Lepton Specific Extended Higgs Model

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Motivation

- 2 Higgs Doublet Models (2HDMs) are a simple extension to Standard Model
  - SUSY
  - Axions
  - CP-Violation
  - Muon-specific 2HDM (1705.01469)
- N Doublet Models
  - Can include more doublets
  - “Private” Higgs
  - Extend muon-specific 2HDM

2HDMs

- 2HDM Potential

$$V_2 = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right)$$

$$\begin{aligned} V_4 = \lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) \\ + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right] \end{aligned}$$

- Yukawa couplings <u>not</u> yet defined
    - Different models

arXiv:1106.0034

Flavor Changing Neutral Current

- General form of Yukawa couplings for $Q = -1/3$ quarks is:

$$\mathcal{L}_Y = y^1_{ij}\bar{\Psi}_i\Psi_j\Phi_1 + y^2_{ij}\bar{\Psi}_i\Psi_j\Phi_2$$

- Yukawa couplings will not, in general, be simultaneously diagonalizable
  - Yukawa couplings will not be flavor diagonal
  - Leads to flavor-changing neutral currents (FCNC)
    - Can lead to processes such as K-$\overline{K}$ mixing at tree level
- FCNC can be allowed but our model avoids it
  - By the Paschos-Glaschow-Weinberg theorem, all fermions with same quantum numbers must couple to the same Higgs doublet
  - For 2HDM, we have 3 groups: $Q = 2/3$ RH quarks, $Q = -1/3$ RH quarks, and RH leptons
  - For our 4HDM, we have 4 groups: quarks (q), electron (e), muon (μ), and tau (τ)

2HDM Models

- There are four possible coupling assignments which have no FCNC at tree-level

- Different Yukawa couplings between models

- All models have same neutral Higgs to W/Z boson couplings

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Type X	Φ_2	Φ_2	Φ_1
Type Y	Φ_2	Φ_1	Φ_2

Alignment Limit

- We can define two important parameters:
  - Angle which diagonalizes scalar mass-squared matrix: α

$$\begin{pmatrix} h_{125} \\ h_2 \end{pmatrix} = R_\alpha \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

  - Angle which diagonalizes pseudoscalar and charged scalar mass-squared matrices: β
    - Rotates into Higgs basis

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = R_\beta \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} \qquad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = R_\beta \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} \qquad \begin{pmatrix} h \\ H \end{pmatrix} = R_\beta \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

- <u>Alignment Limit</u>: SM Higgs is lightest neutral scalar

Our Model

- Scalar Potential:

$$V_2 = \sum_i m_{ii}^2 \Phi_i^\dagger \Phi_i + \sum_{i \neq j} m_{ij}^2 \Phi_i^\dagger \Phi_j$$

$$V_4 = \sum_i \lambda_1^i \left(\Phi_i^\dagger \Phi_i\right)^2 + \frac{1}{2} \sum_{i \neq j} \left[\lambda_3^{ij} \left(\Phi_i^\dagger \Phi_i\right) \left(\Phi_j^\dagger \Phi_j\right) + \lambda_4^{ij} \left(\Phi_i^\dagger \Phi_j\right) \left(\Phi_j^\dagger \Phi_i\right) + \lambda_5^{ij} \left(\Phi_i^\dagger \Phi_j\right)^2\right]$$

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i + i\chi_i)/\sqrt{2} \end{pmatrix}$$

$$\lambda_{3,4}^{ij} = \lambda_{3,4}^{ji}$$

$$\lambda_5^{ij} = \left(\lambda_5^{ji}\right)^*$$

$$i, j \in \{q, e, \mu, \tau\}$$

No $q\tau$-$e\mu$ Mixing

- $q\tau$ and $e\mu$ sectors are decoupled through absence of mixing
  - Results in block-diagonal diagonalization matrices
  - Diagonalization procedure similar to 2HDM

- In Type X model: $v_q^2 + v_\tau^2 = (246\mathrm{GeV})^2$
- In this model: $v_q^2 + v_\tau^2 < (246\mathrm{GeV})^2$

- Yukawa couplings will increase affecting production and decay of 125 GeV Higgs boson

