Leptonic Decays of the Higgs Boson in the Left-Right Symmetric Model

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Outline

- Brief review of the Left-Right Symmetric Model
- Constraints on the Higgs sector from quark flavor violation
- Higgs mediated lepton flavor violation
- Neutrino mass constraints
- Leptonic decays of the Higgs: $h \to \ell_i^+ \ell_j^-$
- Conclusions

Left-Right Symmetric Model

- Explains Parity violation as a spontaneous phenomenon
- Extends the Standard Model gauge group to $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Fermions transform in a left-right symmetric fashion under the gauge group
- Naturally contains the seesaw mechanism for neutrino masses
- Parity breaking scale should be $> (2-3)$ TeV from LHC and flavor constraints

Pati, Salam (1974); Mohapatra, Pati (1975); Mohapatra, Senjanovic (1975)

Particle content of Left-Right Symmetric Model

Fermions:

$$Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} \in (2, 1, 1/3), \qquad Q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix} \in (1, 2, 1/3),$$

$$L_L \equiv \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \in (2, 1, -1), \qquad L_R \equiv \begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix} \in (1, 2, -1)\,,$$

Bosons: $\Phi(1, 2, 2, 0)$, $\Delta_L(1, 3, 1, 2)$, $\Delta_R(1, 1, 3, 2)$

$$\Phi \equiv \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \; \Delta_L \equiv \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}, \; \Delta_R \equiv \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}$$

Under Parity, $Q_L \leftrightarrow Q_R,\ L_L \leftrightarrow L_R,\ \Phi \to \Phi^\dagger,\ \Delta_L \leftrightarrow \Delta_R,\ W_L^\mu \leftrightarrow W_R^\mu$

Δ_R breaks $SU(2)_R \times U(1)_{B-L}$ down to $U(1)_Y$ and induces ν_R mass

Φ generates fermion masses. It has two SM Higgs doublets

Fermion Mass Generation

- Φ and $\tilde{\Phi} = \tau_2 \Phi^* \tau_2$ couple to fermions

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= \overline{Q}_L^i (Y_{ij}^Q \Phi + \tilde{Y}_{ij}^Q \tilde{\Phi}) Q_R^j + \overline{L}_L^i (Y_{ij}^L \Phi + \tilde{Y}_{ij}^L \tilde{\Phi}) L_R^j \\ &+ i Y_{ij}^{\Delta} (L_L^{iT} \mathcal{C} \tau_2 \Delta_L L_L^j + L_R^{iT} \mathcal{C} \tau_2 \Delta_R L_R^j) + h.c. \,, \end{aligned}$$

- Vacuum expectation values:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 e^{i\alpha} \end{pmatrix}, \ \langle \Delta_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \ \langle \Delta_L \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

- Fermion masses given by:

$$\mathbf{M}^u = \frac{1}{\sqrt{2}} (Y^Q \kappa_1 + \tilde{Y}^Q \kappa_2^*) \quad M^d = \frac{1}{\sqrt{2}} (Y^Q \kappa_2 + \tilde{Y}^Q \kappa_1^*),$$

$$\mathbf{M}^l = \frac{1}{\sqrt{2}} (Y^L \kappa_2 + \tilde{Y}^L \kappa_1^*), \quad M_\nu^D = \frac{1}{\sqrt{2}} (Y^L \kappa_1 + \tilde{Y}^L \kappa_2^*), \quad M_\nu^M = \sqrt{2} Y_\Delta v_R$$

Higgs boson coupling to quarks

- It is convenient to define fields ϕ_-^0 and ϕ_+^0 with $\langle \phi_+^0 \rangle = 0$

$$\phi_+^0 = \frac{(-\kappa_2^* \phi_1 + \kappa_1 \phi_2^*)}{\kappa_+}, \quad \phi_-^0 = \frac{(\kappa_1^* \phi_1 + \kappa_2 \phi_2^*)}{\kappa_+}, \kappa_+ = \sqrt{\kappa_1^2 + \kappa_2^2}, \quad \kappa_- = \sqrt{\kappa_1^2 - \kappa_2^2}$$

- ϕ_-^0 and ϕ_+^0 are **not** mass eigenstates. They will mix.

