Higgs bosons with large couplings to up type quarks

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Flavor symmetries of the quark sector

- $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$ Quarks are grouped in 3 Families

- Flavor Symmetries of quark sector: $U(3)^3 \equiv U(3)_Q \times U(3)_{\bar{u}} \times U(3)_{\bar{d}}$

  → The Gauge sector respects all the flavor symmetries

  → Yukawa interactions ("spurions") break the flavor symmetries i.e. $Y_u \sim (3, \bar{3}, 1)$ and $Y_d \sim (3, 1, \bar{3})$

- Choosing a flavor basis we can write:
  $\lambda^u \equiv V^T Y^u$ and $\lambda^d \equiv Y^d$

  $V \rightarrow$ CKM matrix

Extended Flavor Sectors

◇ Flavorful New Physics generically leads to Flavor Changing Neutral Currents

- FCNCs are suppressed in the SM
- Assumptions on the structure of NP are needed
- Most common assumption: Minimal Flavor Violation (MFV)

◇ Minimal Flavor Violation:

- Any NP spurions are tensor products of y^u and y^d
- New Physics scale is allowed to be closer to the energy reach of current experiments
- FCNCs follow SM suppression

Example: $\frac{\left(\bar{d}_L V_{tb} y_t^2 V_{td}^* b_L\right)^2}{\Lambda_{NP}^2} \to \Lambda_{NP} \sim TeV$ **Vs** $\Lambda_{NP} \sim 10^3 - 10^4\, TeV$ for generic $\mathcal{O}(1)$ coupling

Minimal Flavor Violation

What we know:

$\longrightarrow$ FCNCs bounds force flavor alignment of any New Physics couplings

Using MFV:

$\longrightarrow$ Constrained to SM yukawa hierarchy

$\longrightarrow$ Limited collider phenomenology

Spontaneous Flavor Violation *PhysRevLett.123.031802*

- Key idea: The only source of flavor changing processes is the CKM matrix
- What we gain: New spurions that are allowed to deviate from SM hierarchy

Spontaneous Flavor Violation

- Flavor-changing processes & CP breaking come from the wave function renormalization of right handed SM quarks

$$\mathcal{L} \supset iZ^u_{ij}\bar{u}^\dagger_i\bar{\sigma}^\mu D_\mu \bar{u}_j + \bar{d}^\dagger_i\bar{\sigma}^\mu D_\mu \bar{d}_i - \left[\lambda^u_{ij} Q_i H \bar{u}_j - \lambda^d_{ij} Q_i H^c \bar{d}_j + h.c.\right]$$

- **Up-Type:**

$$Z^u_{ij}\bar{u}^\dagger_i\bar{\sigma}^\mu D_\mu \bar{u}_j$$

$$\bar{u} \to \left(\sqrt{Z^u}\right)^{-1}\bar{u}$$

$$\lambda^u \to \left(\sqrt{Z^u}\right)^{-1}\lambda^u = V^T Y^u$$

- **Down-Type:**

$$Z^d_{ij}\bar{d}^\dagger_i\bar{\sigma}^\mu D_\mu \bar{d}_j$$

$$\bar{d} \to \left(\sqrt{Z^d}\right)^{-1}\bar{d}$$

$$\lambda^d \to \left(\sqrt{Z^d}\right)^{-1}\lambda^d = V^T Y^d$$

Spontaneous Flavor Violating Two Higgs Doublet Model

◇ Two complex scalar fields: H_α, $\alpha = 1, 2$

$$D_\mu H_\alpha^\dagger D^\mu H_\alpha - V(H_1, H_2) - \left[\lambda^u_{\alpha ij} Q_i H_\alpha \bar{u}_j - \lambda^{d\dagger}_{\alpha ij} Q_i H^c_\alpha \bar{d}_j - \lambda^{\ell\dagger}_{\alpha ij} L_i H^c_\alpha \bar{\ell}_j + h.c.\right] \quad (1)$$

