Dark Gauge U(1) Symmetry for an Alternative Left-Right Model

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Overview

Introduction/Motivation

- Restore symmetry between Left-Right sectors
- Generate naturally small neutrino masses
- Accomodate dark matter

Minimal Left-Right Model

- Simple extention of the SM gauge group
- Spontaneous/Explicit breaking of P (SU(2)$_L \longleftrightarrow$SU(2)$_R$) (also CP)
- Genartion of naturaly light neutrino masses (Seesaw I/III)

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv [3,2,1,\frac{1}{3}] \quad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv [3,1,2,\frac{1}{3}]$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \equiv [1,2,1,-1] \quad \ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \equiv [1,1,2,-1].$$ *

- $\eta \sim$(1,2,2,0), $\Delta_L \sim$(1,3,1,-1), $\Delta_R \sim$(1,1,3,-1)
- Seesaw I/II
- $\eta \sim$(1,2,2,0), $\phi_L \sim$(1,2,1,1/2), $\phi_R \sim$(1,1,2,1/2)
- Double seesaw through Weinberg dim-5 operator
- Flavour changing neutral currents

* N.G. Deshpande et al., Phys. Rev. D 44, 837 (1991).

Alternative Left-Right Model

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\begin{aligned}
(u,d)_L &: (3,2,1,\tfrac{1}{6}) \quad (h^c,u^c)_L : (\bar{3},1,2,-\tfrac{1}{6}) \\
(\nu_E,E)_L &: (1,2,1,-\tfrac{1}{2}) \quad (e^c,n)_L : (1,1,2,\tfrac{1}{2}) \\
h_L &: (3,1,1,-\tfrac{1}{3}) \quad d^c_L : (\bar{3},1,1,\tfrac{1}{3}) \\
\begin{pmatrix} \nu_e & E^c \\ e & N^c_E \end{pmatrix}_L &: (1,2,2,0) \qquad N^c_L : (1,1,1,0),
\end{aligned}$$ †

- ALRM is motivated by superstring-inspired E_6 model
- Flavour changing neutral currents are naturaly absent tree level
- $W^\pm_R$ has lepton number ± 1 and odd parity so they do not mix with $W^\pm_L$
- $SU(2)_R$ breaking scale can be below as TeV, $W^\pm_R$ and Z' are reachiable at LHC

† E. Ma, Phys. Rev. D 36, 274 (1987); K. S. Babu, X.-G. He, and E. Ma, Phys. Rev. D 36, 878 (1987); J. L. Hewett and T. G. Rizzo,

Fermion	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S
$\psi_L = (\nu, e)_L$	(1, 2, 1, − 1/2)	1
$\psi_R = (n, e)_R$	(1, 1, 2, −1/2)	1/2
$Q_L = (u, d)_L$	(3, 2, 1, 1/6)	0
$Q_R = (u, h)_R$	(3, 1, 2, 1/6)	1/2
d_R	(3, 1, 1, − 1/3)	0
h_L	(3, 1, 1, − 1/3)	1

Scalar	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S
Φ	(1, 2, 2, 0)	1/2
$\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$	(1, 2, 2, 0)	−1/2
Φ_L	(1, 2, 1,1/2)	0
Φ_R	(1, 1, 2,1/2)	−1/2
Δ_L	(1, 3, 1, 1)	−2
Δ_R	(1, 1, 3, 1)	−1 ‡

- No tree level FCNC
- Neutrino masses($m_\nu \sim \langle \Delta_L^0 \rangle \implies$ L $\to$ (-1)^L, R parity)
- Fermionic Dark Matter (Scotinos) ($m_n \sim \langle \Delta_R^0 \rangle$)
- Lepton number given by L=S-T_{3R}
- $\langle \phi_1^0 \rangle = 0$ by S-T_{3R}
- h, $W_R^\pm$ has L=1,$\mp$1
- SM particles are even, n, h, $W_R^\pm$, and $\Delta_R^\pm$ are odd under parity

‡S. Khalil, H.-S. Lee, E. Ma, Phys. Rev. D 79, 041701(R) (2009)

Dark Alternative Left-Right Models II

with Global Symmetries

Fermion	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S
$\psi_L = (\nu, e)_L$	(1, 2, 1, −1/2)	1
$\psi_R = (n, e)_R$	(1, 1, 2, −1/2)	3/2
ν_R	(1, 1, 1, 0)	1
n_L	(1, 1, 1, 0)	2
$Q_L = (u, d)_L$	(3, 2, 1, 1/6)	0
$Q_R = (u, h)_R$	(3, 1, 2, 1/6)	−1/2
d_R	(3, 1, 1, −1/3)	0
h_L	(3, 1, 1, −1/3)	−1

