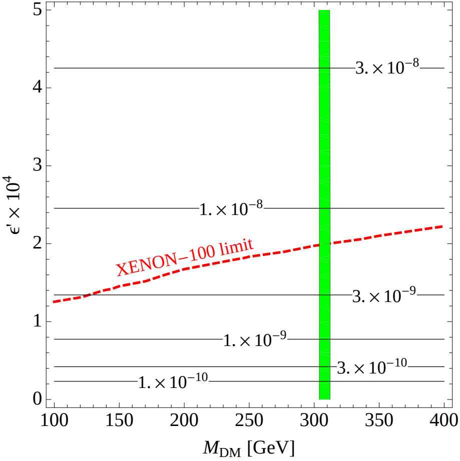


Dark Matter: Direct Detection

- DM can also couple to Z through $Z - Z_L$ mixing giving

$$\mathcal{L} \supset \epsilon' g' Z_\mu \bar{\nu}_X \gamma^\mu \left(L'' P_R + L' P_L\right) \nu_X$$

- For $v_\phi = 1.7$ TeV, $g' = 0.5$ ($M_{Z_L} = 2.55$ TeV), and $L' = 2$



LHC Phenomenology: Charged Lepton Sector

- New particles in this model can have a variety of pheno at LHC
- New charged leptons can be produced directly and affect Higgs decays

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} c_\ell v_\phi (1 + \frac{\phi}{v_\phi}) \bar{e}''_R e'_L - \frac{1}{\sqrt{2}} c_e v_\phi (1 + \frac{\phi}{v_\phi}) \bar{e}''_L e'_R$$
$$-\frac{1}{\sqrt{2}} y''_e v_h (1 + \frac{h}{v_h}) \bar{e}''_R e''_L - \frac{1}{\sqrt{2}} y'_e v_h (1 + \frac{h}{v_h}) \bar{e}'_L e'_R + h.c.$$

- Leads to mass matrix

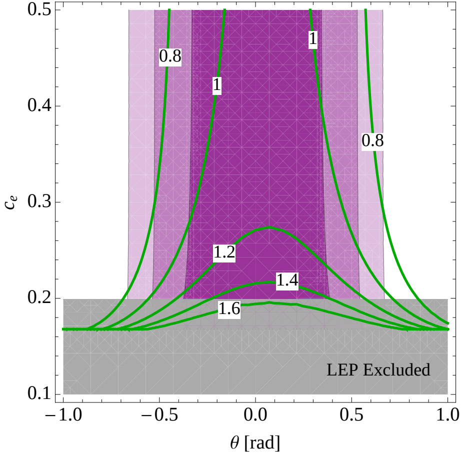
$$\mathcal{M}_e = \frac{1}{\sqrt{2}} \begin{pmatrix} c_\ell v_\phi & y''_e v_h \\ y'_e v_h & c_e v_\phi \end{pmatrix}$$

- Taking limit $c_\ell \approx c_e \equiv c_e$ and $y'_e \approx y''_e \equiv y_e$

$$m_{e_1} \approx \frac{1}{\sqrt{2}} (c_e v_\phi - y_e v_h)$$
$$m_{e_2} \approx \frac{1}{\sqrt{2}} (c_e v_\phi + y_e v_h) \, ,$$

LHC Phenomenology: Modification of Higgs Decays

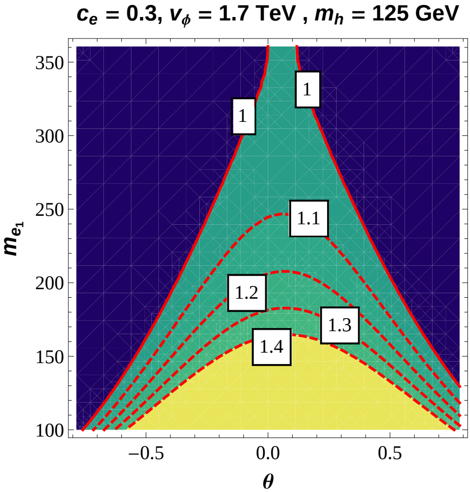
- Fitting to full Higgs data set in $c_e - \theta$ plane ($y_e = 0.8$, $v_\phi = 1.7$ TeV)



- Mixing angles as large $\theta = \pm 0.5$ give good fits

LHC Phenomenology: Modification of Higgs Decays

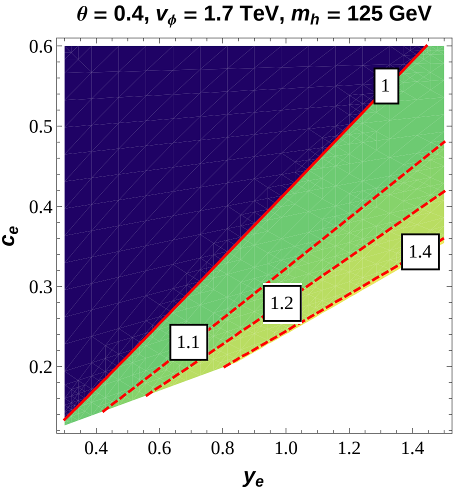
- Fixing c_e and examining contours of $\mu_{\gamma\gamma}$



