Flavoring the Two Higgs Doublet Model

Studying General Solutions to the Flavor Puzzle

Andrew Blechman, Wayne State U.

AEB, A. A. Petrov, G. Yeghiyan, JHEP 1011 (2010) 075, 1009.1612 [hep-ph]

Outline

- Review of Yukawa sector
- Review of Flavor Hierarchy Problem
- Review of Two Higgs Doublet (2HD) Models
- Full Standard Model hierarchy
- Constraints from Flavor Observables (in progress)

Yukawa Lagrangian

$$\mathcal{L} = -y_\psi \bar{\psi}_L \psi_R \phi + h.c. \to -\frac{y_\psi v}{\sqrt{2}} \left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \right)$$

Yukawa Lagrangian

$$\mathcal{L} = -y_\psi \bar{\psi}_L \psi_R \phi + h.c. \to -\frac{y_\psi v}{\sqrt{2}} \left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \right)$$

Doing this for each fermion in the SM:

Yukawa Lagrangian

$$\mathcal{L} = -y_\psi \bar{\psi}_L \psi_R \phi + h.c. \to -\frac{y_\psi v}{\sqrt{2}} \left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \right)$$

Doing this for each fermion in the SM:

$$\begin{aligned}
&y_u \sim 10^{-5}, \quad y_c \sim 10^{-2}, \quad y_t \sim 1, \\
&y_d \sim 10^{-5}, \quad y_s \sim 10^{-3}, \quad y_b \sim 10^{-2}, \\
&y_e \sim 10^{-6}, \quad y_\mu \sim 10^{-3}, \quad y_\tau \sim 10^{-2}.
\end{aligned}$$

Yukawa Lagrangian

$$\mathcal{L} = -y_\psi \bar{\psi}_L \psi_R \phi + h.c. \to -\frac{y_\psi v}{\sqrt{2}} \left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \right)$$

Doing this for each fermion in the SM:

$$\begin{aligned} &y_u \sim 10^{-5}, \quad y_c \sim 10^{-2}, \quad y_t \sim 1, \\ &y_d \sim 10^{-5}, \quad y_s \sim 10^{-3}, \quad y_b \sim 10^{-2}, \\ &y_e \sim 10^{-6}, \quad y_\mu \sim 10^{-3}, \quad y_\tau \sim 10^{-2}. \end{aligned}$$

This is the "Flavor Hierarchy Problem"

Why “Problem”??

Why "Problem"??

Some would say that the flavor problem is not a problem, since the Yukawa couplings are protected by a chiral symmetry.

Why “Problem”??

Some would say that the flavor problem is not a problem, since the Yukawa couplings are protected by a chiral symmetry.

$$\frac{dy}{d\log\mu} \propto y$$

Why "Problem"??

Some would say that the flavor problem is not a problem, since the Yukawa couplings are protected by a chiral symmetry.

$$\frac{dy}{d\log\mu} \propto y \qquad \Longrightarrow$$

Small couplings remain small:
"Technical Naturalness"

Why "Problem"??

Some would say that the flavor problem is not a problem, since the Yukawa couplings are protected by a chiral symmetry.

$$\frac{dy}{d\log\mu} \propto y \quad \Longrightarrow$$

Small couplings remain small:
"Technical Naturalness"

The reason there is a problem is that all these couplings appear to come from the same physics. Therefore they should all start at the same order of magnitude at some UV scale, and the hierarchy should come from RG effects. This is why gauge couplings are not considered hierarchal.

Solving the Flavor Puzzle

Solving the Flavor Puzzle

Notice that an extra scalar boson can help to solve the flavor puzzle:

$$\mathcal{L}_2 = -y_\psi \bar{\psi}_L \psi_R \phi_1 - y_\chi \bar{\chi}_L \chi_R \phi_2 + \text{h.c.}$$

Solving the Flavor Puzzle

Notice that an extra scalar boson can help to solve the flavor puzzle:

$$\mathcal{L}_2 = -y_\psi \bar{\psi}_L \psi_R \phi_1 - y_\chi \bar{\chi}_L \chi_R \phi_2 + \text{h.c.}$$

Then assuming $\tan\beta \gg 1$

$$\frac{m_\chi}{m_\psi} = \frac{y_\chi}{y_\psi}\frac{v_2}{v_1} = \frac{y_\chi}{y_\psi}\tan\beta \gg 1$$

Solving the Flavor Puzzle

Notice that an extra scalar boson can help to solve the flavor puzzle:

$$\mathcal{L}_2 = -y_\psi \bar{\psi}_L \psi_R \phi_1 - y_\chi \bar{\chi}_L \chi_R \phi_2 + \text{h.c.}$$

Then assuming $\tan\beta \gg 1$

$$\frac{m_\chi}{m_\psi} = \frac{y_\chi}{y_\psi}\frac{v_2}{v_1} = \frac{y_\chi}{y_\psi}\tan\beta \gg 1$$

So it looks like we can solve the Flavor puzzle by just having more scalar bosons, letting all Yukawa couplings be $\mathcal{O}(1)$, and let $\tan\beta \gg 1$.