Scalar	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S
Φ	(1, 2, 2, 0)	−1/2
$\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$	(1, 2, 2, 0)	1/2
Φ_L	(1, 2, 1, 1/2)	0
Φ_R	(1, 1, 2, 1/2)	1/2

§

- No tree level FCNC
- Dirac neutrino masses($m_\nu \sim \langle \phi_L^0 \rangle$)
- Dirac Fermionic Dark Matter (Scotinos) ($m_n \sim \langle \phi_R^0 \rangle$)
- Lepton number given by $L = S + T_{3R}$ and is conserved
- $\langle \phi_1^0 \rangle = 0$ by $S + T_{3R}$
- $\nu_R \nu_R$ breaks L and generates Majorana neutrino mass through canonical seesaw
- n remains Dirac fermion protected by residual global U(1) (n, $W_R^+ \sim 1$, h, $\phi_1^{0,-} \sim -1$)

§ S. Khalil, H.-S. Lee, E. Ma, Phys. Rev. D 81, 051702(R) (2010)

Particle Content of the U(1)$_D$ ALRM

particles	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$	$U(1)_S$
$(u,d)_L$	3	2	1	1/6	0
$(u,h)_R$	3	1	2	1/6	−1/2
d_R	3	1	1	−1/3	0
h_L	3	1	1	−1/3	−1
$(\nu,l)_L$	1	2	1	−1/2	0
$(n,l)_R$	1	1	2	−1/2	1/2
ν_R	1	1	1	0	0
n_L	1	1	1	0	1
(ϕ_L^+,ϕ_L^0)	1	2	1	1/2	0
(ϕ_R^+,ϕ_R^0)	1	1	2	1/2	1/2
η	1	2	2	0	−1/2
ζ	1	1	1	0	1
$(\psi_1^0,\psi_1^-)_R$	1	1	2	−1/2	2
$(\psi_2^+,\psi_2^0)_R$	1	1	2	1/2	1
χ_R^+	1	1	1	1	−3/2
χ_R^-	1	1	1	−1	−3/2
χ_{1R}^0	1	1	1	0	−1/2
χ_{2R}^0	1	1	1	0	−5/2
σ	1	1	1	0	3

¶

¶C. Kownacki, E. Ma, N. Pollard, OP, M. Zakeri, 1706.06501

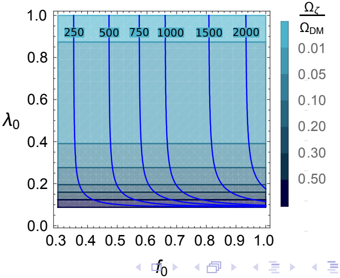
- $\langle\phi_R^0\rangle = 0$, $\langle\eta_2^0\rangle = 0$ and conserve S+T$_{3R}$
- All exotic fermions have half integer charges under S+T$_{3R}$
- Particle content and charge assignments result in additional unbroken Z_2 symmetry, under which exotic ferminons are odd and others are even
- S+T$_{3R}$ is broken to S' by $\langle\sigma\rangle \neq 0$ and gives masses to exotic fermions
- S' charges for exotic fermions are different from S+T$_{3R}$ charges
- Presence of ζ induces $\zeta^3\sigma^*$ and $\chi_{1R}^0\chi_{1R}^0\zeta$ breakes S' further to Z_3

Particle content of proposed model under $(T_{3R} + S) \times Z_2$

particles	gauge $T_{3R}+S$	global S'	Z_3	Z_2
u, d, ν, l	0	0	1	+
$(\phi_L^+, \phi_L^0), (\eta_2^+, \eta_2^0), \phi_R^0$	0	0	1	+
n, ϕ_R^+, ζ	1	1	ω	+
$h, (\eta_1^0, \eta_1^-)$	-1	-1	ω^2	+
ψ_{2R}^+, χ_R^+	$3/2, -3/2$	0	1	$-$
ψ_{1R}^-, χ_R^-	$3/2, -3/2$	0	1	$-$
ψ_{1R}^0, ψ_{2R}^0	$5/2, 1/2$	$1, -1$	ω, ω^2	$-$
χ_{1R}^0, χ_{2R}^0	$-1/2, -5/2$	$1, -1$	ω, ω^2	$-$
σ	3	0	1	+

