Role of the Higgs Sector in the Generation & Flavor Problem

Wolfgang Altmannshofer
waltmann@ucsc.edu

UC SANTA CRUZ

SLAC Summer Institute 2021,
The Higgs State Fare
August 23, 2021
Part 1 (today)

- Higgs and Flavor in the Standard Model

  (flavor symmetries, flavor violating Higgs decays, Standard Model flavor puzzle)
1 Part 1 (today)

- Higgs and Flavor in the Standard Model
  (flavor symmetries, flavor violating Higgs decays, Standard Model flavor puzzle)

2 Part 2 (tomorrow)

- Higgs and Flavor beyond the Standard Model
  (extended Higgs sectors, “flavorful” Higgs bosons, flavor phenomenology, collider phenomenology)
Without the Higgs there is no Flavor in the Standard Model
The Standard Model Lagrangian

\[ \mathcal{L}_{SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 \]

\[ + \bar{\psi} \not{\!D} \psi + (D_{\mu} H)^2 + (F_{\mu \nu})^2 \]

\[ + Y H \bar{\psi} \psi + \frac{1}{\Lambda} (L H)^2 + \cdots \]
The Standard Model Lagrangian

\[ \mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 \]

\[ + \bar{\psi} \phi \psi + (D_\mu H)^2 + (F_{\mu\nu})^2 \]

\[ + Y H \bar{\psi} \psi + \frac{1}{\Lambda} (LH)^2 + \cdots \]
\[ \mathcal{L}_{SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 + \bar{\psi} \phi \psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + Y H \bar{\psi} \psi + \frac{1}{\Lambda} (LH)^2 + \cdots \]
The Standard Model Lagrangian

\[ \mathcal{L}_{SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 + \bar{\psi} \phi \psi + (D_\mu H)^2 + (F_{\mu \nu})^2 + Y H \bar{\psi} \psi + \frac{1}{\Lambda} (LH)^2 + \cdots \]

Yukawa couplings
\[ \mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 + \bar{\psi} \phi \psi + (D_{\mu} H)^2 + (F_{\mu\nu})^2 + Y H \bar{\psi} \psi + \frac{1}{\Lambda} (LH)^2 + \cdots \]

neutrino masses
### The Fermion Gauge Quantum Numbers

<table>
<thead>
<tr>
<th></th>
<th>$SU(3)$</th>
<th>$SU(2)$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^i_L$</td>
<td>$u_L$</td>
<td>$c_L$</td>
<td>$t_L$</td>
</tr>
<tr>
<td>$u_R^i$</td>
<td>$u_R$</td>
<td>$c_R$</td>
<td>$t_R$</td>
</tr>
<tr>
<td>$d_R^i$</td>
<td>$d_R$</td>
<td>$s_R$</td>
<td>$b_R$</td>
</tr>
<tr>
<td>$L^i_L$</td>
<td>$\nu e_L$</td>
<td>$\nu_{\mu L}$</td>
<td>$\nu_{\tau L}$</td>
</tr>
<tr>
<td>$e_R^i$</td>
<td>$e_R$</td>
<td>$\mu_R$</td>
<td>$\tau_R$</td>
</tr>
</tbody>
</table>

3 replica of the basic fermion family
Flavor Symmetry of the Gauge Interactions

\[ \bar{\Psi} \not{\!\!{\!\not{D}}} {\!\!\!\not{\Psi}} = \sum_{i=1}^{3} \bar{Q}_i \not{D} Q_i + \sum_{i=1}^{3} \bar{u}_i \not{D} u_i + \sum_{i=1}^{3} \bar{d}_i \not{D} d_i + \sum_{i=1}^{3} \bar{L}_i \not{D} L_i + \sum_{i=1}^{3} \bar{e}_i \not{D} e_i \]

gauge interactions are flavor universal
Flavor Symmetry of the Gauge Interactions

\[ \bar{\Psi} \mathcal{D} \Psi = \sum_{i=1}^{3} \bar{Q}_i \mathcal{D} Q_i + \sum_{i=1}^{3} \bar{u}_i \mathcal{D} u_i + \sum_{i=1}^{3} \bar{d}_i \mathcal{D} d_i + \sum_{i=1}^{3} \bar{L}_i \mathcal{D} L_i + \sum_{i=1}^{3} \bar{e}_i \mathcal{D} e_i \]

gauge interactions are flavor universal

this part of the SM Lagrangian has a large $U(3)^5$ flavor symmetry

\[ Q \rightarrow V_Q Q \ , \ u \rightarrow V_u u \ , \ d \rightarrow V_d d \ , \ L \rightarrow V_L L \ , \ e \rightarrow V_e e \]
The $U(3)^5$ flavor symmetry can be decomposed in the following way

\[
U(3)^5 = U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_D \times U(1)_E \\
\times SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E
\]
The $U(3)^5$ flavor symmetry can be decomposed in the following way

$$U(3)^5 =$$

$$U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_D \times U(1)_E$$

$$\times SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$

baryon number, lepton number, hypercharge
The $U(3)^5$ flavor symmetry can be decomposed in the following way

$$U(3)^5 = U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_D \times U(1)_E \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$

baryon number, lepton number, hypercharge

RH down-quark number, RH lepton number
The $U(3)^5$ flavor symmetry can be decomposed in the following way

$$U(3)^5 = U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_D \times U(1)_E \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$

baryon number, lepton number, hypercharge

RH down-quark number, RH lepton number

flavor mixing
the flavor symmetry is explicitly broken by the Yukawa couplings

\[
Y \ H\bar{\psi}\psi = \sum_{i,j} (\hat{Y}_u)_{ij} H^c \bar{Q}_i u_j + \sum_{i,j} (\hat{Y}_d)_{ij} H \bar{Q}_i d_j + \sum_{i,j} (\hat{Y}_\ell)_{ij} H \bar{L}_i e_j + \text{h.c.}
\]
the flavor symmetry is explicitly broken by the Yukawa couplings

$$\mathcal{L}_{Y} = \sum_{i,j} (\hat{Y}_u)_{ij} H^c \bar{Q}_i u_j + \sum_{i,j} (\hat{Y}_d)_{ij} H \bar{Q}_i d_j + \sum_{i,j} (\hat{Y}_\ell)_{ij} H \bar{L}_i e_j + \text{h.c.}$$

this part of the Lagrangian is still invariant under

$$U(1)_B \times U(1)_L \times U(1)_Y$$
the flavor symmetry is explicitly broken by the Yukawa couplings