Solving the Flavor Puzzle

Notice that an extra scalar boson can help to solve the flavor puzzle:

$$\mathcal{L}_2 = -y_\psi \bar{\psi}_L \psi_R \phi_1 - y_\chi \bar{\chi}_L \chi_R \phi_2 + \text{h.c.}$$

Then assuming $\tan\beta \gg 1$

$$\frac{m_\chi}{m_\psi} = \frac{y_\chi}{y_\psi}\frac{v_2}{v_1} = \frac{y_\chi}{y_\psi}\tan\beta \gg 1$$

So it looks like we can solve the Flavor puzzle by just having more scalar bosons, letting all Yukawa couplings be $\mathcal{O}(1)$, and let $\tan\beta \gg 1$.

Das, Kao, Phys. Lett. B 392 (1996) 106.

Xu, Phys. Rev. D44, R590 (1991).

2HD Types

2HD Types

- Type I - Only one scalar doublet couples to fermions.

2HD Types

- Type I - Only one scalar doublet couples to fermions.
- Type II - Scalar doublets split between "up-type" and "down-type" fermions (SUSY).

2HD Types

- Type I - Only one scalar doublet couples to fermions.
- Type II - Scalar doublets split between "up-type" and "down-type" fermions (SUSY).
- Type III - Both scalar doublets couple to all fermions.

2HD Types

- Type I - Only one scalar doublet couples to fermions.
- Type II - Scalar doublets split between "up-type" and "down-type" fermions (SUSY).
- Type III - Both scalar doublets couple to all fermions.

Hierarchy Pattern

There is a pattern between the 1-2 and the 1-3 generation case:

$$A \equiv \frac{m_s(m_t)}{m_d(m_t)} \simeq 21 \ , \qquad \frac{m_b(m_t)}{m_d(m_t)} \simeq 2.26 \times A^2$$

$$B \equiv \frac{m_c(m_t)}{m_u(m_t)} \simeq 431 \ , \qquad \frac{m_t(m_t)}{m_u(m_t)} \simeq 0.62 \times B^2$$

If the 1-2 hierarchy was set by $\tan\beta$, then we can fix the 1-3 hierarchy by generating $\tan^2\beta$.

Texture Models

Fritzsch, Xing, Phys. Lett. B 353, 114 (1995)
Fritzsch, Xing, Phys. Lett. B 372, 265 (1996)
Fritzsch, Xing, Phys. Lett. B 413, 396 (1997)

Texture Models

Fritzsch, Xing, Phys. Lett. B 353, 114 (1995)
Fritzsch, Xing, Phys. Lett. B 372, 265 (1996)
Fritzsch, Xing, Phys. Lett. B 413, 396 (1997)

These are models that try to explain the flavor puzzle by setting various off diagonal Yukawa couplings to zero in the "weak isospin basis".

$$-\mathcal{L}_Y = \left(\bar{Q}_L[Y_u]u_R\tilde{\Phi} + \bar{Q}_L[Y_d]d_R\Phi + \bar{L}_L[Y_\ell]\ell_R\Phi\right)$$

Texture Models

Fritzsch, Xing, Phys. Lett. B 353, 114 (1995)
Fritzsch, Xing, Phys. Lett. B 372, 265 (1996)
Fritzsch, Xing, Phys. Lett. B 413, 396 (1997)

These are models that try to explain the flavor puzzle by setting various off diagonal Yukawa couplings to zero in the "weak isospin basis".

$$-\mathcal{L}_Y = \left(\bar{Q}_L[Y_u]u_R\tilde{\Phi} + \bar{Q}_L[Y_d]d_R\Phi + \bar{L}_L[Y_\ell]\ell_R\Phi\right)$$

3 x 3 complex matrices
(not typically diagonal)

Texture Models

By choosing matrix elements carefully, we can reproduce both the mass spectrum as well as the CKM matrix elements.

Texture Models

By choosing matrix elements carefully, we can reproduce both the mass spectrum as well as the CKM matrix elements.

The problem with that is that the “weak isospin basis” is not a well-defined basis, so what does it mean for some Yukawa couplings to vanish in that basis?

Our Goal

We would like to have a model that:

Our Goal

We would like to have a model that:

(A) Solves the hierarchy problem with same-sized Yukawa couplings and large $\tan\beta$.

Our Goal

We would like to have a model that:

(A) Solves the hierarchy problem with same-sized Yukawa couplings and large $\tan\beta$.

(B) Is flavor-basis independent.

