Gauged Lepton Number and Implications for Collider Physics

We-Fu Chang
National Tsing Hua University
(with John Ng)

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Outline

- Lepton number
- anomaly-free solution
- lepton masses
- some phenomenology
- collider signals

lepton number

- $U(1)$lepton: an accidental anomalous symmetry in SM (so that electron is stable)
- In minimal SM, neutrinos are massless (further L_e L_μ L_τ, no $mu \to e\gamma$)
- SM DOF and symmetry,

$$O_W = (LH)^2$$

  (Dirac neutrinos need fine tuning.)
- Majorana mass $\sim v^2/\Lambda$, for 0.1 eV, $\Lambda = 10^{14}$ GeV. The lepton number is explicitly broken.
- SM is an effective theory.

lepton number

- Origin of O_W is unknown
- whether L-number a global symmetry or a gauged one? And how it is broken?
- Or L-number just an accident?
- The (partial) answer to these questions adds to our understanding of fundamental physics.
- type-I seesaw is one of the popular candidates to explain O_W. The arbitrary Majorana masses of the RH singlet break L-number.

lepton-number

- The RH singlet mass can also be generated by SSB of $U(1)$ lepton when a charge two scalar develops a VEV
- the Goldstone of $U(1)_L$, Majoron, provides extra relativistic DOF to the energy density of the universe, dark radiation
- $U(1)$-lepton could also be gauged.
- if unbroken, long-range force, $\alpha_l < 10^{-49}$, Lee and Yang[1955],Okum[1996]
  conjunction with $U(1)_B$, Perez and Wise[2010]
  purely $U(1)_L$, Schwaller, Tait, Vega-Morales[2013]
- emphasize was the DM. Anomaly cancel for all 3 SM generations together.

gauged U(1) lepton

- We are interested in the anomaly-free set for each generation
- Robust consequences:
  (1) exotic fermions
  (2) new gauge boson
  (3) possible kinetic mixing between $U(1)$-lepton and $U(1)_Y$

anomaly-free

- The new anomalies need to be taken care are: $SU(2)^2 L, L^3 Y^2 L, YL^2, G^2 L$
- Also one has to check the SM ones: $SU(2)^2 Y, Y^3, G^2 Y$
- The simplest nontrivial solution we have found is
  $L_{1L}(2, -1/2, -1), E_{1R}(1, -1, -1),$
  $L_{2R}(2, -1/2, 0), E_{2L}(1, -1, 0),$
  (in $[SU(2), Y, L]$) or
  $L_{1L}(2, -1/2, 0), E_{1R}(1, -1, 0),\ L_{2R}(2, -1/2, 1), E_{2L}(1, -1, 1)$
  Note the new fermion DOF form SM vectors.
- A more bizarre solution with rational hypercharge
  $L_{1L}(2, 7/2, 2), E_{1R}(1, 5, 3),\ L_{2R}(2, 7/2, 3), E_{2L}(1, 5, 4).$
  Stable, high electric charge, therefore, ruled out.

- 3 generations need 12 exotic fermions,
- Making use of $L_1 - L_2$ [He et al., 1991] for 2 out of 3 generations
  (same lepton number, and form SM vectors).
- only 4 exotic fermions for the remaining generation, the minimal set as we know
- Because of U(1), the U(1) charges need not be universal
- As an illustration, we choose 1, (1,-1).
  The flavor is meaningful only after mass diagonalization.

Scalar sector

- Scalar sector: SM Higgs + ϕ_1(1,0,1)
- Denote SM leptons as: $l_{L1,L2}(2,-1/2,1)$, $l_{L3}(2,-1/2,-1)$, $e_{R1,R2}(1,-1,1)$, and $e_{R3}(1,-1,-1)$. For the exotic leptons, $l_{L4}\equiv L_{1L}(2,-1/2,-1)$, $e_{R4}\equiv E_{1R}(1,-1,-1)$. $L_{2R}(2,-1/2,0)$ and $E_{2L}(1,-1,0)$ retain their names.
- The general Yukawa interaction is

$$\sum_{i,j=1,2} y_{ij}\,\bar{l}_{Li}He_{Rj}+\sum_{a,b=3,4} y_{ab}\,\bar{l}_{La}He_{Rb}+y_{55}\,\bar{L}_{2R}HE_{2L}$$
$$+\sum_{i=1,2}(f_i\,\bar{l}_{Li}L_{2R}+f_i'\bar{e}_{Ri}E_{2L})\phi_1+\sum_{a=3,4}(f_a\,\bar{l}_{La}L_{2R}+f_a'\bar{e}_{Ra}E_{2L})\phi_1^*+H.c.$$

