Low Scale Flavor Gauge Symmetries

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CERN

in collaboration with
Benjamin Grinstein and Giovanni Villadoro
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Padova,
20 October
Outline

• Flavor Problem
• Gauging the Flavor Group
• The Model
• Experimental Bounds
• Two Examples
One of the most obscure aspects of the SM is the Yukawa sector

\[
\frac{m_u}{m_t} = 10^{-5}
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Very strong bounds from flavor physics. 4-fermion operators must be suppressed by high scale

\[
\frac{1}{\Lambda^2} (\bar{d}_L \gamma^\mu d_L)^2
\]

\[
\frac{1}{\Lambda^2} (\bar{d}_R s_L \bar{d}_L s_R)
\]

\[
\Lambda_{LL} > 10^3 - 10^4 \text{ TeV}
\]

\[
\Lambda_{LR} > 10^4 - 10^5 \text{ TeV}
\]
One of the most obscure aspects of the SM is the Yukawa sector

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\[ \frac{1}{\Lambda^2} \left( \bar{d}_R s_L \bar{d}_L s_R \right) \]

\[ \Lambda_{LL} > 10^3 - 10^4 \text{ TeV} \]

\[ \Lambda_{LR} > 10^4 - 10^5 \text{ TeV} \]

Flavor physics seems very far. Major embarrassment for most BSM scenarios!
Without Yukawas SM (quark sector) has a flavor symmetry

\[ SU(3)_{Q_L} \otimes U(3)_{U_R} \otimes U(3)_{D_R} \]

\[ Q_L = (3, 1, 1) \]
\[ U_R = (1, 3, 1) \]
\[ D_R = (1, 1, 3) \]
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**Minimal Flavor Violation:** Yukawas are the only sources of flavor violation. Higher dimensional operators must be built with positive powers of Yukawas

\[ \bar{q}_L y_u y_u^\dagger \gamma^\mu \bar{q}_L \]
\[ \bar{d}_R y_d y_d^\dagger y_u^\dagger \bar{d}_L \]
\[ \bar{d}_R y_d y_u y_u^\dagger y_d \gamma^\mu \bar{d}_R \]

With MFV new physics can lie around the TeV scale.

But where is MFV coming from?
Can flavor be an exact symmetry of Nature?
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Symmetry must be spontaneously broken.

Most simply flavons with Yukawas quantum numbers:

\[ Y_u = (3, \bar{3}, 1) \]
\[ Y_d = (3, 1, \bar{3}) \]

\[ y_{u,d} = \frac{<Y_{u,d}>}{M_{u,d}} \]
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- Global

Massless Goldstone Bosons. Strong bounds from rare decays and astrophysics.

\[ f > 10^{12} \text{ GeV} \]
Can flavor be an exact symmetry of Nature?

Symmetry must be spontaneously broken.

Most simply flavons with Yukawas quantum numbers:

\[
Y_u = (3, \bar{3}, 1) \quad \text{and} \quad Y_d = (3, 1, \bar{3})
\]

- **Global**

  Massless Goldstone Bosons. Strong bounds from rare decays and astrophysics.

  \[ y_{u,d} = \frac{\langle Y_{u,d} \rangle}{M_{u,d}} \]

  \[ f > 10^{12} \text{ GeV} \]

- **Local**

  GBs are eaten and become longitudinal components of flavor gauge bosons.
\[ \mathcal{L}_{mass} = \text{Tr}|g_U A_U Y_u - g_Q Y_u A_Q|^2 + \text{Tr}|g_D A_D Y_d - g_Q Y_d A_Q|^2 \]
\[ = \frac{1}{2} V_{Aa} (M_V^2)^{Aa,Bb} V_{Bb}, \]

\[ M^2 \sim g^2 < Y^2 > \]

**Flavor gauge bosons mediate FCNC**

\[ \frac{-1}{8} (M_V^2)^{-1}_{Aa,Bb} \chi^a_{ij} \chi^b_{hk} J_{\mu}^{ij,A} J_{\mu}^{hk,B} \]

\[ J_{\mu}^{ij,A} = (g_Q \bar{Q}_L^i \gamma^\mu Q_L^j, g_U \bar{U}_R^i \gamma^\mu U_R^j, g_D \bar{D}_R^i \gamma^\mu D_R^j) \]

\[ \sim \frac{1}{M^2} (\bar{q} \gamma^\mu q)^2 \sim \frac{1}{< Y_{u,d}^2 >} (\bar{q} q)^2 \sim \frac{1}{M^2_{u,d} y_{u,d}^2} (\bar{q} q)^2 \]
\[
\mathcal{L}_{mass} = \text{Tr}|g_U A_U Y_u - g_Q Y_u A_Q|^2 + \text{Tr}|g_D A_D Y_d - g_Q Y_d A_Q|^2 \\
= \frac{1}{2} V_{Aa}(M_V^2)^{Aa,Bb} V_{Bb},
\]