Our Model

$$-\mathcal{L}_Y = \sum_{i=1,2} \left(\bar{Q}_L [Y_u^{(i)}] u_R \tilde{\Phi}_i + \bar{Q}_L [Y_d^{(i)}] d_R \Phi_i + \bar{L}_L [Y_\ell^{(i)}] \ell_R \Phi_i \right) + \mathrm{h.c.}$$

$Y = Y^{(1)} + Y^{(2)} \tan\beta$ is the mass matrix in units of $v \cos\beta$.

Full 3 Generation SM

Full 3 Generation SM

Now the Yukawa matrices are 3x3 matrices whose eigenvalues satisfy:

$$y^3 - (\mathrm{Tr}\ Y)\ y^2 + (\det{}_2 Y)\ y - \det Y = 0$$

$$\text{where } \det{}_2 Y = \sum_{i<j} (Y_{ii}Y_{jj} - Y_{ij}Y_{ji})$$

Full 3 Generation SM

Now the Yukawa matrices are 3x3 matrices whose eigenvalues satisfy:

$$y^3 - (\mathrm{Tr}\ Y)\ y^2 + (\det_2 Y)\ y - \det Y = 0$$

$$\text{where}\ \ \det_2 Y = \sum_{i<j} (Y_{ii}Y_{jj} - Y_{ij}Y_{ji})$$

If no conditions are imposed, we find:

Full 3 Generation SM

Now the Yukawa matrices are 3x3 matrices whose eigenvalues satisfy:

$$y^3 - (\mathrm{Tr}\ Y)\ y^2 + (\det{}_2 Y)\ y - \det Y = 0$$

$$\text{where}\ \ \det{}_2 Y = \sum_{i<j} (Y_{ii}Y_{jj} - Y_{ij}Y_{ji})$$

If no conditions are imposed, we find:

$$y_1 + y_2 + y_3 = \mathrm{Tr}\ Y = \mathrm{Tr}\ \left(Y^{(1)} + Y^{(2)}\tan\beta\right) \sim O(Y^{(2)}\tan\beta)$$

$$y_1 y_2 + y_1 y_3 + y_2 y_3 = \det{}_2 Y = \det{}_2 \left(Y^{(1)} + Y^{(2)}\tan\beta\right) \sim O\left((Y^{(2)})^2\tan^2\beta\right)$$

$$y_1 y_2 y_3 = \det Y = \det\left(Y^{(1)} + Y^{(2)}\tan\beta\right) \sim O\left((Y^{(2)})^3\tan^3\beta\right)$$

Full 3 Generation SM

Now the Yukawa matrices are 3x3 matrices whose eigenvalues satisfy:

$$y^3 - (\mathrm{Tr}\ Y)\ y^2 + (\det{}_2 Y)\ y - \det Y = 0$$

$$\text{where}\ \ \det{}_2 Y = \sum_{i<j} (Y_{ii} Y_{jj} - Y_{ij} Y_{ji})$$

If no conditions are imposed, we find:

$$y_1 + y_2 + y_3 = \mathrm{Tr}\ Y = \mathrm{Tr}\ \left(Y^{(1)} + Y^{(2)} \tan\beta\right) \sim O(Y^{(2)} \tan\beta)$$

$$y_1 y_2 + y_1 y_3 + y_2 y_3 = \det{}_2 Y = \det{}_2 \left(Y^{(1)} + Y^{(2)} \tan\beta\right) \sim O\left((Y^{(2)})^2 \tan^2\beta\right)$$

$$y_1 y_2 y_3 = \det Y = \det \left(Y^{(1)} + Y^{(2)} \tan\beta\right) \sim O\left((Y^{(2)})^3 \tan^3\beta\right)$$

therefore: $y_3 \sim y_2 \sim y_1 \sim O(Y^{(2)} \tan\beta)$

Full 3 Generation SM

Now the Yukawa matrices are 3x3 matrices whose eigenvalues satisfy:

$$y^3 - (\mathrm{Tr}\ Y)\ y^2 + (\det_2 Y)\ y - \det Y = 0$$

where $\det_2 Y = \sum_{i<j} (Y_{ii}Y_{jj} - Y_{ij}Y_{ji})$

If no conditions are imposed, we find:

$$y_1 + y_2 + y_3 = \mathrm{Tr}\ Y = \mathrm{Tr}\ \left(Y^{(1)} + Y^{(2)} \tan\beta\right) \sim O(Y^{(2)} \tan\beta)$$

$$y_1y_2 + y_1y_3 + y_2y_3 = \det_2 Y = \det_2 \left(Y^{(1)} + Y^{(2)} \tan\beta\right) \sim O\left((Y^{(2)})^2 \tan^2\beta\right)$$

$$y_1y_2y_3 = \det Y = \det \left(Y^{(1)} + Y^{(2)} \tan\beta\right) \sim O\left((Y^{(2)})^3 \tan^3\beta\right)$$

therefore: $y_3 \sim y_2 \sim y_1 \sim O(Y^{(2)} \tan\beta)$ XXX

Full 3 Generation SM

What we need is:

$$\det{}_2 Y = \det{}_2 \left(Y^{(1)} + Y^{(2)} \tan\beta \right) \sim O\left(Y^{(1)} Y^{(2)} \tan\beta \right)$$

$$\det Y = \det \left(Y^{(1)} + Y^{(2)} \tan\beta \right) \sim O\left((Y^{(1)})^3 \right)$$