- Since DM provides lower bound on m_{e_1} we see for DM ~ 200 GeV, modifications as large as $10 - 20\%$ can be obtained

LHC Phenomenology: Modification of Higgs Decays

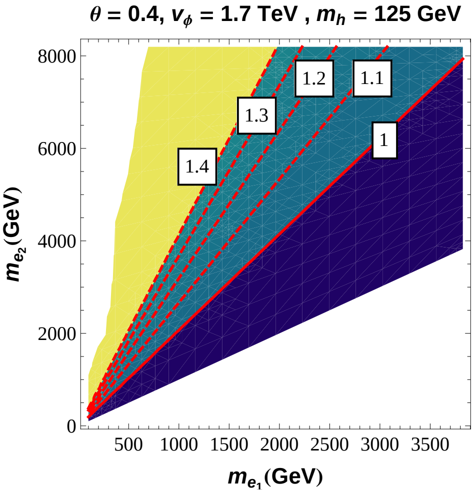
- Fixing the Higgs mixing angle and examine $c_e - y_e$ plane



- Can obtain observables modifications for couplings of $\mathcal{O}(1)$
- For this range of couplings m_{e_1} in range 100 – 500 GeV

LHC Phenomenology: Modification of Higgs Decays

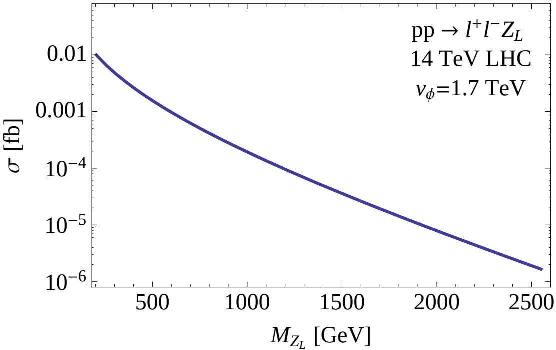
- Allowing couplings to be as large as purturbative limit $\sim 4\pi$



- Since v_ϕ is fixed we see 'non-decoupling' behavior for e_1, e_2 contribution to $h \to \gamma\gamma$

LHC Phenomenology: Other Potential Signatures

- Neglecting $Z_L - Z$ mixing, Z_L can only be produced by radiating off final state leptons in the process $pp \to \ell^+\ell^- Z_L$



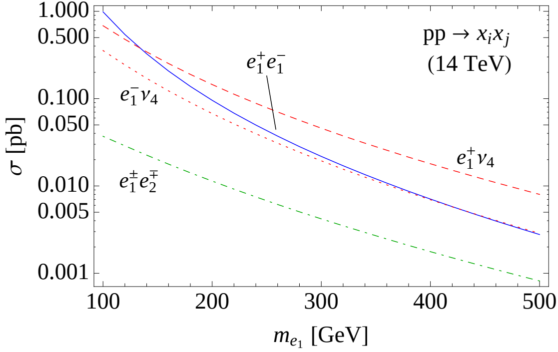
- If $M_{Z_L} < 2m_{e_{1,2}}$, Z_L decays 50/50 to SM charged leptons/neutrinos
- Small background, but difficult to probe Z_L mass $\gtrsim$ 500 GeV

LHC Phenomenology: Other Potential Signatures

- Can also produce pairs of exotic leptons via Drell-Yan
- For limits consider we have the following mass hierarchy

$$m_{e_2} > m_{\nu_4} > m_{e_1} > m_{\nu_X}$$

- Taking $m_{e_2} = m_{e_1} + 280$ GeV implying $m_{\nu_4} = m_{e_1} + 140$ GeV



- For large masses we see $e_1 \nu_4$ production dominates

LHC Phenomenology: Other Potential Signatures

- Exotic charged leptons can decay in variety of ways

$$e_2 \to W\nu_4 \to WWe_1 \to WWW\nu_X$$

$$e_2 \to Wh\nu_X,\ e_2 \to WZ\nu_X,\ e_2 \to W\nu_X$$

$$e_1 \to W\nu_X$$

- Heavy active neutrino has decays

$$\nu_4 \to Z\nu_X,\ \nu_4 \to h\nu_X$$

$$\nu_4 \to We_1 \to WW\nu_X$$

- Assuming lepton decays of *W*-boson can lead to signatures

$$pp \to e_1^+ e_1^- \to WW\not{E}_T \to l^+ l^- \not{E}_T$$

$$pp \to e_1^+ \nu_4 \to WZ\not{E}_T \to l^+ l^+ l^- \not{E}_T$$

- Can also have potential ϕ signal, but generally too heavy

Conclusions/Future Work

- Constructed a simple model of DM out of gauged lepton number
- Correct relic abundance is obtained for DM masses $\gtrsim$ 200 GeV
- Potential direct detection signals
- Automatic consequence is presence of vector-like leptons
- Variety of interesting LHC phenomenology
- Examining embedding into more complete theory
- Examining prospects for baryogenesis
- Perform detailed collider study

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- Thanks!