A Theory of $R(D^*)$ and $R(D)$ With Right-Handed Currents

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"A Theory of $\boldsymbol{R(D^*)}$ and $\boldsymbol{R(D)}$ Anomaly With Right-Handed Currents"

K.S. Babu, Bhaskar Dutta, Rabindra Mohapatra, arXiv: 1811.94496 [hep-ph].

$R(D^*, D)$ Anomaly

- Lepton universality in B meson decay has been tested by BaBar, Belle and LHCb recently

  BaBar (2012, 2013), Belle (2015, 2016, 2016), LHCb (2015)

- There appears to be a combined 3.8 sigma discrepancy with Standard Model predictions in $R(D^*)$ and $R(D)$

$$R(D^*) = \frac{\Gamma(B \to D^* \tau\nu)}{\Gamma(B \to D^* \ell\nu)}, \quad R(D) = \frac{\Gamma(B \to D\tau\nu)}{\Gamma(B \to D\ell\nu)}, \quad \ell = e, \mu$$

$$R(D^*)^{\rm exp} = 0.306 \pm 0.013 \pm 0.007 \quad R(D^*)_{\rm SM} = 0.258 \pm 0.005$$
$$R(D)^{\rm exp} = 0.407 \pm 0.039 \pm 0.024 \quad R(D)_{\rm SM} = 0.300 \pm 0.008$$

$R(D^*)$: Bernlochner, Ligeti, Papucci, Robinson (2017); Jaiswal, Nandi, Patra (2017); Bigi, Gambino, Schacht (2017)
$R(D)$: FLAG Working Group, Aoki et. al. (2017)

$R(D^*, D)$ Anomaly (cont.)

- Recently LHCb has released first measurement of the ratio

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau \nu)}{\mathcal{B}(B_c^+ \to J/\psi \mu \nu)} = 0.71 \pm 0.17 \pm 0.18$$

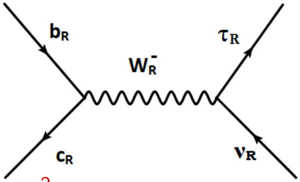
  which differs from standard model prediction by ~ 2 sigma:

$$R(J/\psi)_{\rm SM} = (0.25 - 0.28)$$

- This strengthens the case for $R(D^*, D)$ anomaly
- There may very well be new physics in the $b \to c\tau\nu$ decay
- This new physics may arise as right-handed currents
- A pre-existing model that solves the strong CP problem without the axion can provide the needed new physics
- Model based on left-right symmetry and a universal seesaw mechanism

Right-Handed Currents and $R(D^*, D)$

- If there is a light (< 100 MeV) sterile neutrino, or if ν_τ is a Dirac fermion, right-handed currents can mediate new B decays induced by $W_R^\pm$ gauge bosons:



$$\mathcal{H}_{eff} \simeq \frac{g_R^2}{2M_{W_R}^2} \bar{b}_R \gamma_\mu c_R \bar{\nu}_{\tau_R} \gamma^\mu \tau_R + h.c.$$

- With $g_R = g_L$ and no mixing suppression, $R(D^*, D)$ anomaly requires $M_{W_R} \simeq 700$ GeV.
- What type of models can give us such a W_R, consistent with low energy flavor violation and LHC/LEP limits?

Right-Handed Currents and $R(D^*, D)$

- Assume that the only coupling of $W_R^{\pm}$ relevant for B decay is

$$\mathcal{H}_{eff} \simeq \frac{g_R^2}{2M_{W_R}^2}\bar{b}_R\gamma_\mu c_R \bar{\nu}_{\tau_R}\gamma^\mu \tau_R + h.c.$$

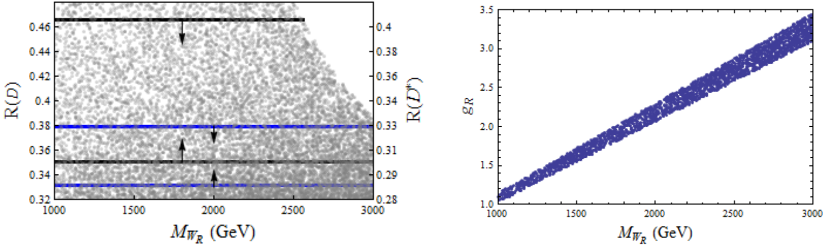
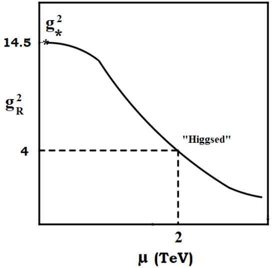


Figure: 1 σ and range allowed regions in g_R versus M_{W_R}

- $g_R = 2$, $M_{W_R} = 2$ TeV can explain $R(D^*, D)$

Phase diagram for $SU(2)_R$

- $SU(2)_R$ gauge coupling $g_R \sim 2$ may appear to be non-perturbative
- $SU(2)$ with $N_f = 6$ is asymptotically free, somewhat similar to QCD
- Phase diagram for $SU(2)$ with $N_f = 6$ has emerged from lattice
- Without Higgs, theory goes to an infrared fixed point $g_*^2 \simeq 14.5$
- Higgs field breaks $SU(2)_R$ before this fixed point is reached



$SU(2)_R$ Phase Diagram

Lattice: Leino, Rummukainen, Suorsa, Tuominen, Thtinen (2018)

Other right-handed current models for $R(D^*$

- This talk will focus of right-handed currents of left-right symmetry
- Other interesting models exist that expalin $R(D^*, D)$ via right-handed currents
- He, Valencia (2013, 2018) suggest a type of left-right symmetry, but only for third family
- Greljo, Robinson, Shakya, Zupan (2018) suggest $SU(2)_R$ under which new fermions transform. Usual third family fermions mix with these new fermions
- Asadi, Buckley, Shih suggest similar idea with $SU(2)_R$ for new fermions with normal fermion mixing with them