Full 3 Generation SM

What we need is:

$$\det{}_2 Y = \det{}_2\left(Y^{(1)} + Y^{(2)}\tan\beta\right) \sim O\left(Y^{(1)}Y^{(2)}\tan\beta\right)$$

$$\det Y = \det\left(Y^{(1)} + Y^{(2)}\tan\beta\right) \sim O\left((Y^{(1)})^3\right)$$

which implies after a lot of algebra:

$$\boxed{\begin{aligned} y_3 &\sim O(Y^{(2)}\tan\beta) \\ y_2 &\sim O(Y^{(1)}) \\ y_1 &\sim O\left(\frac{Y^{(1)}}{Y^{(2)}\tan\beta}\right) \end{aligned}}$$

Full 3 Generation SM

Sufficient conditions for this to happen:

$$\det_2\left(Y^{(2)}Y^{(2)\dagger}\right) = 0$$

$$|\det Y| = |\det Y^{(1)}|$$

Full 3 Generation SM

For $\tan\beta = 20$:

Full 3 Generation SM

For $\tan\beta = 20:$

$$\frac{m_s(m_t)}{m_d(m_t)} \simeq 1.05\tan\beta, \qquad \frac{m_b(m_t)}{m_s(m_t)} \simeq 2.38\tan\beta, \qquad \frac{m_b(m_t)}{m_d(m_t)} \simeq 2.5\tan^2\beta$$

Hierarchy solved!

Full 3 Generation SM

For $\tan\beta = 20:$

$$\frac{m_s(m_t)}{m_d(m_t)} \simeq 1.05\tan\beta, \qquad \frac{m_b(m_t)}{m_s(m_t)} \simeq 2.38\tan\beta, \qquad \frac{m_b(m_t)}{m_d(m_t)} \simeq 2.5\tan^2\beta$$

Hierarchy solved!

$$\frac{m_c(m_t)}{m_u(m_t)} \simeq 21.6\tan\beta, \qquad \frac{m_t(m_t)}{m_c(m_t)} \simeq 13.4\tan\beta, \qquad \frac{m_t(m_t)}{m_u(m_t)} \simeq 290\tan^2\beta$$

requires (for example): $|(Y_u^{(1)})_{ij}|^2 \sim 0.1\ \mathrm{Tr}\ \left(Y_u^{(2)} Y_u^{(2)\dagger}\right)$

Full 3 Generation SM

For $\tan\beta = 20:$

$$\frac{m_s(m_t)}{m_d(m_t)} \simeq 1.05\tan\beta, \qquad \frac{m_b(m_t)}{m_s(m_t)} \simeq 2.38\tan\beta, \qquad \frac{m_b(m_t)}{m_d(m_t)} \simeq 2.5\tan^2\beta$$

Hierarchy solved!

$$\frac{m_c(m_t)}{m_u(m_t)} \simeq 21.6\tan\beta, \qquad \frac{m_t(m_t)}{m_c(m_t)} \simeq 13.4\tan\beta, \qquad \frac{m_t(m_t)}{m_u(m_t)} \simeq 290\tan^2\beta$$

requires (for example): $|(Y_u^{(1)})_{ij}|^2 \sim 0.1 \ \mathrm{Tr} \ \left(Y_u^{(2)} Y_u^{(2)\dagger}\right)$

$$\frac{m_\mu}{m_e} \simeq 10.4\tan\beta, \qquad \frac{m_\tau}{m_\mu} \simeq 0.85\tan\beta, \qquad \frac{m_\tau}{m_e} \simeq 8.8\tan^2\beta$$

can be fixed with a minor amount of tuning.