\[ Y \ H \bar{\Psi} \Psi = \sum_{i,j} (\hat{Y}_u)_{ij} H^c \bar{Q}_i u_j + \sum_{i,j} (\hat{Y}_d)_{ij} H \bar{Q}_i d_j + \sum_{i,j} (\hat{Y}_\ell)_{ij} H \bar{L}_i \ell_j + \text{h.c.} \]

this part of the Lagrangian is still invariant under

\[ U(1)_B \times U(1)_L \times U(1)_Y \]

after electro-weak symmetry breaking we get fermion masses

\[ \rightarrow \sum_{i,j} (\hat{m}_u)_{ij} \bar{u}_i^l u_j^R + \sum_{i,j} (\hat{m}_d)_{ij} \bar{d}_i^l d_j^R + \sum_{i,j} (\hat{m}_\ell)_{ij} \bar{e}_i^l e_j^R + \text{h.c.} \]
Yukawa couplings and fermion masses are generic $3 \times 3$ matrices (not necessarily symmetric, hermitian, ...)

$$\bar{u}^L \hat{m}_u u^R + \bar{d}^L \hat{m}_d d^R + \bar{\ell}^L \hat{m}_\ell \ell^R + \text{h.c.}$$
Yukawa couplings and fermion masses are generic $3 \times 3$ matrices (not necessarily symmetric, hermitian, ...)

\[
\bar{u}^L \hat{m}_u u^R + \bar{d}^L \hat{m}_d d^R + \bar{\ell}^L \hat{m}_\ell \ell^R + \text{ h.c.}
\]

Mass matrices for the fermions can be diagonalized by bi-unitary transformations

\[
\begin{align*}
  u^L &\rightarrow V_u^L u^L, & u^R &\rightarrow V_u^R u^R, & d^L &\rightarrow V_d^L d^L, & d^R &\rightarrow V_d^R d^R \\
  \ell^L &\rightarrow V_{\ell}^L \ell^L, & \ell^R &\rightarrow V_{\ell}^R \ell^R
\end{align*}
\]
Yukawa couplings and fermion masses are generic $3 \times 3$ matrices (not necessarily symmetric, hermitian, ...)

\[
\bar{u}^L \hat{m}_u u^R + \bar{d}^L \hat{m}_d d^R + \bar{\ell}^L \hat{m}_\ell \ell^R + \text{h.c.}
\]

mass matrices for the fermions can be diagonalized by bi-unitary transformations

\[
\begin{align*}
&u^L \rightarrow V^L_u u^L, \quad u^R \rightarrow V^R_u u^R, \quad d^L \rightarrow V^L_d d^L, \quad d^R \rightarrow V^R_d d^R \\
&\ell^L \rightarrow V^L_\ell \ell^L, \quad \ell^R \rightarrow V^R_\ell \ell^R
\end{align*}
\]

\[
( V^L_u )^\dagger ( \hat{m}_u ) ( V^R_u ) = \text{diag}(m_u, m_c, m_t)
\]
\[
( V^L_d )^\dagger ( \hat{m}_d ) ( V^R_d ) = \text{diag}(m_d, m_s, m_b)
\]
\[
( V^L_\ell )^\dagger ( \hat{m}_\ell ) ( V^R_\ell ) = \text{diag}(m_e, m_\mu, m_\tau)
\]

$V^L_u$, $V^R_u$, $V^L_d$, $V^R_d$, $V^L_\ell$, $V^R_\ell$ are unitary matrices
Yukawa couplings and fermion masses are generic $3 \times 3$ matrices (not necessarily symmetric, hermitian, ...)

\[
\bar{u}^L \hat{m}_u u^R + \bar{d}^L \hat{m}_d d^R + \bar{\ell}^L \hat{m}_\ell \ell^R + \text{ h.c.}
\]

mass matrices for the fermions can be diagonalized by bi-unitary transformations

\[
\begin{align*}
\bar{u}^L &\rightarrow V_u^L u^L, & u^R &\rightarrow V_u^R u^R, \\
\bar{d}^L &\rightarrow V_d^L d^L, & d^R &\rightarrow V_d^R d^R \\
\bar{\ell}^L &\rightarrow V_\ell^L \ell^L, & \ell^R &\rightarrow V_\ell^R \ell^R
\end{align*}
\]

\[
\begin{align*}
(V_u^L)^\dagger (\hat{m}_u) (V_u^R) &= \text{diag}(m_u, m_c, m_t) \\
(V_d^L)^\dagger (\hat{m}_d) (V_d^R) &= \text{diag}(m_d, m_s, m_b) \\
(V_\ell^L)^\dagger (\hat{m}_\ell) (V_\ell^R) &= \text{diag}(m_e, m_\mu, m_\tau)
\end{align*}
\]

$V_u^L, V_u^R, V_d^L, V_d^R, V_\ell^L, V_\ell^R$ are unitary matrices

[Exercise: show that any matrix can be diagonalized by a bi-unitary transformation]
What happens to interactions in the mass eigenstate basis?

Lets start with the interactions of the W boson

\[
\bar{\psi} \gamma^\mu \gamma^5 \psi \supset \frac{g^2}{\sqrt{2}} \left( \bar{u}_i \gamma^\mu d^+_i W^+_{\mu} + \bar{d}^+_i \gamma^\mu u^+_i W^-_{\mu} \right)
\]
What happens to interactions in the mass eigenstate basis?

Let's start with the interactions of the W boson

\[ \bar{\Psi} D \Psi \supset \frac{g^2}{\sqrt{2}} \left( \bar{u}^{\mu}_{i} \gamma \mu d^{\mu}_{i} W^{+}_{\mu} + \bar{d}^{\mu}_{i} \gamma \mu u^{\mu}_{i} W^{-}_{\mu} \right) \]

\[ \rightarrow \frac{g^2}{\sqrt{2}} \left( V^{\mu}_{kj} \left( \bar{u}^{\mu}_{k} \gamma \mu d^{\mu}_{j} W^{+}_{\mu} \right) + V^{\mu*}_{kj} \left( \bar{d}^{\mu}_{j} \gamma \mu u^{\mu}_{k} W^{-}_{\mu} \right) \right) \]

\[ V_{CKM} = (V^{L}_{u})^{\dagger} (V^{L}_{d}) \] is the Cabibbo-Kobayashi-Maskawa matrix
What happens to interactions in the mass eigenstate basis?