Charged lepton masses

- Direct search of heavy charged lepton, $> 100\text{GeV}$. $\langle \phi_1 \rangle = v_L/\sqrt{2} \gg v = 246\text{GeV}$.
- The charged lepton mass matrix in the basis of $\{e_1, e_2, e_3, e_4, E_2\}$ is

$$\mathcal{M}^c = \frac{v_L}{\sqrt{2}} \begin{pmatrix} \epsilon_1 & \epsilon_2 & 0 & 0 & f_1 \\ \epsilon_3 & \epsilon_4 & 0 & 0 & f_2 \\ 0 & 0 & \epsilon_5 & \epsilon_6 & f_3 \\ 0 & 0 & \epsilon_7 & \epsilon_8 & f_4 \\ f_1' & f_2' & f_3' & f_4' & \epsilon_9 \end{pmatrix}$$

  where the Yukawa couplings are not displayed.
- Without tuning, one expects $f_i, f_i' \sim \mathcal{O}(1)$, $\epsilon_i \sim \mathcal{O}(v/v_L)$.

universal limit

- In general the mass matrix is not symmetric, $U_L^\dagger \cdot M \cdot U_R = diag\{m_e, m_\mu, m_\tau, M_-, M_+\}$
- We consider a limiting case in which $f_i = f_i'$ and $\epsilon_i = \epsilon$ and M is symmetric.
- It will be justified by the phenomenology.
- Introducing small perturbations, $\delta_{1,2}$, to distinguish electron and muon, the mass matrix becomes

$$\mathcal{M}'^c = \frac{v_L}{\sqrt{2}} \begin{pmatrix} \epsilon & \epsilon(1-\delta_1) & 0 & 0 & 1 \\ \epsilon(1-\delta_1) & \epsilon & 0 & 0 & 1 \\ 0 & 0 & \epsilon & \epsilon(1-\delta_2) & 1 \\ 0 & 0 & \epsilon(1-\delta_2) & \epsilon & 1 \\ 1 & 1 & 1 & 1 & \epsilon \end{pmatrix}$$

Diagonalization and mass eigenvalues

- And $U_L \simeq U_R \simeq$

$$U = \begin{pmatrix} \frac{1}{\sqrt{2}} & 0 & -\frac{1}{2} & -\frac{1}{2\sqrt{2}} & \frac{1}{2\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & 0 & -\frac{1}{2} & -\frac{1}{2\sqrt{2}} & \frac{1}{2\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{2} & -\frac{1}{2\sqrt{2}} & \frac{1}{2\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{2} & -\frac{1}{2\sqrt{2}} & \frac{1}{2\sqrt{2}} \\ 0 & 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

- also, the mass eigenvalues are

$$\simeq \frac{v_L}{\sqrt{2}} \times \{\delta_1\epsilon, \delta_2\epsilon, \epsilon, -2 + \frac{3\epsilon}{2}, 2 + \frac{3\epsilon}{2}\}$$

for mass eigenstates $\tilde{e} = \{e, \mu, \tau, E_-, E_+\}$

SM gauge interactions

- In terms of $\tilde{e}$, no change in the QED part .
- However, the SM CC and NC have extra interactions:

$$\frac{g_2}{2c_W}\left[\overline{\tilde{e}_i}\gamma^\mu\left(g^V_{ij}-g^A_{ij}\gamma_5\right)\tilde{e}_j-\overline{\tilde{\nu}_i}\gamma^\mu\left(g^V_{ij}-g^A_{ij}\gamma_5\right)\tilde{\nu}_j\right]Z_\mu$$
$$+\frac{g_2}{\sqrt{2}}\overline{\tilde{\nu}_i}\gamma^\mu\left(-g^V_{ij}+g^A_{ij}\gamma_5\right)\tilde{e}_jW^+_\mu+H.c.$$

where

$$g^V_{ij}\equiv\frac{1}{2}\left[(U^\dagger_L)_{i5}(U_L)_{5j}-(U^\dagger_R)_{i5}(U_R)_{5j}\right],$$
$$g^A_{ij}\equiv\frac{1}{2}\left[(U^\dagger_L)_{i5}(U_L)_{5j}+(U^\dagger_R)_{i5}(U_R)_{5j}\right].$$

- In general, the new gauge interactions are flavor non-diagonal. Also, the CC part deviates from the SM (V-A).
- $U_{51,52,53}=0$, no problem among e,μ,τ.

some experimental bounds

- The current limit is roughly

$$|g_{aa}^A - g_{aa}^V| \lesssim 0.11$$

  from W_R searches($M_{W_R} > 0.7$ TeV), and

$$(g_{12}^A)^2 + (g_{12}^V)^2 < 1.4 \times 10^{-6}$$

  from $Br(Z \to e\mu) < 7.5 \times 10^{-7}$
- Therefore, the mass matrix cannot be arbitrary.
- For the limiting case, it is OK. However, FCNC for exotic leptons.