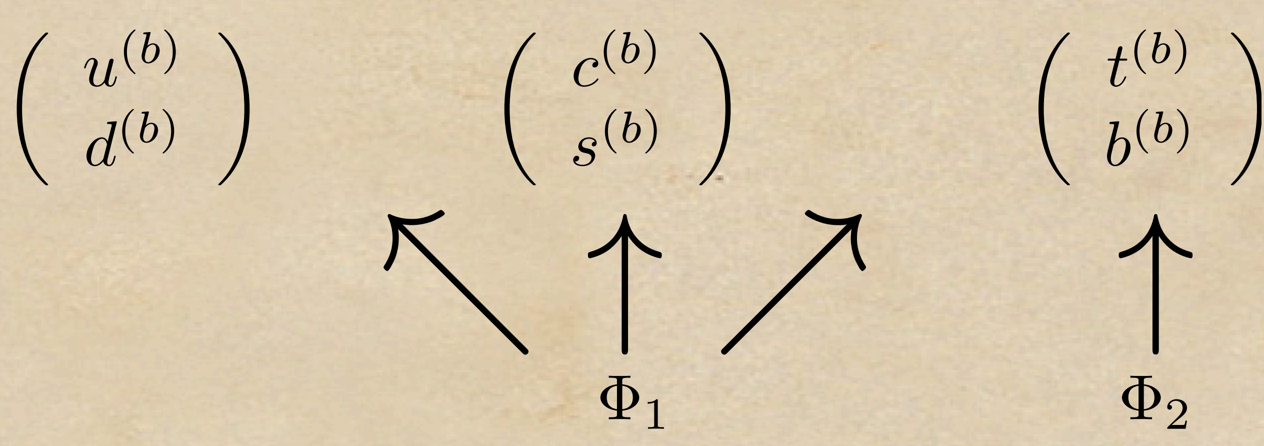
Basis (b)

The condition on $Y^{(2)}$ implies the existence of a basis where only $Y^{(2)}_{33} \neq 0$: $Y^{(2)b} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_3^{(2)} \end{pmatrix}$

Basis (b)

The condition on $Y^{(2)}$ implies the existence of a basis where only $Y_{33}^{(2)} \neq 0$: $\quad Y^{(2)b} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_3^{(2)} \end{pmatrix}$

This implies an interaction scheme in this basis:



Basis (b)

The condition on $Y^{(2)}$ implies the existence of a basis where only $Y^{(2)}_{33} \neq 0$: $Y^{(2)b} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_3^{(2)} \end{pmatrix}$

This implies an interaction scheme in this basis:

$$
\begin{array}{ccc}
\begin{pmatrix} u^{(b)} \\ d^{(b)} \end{pmatrix} & \begin{pmatrix} c^{(b)} \\ s^{(b)} \end{pmatrix} & \begin{pmatrix} t^{(b)} \\ b^{(b)} \end{pmatrix} \\
 & \nwarrow \;\; \uparrow \;\; \nearrow & \uparrow \\
 & \Phi_1 & \Phi_2
\end{array}
$$

This is also true in the mass basis up to corrections of size $O(m_{q_2}/m_{q_3}) \sim O\left(\frac{Y^{(1)}}{Y^{(2)}\tan\beta}\right)$.

$$|\det Y| = |\det Y^{(1)}|$$

This constraint is harder to interpret than in the toy model. It now puts several constraints on various Yukawa couplings:

$$Y_{11}^{(1)b} Y_{22}^{(1)b} - Y_{12}^{(1)b} Y_{21}^{(1)b} = 0$$

$$|\det Y| = |\det Y^{(1)}|$$

This constraint is harder to interpret than in the toy model. It now puts several constraints on various Yukawa couplings:

$$Y_{11}^{(1)b} Y_{22}^{(1)b} - Y_{12}^{(1)b} Y_{21}^{(1)b} = 0$$

This can be accomplished (for example) by setting

$$Y_{11}^{(1)b} = Y_{12}^{(1)b} = 0$$

$$|\det Y| = |\det Y^{(1)}|$$

This constraint is harder to interpret than in the toy model. It now puts several constraints on various Yukawa couplings:

$$Y_{11}^{(1)b} Y_{22}^{(1)b} - Y_{12}^{(1)b} Y_{21}^{(1)b} = 0$$

This can be accomplished (for example) by setting

$$Y_{11}^{(1)b} = Y_{12}^{(1)b} = 0$$

However, this is <u>NOT</u> going to remain true in the mass basis.

Cabibbo Angle

One may have $\theta_{12}^{(b\to m)} \sim \theta_C$ if one assumes a slight hierarchy: $Y_{11}^{(1)b} \sim 0.25 Y_{22}^{(1)b}$.

Cabibbo Angle

One may have $\theta_{12}^{(b\to m)} \sim \theta_C$ if one assumes a slight hierarchy: $Y_{11}^{(1)b} \sim 0.25 Y_{22}^{(1)b}$.

In this scenario, basis (b) can correspond to the "weak isospin" basis without significant tuning between u and d sectors.

Flavor Physics

Flavor Physics

In the mass basis we can write the Yukawa Lagrangian as:

$$-\mathcal{L}_Y = \bar{Q}_L[Y_u]u_R\tilde{\Phi}_1 + \bar{Q}_L[Y_u^{(2)}]u_R\tilde{\Psi} + (u \to d) + \text{ leptons} + \text{h.c.}$$

Flavor Physics

In the <u>mass basis</u> we can write the Yukawa Lagrangian as:

$$-\mathcal{L}_Y = \bar{Q}_L[Y_u]u_R\tilde{\Phi}_1 + \bar{Q}_L[Y_u^{(2)}]u_R\tilde{\Psi} + (u \to d) + \text{ leptons} + \text{h.c.}$$

Diagonal!