Let's start with the interactions of the W boson

\[ \bar{\Psi} \gamma^{\mu} d_L^{\dagger} W_{\mu}^{+} + \bar{d}_L^{\dagger} \gamma^{\mu} u_L^{\dagger} W_{\mu}^{-} \]

\[ \rightarrow \frac{g^2}{\sqrt{2}} \left( V_{kj} (\bar{u}_k^{\dagger} \gamma^{\mu} d_j^{\dagger} W_{\mu}^{+}) + V_{kj}^* (\bar{d}_j^{\dagger} \gamma^{\mu} u_k^{\dagger} W_{\mu}^{-}) \right) \]

\[ V_{\text{CKM}} = (V^L_u)^\dagger (V^L_d) \]

is the Cabibbo-Kobayashi-Maskawa matrix

The CKM matrix is unitary (product of 2 unitary matrices)
How many flavor parameters are physical?

We started out with 3 Yukawa matrices: $\hat{Y}_u$, $\hat{Y}_d$, $\hat{Y}_\ell$

- **Generic rule:** Number of physical parameters =
  = Number of total free parameters
  - Number of *broken* symmetry generators

Let's start with the lepton sector

Number of total free parameters = $3 \times 3 \times 2 = 18$

(Number of 9 magnitudes and 9 phases in the lepton Yukawa matrix)

Number of broken symmetry generators = $2 \times 9 - 3 = 15$

(Number of 6 mixing angles and 12 phases in $U(3)_L \times U(3)_E$ minus 3 phases in $U(1)_e \times U(1)_\mu \times U(1)_\tau$)

$\Rightarrow$ we are left with 3 real physical parameters, which can be identified with the masses of the electron, muon, and tau.
How many flavor parameters are physical?

We started out with 3 Yukawa matrices: $\hat{Y}_u, \hat{Y}_d, \hat{Y}_\ell$

- **Generic rule:** Number of physical parameters =
  = Number of total free parameters
  - Number of broken symmetry generators

Let’s start with the lepton sector

- Number of total free parameters = $3 \times 3 \times 2 = 18$
  (9 magnitudes and 9 phases in the lepton Yukawa matrix)
Parameter Counting

How many flavor parameters are physical?

We started out with 3 Yukawa matrices: $\hat{Y}_u$, $\hat{Y}_d$, $\hat{Y}_\ell$

- Generic rule: Number of physical parameters =
  = Number of total free parameters
  - Number of broken symmetry generators

Let’s start with the lepton sector

- Number of total free parameters = $3 \times 3 \times 2 = 18$
  (9 magnitudes and 9 phases in the lepton Yukawa matrix)

- Number of broken symmetry generators = $2 \times 9 - 3 = 15$
  (6 mixing angles and 12 phases in $U(3)_L \times U(3)_E$
  minus 3 phases in $U(1)_e \times U(1)_\mu \times U(1)_\tau$)

$\Rightarrow$ we are left with 3 real physical parameters, which can be identified with the masses of the electron, muon, and tau.
Parameter Counting

How many flavor parameters are physical?

We started out with 3 Yukawa matrices: $\hat{Y}_u, \hat{Y}_d, \hat{Y}_\ell$

- **Generic rule:** Number of physical parameters = Number of total free parameters - Number of broken symmetry generators

Let’s start with the lepton sector

- Number of total free parameters = $3 \times 3 \times 2 = 18$ (9 magnitudes and 9 phases in the lepton Yukawa matrix)

- Number of broken symmetry generators = $2 \times 9 - 3 = 15$ (6 mixing angles and 12 phases in $U(3)_L \times U(3)_E$ minus 3 phases in $U(1)_e \times U(1)_\mu \times U(1)_\tau$)

$\Rightarrow$ we are left with **3 real physical parameters**, which can be identified with the masses of the electron, muon, and tau
Now the quark sector:

- Number of total free parameters $= 2 \times 3 \times 3 \times 2 = 36$
  - (18 magnitudes and 18 phases in the quark Yukawa matrices)
Now the quark sector:

- Number of total free parameters $= 2 \times 3 \times 3 \times 2 = 36$
  (18 magnitudes and 18 phases in the quark Yukawa matrices)

- Number of broken symmetry generators $= 3 \times 9 - 1 = 26$
  (9 mixing angles and 18 phases in $U(3)_Q \times U(3)_U \times U(3)_D$
  minus 1 phase in the unbroken symmetry $U(1)_B$)
Now the quark sector:

- Number of total free parameters $= 2 \times 3 \times 3 \times 2 = 36$
  (18 magnitudes and 18 phases in the quark Yukawa matrices)

- Number of broken symmetry generators $= 3 \times 9 - 1 = 26$
  (9 mixing angles and 18 phases in $U(3)_Q \times U(3)_U \times U(3)_D$
  minus 1 phase in the unbroken symmetry $U(1)_B$)

$\Rightarrow$ we are left with 10 physical parameters, one of which is a phase;
  can be identified with the 6 masses of the quarks
  + 3 CKM mixing angles + 1 CKM phase
Let's look at the couplings of the Higgs

\[ Y H \bar{\psi} \psi \supset \frac{1}{\sqrt{2}} h \left( (\hat{Y}_u)_{ij} \bar{u}_i^L u_j^R + (\hat{Y}_d)_{ij} \bar{d}_i^L d_j^R + (\hat{Y}_\ell)_{ij} \bar{\ell}_i^L \ell_j^R + h.c \right) \]
Let's look at the couplings of the Higgs

\[ Y H \bar{\psi} \psi \supset \frac{1}{\sqrt{2}} h \left( (\hat{Y}_u)_{ij} \bar{u}_i^L u_j^R + (\hat{Y}_d)_{ij} \bar{d}_i^L d_j^R + (\hat{Y}_\ell)_{ij} \bar{\ell}_i^L \ell_j^R + h.c \right) \]

\[ \rightarrow \frac{1}{\sqrt{2}} h \left( (\hat{Y}_u)_{ij} (V_u^L)_{im} (V_u^R)_{jn} \bar{u}_m^L u_n^R + (\hat{Y}_d)_{ij} (V_d^L)_{im} (V_d^R)_{jn} \bar{d}_m^L d_n^R \right. \]

\[ \left. + (\hat{Y}_\ell)_{ij} (V_\ell^L)_{im} (V_\ell^R)_{jn} \bar{\ell}_m^L \ell_n^R + h.c \right) \]
No Flavor Changing Neutral Currents at Tree Level