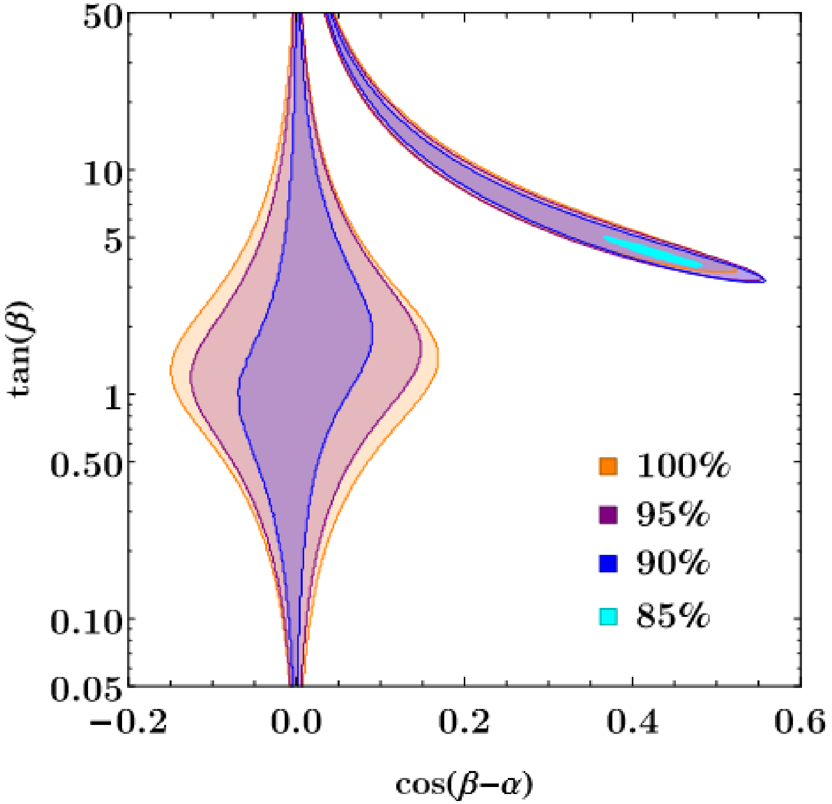
VEV Analysis

- Compare production/decay to SM values
- Require μ_X to be consistent with unity within 20% at 95% CL

$$r \equiv \left(v_q^2 + v_\tau^2\right)^{1/2} / v$$

$$\mu_X \equiv \frac{\sigma\left(pp \to H\right) BR\left(H \to X\right)}{\sigma\left(pp \to H\right)_{SM} BR\left(H \to X\right)_{SM}}$$

$$X = gg, \mu\mu, \tau\tau, \bar{c}c, \bar{b}b, \bar{t}t, \gamma\gamma, \gamma Z, WW, ZZ$$



Perturbation Theory

- Model produces extra massless scalars
  - Extra SU(2) symmetry
- Must be non-zero off-diagonal terms

$$\Phi_q = V_{11} h_1 + V_{12} h_2 + \ldots$$

$$V_{11} = 1 - \frac{1}{2} \left(\lambda_5^{q\mu} v_q v_\mu \right)^2 \left[\left(\frac{c_{34} s_{12}}{m_{h_1}^2 - m_{h_3}^2} \right)^2 + \left(\frac{c_{12} s_{34}}{m_{h_1}^2 - m_{h_4}^2} \right)^2 \right]$$

- Using perturbation theory, V_{11} decreases which counteracts smaller v_q in Yukawa couplings
- $\lambda_5^{q\mu}$ has minimum value but neutral scalar mass (m_{h_3}) can be large

Aligned Model

- 125 GeV Higgs decays are consistent with SM
  - Multi-doublet models must be near alignment limit