Flavor Physics

In the mass basis we can write the Yukawa Lagrangian as:

$$-\mathcal{L}_Y = \bar{Q}_L[Y_u]u_R\tilde{\Phi}_1 + \bar{Q}_L[Y_u^{(2)}]u_R\tilde{\Psi} + (u \to d) + \text{ leptons} + \text{h.c.}$$

Diagonal!

Only source of FCNC.

Flavor Physics

In the mass basis we can write the Yukawa Lagrangian as:

$$-\mathcal{L}_Y = \bar{Q}_L[Y_u]u_R\tilde{\Phi}_1 + \bar{Q}_L[Y_u^{(2)}]u_R\tilde{\Psi} + (u \to d) + \text{ leptons} + \text{h.c.}$$

Diagonal!

Only source of FCNC.

$$\Psi = \Phi_2 - \Phi_1 \tan\beta = -\frac{\sec\beta}{\sqrt{2}}\begin{pmatrix} -\sqrt{2}H^+ \\ \sin\epsilon\, h^0 + \cos\epsilon\, H^0 + iA^0 \end{pmatrix}$$

$$\epsilon = \alpha - \beta + \pi/2 \to 0 \text{ as } m_A \to \infty$$

Flavor Physics

In the mass basis we can write the Yukawa Lagrangian as:

$$-\mathcal{L}_Y = \bar{Q}_L[Y_u]u_R\tilde{\Phi}_1 + \bar{Q}_L[Y_u^{(2)}]u_R\tilde{\Psi} + (u \to d) + \text{ leptons} + \text{h.c.}$$

Diagonal!

Only source of FCNC.

$$\Psi = \Phi_2 - \Phi_1 \tan\beta = -\frac{\sec\beta}{\sqrt{2}}\begin{pmatrix} -\sqrt{2}H^+ \\ \sin\epsilon\; h^0 + \cos\epsilon\; H^0 + iA^0 \end{pmatrix}$$

$$\epsilon = \alpha - \beta + \pi/2 \to 0 \text{ as } m_A \to \infty$$

In this "decoupling limit" all FCNC vanish.

Flavor Physics: $K - \bar{K}$ mixing

Parameter space is: $\{Y^{(2)}_{d12},\ Y^{(2)}_{d21},\ x,\ y,\ \beta,\ \epsilon,\ m_A\}$

Flavor Physics: $K - \bar{K}$ mixing

Parameter space is: $\{Y^{(2)}_{d12},\ Y^{(2)}_{d21},\ x,\ y,\ \beta,\ \epsilon,\ m_A\}$

Assuming $Y^{(2)}_{d12} = Y^{(2)}_{d21}$ and ignoring phases, mixing is dominated by C_4 and we require (for example):

$$\boxed{m_A = 20\ \text{TeV} \qquad Y^{(2)}_{d12} = 10^{-4}}$$

Flavor Physics: $K - \bar{K}$ mixing

Parameter space is: $\{Y^{(2)}_{d12},\ Y^{(2)}_{d21},\ x,\ y,\ \beta,\ \epsilon,\ m_A\}$

Assuming $Y^{(2)}_{d12} = Y^{(2)}_{d21}$ and ignoring phases, mixing is dominated by C_4 and we require (for example):

$$\boxed{m_A = 20\ \text{TeV} \qquad Y^{(2)}_{d12} = 10^{-4}}$$

Assuming $Y^{(2)}_{d12} = 0$ and ignoring phases, mixing is sensitive to ϵ and we require (for example):

$$\boxed{m_A = 2\ \text{TeV} \quad Y^{(2)}_{d21} = 0.1 \quad \epsilon = 10^{-5}}$$

Flavor Physics: $K - \bar{K}$ mixing

Parameter space is: $\{Y^{(2)}_{d12},\ Y^{(2)}_{d21},\ x,\ y,\ \beta,\ \epsilon,\ m_A\}$

Assuming $Y^{(2)}_{d12} = Y^{(2)}_{d21}$ and ignoring phases, mixing is dominated by C_4 and we require (for example):

$$\boxed{m_A = 20 \text{ TeV} \qquad Y^{(2)}_{d12} = 10^{-4}}$$

Assuming $Y^{(2)}_{d12} = 0$ and ignoring phases, mixing is sensitive to ϵ and we require (for example):

$$\boxed{m_A = 2 \text{ TeV} \quad Y^{(2)}_{d21} = 0.1 \quad \epsilon = 10^{-5}}$$

Always for $\tan\beta = 20$ and $m_h = 120$ GeV.

Discussion

Discussion

- Flavor puzzle: where does the mass hierarchy of fermions come from?