Left-Right Symmetric Models and $R(D^*, D)$

- Left-right symmetric models are well motivated as they explain Parity violation as a spontaneous phenomenon
  Pati, Salam (1974); Mohapatra, Pati (1975); Senjanovic, Mohapatra (1975)
- Gauge symmetry is $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- ν_R is required to exist in these models, which leads to small neutrino masses via seesaw
- A universal seesaw mechanism for quarks, leptons and neutrinos can be realized in this context
  Berezhiani (1983), Chang, Mohapatra (1987), Davidson, Wali (1987), Rajpoot (1987), Babu, Mohapatra (1989), (1990)
- Such universal seesaw models can solve the strong CP problem without an axion Babu, Mohapatra (1989), (1990)
- A low mass $W_R^\pm$ can explain $R(D^*, D)$. The $W_R^\pm$ and an accompanying low mass Z_R satisfy LHC and LEP constraints
  Babu, Dutta, Mohapatra (2018)

Left-Right Symmetric Models

- Gauge symmetry: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Fermion assignment:

$$Q_{L,i}\left(3,2,1,+\frac{1}{3}\right) = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i, \quad Q_{R,i}\left(3,1,2,+\frac{1}{3}\right) = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i,$$

$$\psi_{L,i}(1,2,1,-1) = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_i, \quad \psi_{R,i}(1,1,2,-1) = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}_i$$

- Very simple Higgs sector:

$$\chi_L(1,2,1,+1) = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}, \quad \chi_R(1,1,2,+1) = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}$$

- Only 2 physical Higgs bosons: $\sigma_{L,R}$
- With this simple Higgs sector, fermion masses cannot be generated

Universal seesaw mechanism

- Vector-like iso-singlet fermions introduced for mass generation:

$$U_a(3,1,1,+\frac{4}{3}), \quad D_a(3,1,-\frac{2}{3}), \quad E_a(1,1,1,-2), \quad N_a(1,1,1,0)$$

- Yukawa couplings:

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} &= Y_U \overline{Q}_L \tilde{\chi}_L U_R + Y'_U \overline{Q}_R \tilde{\chi}_R U_L + M_U \overline{U}_L U_R \\ &+ Y_D \overline{Q}_L \chi_L D_R + Y'_D \overline{Q}_R \chi_R D_L + M_D \overline{D}_L D_R \\ &+ Y_E \overline{\psi}_L \chi_L E_R + Y'_E \overline{\psi}_R \chi_R E_L + M_E \overline{E}_L E_R + h.c. \end{aligned}$$

- Mass matrices:

$$\mathcal{M}_{U,D,E} = \begin{pmatrix} 0 & Y_{U,D,E}\kappa_L \\ Y'^{\dagger}_{U,D,E}\kappa_R & M_{U,D,E} \end{pmatrix} \qquad \{\langle \chi_L^0 \rangle = \kappa_L, \quad \langle \chi_R^0 \rangle = \kappa_R\}$$

- Parity symmetry:

$$Q_L \leftrightarrow Q_R, \quad \psi_L \leftrightarrow \psi_R, \quad U_L \leftrightarrow U_R, \quad D_L \leftrightarrow D_R, \quad E_L \leftrightarrow E_R, \quad \chi_L \leftrightarrow \chi_R$$

$$\Rightarrow Y_U = Y'_U, \quad Y_D = Y'_D, \quad Y_E = Y'_E, \quad M_U = M_U^{\dagger}, \quad M_D = M_D^{\dagger}, \quad M_E = M_E^{\dagger}$$

Parity symmetric mass matrices

- If parity is imposed,

$$\mathcal{M}_{U,D,E} = \begin{pmatrix} 0 & Y_{U,D,E}\kappa_L \\ Y^\dagger_{U,D,E}\kappa_R & M_{U,D,E} \end{pmatrix}$$

- Light down-type quark mass matrix:

$$\mathcal{M}^d_{\text{light}} = -Y_D\,(M_D)^{-1}\,Y_D^\dagger\,\kappa_L\,\kappa_R$$

- This is universal seesaw mechanism
- $M_{U,D,E}$ need not be hermitian, since P may be broken softly

$$\text{Eg}: Y_D = y_d \times \text{diag}(1,1,1), \quad M_D = V_R.\,\text{diag}(M_1^d, M_2^d, M_3^d).\,V_L^\dagger$$

$$\Rightarrow M^d_{\text{light}} = y_d^2\,V_L \begin{pmatrix} (M_1^d)^{-1} & & \\ & (M_2^d)^{-1} & \\ & & (M_3^d)^{-1} \end{pmatrix} V_R^\dagger\,\kappa_L\kappa_R$$

$$m_i^d \simeq \frac{y_d^2\kappa_L\kappa_R}{M_i^d}$$

Parity symmetric mass matrices

- V_L and V_R are unrelated since $M_D \neq M_D^\dagger$
- $V_L = V_{\rm CKM}$ can be chosen, while

$$(i) \quad V_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \qquad (ii) \quad V_R = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

- These forms of V_R maximize right-handed contributions to $R(D^*, D)$
- However, if this was the whole story, $W_L - W_R$ box diagrams would lead to large $K^0 - \overline{K^0}$, $B^0_{d,s} - \overline{B}_{d,s}$ and $D^0 - \overline{D^0}$ mixing
- These left-right box diagrams are enhanced by a factor of 10^3 compared to SM box diagram, and would require $M_{W_R}/g_R > 2.5$ TeV if $V_L = V_R$
- In the up-quark sector top quark mixes strongly with top-partner T quark, which helps solve the FCNC issue