- ϕ_-^0 is approximately the light Higgs boson of mass 125 GeV

- Yukawa couplings of ϕ_-^0 and ϕ_+^0 fields in the quark mass eigenbasis is:

$$\mathcal{L}_{\rm Yuk}^q = \frac{\sqrt{2}}{\kappa_-^2} \bar{\mathbf{u}}_L \left\{ \phi_-^0 \frac{\kappa_-^2}{\kappa_+} M^u + \phi_+^0 \left(\frac{-2\kappa_1^* \kappa_2}{\kappa_+} M^u + \kappa_+ V_L^{CKM} M^d V_R^{CKM^\dagger} \right) \right\} \mathbf{u}_R$$
$$+ \frac{\sqrt{2}}{\kappa_-^2} \bar{\mathbf{d}}_L \left\{ \phi_-^{0*} \frac{\kappa_-^2}{\kappa_+} M^d + \phi_+^{0*} \left(\frac{-2\kappa_1 \kappa_2^*}{\kappa_+} M^d + \kappa_+ V_L^{CKM^\dagger} M^u V_R^{CKM} \right) \right\} \mathbf{d}_R$$

Neutral Higgs boson mass matrix

- Matrix elements in $\{\mathrm{Re}(\Phi^0_-), \mathrm{Re}(\Phi^0_+), \mathrm{Re}(\Delta^0_R)\}$ basis:

$$
\begin{aligned}
\tilde{\mathcal{M}}^{\mathrm{Re}^2}_{11} &= 2\lambda_1\kappa_+^2 + 8\kappa_1^2\kappa_2^2(2\lambda_2+\lambda_3)/\kappa_+^2 + 8\kappa_1\kappa_2\lambda_4 \\
\tilde{\mathcal{M}}^{\mathrm{Re}^2}_{12} &= 4\kappa_1\kappa_2\kappa_-^2(2\lambda_2+\lambda_3)/\kappa_+^2 + 2\lambda_4\kappa_-^2 \\
\tilde{\mathcal{M}}^{\mathrm{Re}^2}_{13} &= \alpha_1 v_R\kappa_+ + \kappa_2 v_R(4\alpha_2\kappa_1+\alpha_3\kappa_2)/\kappa_+ \\
\tilde{\mathcal{M}}^{\mathrm{Re}^2}_{22} &= (4\lambda_2+2\lambda_3)\kappa_-^4/\kappa_+^2 + \alpha_3 v_R^2\kappa_+^2/(2\kappa_-^2) \\
\tilde{\mathcal{M}}^{\mathrm{Re}^2}_{23} &= v_R(2\alpha_2\kappa_-^2+\alpha_3\kappa_1\kappa_2)/\kappa_+ \\
\tilde{\mathcal{M}}^{\mathrm{Re}^2}_{33} &= 2\rho_1 v_R^2
\end{aligned}
$$

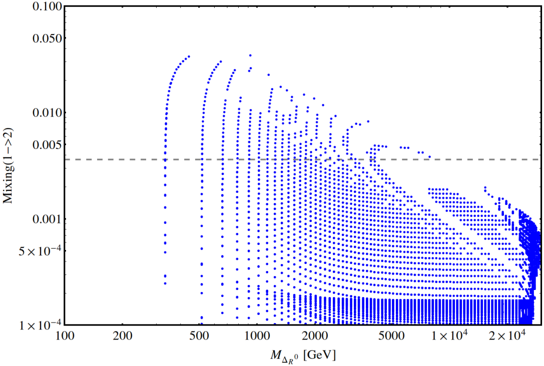
Gunion *et. al.*(1989)

- ϕ^0_+ mass should be > 20 TeV from $K^0 - \overline{K^0}$ mixing.