Let's look at the couplings of the Higgs

\[
\mathcal{L} = \frac{1}{\sqrt{2}} h \left( (\hat{Y}_u)_{ij} \bar{u}^L_i u^R_j + (\hat{Y}_d)_{ij} \bar{d}^L_i d^R_j + (\hat{Y}_\ell)_{ij} \bar{\ell}^L_i \ell^R_j + h.c. \right)
\]

\[
\rightarrow \frac{1}{\sqrt{2}} h \left( (\hat{Y}_u)_{ij} (V^L_u)_{im} (V^R_u)_{jn} \bar{u}^L_m u^R_n + (\hat{Y}_d)_{ij} (V^L_d)_{im} (V^R_d)_{jn} \bar{d}^L_m d^R_n + (\hat{Y}_\ell)_{ij} (V^L_\ell)_{im} (V^R_\ell)_{jn} \bar{\ell}^L_m \ell^R_n + h.c. \right)
\]

\[
= h \left( \frac{(m^\text{diag}_u)_i}{\nu} \bar{u}^L_i u^R_i + \frac{(m^\text{diag}_d)_i}{\nu} \bar{d}^L_i d^R_i + \frac{(m^\text{diag}_\ell)_i}{\nu} \bar{\ell}^L_i \ell^R_i + h.c. \right)
\]
No Flavor Changing Neutral Currents at Tree Level

Let's look at the couplings of the Higgs

\[ \mathcal{Y} \ H \bar{\Psi} \Psi \supset \frac{1}{\sqrt{2}} h \left( (\hat{\mathcal{Y}}_u)_{ij} \bar{u}_i^L u_j^R + (\hat{\mathcal{Y}}_d)_{ij} \bar{d}_i^L d_j^R + (\hat{\mathcal{Y}}_\ell)_{ij} \bar{\ell}_i^L \ell_j^R + h.c \right) \]

\[ \rightarrow \frac{1}{\sqrt{2}} h \left( (\hat{\mathcal{Y}}_u)_{ij} (V^L_{ij})^*_m (V^R_{ij})^*_n \bar{u}_m^L u_n^R + (\hat{\mathcal{Y}}_d)_{ij} (V^L_{ij})^*_m (V^R_{ij})^*_n \bar{d}_m^L d_n^R \right. \]

\[ \left. + (\hat{\mathcal{Y}}_\ell)_{ij} (V^L_{ij})^*_m (V^R_{ij})^*_n \bar{\ell}_m^L \ell_n^R + h.c \right) \]

\[ = h \left( (m^\text{diag}_{u})_{i} \bar{u}_i^L u_i^R + (m^\text{diag}_{d})_{i} \bar{d}_i^L d_i^R + (m^\text{diag}_{\ell})_{i} \bar{\ell}_i^L \ell_i^R + h.c \right) \]

[Exercise: show that also the couplings of the photon, Z, and the gluons are flavor diagonal]

\[ \rightarrow \text{There are no Flavor Changing Neutral Currents (FCNCs) in the Standard Model at tree level (GIM mechanism)} \]
Flavor Transitions

no FCNCs at tree level

The transitions among the generations are mediated by the $W^\pm$ bosons and their relative strength is parametrized by the CKM matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Note that without the Higgs, the concept of the CKM matrix does not exist.
Flavor Transitions

no FCNCs at tree level

transitions among the generations are mediated by the $W^\pm$ bosons and their relative strength is parametrized by the CKM matrix

$$V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}$$
Flavor Transitions

no FCNCs at tree level

transitions among the generations are mediated by the $W^\pm$ bosons and their relative strength is parametrized by the CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

note that without the Higgs the concept of the CKM matrix does not exist
Flavor Changing Neutral Currents at Loop Level

FCNCs can arise at the loop level. They are suppressed by loop factors and small CKM elements.
Flavor Changing Neutral Currents at Loop Level

FCNCs can arise at the loop level. They are suppressed by loop factors and small CKM elements.
the tree level couplings of the Higgs to fermion mass eigenstates are flavor diagonal and CP conserving

\[
\frac{1}{v} \begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix}
\]
the tree level couplings of the Higgs to fermion mass eigenstates are
flavor diagonal and CP conserving

\[ \frac{1}{\sqrt{v}} \begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix} + \text{loop factors} \times \begin{pmatrix} \ast & \ast & \ast \\ \ast & \ast & \ast \\ \ast & \ast & \ast \end{pmatrix} \]

at the loop level there can be also
flavor changing and CP violating couplings

- How big are the flavor changing and CP violating couplings?
Recap: Flavor Properties of the Higgs in the SM

The tree level couplings of the Higgs to fermion mass eigenstates are

\[ \frac{1}{\nu} \begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix} + \text{loop factors} \times \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \]

At the loop level there can be also

flavor changing and CP violating couplings

- How big are the flavor changing and CP violating couplings?
- What are the SM predictions?
Recap: Flavor Properties of the Higgs in the SM

The tree level couplings of the Higgs to fermion mass eigenstates are 

\[
\begin{pmatrix}
0 & 0 & 0 \\
0 & m_{c,s,\mu} & 0 \\
0 & 0 & m_{t,b,\tau}
\end{pmatrix}
\]


flavor diagonal and CP conserving

At the loop level there can be also 

\[
\begin{pmatrix}
\star & \star & \star \\
\star & \star & \star \\
\star & \star & \star
\end{pmatrix}
\]


flavor changing and CP violating couplings

How big are the flavor changing and CP violating couplings?
What are the SM predictions?
What do we know experimentally?
To understand the parametric dependence of flavor changing decay rates it is useful to promote the Yukawa couplings to “spurions”.
To understand the parametric dependence of flavor changing decay rates it is useful to promote the Yukawa couplings to "spurions". We assign them transformation properties under the $SU(3)^5$ flavor symmetry, such that the SM Lagrangian is formally invariant.
To understand the parametric dependence of flavor changing decay rates it is useful to promote the Yukawa couplings to “spurions”.

We assign them transformation properties under the $SU(3)^5$ flavor symmetry, such that the SM Lagrangian is formally invariant.

This allows us to track how Yukawa couplings need to show up in amplitudes simply based on symmetry arguments.
To understand the parametric dependence of flavor changing decay rates it is useful to promote the Yukawa couplings to “spurions”.

We assign them transformation properties under the $SU(3)^5$ flavor symmetry, such that the SM Lagrangian is formally invariant.