Partial seesaw in the up-quark sector

- Take the up-quark mass matrix to be block-diagonal
- For up, charm and top quarks, the mass matrices are:

$$\mathcal{M}_{U_i} = \begin{pmatrix} 0 & Y_u^i \kappa_L \\ Y_u^i \kappa_R & M_U^i \end{pmatrix} \qquad m_u^i \simeq \frac{(Y_u^i)^2 \kappa_L \kappa_R}{M_U^i} \qquad (i = u, c)$$

- t_R and T_R can mix strongly:

$$t_R^0 = c_t t_R + s_t T_R^0, \quad T_R^0 = -s_t t_R^0 + c_t T_R^0, \qquad \tan\theta_t = \frac{Y_u^3 \kappa_R}{M_U^3}$$

- The limit $M_U^3 \to 0$ is possible, whence $\cos\theta_t \to 0$
- This limit evades all FCNC arising from $W_L - W_R$ box diagrams
- An interesting consequence is:

$$M_T/m_t = \kappa_R/\kappa_L \simeq (10 - 15) \quad \Rightarrow M_T = (1.5 - 2.5)\ \mathrm{TeV}$$

Suppression of FCNC

- Including $t_R - T_R$ mixing, the $W_R^{\pm}$ couplings to quarks is:

$$(i) \quad \mathcal{L}_{W_R} = \frac{g_R}{\sqrt{2}} \left(\overline{u_R^0},\ \overline{c_R^0},\ \overline{t_R^0},\ \overline{T_R^0}\right) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & c_t & 0 \\ 0 & -s_t & 0 \end{pmatrix} \gamma^\mu \begin{pmatrix} d_R^0 \\ s_R^0 \\ b_R^0 \end{pmatrix} W_R^{+\mu} + h.c.$$

$$(ii) \quad \mathcal{L}_{W_R} = \frac{g_R}{\sqrt{2}} \left(\overline{u_R^0},\ \overline{c_R^0},\ \overline{t_R^0},\ \overline{T_R^0}\right) \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ c_t & 0 & 0 \\ -s_t & 0 & 0 \end{pmatrix} \gamma^\mu \begin{pmatrix} d_R^0 \\ s_R^0 \\ b_R^0 \end{pmatrix} W_R^{+\mu} + h.c.$$

- All $W_L - W_R$ box diagrams highly suppressed in the limit $M_U^3 \to 0$ (or $c_t \to 0$) – flipping of t_R with T_R

Suppression of FCNC (cont.)

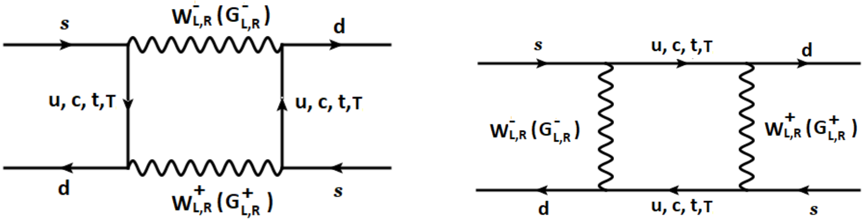


Figure: Leading $W_L - W_R$ exchange diagram contribution to $K^0 - \overline{K^0}$ mass splitting in the parity symmetric LR model.

$$H^{LR}_{\mathrm{efff}} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{4\pi s_W^2} \lambda_i \lambda_j 2\eta (x_i x_j)^{1/2} \left[(4 + x_i x_j \eta) I_1(x_i, x_j, \eta) - (1+\eta) I_2(x_i, x_j, \eta)\right] (\bar{s}_R d_L)(\bar{s}_L d_R)$$

$\eta = M^2_{W_L}/M^2_{W_R}$, $x_i = m_i^2/M^2_{W_L}$ for $i = u, c, t, T$, $\lambda_i \equiv (V_L)^*_{is}(V_R)_{id}$

As $c_t \to 0$, new contributions to $K^0 - \overline{K^0}$ mixing vanishes for case (i)

Suppression of FCNC (cont.)

- All FCNC processes arising from box diagrams are suppressed
- When $T_R - T_L$ flip occurs, the $W_L - W_R$ box diagram gives no contribution, as T_L does not couple to W_L
- $B_d - \overline{B_d}$ mixing amplitude goes as $V_{cb} V_{ub} m_u m_c / M_W^2$, which is negligible
- $B_s - \overline{B_s}$ mixing vanishes due to $T_R - T_R$ chiral flip
- $D^0 - \overline{D^0}$ mixing goes as $V_{ub} V_{cd} m_d m_b$, which yields a value $\Delta M_D \simeq 5 \times 10^{-18}$ GeV
- Such suppression is not available in standard left-right symmetric models

Other flavor violating processes

- $\tau_L - E_{3L}$ mixing causes universality violation:

$$\mathcal{L}_\tau^{W_L} = \frac{g_L}{\sqrt{2}} \cos\theta_\tau \overline{\tau}_L \gamma^\mu \nu_{\tau L} W_L^- + h.c.$$

$$A_\pi = \frac{G_{\tau\pi}^2}{G_F^2} = 1 - s_\tau^2 = 1.0020 \pm 0.0073$$

- Using 1 sigma error, this would lead to the bound $s_\tau \leq 0.073$, easily satisfied since $s_\tau = m_\tau/(Y_\tau \kappa_R)$ can be as low as 0.001.
- Fermion couplings to Z boson are modified due to $f_L - F_L$ mixing denoted as s_f:

$$\mathcal{L}^Z = \frac{g}{2c_W}\left[\overline{f}_L\left\{T_{3L}^f(1-s_f^2) - Q_f s_W^2\right\}\gamma^\mu f_L + \overline{f}_R(-Q_f s_W^2)\gamma^\mu f_R\right] Z^\mu$$