Zhang, An, Ji, Mohapatra (2008)

- $R_3\mathcal{M}^2R_3^T = \mathcal{M}^{d2}$ diagonalizes the mass matrix
- Direct $\phi^0_- - \phi^0_+$ mixing is small
- However, $(R_3)_{12} = (R_3)_{13}\times(R_3)_{32}$ can be a few percent
- $\mathrm{Re}(\Delta^0_R)$ mass is not strongly constrained

$\phi^0_- - \phi^0_+$ mixing angle



$\phi^0_- - \phi^0_+$ mixing angle allowed by model as function of Δ^0_R mass

Constraints from quark flavor violation

- Once $\mathrm{Re}(\phi^0_-) - \mathrm{Re}(\phi^0_+)$ mixing occurs, light Higgs boson h^0 will inherit some FCNC couplings
- This coupling depends on the right-handed CKM matrix V_R^{CKM}
- Parity implies that Yukawa coupling matrices are hermitian.

$$\begin{aligned}(V_R^{CKM})_{ij} \quad &= \quad (V_L^{CKM})_{ij} + i \sin\alpha \tan 2\beta \Bigg[\tan\beta \, (V_L^{CKM})_{ij} + \frac{(V_L^{CKM} \mathbf{M}^d V_L^{CKM\,\dagger})_{ik} (V_L^{CKM})_{kj}}{m_{u_i} + m_{u_k}} \\ &+ \frac{(V_L^{CKM})_{ik} (V_L^{CKM\,\dagger} \mathbf{M}^u V_L^{CKM})_{kj}}{m_{d_k} + m_{d_j}} \Bigg] + \mathcal{O}(\sin^2\alpha \tan^2 2\beta) \qquad \textit{Senjanovic}, \; \textit{Tello}(2015)\end{aligned}$$

- Here α is phase of κ_2 and $\tan\beta = -\kappa_2/\kappa_1$.
- Except for CP violating observables, V_R^{CKM} can be taken to be

$$V_R^{CKM} \simeq \mathbf{W}^u V_L^{CKM} \mathbf{W}^d$$

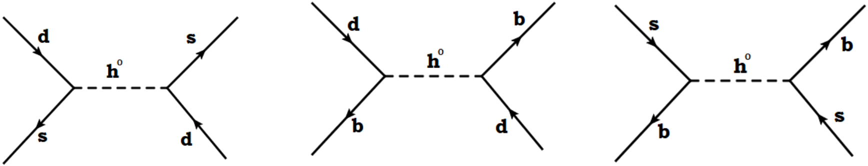
$$\mathbf{W}^u = diag(s_u, s_c, s_t), \; \mathbf{W}^d = diag(s_d, s_s, s_b), \; s_i = \pm 1$$

Meson mixing mediated by the Higgs boson

- Flavor changing coupling of light Higgs:

$$\mathcal{L}^{h}_{FCNC} = (R_3)_{12}\,\frac{1}{\kappa_+}\,\overline{\mathbf{d}}_L\,h^0\left\{V_L^{CKM\dagger}\,\mathbf{M}^u\,V_R^{CKM}\right\}\mathbf{d}_R$$

- $K^0 - \overline{K^0}$ mixing, $B_d^0 - \overline{B_d^0}$ mixing and $B_s^0 - \overline{B_s^0}$ mixing induced by h^0:



Meson mixing mediated by the Higgs boson (cont.)

$$\mathcal{H}_{eff} = -\frac{1}{2M_k^2}\left\{\overline{q_i}\left(y_{ij}^k\frac{1+\gamma_5}{2} + y_{ji}^{k*}\frac{1-\gamma_5}{2}\right)q_j\right\}^2$$

$$\begin{aligned} M_{12}^{\zeta} = \left\langle\zeta|\mathcal{H}_{eff}|\overline{\zeta}\right\rangle &= -\frac{f_\zeta^2 m_\zeta}{2M_k^2}\left\{-\frac{5}{24}\frac{m_\zeta^2}{(m_{q_i}+m_{q_j})^2}({y_{ij}^k}^2 + {y_{ji}^{k*}}^2)\cdot B_2\cdot\eta_2(\mu)\right. \\ &\left. + y_{ij}^k y_{ji}^{k*}(\frac{1}{12}+\frac{1}{2}\frac{m_\zeta^2}{(m_{q_i}+m_{q_j})^2})\cdot B_4\cdot\eta_4(\mu)\right\} \end{aligned}$$