Constraints on the U(1)$_D$ ALRM

- M(Z')>4TeV
- DM candidates: Fermionic DM(χ_0) ($\chi_0\bar{\chi}_0 \implies \zeta\zeta^*$), Scalar DM ($\zeta$) ($\zeta\zeta^* \implies HH$)
- $< \sigma \times v_{rel} >_\chi = \frac{f_0^4}{4\pi m_{\chi_0}} \frac{\left(m_{\chi_0}^2 - m_\zeta^2\right)^{3/2}}{\left(2m_{\chi_0}^2 - m_\zeta^2\right)^2}$ $(f_0\zeta\chi_{0R}\chi_{0R})$
- $< \sigma \times v_{rel} >_\zeta = \frac{\lambda_0^2}{16\pi} \frac{\left(m_\zeta^2 - m_H^2\right)^{1/2}}{m_\zeta^3}$ $(\lambda_0\zeta\zeta^* HH)$
- $\nu_R > 35\,TeV \implies M_{Z'} > 18\,TeV,\, M_{W_R} > 16\,TeV$



Conclusions

- (Alternative, Dark)Left-Right Models have no tree level FCNC
- Generate naturally small neutrino masses (Seesaw I/II/III/Double)
- Rich phenomenology accessable at LHC
- Different variations are possible
- Natural Dark Matter candidates due to residual symmetry
- 2 layers of DM stabilized by Z_3 and Z_2 in case of Gauged DLRM

Particle Content of the Model

Particle	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	L	copies	Z_2
$\mathrm{Q_i} = (u, d)_i$	3	2	1/6	0	3	+
u^c	3*	1	-2/3	0	3	+
d^c	3*	1	1/3	0	3	+
$L_i = (\nu, e)_i$	1	2	-1/2	1	3	+
e^c	1	1	1	-1	3	+
$(E^0, E^-)_{L,R}$	1	2	-1/2	1	1	-
$N_{L,R}$	1	1	0	1	1	-
$\Phi = (\phi^+, \phi^0)$	1	2	1/2	0	1	+
s_i^0	1	1	0	0	3	-

New $\mathcal{L}$agrangian

$$\mathscr{L}_{new} \supset \overline{N_L}\left(E_R^0\phi^0 - E_R^-\phi^+\right)$$

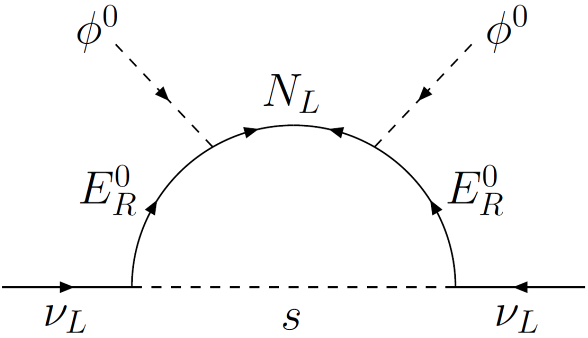
$$\left(\overline{E_R^0}E_L^0 + E_R^+E_L^-\right)$$

$$\left(\overline{\nu_{Li}}E_R^0 + \overline{e_{Li}^-}E_R^-\right)s_j$$

$$N_L N_L$$

$$m_i^2 s_i^2$$

Scotogenic Neutrino Mass



Mixing of Leptons, $\mathbb{Z}_2$ odd

$$\mathscr{M}_{E,N} = \begin{pmatrix} 0 & m_E & m_D \\ m_E & 0 & 0 \\ m_D & 0 & m_N \end{pmatrix}$$

$$m_1 = \frac{m_E^2 m_N}{m_E^2 + m_D^2}$$

$$m_{2,3} = \pm\sqrt{m_E^2 + m_D^2} + \frac{m_D^2 m_N}{2\left(m_E^2 + m_D^2\right)}$$

$$m_N \ll m_E, m_D$$

Neutrino Mass

$$m_\nu = f^2 \frac{m_D^2 m_N}{m_E^2 + m_D^2} F(x)$$

$$F(x) = \frac{1}{1-x}\left(1 + \frac{x \ln x}{1-x}\right)$$

$$x = \frac{m_s^2}{(m_E^2 + m_D^2)}$$

$f_{e,\mu,\tau}$	0.1
x	≈ 0
m_N	10 MeV
m_D	10 GeV
m_E	1 TeV
m_ν	0.1 eV

Z_3 symmetry and Neutrino Mixing

$$(\nu_i, l_i) \sim \underline{1}, \underline{1}', \underline{1}'', \quad s_1 \sim \underline{1}, \quad (s_2 \pm i s_3)/\sqrt{2} \sim \underline{1}', \underline{1}'', \quad l_{iR} \sim \underline{1}, \underline{1}', \underline{1}''$$

$$m_s^2 s^2 + m_s'^2 \left(s_2^2 + s_3^2\right)$$

$$\mathcal{M}_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & i/\sqrt{2} \\ 0 & 1/\sqrt{2} & -i/\sqrt{2} \end{pmatrix} O^T \begin{pmatrix} I(m_{s_1}^2) & 0 & 0 \\ 0 & I(m_{s_2}^2) & 0 \\ 0 & 0 & I(m_{s_3}^2) \end{pmatrix} O \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & i/\sqrt{2} & -i/\sqrt{2} \end{pmatrix}$$

$$\mathcal{M}_\nu|_{f_\mu = f_\tau} = \begin{pmatrix} A & C & C^* \\ C & D^* & B \\ C^* & B & D \end{pmatrix}$$