- Polarization asymmetry parameters A_b, A_c, A_τ are modified

Other flavor violation

- Experimental constraints on mixing:

$$\frac{\delta A_b}{A_b^{\rm SM}} = -0.158\, s_b^2, \quad \frac{\delta A_c}{A_c^{\rm SM}} = -1.20\, s_c^2, \quad \frac{\delta A_\tau}{A_\tau^{\rm SM}} = -12.38\, s_\tau^2$$

$$s_b \leq 0.463, \quad s_c \leq 0.176, \quad s_\tau \leq 0.048$$

- $Z \to f\overline{f}$ is modified:

$$\Gamma(A \to \tau\tau)/\Gamma(Z \to ee) = 1 - s_\tau^2 = 1.0019 \pm 0.0032 \quad \Rightarrow$$

$$s_\tau \leq 0.053$$

- $R_b = \Gamma(Z \to bb)/\Gamma(Z \to \mathrm{hadron})$ and R_c are modified:

$$R_b = R_b^{\rm SM}(1 + 0.418 s_b^2), \quad R_c = R_c^{\rm SM}(1 + 1.077 s_c^2)$$

$$s_b \leq 0.085, \quad s_c \leq 0.127$$

- All constraints are easily satisfied, since $s_c, s_b, s_\tau \sim 10^{-3}$ allowed in the model

Charged Lepton mass matrix

- Various blocks of $\mathcal{M}_E$ take the form:

$$Y_E = \begin{pmatrix} * & * & Y_1^e \\ * & * & Y_2^e \\ * & * & Y_3^e \end{pmatrix}, \quad M_E = \begin{pmatrix} M_{11} & * & * \\ * & * & M_{23} \\ * & M_{32} & * \end{pmatrix}$$

- The * entries are taken to be small. In the limit of * entries going to zero, e, μ, τ masses go to zero
- The leptonic Yukawa couplings Y_i^e may be large, not constrained by $m_{e,\mu,\tau}$. Large $e_R - E_R$ mixing possible
- Exact diagonalizing matrix in the limit of * entries being zero:

$$\begin{pmatrix} e_{1R}^0 \\ e_{2R}^0 \\ e_{3R}^0 \\ E_{1R}^0 \\ E_{2R}^0 \\ E_{3R}^0 \end{pmatrix} = \begin{bmatrix} c_{\alpha_R} c_\theta & c_{\alpha_R} s_\theta c_\phi & c_{\alpha_R} s_\theta s_\phi & 0 & -s_{\alpha_R} & 0 \\ 0 & s_\phi & -c_\phi & 0 & 0 & 0 \\ s_\theta & -c_\theta c_\phi & -c_\theta s_\phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ s_{\alpha_R} c_\theta & s_{\alpha_R} s_\theta c_\phi & s_{\alpha_R} s_\theta s_\phi & 0 & c_{\alpha_R} & 0 \end{bmatrix} \begin{pmatrix} e_{1R} \\ e_{2R} \\ e_{3R} \\ E_{1R} \\ E_{2R} \\ E_{3R} \end{pmatrix}$$

Charged Lepton mass matrix

- Definitions:

$$\begin{aligned} Y_1^e &= Y^e \cos\theta, \quad Y_2^e = Y^e \sin\theta\cos\phi, \quad Y_3^e = Y^e \sin\theta\sin\phi, \\ \tan\alpha_R &= \frac{\kappa_R Y^e}{M_{32}}, \quad \tan\alpha_L = \frac{\kappa_L Y^e}{M_{23}} \end{aligned}$$

- The mass terms read as:

$$\mathcal{L}_{\rm mass}^{\rm lep} = M_{11}\overline{E^0}_{1L}E^0_{1R} + \frac{M_{23}}{c_{\alpha_L}}\overline{E^0}_{2L}E^0_{2R} + \frac{M_{32}}{c_{\alpha_R}}\overline{E^0}_{3L}E^0_{3R} + h.c.$$

- If $c_{\alpha_R} \to 0$ (i.e., $M_{32} \to 0$), e_R and E_{2R} are flipped
- Such a flip helps with constraints on the model from LEP

Neutrino mass matrix

- Yukawa Lagrangian for the neutral leptons:

$$\begin{aligned}\mathcal{L}^{\nu}_{\rm Yuk} &= Y_\nu \overline{\psi}_L \tilde{\chi}_L N_R + Y'_\nu \overline{\psi}_R \tilde{\chi}_R N_L + \tilde{Y}_\nu \overline{\psi}_L \tilde{\chi}_L N_R^c + \tilde{Y}'_\nu \overline{\psi}_R \tilde{\chi}_R N_L^c \\ &+ M_N \overline{N}_L N_R + \mu_L N_L^T C N_L + \mu_R N_R^T C N_R + h.c.\end{aligned}$$

- Resulting 12×12 neutrino mass matrix:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & 0 & Y_\nu \kappa_L & \tilde{Y}_\nu \kappa_L \\ 0 & 0 & Y'_\nu \kappa_R & \tilde{Y}'_\nu \kappa_R \\ Y_\nu^T \kappa_L & Y'^T_\nu \kappa_R & \mu_L & M_N \\ \tilde{Y}_\nu^T \kappa_L & \tilde{Y}'^T_\nu \kappa_R & M_N^T & \mu_R \end{pmatrix}$$

- Two neutrinos per family have mass of order M, μ
- Mass of ν_L and ν_R given by

$$m_{\nu_R} \sim Y_\nu^2 \kappa_R^2 / M_N, \quad m_{\nu_L} \sim Y_\nu^2 \kappa_L^2 / M_N$$

- Naturally light $\nu_{\tau R}$. with $m_{\nu_R}/m_{\nu_L} \sim 60$, or $m_{\nu_R} \sim 3$ eV. May explain MiniBoone/LSND. (ν_{μ_R} assumed heavier than 100 MeV)