Z_l couplings

- In the mass basis, the Z_l coupling matrix is

$$Q_l \equiv U^T \cdot Q_{0\ell} \cdot U = U^T \cdot \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & -1 & & \\ & & & -1 & \\ & & & & 0 \end{pmatrix} \cdot U = \begin{pmatrix} 1 & & & & \\ & -1 & & & \\ & & 0 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ & & \frac{1}{\sqrt{2}} & 0 & 0 \\ & & -\frac{1}{\sqrt{2}} & 0 & 0 \end{pmatrix}$$

- Note there is no $Z_l - \tau$ coupling, and note that $e - Z_\ell, \mu - Z_\ell$ couplings take opposite signs.

LEP2 bound

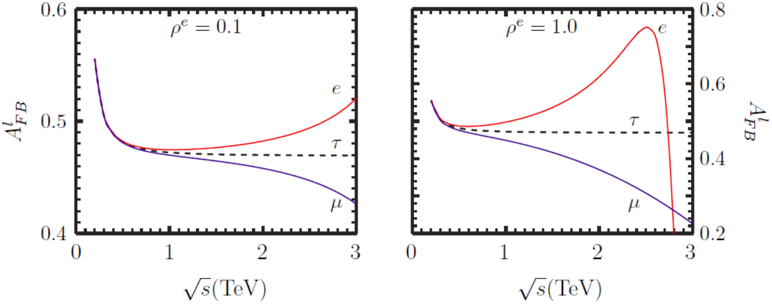
- If $M_X \gg v$, one has the following contact interaction

$$\frac{g_\ell^2}{M_X^2}\left(\frac{1}{2}\bar{e}\gamma^\mu e\bar{e}\gamma_\mu e - \bar{e}\gamma^\mu e\bar{\mu}\gamma_\mu\mu\right)$$

- From LEP2($\Lambda^+_{\mu\mu} > 18.9$TeV), $g_l/M_X < 1/5.33$TeV, or $v_L > 7.54$ TeV, and $M_X > 1.67(g_l/e)$TeV.
- Δa_μ cannot be accommodated by Z_l alone.

Front-back asymmetry

- On-shell production followed by $Z_l \to ee, \mu\mu$ will be clean.
- Before that, the non-universal Z_l couplings can be tested.
  ($\rho_e \equiv (g_l/e)^2$, $M_X = 4$TeV.)



LFV at e^+e^- collider

- Tree-level LFV processes like $\mu \to 3e$ can be mediated by Z_l. The BR is
$$\frac{3}{4G_F^2}\frac{g_l^4}{M_X^4}|Q_l^{ee}Q_l^{\mu e}|^2$$
- from exp limits$(10^{-12}, 10^{-8})$, $|Q_l^{\mu e}| < 4 \times 10^{-4}$, $|Q_l^{\mu\tau}|, |Q_l^{e\tau}| < 0.1$
- At the e^+e^- collider with $\sqrt{s} < M_X$, the LFV BR can be estimated

$$B_{ij} \equiv \frac{\sigma(e^+e^- \to l_i l_j)}{\sigma(e^+e^- \to \mu^+\mu^-)} \simeq \frac{g_\ell^4}{e^4}\frac{|Q_l^{ee}Q_l^{ij}|^2}{(1 - M_X^2/s)^2}, \text{ where } i \neq j\,.$$

- $e^+e^- \to \mu\tau, \tau e$ are possible if CLFV tau decay is not too smaller then the current limits.

- At the LHC, Z_ℓ can be produced via $pp \to e^+e^-Z_\ell$.
- In the simplified scenario, signal will be an e^+e^- or a $\mu^+\mu^-$ pair peaking at M_X. (No jet activities).
- Limited by the contact interaction, v_L can only be modestly probed up to $\sim 0.5(1)$ TeV at the LHC13(30) if $S/\sqrt{B} = 3$ is required.
- Similarly, the heavy leptons can be pair produced at the LHC via the SM Drell-Yan process.
- Note that their production cross sections, $\sim \mathcal{O}(1 - 100fb)$ if they are lighter than 500GeV, are independent of g_ℓ and M_X.

Summary

- Novel anomaly-free gauged $U(1)_\ell$ with exotic $L_{1,2}$ and $E_{1,2}$.
- One singlet scalar for heavy exotic and the SSB of $U(1)_\ell$.
- New flavor-changing, SM NC and CC interactions. Special charged lepton mass matrix is required.
- Simplified limit with universal Yukawa couplings. Symmetric charged lepton mass matrix.
- Natural hierarchy $m_e, m_\mu \ll m_\tau \sim v$ is predicted.
- e, μ, τ have different A_{FB} and can be searched for.
- Possible $e^+e^- \to \tau\mu, \tau e$ at e^+e^- collider, with $\sqrt{s}$ ~TeV and $\sim ab^{-1}$.
- Lepton charges for the three SM generations need not be the same.