◇ **Up-Type:**

$$\lambda_2^u = \xi V^T Y^u$$
$$\lambda_2^d = K^d \equiv diag(\kappa_d, \kappa_s, \kappa_b)$$

◇ **Down-Type:**

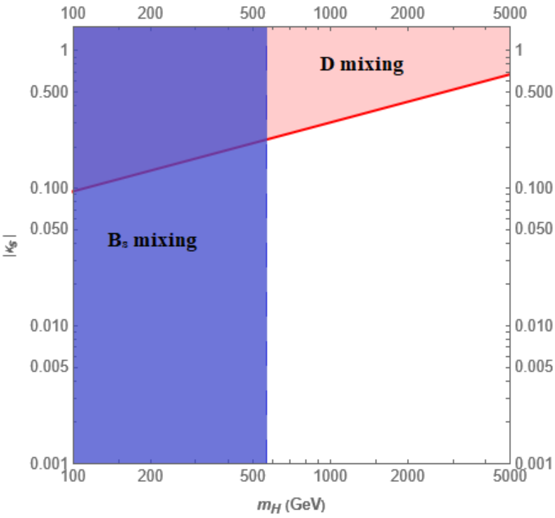
$$\lambda_2^u = V^T K^u \equiv V^T diag(\kappa_u, \kappa_c, \kappa_t)$$
$$\lambda_2^d = \xi Y^d$$

✓ The yukawa couplings of H_2 are free parameters, allowed to deviate from SM hierarchy

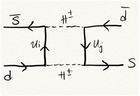
Flavor Phenomenology of neutral meson mixing

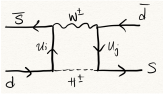
- Higgs mass eigenstates: $H^{\pm}$, H, h, & A
- $\mathcal{H}_{eff}^{\Delta F=2} = \sum_{i=1} C_i \mathcal{O}_i$
  - $\mathcal{O}_1 = \left(\bar{d}_J \gamma_\mu P_L d_I\right)\left(\bar{d}_J \gamma^\mu P_L d_I\right)$
  - $\mathcal{O}_2 = \left(\bar{d}_J P_L d_I\right)\left(\bar{d}_J P_R d_I\right)$
  - And a few more
- Use bounds on the C_i of these operators *[UTfit Collaboration, JHEP 03 (2008) 049]*

Bounds from neutral meson mixing (up-type)



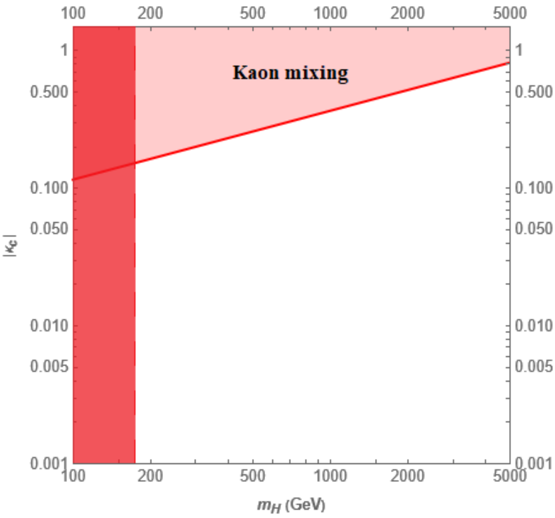
Set: $\xi = 1,\ \kappa_d = \kappa_b = 0$





- D meson mixing $\rightarrow$ constraints $(\lambda_2^u = \xi V^T Y^u, \lambda_2^d = K^d)$
- Couplings of ~ 0.1 are allowed for masses $500\,GeV$
- Depending on value of ξ the B_s bounds become irrelevant

Bounds from neutral meson mixing (down-type)

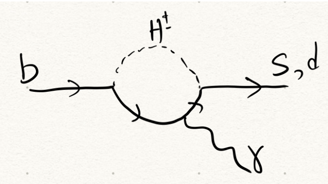


- Kaon mixing is important $(\lambda_2^u = V^T K^u, \lambda_2^d = \xi Y^d)$
- Couplings of ~ 0.1 are allowed for masses $\lesssim 200\,GeV$
- Relevant to recent ATLAS result for charm yukawa
  CERN-EP-2021-251

Set: $\xi = 1$, $\kappa_d = \kappa_b = 0$

More bounds?