This allows us to track how Yukawa couplings need to show up in amplitudes simply based on symmetry arguments

\[ Y \ H \bar{\psi} \psi \supset \sum_{i,j} (\hat{Y}_u)_{ij} H^c \bar{Q}_i u_j + \sum_{i,j} (\hat{Y}_d)_{ij} H \bar{Q}_i d_j + \sum_{i,j} (\hat{Y}_\ell)_{ij} H \bar{L}_i e_j + \text{h.c.} \]

- quark and lepton fields are triplets under the respective flavor $SU(3)$
  \[ Q \rightarrow 3_Q \ , \quad u \rightarrow 3_U \ , \quad d \rightarrow 3_D \ , \quad L \rightarrow 3_L \ , \quad e \rightarrow 3_E \]
Flavor Changing Decays: Spurion Analysis

- To understand the parametric dependence of flavor changing decay rates it is useful to promote the Yukawa couplings to “spurions”.
- We assign them transformation properties under the $SU(3)^5$ flavor symmetry, such that the SM Lagrangian is formally invariant.
- This allows us to track how Yukawa couplings need to show up in amplitudes simply based on symmetry arguments.

$$Y \ H \bar{\psi} \psi \supset \sum_{i,j} (\hat{Y}_u)_{ij} H^c \bar{Q}_i u_j + \sum_{i,j} (\hat{Y}_d)_{ij} H \bar{Q}_i d_j + \sum_{i,j} (\hat{Y}_\ell)_{ij} H \bar{L}_i e_j + \text{h.c.}$$

- Quark and lepton fields are triplets under the respective flavor $SU(3)$
  - $Q \rightarrow 3_Q$, $u \rightarrow 3_U$, $d \rightarrow 3_D$, $L \rightarrow 3_L$, $e \rightarrow 3_E$

- To restore invariance under the $SU(3)^5$ flavor symmetry, we declare
  - $\hat{Y}_u \rightarrow 3_Q \times \bar{3}_U$, $\hat{Y}_d \rightarrow 3_Q \times \bar{3}_D$, $\hat{Y}_\ell \rightarrow 3_L \times \bar{3}_E$
Let's consider a flavor changing decay of the Higgs into down quarks

\[ h \rightarrow \bar{d}_i^L d_j^R \]
Let’s consider a flavor changing decay of the Higgs into down quarks

\[ h \rightarrow \bar{d}_i^L d_j^R \]

Removing the quark spinors, the decay amplitude has to transform as

\[ A(h \rightarrow \bar{d}_i^L d_j^R) \rightarrow 3_Q \times \bar{3}_D \]
Let’s consider a flavor changing decay of the Higgs into down quarks

\[ h \rightarrow \bar{d}_i^L d_j^R \]

Removing the quark spinors, the decay amplitude has to transform as

\[ A(h \rightarrow \bar{d}_i^L d_j^R) \rightarrow 3_Q \times \bar{3}_D \]

\[ A(h \rightarrow \bar{d}_i^L d_j^R) \propto \hat{Y}_d \] diagonal in the mass basis \( \rightarrow \) no flavor change
Flavor Changing Decays: Spurion Analysis

Let’s consider a flavor changing decay of the Higgs into down quarks

\[ h \rightarrow \bar{d}_i^L d_j^R \]

Removing the quark spinors, the decay amplitude has to transform as

\[ \mathcal{A}(h \rightarrow \bar{d}_i^L d_j^R) \rightarrow 3_Q \times 3_D \]

\[ \mathcal{A}(h \rightarrow \bar{d}_i^L d_j^R) \propto \hat{Y}_d \text{ diagonal in the mass basis} \rightarrow \text{no flavor change} \]

\[ \mathcal{A}(h \rightarrow \bar{d}_i^L d_j^R) \propto \hat{Y}_d \hat{Y}_d^\dagger \hat{Y}_d \text{ diagonal in the mass basis} \rightarrow \text{no flavor change} \]
Let's consider a flavor changing decay of the Higgs into down quarks

\[ h \rightarrow \bar{d}_i \bar{d}_j^R \]

Removing the quark spinors, the decay amplitude has to transform as

\[ \mathcal{A}(h \rightarrow \bar{d}_i \bar{d}_j^R) \rightarrow \mathbf{3}_Q \times \mathbf{ar{3}}_D \]

\[ \mathcal{A}(h \rightarrow \bar{d}_i \bar{d}_j^R) \propto \hat{Y}_d \text{ diagonal in the mass basis } \rightarrow \text{ no flavor change} \]

\[ \mathcal{A}(h \rightarrow \bar{d}_i \bar{d}_j^R) \propto \hat{Y}_d \hat{Y}_d^\dagger \hat{Y}_d \text{ diagonal in the mass basis } \rightarrow \text{ no flavor change} \]

\[ \mathcal{A}(h \rightarrow \bar{d}_i \bar{d}_j^R) \propto \hat{Y}_u \hat{Y}_u^\dagger \hat{Y}_d \text{ not diagonal in the mass basis } \rightarrow \text{ flavor change} \]
Let’s be more concrete and consider $h \to \bar{s}b$

In the **mass eigenbasis**, the amplitude has to be proportional to

$$\mathcal{A}(h \to \bar{s}b) \sim \frac{1}{16\pi^2} \left( (V_d^L)^\dagger \hat{Y}_u \hat{Y}_d^\dagger (V_d^R) \right)_{23}$$
Let’s be more concrete and consider $h \to \bar{s}b$

In the **mass eigenbasis**, the amplitude has to be proportional to

$$\mathcal{A}(h \to \bar{s}b) \sim \frac{1}{16\pi^2} \left( (V^L_d)\dagger \hat{Y}_u \hat{Y}_u \hat{Y}_d (V^R_d) \right)_{23}$$

$$\sim \frac{1}{16\pi^2} \left( (V^L_d)\dagger (V^L_u)(V^L_u)\dagger \hat{Y}_u (V^L_u)(V^L_u)\dagger \hat{Y}_u (V^L_d)(V^L_d)\dagger Y_d (V^R_d) \right)_{23}$$
Let’s be more concrete and consider $h \rightarrow \bar{s}b$

In the **mass eigenbasis**, the amplitude has to be proportional to

$$
\mathcal{A}(h \rightarrow \bar{s}b) \sim \frac{1}{16\pi^2} ((V_d^L)^\dagger \hat{Y}_u \hat{Y}_u \hat{Y}_d (V_d^R))_{23}
$$

$$
\sim \frac{1}{16\pi^2} ((V_d^L)^\dagger (V_u^L)(V_u^L)^\dagger \hat{Y}_u (V_u^L)(V_u^L)^\dagger \hat{Y}_u (V_u^L)(V_u^L)^\dagger Y_d (V_d^R))_{23}
$$

$$
\sim \frac{1}{16\pi^2} \frac{1}{v^3} (V_{\text{CKM}}^\dagger \hat{m}_u^{\text{diag}})^2 V_{\text{CKM}} \hat{m}_d^{\text{diag}})_{23}
$$
Let’s be more concrete and consider $h \rightarrow \bar{s}b$