Gauge boson sector

- At tree-level there is no mixing between $W_L^\pm$ and $W_R^\pm$. Their masses are:

$$M^2_{W_L^\pm} = \frac{g_L^2 \kappa_L^2}{2}, \quad M^2_{W_R^\pm} = \frac{g_R^2 \kappa_R^2}{2}$$

- In the neutral gauge boson sector, the states $(W_{3L},\, W_{3R},\, B)$ mix:

$$A^\mu = \frac{g_L g_R B^\mu + g_B g_R W_{3L}^\mu + g_L g_B W_{3R}^\mu}{\sqrt{g_B^2(g_L^2 + g_R^2) + g_L^2 g_R^2}}$$

$$Z_R^\mu = \frac{g_B B^\mu - g_R W_{3R}^\mu}{\sqrt{g_R^2 + g_B^2}}$$

$$Z_L^\mu = \frac{g_B g_R B^\mu - g_L g_R \left(1 + \frac{g_B^2}{g_R^2}\right) W_{3L}^\mu + g_B^2 W_{3R}^\mu}{\sqrt{g_B^2 + g_R^2}\sqrt{g_B^2 + g_L^2 + \frac{g_B^2 g_L^2}{g_R^2}}}$$

Gauge boson masses

- $Z_L - Z_R$ mixing matrix:

$$\mathcal{M}^2_{Z_L-Z_R} = \frac{1}{2}\begin{pmatrix} (g_Y^2+g_L^2)\,\kappa_L^2 & g_Y^2\sqrt{\frac{g_Y^2+g_L^2}{g_R^2-g_Y^2}}\,\kappa_L^2 \\ g_Y^2\sqrt{\frac{g_Y^2+g_L^2}{g_R^2-g_Y^2}}\,\kappa_L^2 & \frac{g_R^4}{g_R^2-g_Y^2}\,\kappa_R^2+\frac{g_Y^4}{g_R^2-g_Y^2}\,\kappa_L^2 \end{pmatrix}$$

- Gauge couplings related by the embedding

$$\frac{Y}{2} = T_{3R} + \frac{B-L}{2} \qquad \Rightarrow \qquad g_Y^{-2} = g_R^{-2} + g_B^{-2}$$

- The physical states and their masses are given by:

$$\begin{aligned} Z_1 &= \cos\xi\, Z_L - \sin\xi\, Z_R, \qquad Z_2 = \sin\xi\, Z_L + \cos\xi\, Z_R, \\ M^2_{Z_1} &\simeq \frac{1}{2}(g_Y^2+g_L^2)\,\kappa_L^2, \qquad M^2_{Z_2} \simeq \frac{g_R^4}{g_R^2-g_Y^2}\,\kappa_R^2 + \frac{g_Y^4}{g_R^2-g_Y^2}\,\kappa_L^2 \end{aligned}$$

$$\xi \simeq \frac{g_Y^2}{g_R^4}\sqrt{(g_L^2+g_Y^2)(g_R^2-g_Y^2)}\,\frac{\kappa_L^2}{\kappa_R^2}$$

Collider constraints: LHC and LEP

- Z_R is nearly degenerate in mass with W_R. Its interactions with fermions:

$$\mathcal{L}_{Z_R} = \frac{g_R^2}{\sqrt{g_R^2 - g_Y^2}}\, \overline{f}_{L,R}\, \gamma_\mu \left[T_{3R} - \frac{Y_{L,R}}{2}\, \frac{g_Y^2}{g_R^2}\right] f_{L,R}\, Z_R^\mu$$

- Decay widths for Z_R:

$$\Gamma(Z_R \to \overline{f} f) = \frac{g_R^4}{g_R^2 - g_Y^2}\, \frac{M_{Z_R}}{48\pi}\, \beta \left[\frac{3-\beta^2}{2}\, a_f^2 + \beta^2\, b_f^2\right]$$

$$\beta = \sqrt{1 - \frac{4 m_f^2}{M_{Z_R}^2}}, \quad a_f = T_{3R} - \frac{Y_L + Y_R}{2}\, \frac{g_Y^2}{g_R^2}, \quad b_f = T_{3R} - \frac{Y_R - Y_L}{2}\, \frac{g_Y^2}{g_R^2}$$

- Decay rates for $Z_R \to W^+ W^-$ and $Z_R \to Z + h$ are small

Collider constraints: LHC and LEP

- Branching ratios to various fermions defined as:

$$B_\ell = \frac{\Gamma(e^+e^-)+\Gamma(\mu^+\mu^-)}{\Gamma_{\rm total}}, \quad B_\tau = \frac{\Gamma(\tau^+\tau^-)}{\Gamma_{\rm total}}, \quad B_\nu = \frac{3\Gamma(\nu_L\bar\nu_L)+3\Gamma(\nu_R\bar\nu_R)}{\Gamma_{\rm total}}$$

$$B_{\rm jet} = \frac{\Gamma(u\bar u)+\Gamma(d\bar d)+\Gamma(s\bar s)+\Gamma(c\bar c)+\Gamma(b\bar b)}{\Gamma_{\rm total}}, \quad B_t = \frac{\Gamma(t\bar t)}{\Gamma_{\rm total}}$$

g_R	B_ℓ (%)	B_τ (%)	B_ν (%)	$B_{\rm jet}$ (%)	B_t (%)	$\frac{\Gamma_{\rm total}}{M_{Z_R}}$ (%)
1	3.6	3.2	16.9	64.82	11.5	6.85
1.5	3.89	3.82	14.58	65.26	12.42	16.31
2.0	4.08	4.05	13.87	65.27	12.71	29.65
2.5	4.17	4.16	13.56	65.26	12.83	46.80
3.0	4.22	4.22	13.41	65.25	12.90	67.76

- Z_R width rather large, which evades LHC limits. ATLAS and CMS have no searches for $\Gamma/M > 30\%$