- Previously $\to$ bounds from neutral meson mixing
- Can use $B \to X_{s,d}\gamma$ transitions $\left[\mathcal{O}_7 \sim \frac{e}{16\pi^2} m_b \left(Q_2 \sigma_{\mu\nu} \bar{d}_3\right)^\dagger F^{\mu\nu}\right]$



Work in progress

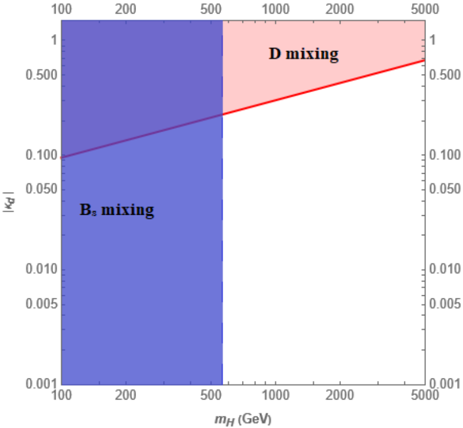
Conclusions

- Extended Higgs sectors do not need to follow SM coupling hierarchy
- Viable parameter space for flavorful couplings of significant size
- Motivation for studying theories with large couplings to light quarks

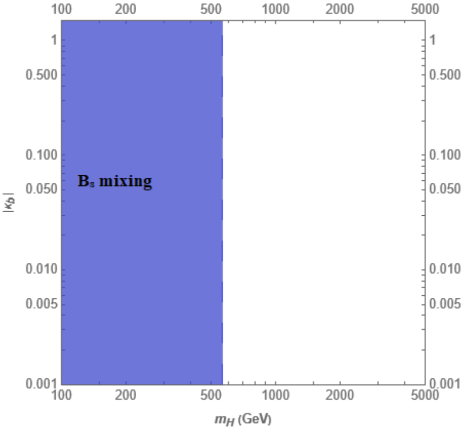
Thank you!

Extra Slides

Bounds from neutral meson mixing (up-type)

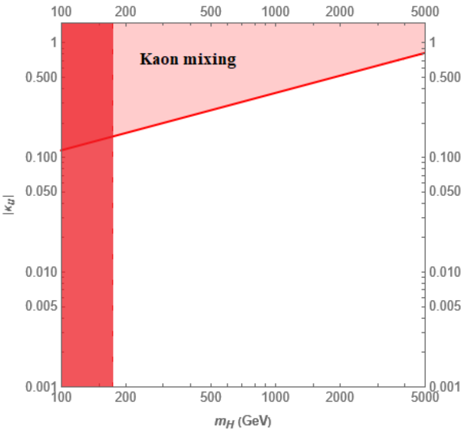


Set: $\xi = 1,\ \kappa_s = \kappa_b = 0$

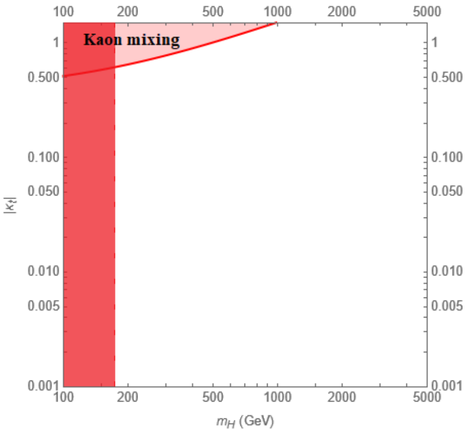


Set: $\xi = 1,\ \kappa_d = \kappa_s = 0$

Bounds from neutral meson mixing (down-type)



Set: $\xi = 1,\ \kappa_t = \kappa_c = 0$



Set: $\xi = 1,\ \kappa_u = \kappa_c = 0$