Discussion

- Flavor puzzle: where does the mass hierarchy of fermions come from?
- Type-III 2HD model explains this with a large $\tan\beta$, as long as two additional criteria are met:

Discussion

- Flavor puzzle: where does the mass hierarchy of fermions come from?
- Type-III 2HD model explains this with a large $\tan\beta$, as long as two additional criteria are met:

$$\det{}_2(Y^{(2)}Y^{(2)\dagger}) = 0$$
$$|\det(Y)| = |\det(Y^{(1)})|$$

Discussion

- The first condition implies the existence of a special basis called "Basis (b)".

Discussion

- The first condition implies the existence of a special basis called "Basis (b)".
- We can chose this as the WIB, which would allow us to realize texture models in a well defined way.

Discussion

- The first condition implies the existence of a special basis called "Basis (b)".
- We can chose this as the WIB, which would allow us to realize texture models in a well defined way.
- The second condition is much harder to understand intuitively and requires further study.

Discussion

- The first condition implies the existence of a special basis called "Basis (b)".
- We can chose this as the WIB, which would allow us to realize texture models in a well defined way.
- The second condition is much harder to understand intuitively and requires further study.
- This talk has considered these conditions as axioms, but they can also be generated dynamically (Z_3 symmetry; PQ symmetry; ....).

Future Work

- How do these constraints do in forbidding dangerous flavor changing decays and CP violation?

Future Work

- How do these constraints do in forbidding dangerous flavor changing decays and CP violation?
- How do these constraints do in generating the full CKM matrix structure?

Future Work

- How do these constraints do in forbidding dangerous flavor changing decays and CP violation?

- How do these constraints do in generating the full CKM matrix structure?

- Now that Yukawas are the same order of magnitude, this could imply changes in Higgs production and decay expectations.....

Thank you very much!

Flavoring 2HD Models

- Type-III 2HD model explains flavor hierarchy (masses, CKM matrix) with a large $\tan\beta$, as long as two additional (flavor basis independent) criteria are met:

$$\det{}_2(Y^{(2)}Y^{(2)\dagger}) = 0$$

One Higgs only talks to third generation

$$|\det(Y)| = |\det(Y^{(1)})|$$

No pure first generation couplings

- Constraints are generic and can be used to test or generate models of flavor. FCNC also under control in the decoupling limit.
- Yukawa structure can lead to potentially interesting changes in Higgs production/decay. Work in progress...

Backup Slides

Two Higgs Doublet Models

The physical scalar states are

$$\Phi_1 = \begin{pmatrix} G^+ \cos\beta - H^+ \sin\beta \\ \frac{1}{\sqrt{2}}\left[v_1 + h_1 + i\left(G^0 \cos\beta - A^0 \sin\beta\right)\right] \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} G^+ \sin\beta + H^+ \cos\beta \\ \frac{1}{\sqrt{2}}\left[v_2 + h_2 + i\left(G^0 \sin\beta + A^0 \cos\beta\right)\right] \end{pmatrix}$$

where $v^2 = v_1^2 + v_2^2$ and $\tan\beta \equiv v_2/v_1$

Two Higgs Doublet Models

The physical scalar states are

$$\Phi_1 = \begin{pmatrix} G^+ \cos\beta - H^+ \sin\beta \\ \frac{1}{\sqrt{2}}\left[v_1 + h_1 + i\left(G^0 \cos\beta - A^0 \sin\beta\right)\right] \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} G^+ \sin\beta + H^+ \cos\beta \\ \frac{1}{\sqrt{2}}\left[v_2 + h_2 + i\left(G^0 \sin\beta + A^0 \cos\beta\right)\right] \end{pmatrix}$$

where $v^2 = v_1^2 + v_2^2$ and $\tan\beta \equiv v_2/v_1$

CP even neutral states are

$H^0 = h_1 \cos\alpha + h_2 \sin\alpha$ and $h^0 = -h_1 \sin\alpha + h_2 \cos\alpha$

Two Higgs Doublet Models

The physical scalar states are

$$\Phi_1 = \begin{pmatrix} G^+ \cos\beta - H^+ \sin\beta \\ \frac{1}{\sqrt{2}} \left[v_1 + h_1 + i \left(G^0 \cos\beta - A^0 \sin\beta \right) \right] \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} G^+ \sin\beta + H^+ \cos\beta \\ \frac{1}{\sqrt{2}} \left[v_2 + h_2 + i \left(G^0 \sin\beta + A^0 \cos\beta \right) \right] \end{pmatrix}$$

where $v^2 = v_1^2 + v_2^2$ and $\tan\beta \equiv v_2/v_1$

CP even neutral states are

$H^0 = h_1 \cos\alpha + h_2 \sin\alpha$ and $h^0 = -h_1 \sin\alpha + h_2 \cos\alpha$

where $m_{h^0}^2 \leq \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + 2\tilde{\lambda} \sin^2\beta \cos^2\beta \right) v^2$