LHC and LEP constraints

- Width of $W_R^\pm$ is also rather large:

$$\frac{\Gamma_{\rm total}}{M_{W_R}}\{7.3\%,\, 16.4\%,\, 29\%,\, 46\%,\, 66\%\} \;\; {\rm for}\; g_R = (1,\, 1.5,\, 2.0,\, 2.5,\, 3.0)$$

- Searches for $W_R^\pm$ have limited $\Gamma/M < 30\%$. For $g_R > 2.0$ there is no LHC limit on $W_R^\pm$
- LEP-2 provides important limits on contact interactions:

$$\mathcal{L}_{\rm eff} = -\frac{g_Y^4}{g_R^2 - g_Y^2}\frac{1}{M_{Z_R}^2}\frac{1}{\{1+(\Gamma_{\rm total}/M_{Z_R})^2\}^{1/2}}\left[\bar{e}_R\gamma_\mu e_R + \frac{1}{2}\bar{e}_L\gamma_\mu e_L\right]\left[\bar{\mu}_R\gamma^\mu\mu_R + \frac{1}{2}\bar{\mu}_L\gamma^\mu\mu_L\right] .$$

- Best limit comes from $e^+e^- \to \tau^+\tau^-$ which gives $\Lambda_{RR}^- > 8.7$ TeV. $\Rightarrow$

$$M_{Z_R} > \{611,\, 634,\, 638,\, 624,\, 598\}\ {\rm GeV} \;\; {\rm for} \;\; g_R = (1,\, 1.5,\, 2.0,\, 2.5,\, 3.0)$$

Allowed regions for $R(D^*, D)$

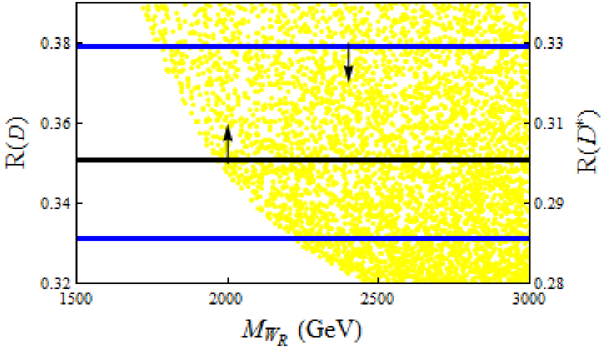


Figure: LHC allowed regions that explains $R(D^*, D)$ at 1 sigma.

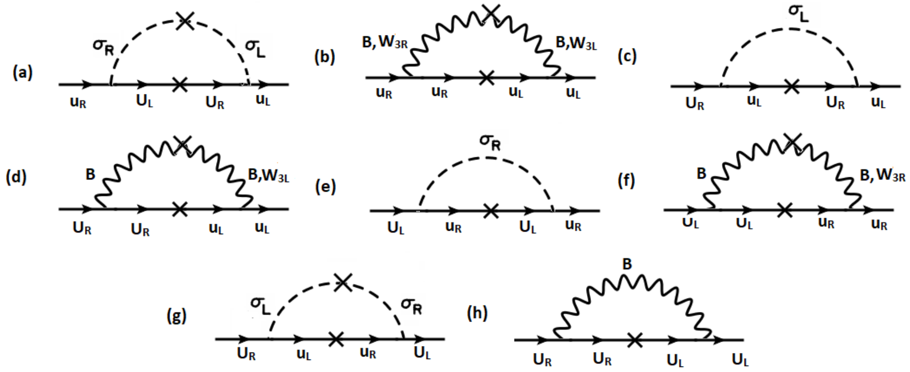
Solving the Strong CP problem

- The quark mass matrices are given by

$$\mathcal{M}_{U,D} = \begin{pmatrix} 0 & Y_{U,D}\,\kappa_L \\ Y^\dagger_{U,D}\,\kappa_R & M_{U,D} \end{pmatrix}$$

- Parity symmetry sets θ_{QCD} to zero
- The determinant of $\mathcal{M}_{U,D}$ is real. Hence $\overline{\theta} = 0$ at tree level
  Babu, Mohapatra (1990)
- All one-loop corrections to $\overline{\theta}$ vanishes
- $\overline{\theta}$ arises only at two-loop level, and is of order 10^{-10}
  Babu, Mohapatra (1990), Hall, Harigaya (2018)

One-loop corrections to $\overline{\theta}$



$\overline{\theta}$ contributions from these diagrams go as $\mathrm{Im Tr}(H)$ or $\mathrm{Im Tr}(H_1 H_2)$ where H, $H_{1,2}$ are hermitian matrices. These traces are automatically real. $\Rightarrow \overline{\theta}_{1-\mathrm{loop}} = 0$. Induced $\overline{\theta}$ at 2-loop $\sim 10^{-10}$.

A complete theory with Parity

- A complete theory with Parity should explain why $g_R \neq g_L$
- One way is to extend gauge symmetry to $SU(3)_c \times SU(2)_L \times SU(2)_R \times SU(2)_D \times U(1)_{B-L}$.
- A scalar field $\Phi_L(1,2,1,2,0)$ spontaneously breaks

  $SU(2)_L \times SU(2)_D$ down to its diagonal subgroup $SU(2)_{\rm weak}$

$$g_w^{-2} = g_L^{-2} + g_D^{-2}$$

  Even with $g_L = g_R$, one obtains $g_w \neq g_R$
- The parity partner of Φ_L, a scalar field $\Phi_R(1,1,2,2,0)$, which does not acquire a VEV, can be an interesting dark matter candidate. It has quantum numbers of an inert doublet!

