

Gauged Lepton Number and Implications for Collider Physics

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- $U(1)$ lepton: an accidental anomalous symmetry in SM (so that the lightest lepton is stable)
- In minimal SM, neutrinos are massless (further $L_e L_\mu L_\tau$, no $\mu \rightarrow e \gamma$)
- 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.

- Origin of O_W is unknown
- whether L-number a global symmetry or a gauged one? And how it is broken?
- Maybe, accidental?
- 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.

- The RH singlet mass can also be generated by SSB of $U(1)_L$ 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, WFC, J. Ng, J.Wu [2014]; WFC,J.Ng[2014,2016]
- $U(1)$ -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.

- We are interested in the anomaly-free set for each generation
- The new anomalies need to be taken care are:
 $SU(2)^2L, L^3Y^2L, YL^2, G^2L$
- Also one has to check the SM ones: $SU(2)^2Y, Y^3, G^2Y$
- Robust consequences:
 - (1) exotic fermions
 - (2) new gauge boson
 - (3) possible kinetic mixing between $U(1)$ -lepton and $U(1)_Y$

- 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 $[SU(2), Y, L]$, vector-like with SM)

WFC and J Ng.[PRD 2018, JHEP 2018]

- Another solution is

$$L_{1L}(2, -1/2, 0), E_{1R}(1, -1, 0), L_{2R}(2, -1/2, 1), E_{2L}(1, -1, 1)$$

- 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 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
- If all different, no mixing.
- For nontrivial mixing, we choose 1, (1,-1).
The flavor is meaningful only after mass diagonalization.
WFC and J Ng[PRD 2019]

- Scalar sector: SM Higgs + $\phi_1(1,0,1)$
- 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

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

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

$$M^c = \frac{v_L}{\sqrt{2}} \begin{pmatrix} \epsilon_1 & \epsilon_2 & 0 & 0 & f_1 \\ \epsilon_3 & \epsilon_4 & 0 & 0 & f_2 \\ 0 & 0 & \epsilon_5 & \epsilon_6 & f_3 \\ 0 & 0 & \epsilon_7 & \epsilon_8 & f_4 \\ f'_1 & f'_2 & f'_3 & f'_4 & \epsilon_9 \end{pmatrix}$$

where the Yukawa couplings are not displayed.

- Without tuning, one expects $f_i, f'_i \sim \mathcal{O}(1)$, $\epsilon_i \sim \mathcal{O}(v/v_L)$.

SM gauge interactions

- In general the mass matrix is not symmetric, $U_L^\dagger \cdot M \cdot U_R = \text{diag}\{m_e, m_\mu, m_\tau, M_-, M_+\}$ with mass eigenstates $\tilde{e} = \{e, \mu, \tau, E_-, E_+\}$.
- In terms of \tilde{e} , no change in the QED part .
- However, the SM CC and NC have **extra** interactions:

$$\frac{g_2}{2c_W} \left[\bar{\tilde{e}}_i \gamma^\mu \left(g_{ij}^V - g_{ij}^A \gamma_5 \right) \tilde{e}_j - \bar{\tilde{\nu}}_i \gamma^\mu \left(g_{ij}^V - g_{ij}^A \gamma_5 \right) \tilde{\nu}_j \right] Z_\mu \\ + \frac{g_2}{\sqrt{2}} \bar{\tilde{\nu}}_i \gamma^\mu \left(-g_{ij}^V + g_{ij}^A \gamma_5 \right) \tilde{e}_j W_\mu^+ + H.c.$$

where

$$g_{ij}^V \equiv \frac{1}{2} \left[(U_L^\dagger)_{i5} (U_L)_{5j} - (U_R^\dagger)_{i5} (U_R)_{5j} \right], \\ g_{ij}^A \equiv \frac{1}{2} \left[(U_L^\dagger)_{i5} (U_L)_{5j} + (U_R^\dagger)_{i5} (U_R)_{5j} \right].$$

- In general, the new gauge interactions are flavor non-diagonal. Also, the CC part deviates from the SM (V-A).

- 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 $Br(Z \rightarrow e\mu) < 7.5 \times 10^{-7}$

- Therefore, the mass matrix cannot be arbitrary.
- If $U_L = U_R$, no problem with vector part.
- If $U_{51,52,53} = 0$, no problem among e, μ, τ . Still, FCNC for exotic leptons.

- We consider a limiting case in which $f_i = f'_i$ and $\epsilon_i = \epsilon$ and M is symmetric (so $U_L = U_R$).
- It is motivated by the phenomenology.
- Introducing small perturbations, $\delta_{1,2}$, to distinguish electron and muon, the mass matrix becomes

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

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

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

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

- $\delta_1 = m_e/m_\tau$, $\delta_2 = m_\mu/m_\tau$.
- Higgs portal like for leptons.

- In the mass basis, the Z_I coupling matrix is

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

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

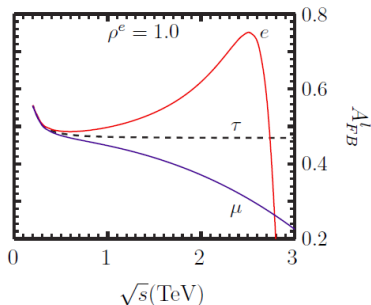
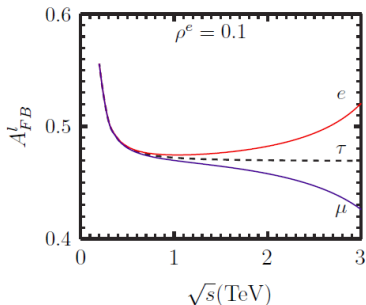
- If $M_X \gg v$, one has the following contact interaction

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

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

Front-back asymmetry

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



- Tree-level LFV processes like $\mu \rightarrow 3e$ 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

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

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

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 $e^+e^- \rightarrow \tau\mu, \tau e$ at e^+e^- collider, with $\sqrt{s} \sim \text{TeV}$ and $\sim ab^{-1}$.
- Lepton charges for the three SM generations need not be the same.

- At the LHC, Z_ℓ can be produced via $pp \rightarrow e^+ e^- Z_\ell$.
- 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, ν_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, $\sim \mathcal{O}(1 - 100\text{fb})$ if they are lighter than 500GeV, are independent of g_ℓ and M_X .

- In symmetric limit, the mass matrix is

$$\mathcal{M}^n = \frac{v_L}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 & 0 & f_1 \\ 0 & 0 & 0 & 0 & f_2 \\ 0 & 0 & 0 & 0 & f_3 \\ 0 & 0 & 0 & 0 & f_4 \\ f_1 & f_2 & f_3 & f_4 & 0 \end{pmatrix}$$

- $U^T \cdot \mathcal{M}^n \cdot U \simeq (v_L/\sqrt{2}) \times \text{diag}\{0,0,0,-2,2\}$, the light and heavy ν decouple at leading order.
- A heavy Dirac pair with mass $\sim v_L$, three massless active neutrinos.
- Further model building for realistic neutrino masses:
SS-1,SS-2,1-loop(needs two $(2, 1/2, \pm 2)$, one $(1, 0, 2)$, and one $(1 - 1, 0)$)