$K^0 - \overline{K^0}$: $\left|(R_3)_{12}\right| \lesssim 7.2\times 10^{-3}$

$B_d^0 - \overline{B_d^0}$: $\left|(R_3)_{12}\right| \lesssim 1.6\times 10^{-2}$,

$B_s^0 - \overline{B_s^0}$: $\left|(R_3)_{12}\right| \lesssim 1.4\times 10^{-2}$

Higgs boson coupling to leptons

- Leptonic coupling of Higgs is analogous to quarks. M^u should be replaced by M_ν^D.
- In charged lepton eigenbasis, $M_\nu^D = U^\dagger . M^D . U$ where U is some unitary matrix.
- If M^D has entries as large as M^u, then potentially that can lead to large neutrino masses.
- If M^D has rank one, then large neutrino masses need not arise:

$$M_\nu^D = m_D^0 U \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} U^\dagger, \; M_R = U^* \begin{pmatrix} M_{11} & 0 & 0 \\ 0 & 0 & M_{23} \\ 0 & M_{23} & 0 \end{pmatrix} U^\dagger$$

$$M_\nu^\ell = -M_\nu^D M_R^{-1} M_\nu^{DT} = 0$$

- There is an unbroken lepton number symmetry under which (N_1, N_2, N_3) have charges $(0, 1, -1)$.
- Mass matrices stable under radiative corrections.

Higgs boson coupling to leptons (cont.)

- Yukawa couplings of charged leptons to h^0:

$$\mathcal{L}^{l}_{\rm Yuk} = \frac{\sqrt{2}}{\kappa_-^2}\bar{\mathbf{l}}_L\left\{\phi_-^{0*}\frac{\kappa_-^2}{\kappa_+}M^l + \phi_+^{0*}\left(\frac{-2\kappa_1\kappa_2^*}{\kappa_+}M^l + \kappa_+ U^\dagger M^D U\right)\right\}\mathbf{l}_R$$

- here U is an unphysical unitary matrix that diagonalizes M_ν^D.
- As long as the diagonal Dirac neutrino mass matrix M^D has rank one, neutrino mass can remain small.
- b-quark and τ-lepton Yukawa couplings to h^0 are modified:

$$\begin{aligned}\mathcal{L} &= \frac{m_b}{\kappa_+}\bar{b}_L h^0\left\{1 + (R_3)_{12}\frac{s_t s_b m_t}{m_b}\right\} b_R \\ &+ \frac{m_\tau}{\kappa_+}\bar{\tau}_L h^0\left\{1 + (R_3)_{12}\frac{M^D|U_{33}|^2}{m_\tau}\right\}\tau_R\end{aligned}$$

- $h \to b\bar{b}$ and $h \to \tau^+\tau^-$ from LHC data constrain $(R_3)_{12}$.

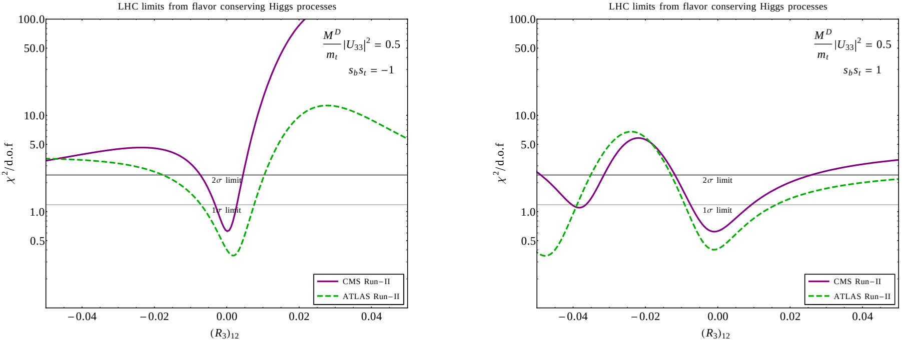
Constraints on Higgs mixing from LHC

LHC dataset used for $h \to b\bar{b}$ and $h \to \tau^+\tau^-$:

Dataset	Decay Mode	Production Channels $\sigma_{t\bar{t}h^0}$	Production channels σ_{Vh^0}
CMS Run-II ATLAS Run-II	$h^0 \to b\bar{b}$	$-0.19^{+0.45+0.66}_{-0.44-0.68}$ $2.10^{+1.20+0.50+0.90}_{-0.90-0.50-0.70}$	$1.06^{+0.31}_{-0.29}$ $0.90 \pm 0.18^{+0.21}_{-0.19}$

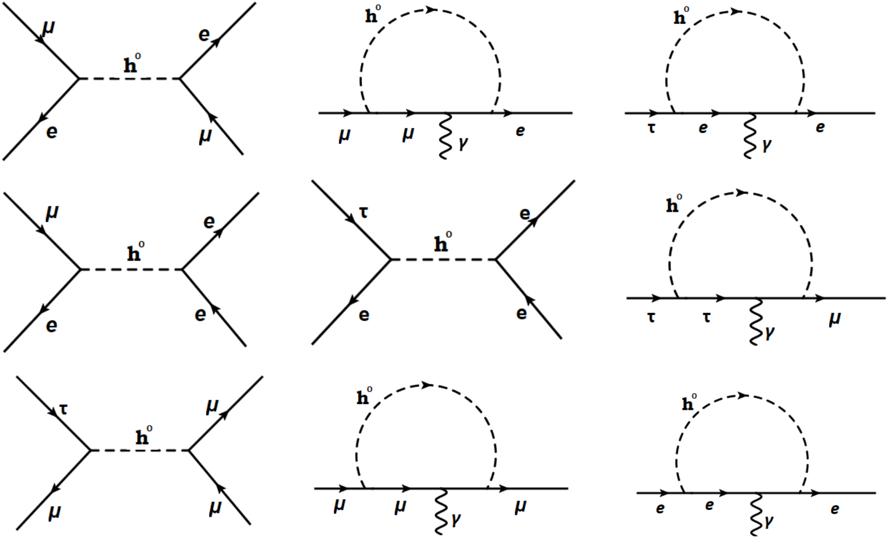
Dataset	Decay Mode	Production Channels $\sigma_{t\bar{t}h^0}$	Production channels σ_{VBF}	Production channel ggh
ATLAS Run-II CMS Run-II	$h^0 \to \tau\overline{\tau}$	$1,5^{+1.2+0.9+0.8}_{-1.0-0.8-0.6}$ $0.72^{+0.62}_{-0.53}$	$1.11^{+0.34}_{-0.35}$	$0.84^{+0.89}_{-0.89}$