In the **mass eigenbasis**, the amplitude has to be proportional to

$$
\mathcal{A}(h \rightarrow \bar{s}b) \sim \frac{1}{16\pi^2} ((V^L_d)^\dagger \hat{Y}_u \hat{Y}^\dagger_u \hat{Y}_d (V^R_d))_{23}
$$

$$
\sim \frac{1}{16\pi^2} ((V^L_d)^\dagger (V^L_u)(V^L_u)^\dagger \hat{Y}_u (V^L_u)(V^L_u)^\dagger \hat{Y}^\dagger_u (V^L_d)(V^L_d)^\dagger Y_d (V^R_d))_{23}
$$

$$
\sim \frac{1}{16\pi^2} \frac{1}{\nu^3} (V^\dagger_{CKM}(\hat{m}^\text{diag}_u)^2 V_{CKM} \hat{m}^\text{diag}_d)_{23}
$$

$$
\sim \frac{1}{16\pi^2} \frac{m_b m_t^2}{\nu^3} V^*_{ts} V_{tb}
$$
Let’s be more concrete and consider $h \rightarrow \bar{s}b$

In the mass eigenbasis, the amplitude has to be proportional to

$$\mathcal{A}(h \rightarrow \bar{s}b) \sim \frac{1}{16\pi^2} \left( (V_d^L)\dagger \hat{Y}_u \hat{Y}_d (V_d^R) \right)_{23}$$

$$\sim \frac{1}{16\pi^2} \left( (V_d^L)\dagger (V_u^L)(V_u^L)\dagger \hat{Y}_u (V_u^L)(V_u^L)\dagger \hat{Y}_d (V_d^L)(V_d^L)\dagger Y_d (V_d^R) \right)_{23}$$

$$\sim \frac{1}{16\pi^2} \frac{1}{v^3} (V_{\text{CKM}}^{\dagger} (\hat{m}_u^{\text{diag}})^2 V_{\text{CKM}} \hat{m}_d^{\text{diag}})_{23}$$

$$\sim \frac{1}{16\pi^2} \frac{m_b m_t^2}{v^3} V_{ts} V_{tb}$$

[Exercise: Reproduce this result using Feynman diagrams / Feynman rules]
Estimate of Flavor Changing Decay Rates

\[
\begin{align*}
\text{BR}(h \rightarrow \bar{s}b) & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{v^4} |V_{ts}^* V_{tb}|^2 \sim 10^{-7} \\
\text{BR}(h \rightarrow \bar{b}b) & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{v^4} |V_{td}^* V_{tb}|^2 \sim 10^{-9} \\
\text{BR}(h \rightarrow \bar{d}b) & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{v^4} \frac{m_s^2}{m_b^2} |V_{td}^* V_{ts}|^2 \sim 10^{-15} \\
\text{BR}(h \rightarrow \bar{b}b) & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{v^4} |V_{ub}^* V_{cb}|^2 \sim 10^{-19}
\end{align*}
\]
Estimate of Flavor Changing Decay Rates

\[
\begin{align*}
\frac{\text{BR}(h \to \bar{s}b)}{\text{BR}(h \to \bar{b}b)} & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{V^4} |V_{ts}^* V_{tb}|^2 \sim 10^{-7} \\
\frac{\text{BR}(h \to \bar{d}b)}{\text{BR}(h \to \bar{b}b)} & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{V^4} |V_{td}^* V_{tb}|^2 \sim 10^{-9} \\
\frac{\text{BR}(h \to \bar{d}s)}{\text{BR}(h \to \bar{b}b)} & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4 m_s^2}{V^4 m_b^2} |V_{td}^* V_{ts}|^2 \sim 10^{-15} \\
\frac{\text{BR}(h \to \bar{u}c)}{\text{BR}(h \to \bar{c}c)} & \sim \frac{1}{(16\pi^2)^2} \frac{m_b^4}{V^4} |V_{ub}^* V_{cb}|^2 \sim 10^{-19}
\end{align*}
\]

\[
\text{BR}(h \to \bar{e}\mu) = \text{BR}(h \to \bar{\tau}e) = \text{BR}(h \to \bar{\tau}\mu) = 0
\]

(In the absence of neutrino masses)
Estimate of Flavor Changing Decay Rates

\[
\begin{align*}
\frac{\text{BR}(h \to \bar{s}b)}{\text{BR}(h \to \bar{b}b)} & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{V^4} \left| V_{ts}^* V_{tb} \right|^2 \sim 10^{-7} \\
\frac{\text{BR}(h \to \bar{d}b)}{\text{BR}(h \to \bar{b}b)} & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{V^4} \left| V_{td}^* V_{tb} \right|^2 \sim 10^{-9} \\
\frac{\text{BR}(h \to \bar{d}s)}{\text{BR}(h \to \bar{b}b)} & \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{V^4} \frac{m_s^2}{m_b^2} \left| V_{td}^* V_{ts} \right|^2 \sim 10^{-15} \\
\frac{\text{BR}(h \to \bar{u}c)}{\text{BR}(h \to \bar{c}c)} & \sim \frac{1}{(16\pi^2)^2} \frac{m_b^4}{V^4} \left| V_{ub}^* V_{cb} \right|^2 \sim 10^{-19}
\end{align*}
\]

\[\text{BR}(h \to \bar{e}\mu) = \text{BR}(h \to \bar{\tau}e) = \text{BR}(h \to \bar{\tau}\mu) = 0\]

(In the absence of neutrino masses)

All those branching ratios are far below foreseeable sensitivities.

Flavor changing Higgs decay are clear signatures of physics beyond the Standard Model.
Flavor Conserving Couplings: Experiment

good agreement with SM predictions!
Let’s assume the Higgs has flavor changing couplings (due to some physics beyond the SM)

What do we know about the flavor changing couplings experimentally?
Let’s assume the Higgs has **flavor changing couplings** (due to some physics beyond the SM)

What do we know about the flavor changing couplings experimentally?