Two Higgs Doublet Models

The physical scalar states are

$$\Phi_1 = \begin{pmatrix} G^+ \cos\beta - H^+ \sin\beta \\ \frac{1}{\sqrt{2}}\left[v_1 + h_1 + i\left(G^0\cos\beta - A^0\sin\beta\right)\right] \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} G^+ \sin\beta + H^+ \cos\beta \\ \frac{1}{\sqrt{2}}\left[v_2 + h_2 + i\left(G^0\sin\beta + A^0\cos\beta\right)\right] \end{pmatrix}$$

where $v^2 = v_1^2 + v_2^2$ and $\tan\beta \equiv v_2/v_1$

CP even neutral states are

$H^0 = h_1\cos\alpha + h_2\sin\alpha$ and $h^0 = -h_1\sin\alpha + h_2\cos\alpha$

where $m_{h^0}^2 \leq \left(\lambda_1\cos^4\beta + \lambda_2\sin^4\beta + 2\tilde{\lambda}\sin^2\beta\cos^2\beta\right)v^2$

When $m_{A,H^0,H^\pm} \to \infty \quad \Rightarrow \quad \alpha = \beta - \pi/2$.

Flavor Physics: $K - \bar{K}$ mixing

$K - \bar{K}$ mixing is described by the effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{1}{m_A^2} \sum_n C_n(x, y; \mu) \mathcal{O}_n(\mu)$$

where: $\quad x \equiv \dfrac{m_h^2}{m_A^2}\,, \qquad y \equiv \dfrac{m_H^2}{m_A^2}$

Flavor Physics: $K - \bar{K}$ mixing

$K - \bar{K}$ mixing is described by the effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{1}{m_A^2}\sum_n C_n(x,y;\mu)\mathcal{O}_n(\mu)$$

where: $x \equiv \frac{m_h^2}{m_A^2}\,, \qquad y \equiv \frac{m_H^2}{m_A^2}$

The operator basis we use is

$$\mathcal{O}_1 = (\bar{d}^i_L\gamma^\mu s^i_L)(\bar{d}^j_L\gamma_\mu s^j_L) \qquad \widetilde{\mathcal{O}}_1 = (\bar{d}^i_R\gamma^\mu s^i_R)(\bar{d}^j_R\gamma_\mu s^j_R)$$

$$\mathcal{O}_2 = (\bar{d}^i_R s^i_L)(\bar{d}^j_R s^j_L) \qquad \mathcal{O}_3 = (\bar{d}^i_R s^j_L)(\bar{d}^j_R s^i_L)$$

$$\widetilde{\mathcal{O}}_2 = (\bar{d}^i_L s^i_R)(\bar{d}^j_L s^j_R) \qquad \widetilde{\mathcal{O}}_3 = (\bar{d}^i_L s^j_R)(\bar{d}^j_L s^i_R)$$

$$\mathcal{O}_4 = (\bar{d}^i_R s^i_L)(\bar{d}^j_L s^j_R) \qquad \mathcal{O}_5 = (\bar{d}^i_R s^j_L)(\bar{d}^j_L s^i_R)$$

Flavor Physics: $K - \bar{K}$ mixing

The nonzero Wilson coefficients are (ignoring RG effects):

$$C_2 = -\frac{1}{4}(Y_{d21}^{(2)*})^2 \sec^2\beta \left(\frac{\sin^2\epsilon}{x} + \frac{\cos^2\epsilon}{y} - 1\right)$$

$$\tilde{C}_2 = -\frac{1}{4}(Y_{d12}^{(2)*})^2 \sec^2\beta \left(\frac{\sin^2\epsilon}{x} + \frac{\cos^2\epsilon}{y} - 1\right)$$

$$C_4 = -\frac{1}{2}(Y_{d12}^{(2)}Y_{d21}^{(2)*}) \sec^2\beta \left(\frac{\sin^2\epsilon}{x} + \frac{\cos^2\epsilon}{y} + 1\right)$$

Flavor Physics: $K - \bar{K}$ mixing

The nonzero Wilson coefficients are (ignoring RG effects):

$$C_2 = -\frac{1}{4}(Y_{d21}^{(2)*})^2 \sec^2\beta \left(\frac{\sin^2\epsilon}{x} + \frac{\cos^2\epsilon}{y} - 1 \right)$$

$$\tilde{C}_2 = -\frac{1}{4}(Y_{d12}^{(2)*})^2 \sec^2\beta \left(\frac{\sin^2\epsilon}{x} + \frac{\cos^2\epsilon}{y} - 1 \right)$$

$$C_4 = -\frac{1}{2}(Y_{d12}^{(2)} Y_{d21}^{(2)*}) \sec^2\beta \left(\frac{\sin^2\epsilon}{x} + \frac{\cos^2\epsilon}{y} + 1 \right)$$

In the decoupling limit, $C_2 = \tilde{C}_2 = 0$ but C_4 is finite.

Thus $K - \bar{K}$ mixing can be dangerous unless one of the Yukawa couplings vanishes.