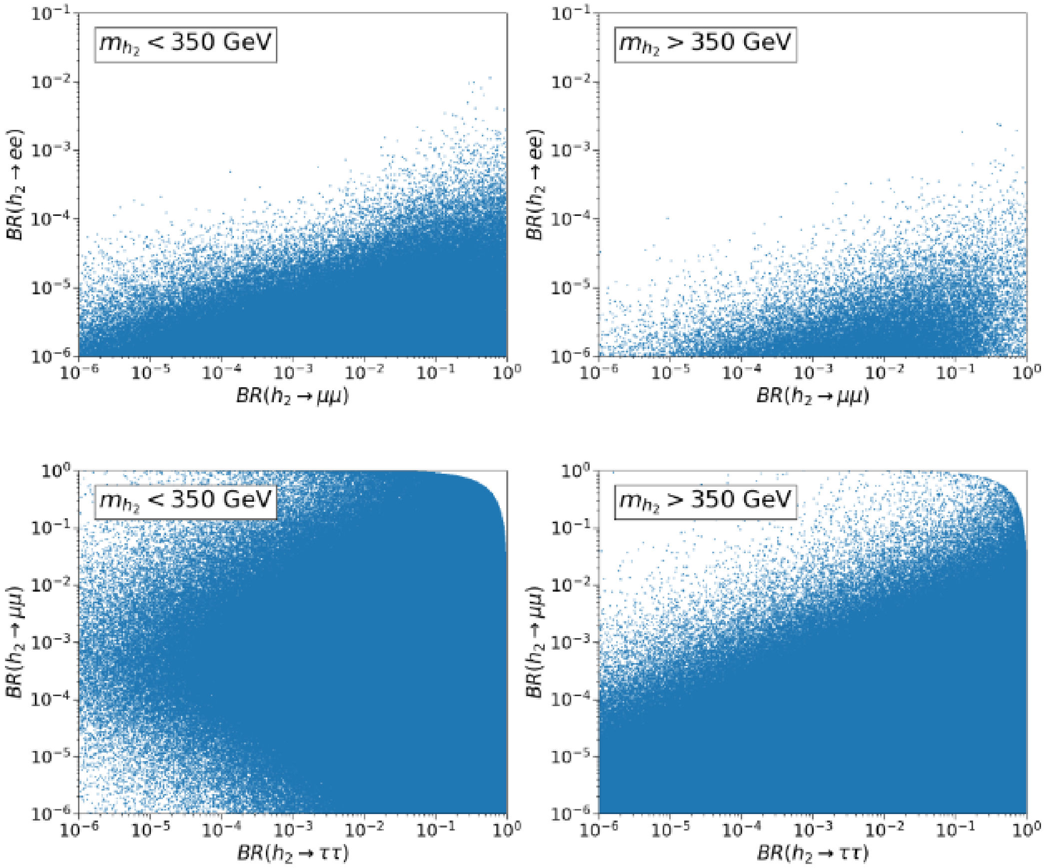
- Model can be described using 31 parameters
  - 18 rotation angles (6 scalar, 6 pseudoscalar, 6 charged)
  - 12 masses (4 scalar, 4 pseudoscalar, 4 charged)
  - 1 vev (246 GeV)

$$\alpha_{1j} = \beta_j$$

Computational Technique

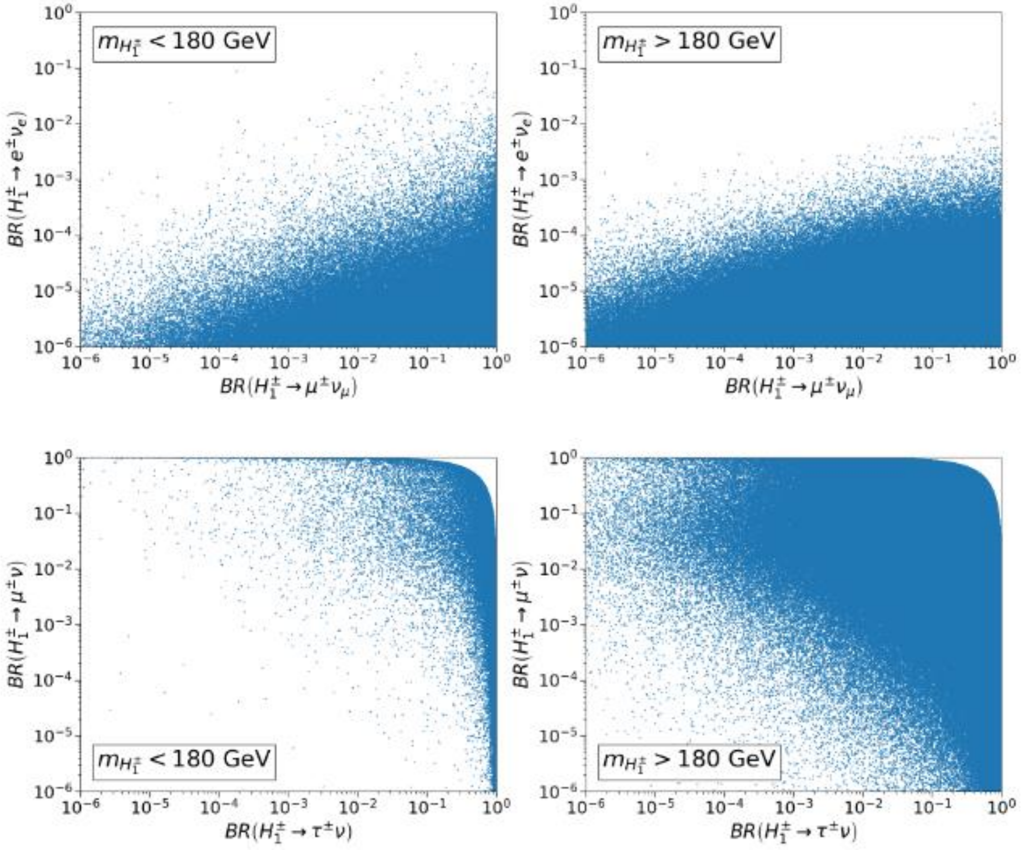
- Probing a 31-dimensional parameter space can be computationally expensive
- Generate random set of angles such that the alignment limit is obeyed
- Generate random masses
  - Still require 125 GeV scalar Higgs, 0 GeV pseudoscalar Higgs, and 0 GeV charged Higgs
- Calculate vevs
- Calculate Lagrangian parameters such that perturbativity is maintained
- Check BFB conditions
- Check experimental bounds