In many cases, the highest sensitivity comes from **low energy flavor observables**.
Let’s assume the Higgs has **flavor changing couplings**
(due to some physics beyond the SM)

What do we know about the flavor changing couplings experimentally?

In many cases, the highest sensitivity comes from low energy flavor observables.

For example, **flavor changing higgs-quark couplings** are strongly constrained by **neutral meson oscillations**

Such a diagram gives tree-level contributions to Kaon mixing. Kaon mixing is known to have extreme sensitivity to “flavored” new physics.
Estimating Sensitivity of Meson Mixing

**SM contribution**

\[
M_{12}^K \sim \frac{G_F^2}{16\pi^2} f_K^2 m_W^2 (V_{td}^* V_{ts})^2
\]
Estimating Sensitivity of Meson Mixing

**SM contribution**

\[ M_{12}^K \sim \frac{G_F^2}{16\pi^2} f_K^2 m_W^2 (V_{td}^* V_{ts})^2 \]

**Flavor changing Higgs**

\[ M_{12}^K \sim f_K^2 \frac{m_K^2}{m_s^2} \frac{Y_{sd}^2}{m_h^2} \]
Estimating Sensitivity of Meson Mixing

SM contribution

$$M_{12}^K \sim \frac{G_F^2}{16\pi^2} f_K^2 m_W^2 (V_{td}^* V_{ts})^2$$

Flavor changing Higgs

$$M_{12}^K \sim f^2_K \frac{m_K^2}{m_s^2} \frac{Y_{sd}^2}{m_h^2}$$

Generously allowing an O(1) contribution from new physics we can estimate a bound on the flavor changing coupling

$$Y_{sd}^2 \lesssim \frac{m_s^2}{m_K^2} \frac{1}{16\pi^2} (V_{td}^* V_{ts})^2 \sim 10^{-10}$$
### Summary of Constraints: Quarks

<table>
<thead>
<tr>
<th>Technique</th>
<th>Coupling</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$ oscillations [48]</td>
<td>$</td>
<td>Y_{ud}</td>
</tr>
<tr>
<td>$B_d^0$ oscillations [48]</td>
<td>$</td>
<td>Y_{db}</td>
</tr>
<tr>
<td>$B_s^0$ oscillations [48]</td>
<td>$</td>
<td>Y_{sb}</td>
</tr>
<tr>
<td>$K^0$ oscillations [48]</td>
<td>$\text{Re}(Y_{ds}^2)$, $\text{Re}(Y_{sd}^2)$, $\text{Im}(Y_{ds}^2)$, $\text{Im}(Y_{sd}^2)$, $\text{Re}(Y_{ds}^*Y_{sd})$, $\text{Im}(Y_{ds}^*Y_{sd})$</td>
<td>$[-5.9 \ldots 5.6] \times 10^{-10}$, $[-2.9 \ldots 1.6] \times 10^{-12}$, $[-5.6 \ldots 5.6] \times 10^{-11}$, $[-1.4 \ldots 2.8] \times 10^{-13}$</td>
</tr>
<tr>
<td>single-top production [49]</td>
<td>$\sqrt{</td>
<td>Y_{tc}</td>
</tr>
<tr>
<td>$t \to hj$ [50]</td>
<td>$\sqrt{</td>
<td>Y_{tc}</td>
</tr>
<tr>
<td>$D^0$ oscillations [48]</td>
<td>$</td>
<td>Y_{ut}Y_{ct}</td>
</tr>
<tr>
<td>neutron EDM [37]</td>
<td>$\text{Im}(Y_{ut}Y_{tu})$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Blanenburg, Ellis, Isidori 1202.5704; Harnik, Kopp, Zupan 1209.1397; ...
Lepton flavor violating Higgs couplings can be constrained by processes like $\mu \to e\gamma$, $\tau \to \mu\gamma$, ...
Lepton flavor violating Higgs couplings can be constrained by processes like $\mu \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$, ...

In some cases 2-loop effects are important
Lepton flavor violating Higgs couplings can be constrained by processes like $\mu \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$, ...

In some cases 2-loop effects are important

[Note: loop calculations with modified Higgs couplings that are introduced by hand might not lead to consistent results.]
Summary of Constraints: Leptons

<table>
<thead>
<tr>
<th>Channel</th>
<th>Coupling</th>
<th>Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$\sqrt{</td>
<td>Y_{\mu e}</td>
</tr>
<tr>
<td>$\mu \to 3e$</td>
<td>$\sqrt{</td>
<td>Y_{\mu e}</td>
</tr>
<tr>
<td>electron $g - 2$</td>
<td>$\text{Re}(Y_{e\mu} Y_{\mu e}^*)$</td>
<td>$-0.019 \ldots 0.026$</td>
</tr>
<tr>
<td>electron EDM</td>
<td>$</td>
<td>\text{Im}(Y_{e\mu} Y_{\mu e}^*)</td>
</tr>
<tr>
<td>$\mu \to e$ conversion</td>
<td>$\sqrt{</td>
<td>Y_{\mu e}</td>
</tr>
<tr>
<td>$M - \bar{M}$ oscillations</td>
<td>$</td>
<td>Y_{\mu e} + Y_{e\mu}^*</td>
</tr>
<tr>
<td>$\tau \to e\gamma$</td>
<td>$\sqrt{</td>
<td>Y_{\tau e}</td>
</tr>
<tr>
<td>$\tau \to 3e$</td>
<td>$\sqrt{</td>
<td>Y_{\tau e}</td>
</tr>
<tr>
<td>electron $g - 2$</td>
<td>$\text{Re}(Y_{e\tau} Y_{\tau e}^*)$</td>
<td>$[-2.1 \ldots 2.9] \times 10^{-3}$</td>
</tr>
<tr>
<td>electron EDM</td>
<td>$</td>
<td>\text{Im}(Y_{e\tau} Y_{\tau e}^*)</td>
</tr>
<tr>
<td>$\tau \to \mu\gamma$</td>
<td>$\sqrt{</td>
<td>Y_{\tau \mu}</td>
</tr>
<tr>
<td>$\tau \to 3\mu$</td>
<td>$\sqrt{</td>
<td>Y_{\tau \mu}</td>
</tr>
<tr>
<td>muon $g - 2$</td>
<td>$\text{Re}(Y_{\mu\tau} Y_{\tau \mu}^*)$</td>
<td>$(2.7 \pm 0.75) \times 10^{-3}$</td>
</tr>
<tr>
<td>muon EDM</td>
<td>$\text{Im}(Y_{\mu\tau} Y_{\tau \mu}^*)$</td>
<td>$-0.8 \ldots 1.0$</td>
</tr>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$(</td>
<td>Y_{\tau \mu} Y_{e\tau}</td>
</tr>
</tbody>
</table>

Blankenburg, Ellis, Isidori 1202.5704; Harnik, Kopp, Zupan 1209.1397; ...
In the case of $h \rightarrow \tau \mu$ and $h \rightarrow \tau e$ couplings, direct searches at the LHC have the highest sensitivity.
In the case of $h \to \tau \mu$ and $h \to \tau e$ couplings, direct searches at the LHC have the highest sensitivity.