A Parity asymmetric scenario

- We have developed an interesting scenario which does not have parity symmetry in the same setup
- Flavor violation constraints are readily satisfied by flipping of certain fermions under $SU(2)_R$
- This model explains $R(D^*, D)$ anomaly consistent with LHC and LEP data
- The fermion mass matrices are given by

$$\mathcal{M}_{U,D,E} = \begin{pmatrix} 0 & Y_{U,D,E}\kappa_L \\ Y'^{\dagger}_{U,D,E}\kappa_R & M_{U,D,E} \end{pmatrix}$$

- We choose a specific texture sfor $M_{U,D,E}$, $Y_{U,D,E}$ and $Y'_{U,D,E}$ without restricting $Y'_{U,D,E} = Y_{U,D,E}$

A Parity asymmetric scenario-II

- Specific flavor choice:

$$
\begin{aligned}
Y_U &= V_L^\dagger Y_U^{\text{diag}}, \quad Y'_U = V_R^\dagger Y_U'^{\,\text{diag}}, \quad M_U = \text{diag}(0, M_2, 0) \\
Y_D &= Y_D^{\text{diag}}, \quad Y'_D = Y_D'^{\,\text{diag}}, \quad M_D = \text{diag}(0, 0, M_3)
\end{aligned}
$$

$Y_U^{\text{diag}} = \text{diag}(Y_1^u, Y_2^u, Y_3^u)$, $Y_U'^{\,\text{diag}} = \text{diag}(Y_1'^u, Y_2'^u, Y_3'^u)$,
$Y_D^{\text{diag}} = \text{diag}(Y_1^d, Y_2^d, Y_3^d)$ and $Y_D'^{\,\text{diag}} = \text{diag}(Y_1'^d, Y_2'^d, Y_3'^d)$

- V_L is the left-handed CKM matrix, while V_R is to have the form:

$$
V_R = \begin{pmatrix} 1 & \epsilon_1 & \epsilon_2 \\ -\epsilon_1 & \epsilon_3 & 1 \\ -\epsilon_2 & 1 & \epsilon_4 \end{pmatrix}
$$

- This choice suppresses all FCNC to adequate level

A Parity asymmetric scenario-III

- Seesaw only works in the $b-B$ and $c-C$ sectors:

$$\mathcal{M}_{c-C} = \begin{pmatrix} 0 & Y_2^u \kappa_L \\ Y_2'^u \kappa_R & M_2 \end{pmatrix}, \quad \mathcal{M}_{b-B} = \begin{pmatrix} 0 & Y_3^d \kappa_L \\ Y_3'^d \kappa_R & M_3 \end{pmatrix}$$

- The light quark masses are then obtained as:

$$m_u = Y_1^u \kappa_L, \quad m_c \simeq \frac{Y_2^u Y_2'^u \kappa_L \kappa_R}{M_2}, \quad m_t = Y_3^u \kappa_L$$
$$m_d = Y_1^d \kappa_L, \quad m_s = Y_2^d \kappa_L, \quad m_b \simeq \frac{Y_3^d Y_3'^d \kappa_L \kappa_R}{M_3}$$

- The heavy quark masses are:

$$M_U = Y_1'^u \kappa_R, \quad M_C \simeq M_2, \quad M_T = Y_3'^u \kappa_R$$
$$M_D = Y_1'^d \kappa_R, \quad M_S \simeq Y_2'^d \kappa_R, \quad M_B \simeq M_3$$

- Note: M_U, M_T, M_D, M_S vector-like quarks acquire masses from $SU(2)_R$ breaking VEV κ_R

A Parity asymmetric scenario-IV

- The $W_R^{\pm}$ interactions with quarks is given by:

$$\mathcal{L}^q_{W_R^{\pm}} = \frac{g_R}{\sqrt{2}} \left(\overline{U}_R \; \overline{c}_R \; \overline{T}_R\right) \gamma_\mu V_R \begin{pmatrix} D_R \\ S_R \\ b_R \end{pmatrix} W_R^{+\mu} + h.c.$$

- With the form of V_R chosen, there are no $W_L - W_R$ box diagrams for meson-antimeson mixing

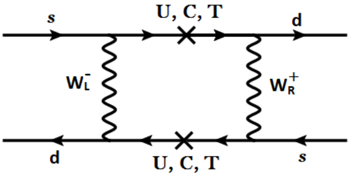


Figure: Dominant diagrams inducing $\Delta F = 2$ interactions such as $K^0 - \bar{K}^0$ mixing in the LR parity asymmetric quark seesaw model.

Parity asymmetric leptonic sector

- In the charged lepton sector, the mass matrices are chosen as:

  $Y_E = \mathrm{diag}(Y_1^e, Y_2^e, Y_3^e), \quad Y'_E = \mathrm{diag}(Y_1'^e, Y_2'^e, Y_3'^e), \quad M_E = \mathrm{diag}(0, 0, M_E)$

- Only $\tau - E_3$ mix via the mass matrix

$$\mathcal{M}_{\tau - E_3} = \begin{pmatrix} 0 & Y_3^e \kappa_L \\ Y_3'^e \kappa_R & M_E \end{pmatrix}$$

- Heavy and light lepton masses are:

$$\begin{aligned} m_e &= Y_1^e \kappa_L, \quad m_\mu = Y_2^e \kappa_L, \quad m_\tau \simeq \frac{Y_3^e Y_3'^e \kappa_L \kappa_R}{M_E} \\ M_{E_1} &= Y_1'^e \kappa_R, \quad M_{E_2} = Y_2'^e \kappa_R, \quad M_{E_3} \simeq M_E \end{aligned}$$

- This structure leads to the leptonic interactions of W_R given by

$$\mathcal{L}^{\ell}_{W_R^\pm} = \frac{g_R}{\sqrt{2}} \left(\overline{E}_{1R} \; \overline{E}_{2R} \; \overline{\tau}_R \right) \gamma_\mu \begin{pmatrix} \nu_{e_R} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix} W_R^{-\mu} + h.c.$$

Collider constraints: P asymmetric scheme

g_R	B_ℓ (%)	B_τ (%)	B_ν (%)	$B_{\rm jet}$ (%)	B_t (%)	$\frac{\Gamma_{\rm total}}{M_{Z_R}}$ (%)
1	1.89	6.6	35.4	54.98	1.07	3.3
1.5	0.349	8.55	32.6	58.25	0.20	7.3
2.0	0.11	9.2	31.5	59.11	0.061	13
2.5	0.043	9.4	30.97	59.5	0.024	20.5
3.0	0.021	9.65	30.67	59.6	0.011	29.6

Table: Values of the branching ratios of Z_R for decays into fermion pairs as a function of g_R in the Parity asymmetric scenario. B_x's are defined in Eq. (0.1). The last column lists the total width of Z_R as a fraction of its mass.