Constraints on Higgs mixing from LHC



χ^2 analysis of $h^0 \to b\bar{b}$ and $h^0 \to \tau^+\tau^-$ from LHC data

Lepton Flavor Violation induced by Higgs



Limits on flavor violating couplings of Higgs

Process	Coupling	Constraint
$\mu \to e\gamma$	$\left\|(R_3)_{12}\tilde{y}_{e\mu}\right\|$	$< 2.5 \times 10^{-6}$
$\mu \to 3e$	$\left\|(R_3)_{12}\tilde{y}_{e\mu}\right\|$	$\lesssim 2.2 \times 10^{-5}$
electron $g-2$	$\left\|(R_3)_{12}\tilde{y}_{e\mu}\right\|^2$	$[-1.9 - 2.6] \times 10^{-2}$
$\mu \to e$ conversion	$\left\|(R_3)_{12}\tilde{y}_{e\mu}\right\|$	$< 8.5 \times 10^{-6}$
$M - \overline{M}$ oscillation	$\left\|(R_3)_{12}\tilde{y}_{e\mu}\right\|$	$< 4.0 \times 10^{-2}$
$\tau \to e\gamma$	$\left\|(R_3)_{12}\tilde{y}_{e\tau}\right\|$	$< 9.9 \times 10^{-3}$
$\tau \to 3e$	$\left\|(R_3)_{12}\tilde{y}_{e\tau}\right\|$	$\lesssim 8.5 \times 10^{-2}$
electron $g-2$	$\left\|(R_3)_{12}\tilde{y}_{e\tau}\right\|^2$	$[-2.1 - 2.9] \times 10^{-3}$
$\tau \to \mu\gamma$	$\left\|(R_3)_{12}\tilde{y}_{\mu\tau}\right\|$	$< 1.1 \times 10^{-2}$
$\tau \to 3\mu$	$\left\|(R_3)_{12}\tilde{y}_{\mu\tau}\right\|$	$\lesssim 1.8 \times 10^{-1}$
muon $g-2$	$\left\|(R_3)_{12}\tilde{y}_{\mu\tau}\right\|^2$	$(2.7 \pm 0.75) \times 10^{-3}$
$\mu \to e\gamma$	$\sqrt{\left\|(R_3)^2_{12}\tilde{y}_{\tau\mu}\tilde{y}_{e\tau}\right\|}$	$< 2.9 \times 10^{-4}$

$$\tilde{y} = \frac{\kappa_+}{\kappa_-^2} M^D$$

Harnik, Kopp, Zupan (2013)

LHC limits on leptonic decays of the Higgs

- $h \to \mu\tau$: 0.25% (limit on Branching ratio (BR)) CMS [arXiv:1712.07173]
- $h \to e\tau$: 0.61% (limit on BR) CMS [arXiv:1712.07173]
- $h \to e\mu$: 0.035% (limit on BR) CMS [arXiv:1607.03561]
- $h \to ee$: 1.9×10^{-3} (limit on BR) CMS [arXiv:1410.6679]
- $h \to \mu\mu$: 0.7 ± 1.0 (limit on μ value) CMS [arXiv:CMS-PAS-HIG-17-019]
- $h \to \mu\mu$: -0.1 ± 1.5 (limit on μ value) ATLAS [arXiv:1705.04582]
- $h \to \tau\tau$: 1.06 ± 0.25 (limit on μ value) CMS [CMS-PAS-HIG-16-043]
- $h \to \tau\tau$: 1.43 ± 0.39 (limit on μ value) ATLAS [arXiv:1501.0494]

- Left-right model can make any one of flavor conserving lepton decays near the current limit.
- Flavor violating decays can also be near limit, except for $h^0 \to e\mu$.

Leptonic Higgs Decays

- $h \to \mu\mu$ can be enhanced by a factor

$$\frac{|U_{32}|^2 M^D (R_3)_{12}}{m_\mu}$$

  and can be near current limit

- $h \to ee$ enhaned by

$$\frac{|U_{31}|^2 M^D (R_3)_{12}}{m_e}$$

  and can also be near current limit

- If $h \to \mu^- \tau^+$ is observed, it obeys

$$\Gamma(h \to \mu^- \tau^+) = [\Gamma_{\rm new}(h \to \tau\tau).\Gamma_{\rm new}(h \to \mu\mu)]^{1/2}$$

Conclusions

- Standard Model Higgs can mix at the level a 1% with FCNC Higgs of Left-Right Model
- This leads to modifications in $hb\bar{b}$ and $h\tau^+\tau^-$ couplings
- Meson mixing and LHC searches constrain such mixings
- $h \to e^+e^-$ and $h \to \mu^+\mu^-$ can be near current limit
- FCNC Higgs decays can also be near current LHC limit, except for $h \to e\mu$
- Neutrino mass provides some information, but neutrino mass arising via seesaw is under control