Cobimaximal Mixing: $\theta_{23} = \pi/4, \quad exp(-i\delta) = \pm i, \quad \theta_{13} \neq 0$

$f_\mu \neq f_\tau$ case

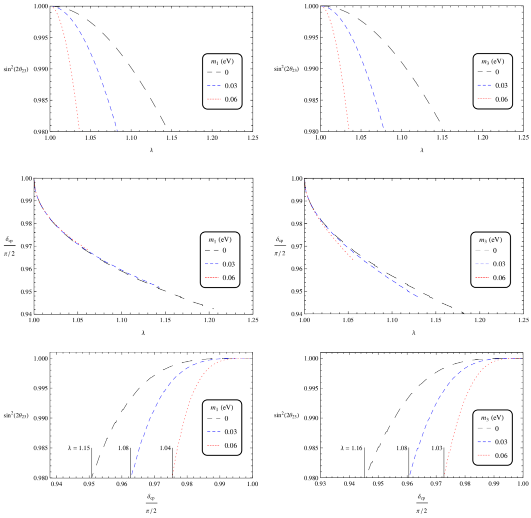
$$
\begin{aligned}
M_\nu &= E_\alpha U E_\beta M_d E_\beta U^T E_\alpha \\
M_\nu M_\nu^\dagger &= E_\alpha U M_d^2 U^\dagger E_\alpha^\dagger \\
M_\nu^\lambda M_\nu^{\lambda\dagger} &= E_\alpha U \underbrace{\left[1+\Delta\right] M_{\lambda d}^2 \left[1+\Delta^\dagger\right]}_{O M_{new}^2 O^T} U^\dagger E_\alpha^\dagger
\end{aligned}
$$

$$
\Delta = U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda - 1 \end{pmatrix} U, \quad M_{\lambda d}^2 = \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & \lambda^2 m_3^2 \end{pmatrix}
$$

$$
\lambda = \frac{f_\mu}{f_\tau}
$$

$f_\mu \neq f_\tau$ case

$\Longrightarrow$ Normal ordering (left) and Inverted ordering (right).



Muon Anomalous Magnetic Moment

$$\Delta a_\mu = \frac{(g-2)_\mu}{2} = \frac{f_\mu^2 m_\mu^2}{16\pi^2 m_E^2} \sum_i |U_{\mu i}|^2 \, G(x_i)^\S$$

$$G(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{6(1-x)^4}, \quad x_i = m_{s_i}^2 / m_E^2$$

$$U = O \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & i/\sqrt{2} & -i/\sqrt{2} \end{pmatrix}$$

$$\left.\begin{matrix} x_i \ll 1 \\ m_E \sim 1\,TeV \end{matrix}\right\} \qquad \Delta a = \frac{f_\mu^2 m_\mu^2}{96\pi^2 m_E^2} \approx 10^{-11} f_\mu^2$$

§S. Kanemitsu and K. Tobe, Phys. Rev. D86, 095025 (2012).

$\mu \to e\gamma$

$$A_{\mu e} = \frac{e f_\mu f_e m_\mu}{32\pi^2 m_E^2} \sum_i U_{ei}^* U_{\mu i} G(x_i)$$

$$Br(\mu \to e\gamma) = \frac{12\pi^2 |A_{\mu e}|^2}{m_\mu^2 G_F^2} < 5.7 \times 10^{-13} \ddagger$$

$$f_\mu f_e < 0.03$$

‡MEG Collaboration, J. Adams et al., Phys. Rev. Lett. 110, 201801 (2013).

Dark Matter

Dark Matter Candidates: N_L, S

$$-\mathcal{L}_{int} = \frac{\lambda_{hS}}{2} \nu h S^2 + \frac{\lambda_{hS}}{4} h^2 S^2$$

$$m_S \lesssim m_h/2 \text{ or } m_S > 150\ GeV$$

Conclusions

- Inverse Seesaw Neutrino Mass
- Z_3 Flavor Symmetry $\Longrightarrow$ Cobimaximal Mixing
- Deviation from Cobimaximal Mixing
- g-2 and $\mu \to e\gamma$