Here Γ/M does not exceed 30%

Z_R Production rate

g_R	M_{Z_R}(TeV)	σ(fb)
1.0	1.0	0.8
1.5	1.5	5.2×10^{-2}
2.0	2.0	7×10^{-3}
2.5	2.5	1.2×10^{-3}
3.0	3.0	2.5×10^{-4}

Table: Z_R production cross-section at the LHC for the Parity asymmetric scenario

These rates are consistent with LHC constraints

Combined allowed region for $R(D^*, D)$

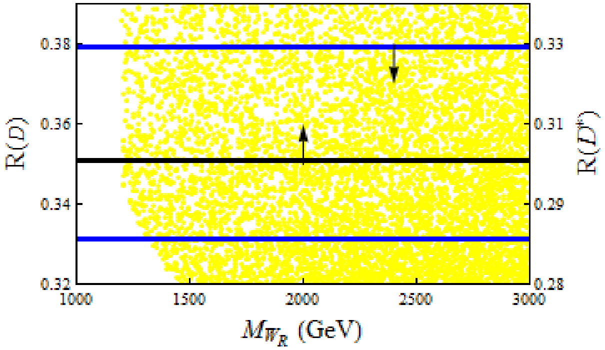


Figure: LHC allowed regions in the Parity asymmetric case.

Boundedness of Higgs potential

- Higgs potential of the model:

$$V = -(\mu_L^2 \chi_L^\dagger \chi_L + \mu_R^2 \chi_R^\dagger \chi_R) + \frac{\lambda_{1L}}{2}(\chi_L^\dagger \chi_L)^2 + \frac{\lambda_{1R}}{2}(\chi_R^\dagger \chi_R)^2 + \lambda_2 (\chi_L^\dagger \chi_L)(\chi_R^\dagger \chi_R)$$

- Physical Higgs spectrum obtained from:

$$\mathcal{M}^2_{\sigma_{L,R}} = \begin{bmatrix} 2\lambda_{1L}\kappa_L^2 & 2\lambda_2 \kappa_L \kappa_R \\ 2\lambda_2 \kappa_L \kappa_R & 2\lambda_{1R}\kappa_R^2 \end{bmatrix}$$

- Boundedness conditions:

$$\lambda_{1L} \geq 0, \quad \lambda_{1R} \geq 0, \quad \lambda_2 \geq -\sqrt{\lambda_{1L}\lambda_{1R}}$$

- RGE for λ_{1R} given by:

$$16\pi^2 \frac{d\lambda_{1R}}{dt} = 12\lambda_{1R}^2 + 4\lambda_2^2 - \lambda_{1R}(3g_B^2 + 9g_R^2) + \frac{3}{4}g_B^4 + \frac{3}{2}g_B^2 g_R^2 + \frac{9}{4}g_R^4 +$$
$$\lambda_{1R}\mathrm{Tr}\left(3Y_U'^\dagger Y_U' + 3Y_D'^\dagger Y_D' + Y_E'^\dagger Y_E'\right) - 4\mathrm{Tr}\left(3(Y_U'^\dagger Y_U')^2 + 3(Y_D'^\dagger Y_U')^2 + (Y_E'^\dagger Y_E')^2\right)$$

- For λ_{1R} not to turn negative for an order of magnitude above κ_R, $M_F < 2.5$ TeV is required

Astrophysics and Cosmology

- Light sterile neutrino involved in B meson decay can affect supernova dynamics
- If produced inside, it should either be trapped, or cross section should be small
- Only neutral current processes are effective: $e^+e^- \to \nu_R\overline{\nu}_R$

$$\sigma(e^+e^- \to \overline{\nu}_R\nu_R) = \left(\frac{5}{16}\right)\frac{1}{48\pi}\frac{g_Y^4 g_R^4}{(g_R^2 - g_Y^2)^2}\frac{s}{M_{Z_R}^2}$$

- Demanding energy loss in ν_R, $Q(\nu_R)$ is not larger than $20Q(\nu_L)$ yields:

$$(239 - 429)\ \mathrm{GeV} \le M_{Z_R} \le (748 - 3890)\ \mathrm{GeV} \qquad (g_R = 2)$$

- For BBN, if ν_R decouples from plasma before QCD transition, it will contribute $\Delta N_\nu \simeq 0.1$, which is acceptable

Conclusions

- Right-handed currents mediated by W_R gauge boson of left-right symmetry can explain $R(D^*, D)$ anomaly
- Universal seesaw scheme suppresses other flavor violation processes
- W_R must lie in the range $1.2\,(1.8)\ \mathrm{TeV} \leq M_{W_R} \leq 3\ \mathrm{TeV}$ for P-asymmetric (symmetric) scenario
- The Parity symmetric model solves the strong CP problem without an axion
- Vector-like top partner is predicted to be in the mass range $M_T = (1.5 - 2.5)$ TeV with Parity symmetry
- Several vector quarks acquire mass from $SU(2)_R$ breaking VEV in the P-asymmetric scenario. These quarks must have mass < 2.5 TeV
- Rich spectrum to be explored at LHC and SuperB factory