Neutral Higgs Decay



- Heavy neutral Higgs branching ratios
  - $t\bar{t}$ decay channel opens at 350 GeV
- Heavy neutral Higgs decays into leptons can probe this model
  - Current searches look at tauonic decays
  - Should also search for muonic and electronic decays

Charged Higgs Decay



- Heavy charged Higgs branching ratios
  - $t\bar{b}$ channel opens at 180 GeV

- Electronic decay branching ratio can be large when muonic decay branching ratio is near 1

- Possible to have electronic decay branching ratio larger than muonic decay branching ratio by order of magnitude

Conclusion

- We presented a 4HDM extension of the SM
  - Extends muon-specific model

- No $q\tau$-$e\mu$ Mixing:
  - Place limit of 85% on $\left(v_q^2 + v_\tau^2\right)^{1/2}/v$

- Aligned Model:
  - Neutral and charged Higgs decays can have substantial electronic and muonic decays
    - Heavy Higgs decays can be searched through muonic or electronic branching ratios

EXTRA: Oblique Parameters

$$\begin{aligned}
\frac{\alpha S}{4 s_w^2 c_w^2} &= \left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2}\right] - \frac{(c_w^2 - s_w^2)}{s_w c_w}\, \delta\Pi'_{Z\gamma}(0) - \delta\Pi'_{\gamma\gamma}(0), \\
\alpha T &= \frac{\delta\Pi_{WW}(0)}{M_W^2} - \frac{\delta\Pi_{ZZ}(0)}{M_Z^2}, \\
\frac{\alpha U}{4 s_w^2} &= \left[\frac{\delta\Pi_{WW}(M_W^2) - \delta\Pi_{WW}(0)}{M_W^2}\right] - c_w^2 \left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2}\right] \\
&\quad - s_w^2 \delta\Pi'_{\gamma\gamma}(0) - 2 s_w c_w \delta\Pi'_{Z\gamma}(0).
\end{aligned}$$

arXiv:hep-ph/9306267v3

EXTRA: Conditions checked

- BFB Satisfied
- Perturbativity for lambda and Yukawas
- S,T are in acceptable range
- Charged Higgs < 80 GeV
- Charged scalar constributions to Higgs diphoton compatible with experiment
- Bounds from new physics contributions to B meson oscillations, K mesons are compatible with experiment
- $b \rightarrow s\gamma$ from charged Higgs are acceptable
- Heavy neutral Higgs decaying into tau pairs
- LHC direct searches for heavy charged Higgs

EXTRA: Lambda Extraction

$$\lambda_1^i = \frac{1}{2v_i^3}\left(v_i M_{s,ii}^2 + \sum_{j\neq i} v_j m_{ij}^2\right) ,$$

$$\lambda_3^{ij} = \frac{1}{v_i v_j}\left(M_{s,ij}^2 - 2M_{c,ij}^2 + m_{ij}^2\right) ,$$

$$\lambda_4^{ij} = \frac{1}{v_i v_j}\left(2M_{c,ij}^2 - M_{p,ij}^2 - m_{ij}^2\right) ,$$

$$\lambda_5^{ij} = \frac{1}{v_i v_j}\left(M_{p,ij}^2 - m_{ij}^2\right) ,$$