But $\mu \to e\gamma$ strongly constrains $\text{BR}(h \to \mu e)$ and $\text{BR}(h \to \tau \mu) \times \text{BR}(h \to \tau e)$
New physics that generates the LFV Higgs coupling, will typically also give direct contributions to radiative decays \cite{Dorsner:2015jka}.

Contributions to lepton Yukawa couplings (a), electromagnetic dipole (b)
New physics that generates the LFV Higgs coupling will typically also give direct contributions to radiative decays (Dorsner et al. 1502.07784)

\[
\text{Contributions to lepton Yukawa couplings (a), electromagnetic dipole (b)}
\]

Generic upper bound in many models

\[
\text{BR}(h \rightarrow \tau \mu) \sim 26 \times \text{BR}(\tau \rightarrow \mu \gamma) \lesssim 10^{-6}
\]

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Note: this is not a robust bound. It is based on theory bias.

⇒ If LFV Higgs decays are observed above that bound, we learn something profound
So far, all measured Higgs properties agree with SM predictions. But in the SM, quark and lepton flavor is only accommodated, not explained.
Flavor Hierarchies

Particle masses in GeV/c^2

- $m_t$
- $m_b$
- $m_c$
- $m_s$
- $m_d$
- $m_u$
- $m_e$
- $m_\tau$
- $m_\mu$

$m_t$, $m_b$, $m_c$, $m_s$, $m_d$, $m_u$, $m_e$, $m_\tau$, $m_\mu$. 

Wolfgang Altmannshofer
Higgs & Flavor - Theory
Flavor Hierarchies

\[ |V_{ub}| \quad |V_{us}| \quad |V_{ts}| \quad |V_{td}| \quad |V_{cb}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{tb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| \quad |V_{cd}| \quad |V_{cs}| \quad |V_{cb}| \quad |V_{td}| \quad |V_{ct}| }
Flavor Hierarchies

PMNS elements

$|U_{11}|$ $|U_{12}|$ $|U_{23}|$ $|U_{33}|$

$|U_{21}|$ $|U_{31}|$

$|U_{22}|$ $|U_{32}|$

$|U_{13}|$

$10^{-3}$ $0.01$ $0.1$ $1$
The Standard Model Flavor Puzzle

Why are there three flavors of quarks and leptons?

What is the origin of the hierarchies in the fermion spectrum?

What is the origin of the hierarchies in the quark mixing?

Is lepton mixing anarchic?
Addressing the SM Flavor Puzzle

- Option 1: Electroweak symmetry breaking is as in the SM
  - Hierarchical structure of fermion masses and CKM matrix originates solely from the Yukawa couplings
  - Introduce new physics that gives the Yukawa couplings a hierarchical structure
Option 1: Electroweak symmetry breaking is as in the SM
→ Hierarchical structure of fermion masses and CKM matrix originates solely from the Yukawa couplings
→ Introduce new physics that gives the Yukawa couplings a hierarchical structure

Option 2: Extended electroweak symmetry breaking sector
→ Small quark and lepton masses from a subdominant source of electroweak symmetry breaking
Origin of Hierarchical Yukawa Couplings

- loop effects
- flavor symmetries
- extra dimensions
- flavor clockwork
fermion masses are forbidden by flavor symmetries and arise only after spontaneous breaking of the symmetry.

(Froggatt, Nielsen '79; ...)

Simple U(1) model:

\[ Q(t_L) = Q(t_R) = 0 \]
\[ Q(u_L) = -Q(u_R) = 3 \]
\[ Q(h) = 0 \]
\[ Q(\varphi) = -1 \]

\[ h t_R t_L \]

\[ \frac{\varphi^6}{M^6} h u_R u_L \]
mass and mixing hierarchies given by powers of the “spurion” $\langle \varphi \rangle / M$. In the example from the previous slide we have

$$
\frac{m_u}{m_t} \sim \left( \frac{\langle \varphi \rangle}{M} \right)^6 \sim \epsilon^6
$$
mass and mixing hierarchies given by powers of the “spurion” $\langle \varphi \rangle / M$. In the example from the previous slide we have

$$\frac{m_u}{m_t} \sim \left( \frac{\langle \varphi \rangle}{M} \right)^6 \sim \epsilon^6$$

Exercise: Construct a U(1) model with the following hierarchies

\[
\begin{align*}
m_u &\sim \epsilon^6, \quad m_c \sim \epsilon^3, \quad m_t \sim 1 \\
m_d &\sim \epsilon^5, \quad m_s \sim \epsilon^4, \quad m_b \sim \epsilon^2
\end{align*}
\]

Which predictions does your model make for the CKM hierarchies?
The flavor clockwork mechanism (Giudice, McCullough 1610.07962), is similar to Froggatt-Nielsen with many individual $U(1)$ symmetries for each flavor.

(Alonso et al. 1807.09792)
The numbers of clockwork sites play a similar role as the U(1) charges in the Froggatt-Nielsen setup

$$\frac{m_u}{m_t} \sim \epsilon^{N_{Q_1} + N_{U_1} - N_{Q_3} - N_{U_3}}$$
fermions are localized at different positions in an extra dimension

hierarchies from exponentially small wave-function overlap between left-handed and right-handed fermions and the Higgs

$$\frac{m_u}{m_t} \sim e^{-\Delta}$$
light fermion masses arise only from quantum effects

light fermions do not couple to the higgs directly
couplings are loop-induced by flavor violating new particles

mass and mixing hierarchies from loop factors

$$\frac{m_u}{m_t} \sim \left(\frac{1}{16\pi^2}\right)^n$$
Part 1 (today)

- Higgs and Flavor in the Standard Model
  (flavor symmetries, flavor violating Higgs decays, Standard Model flavor puzzle)

Part 2 (tomorrow)

- Higgs and Flavor beyond the Standard Model
  (extended Higgs sectors, “flavorful” Higgs bosons, flavor phenomenology, collider phenomenology)