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**Flavor gauge bosons mediate FCNC**

\[
-\frac{1}{8}(M_V^2)^{-1}_{Aa,Bb} \lambda^a_{ij} \lambda^b_{hk} J^{ij,A}_{\mu} J^{\mu hk,B}
\]

\[
J^{\mu ij,A} = (g_Q \bar{Q}_L^i \gamma^\mu Q^j_L, g_U \bar{U}_R^i \gamma^\mu U^j_R, g_D \bar{D}_R^i \gamma^\mu D^j_R)
\]

\[
\sim \frac{1}{M^2} (\bar{q} \gamma^\mu q)^2 \sim \frac{1}{\langle Y^2_{u,d} \rangle} (\bar{q}q)^2 \sim \frac{1}{(M_{u,d} y^2_{u,d})^2}(\bar{q}q)^2
\]

**Maximal Flavor Violation!**

**Flavor must be broken at very high scale,**

\[
\langle Y \rangle \gtrsim 10^5 \text{ TeV} \quad \langle M \rangle \gg 10^5 \text{ TeV}
\]

Wednesday, October 20, 2010
But is $y = \langle Y \rangle / M$ really? In a renormalizable theory this could originate from,

$$L_{yuk} = \bar{Q} \tilde{H} \Psi_R + \bar{\Psi}_L M_u \Psi_R + \bar{\Psi}_L Y_u U_R$$
But is \( y = \langle Y \rangle / M \) really? In a renormalizable theory this could originate from,

\[
\mathcal{L}_{yuk} = \bar{Q} \tilde{H} \psi_R + \bar{\psi}_L M_u \psi_R + \bar{\psi}_L Y_u U_R
\]

However functions of \( Y \) can transform as \( Y \).

We could imagine an inverted hierarchy,

\[ y \sim \frac{M}{Y^*} \]

**FCNC:**

\[
\sim \frac{1}{\langle Y_{u,d}^2 \rangle} (\bar{q}q)^2 \sim \frac{y_{u,d}^2}{M_{u,d}^2} (\bar{q}q)^2
\]
Anomalies

Flavor gauge symmetries are anomalous:

\[ SU(3)^3_{Q_L} \quad SU(3)^3_{U_R} \quad SU(3)^3_{D_R} \]

\[ U(1)_Y \times SU(3)^2_{Q_L} \quad U(1)_Y \times SU(3)^2_{U_R} \quad U(1)_Y \times SU(3)^2_{D_R} \]
Anomalies

Flavor gauge symmetries are anomalous:

\[ SU(3)_Q^3 \quad SU(3)_U^3 \quad SU(3)_D^3 \]

\[ U(1)_Y \times SU(3)_Q^2 \quad U(1)_Y \times SU(3)_U^2 \quad U(1)_Y \times SU(3)_D^2 \]

New fermions need to be added,

\[ \Psi_{uR} = (3, 1, 1) \]
\[ \Psi_{dR} = (3, 1, 1) \]
\[ \Psi_u = (1, 3, 1) \]
\[ \Psi_d = (1, 1, 3) \]
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\[ U(1)_Y \times SU(3)^2_{Q_L} \quad U(1)_Y \times SU(3)^2_{U_R} \quad U(1)_Y \times SU(3)^2_{D_R} \]

New fermions need to be added,

\[ \Psi_{u_R} = (3, 1, 1)^{\frac{2}{3}} \]
\[ \Psi_{d_R} = (3, 1, 1)^{-\frac{1}{3}} \]
\[ \Psi_u = (1, 3, 1)^{\frac{2}{3}} \]
\[ \Psi_d = (1, 1, 3)^{-\frac{1}{3}} \]

Flavor \( U(1) \) anomalies also cancel.
Model

<table>
<thead>
<tr>
<th></th>
<th>SU(3)$_{Q_L}$</th>
<th>SU(3)$_{U_R}$</th>
<th>SU(3)$_{D_R}$</th>
<th>SU(3)$_{c}$</th>
<th>SU(2)$_{L}$</th>
<th>U(1)$_{Y}$</th>
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</thead>
<tbody>
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<td>1</td>
<td>3</td>
<td>2</td>
<td>1/6</td>
</tr>
<tr>
<td>$U_R$</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2/3</td>
</tr>
<tr>
<td>$D_R$</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$\Psi_{uR}$</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2/3</td>
</tr>
<tr>
<td>$\Psi_{dR}$</td>
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<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
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</tr>
<tr>
<td>$\Psi_u$</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2/3</td>
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<tr>
<td>$\Psi_d$</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$Y_u$</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$Y_d$</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$H$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
</tr>
</tbody>
</table>

$$
\mathcal{L} = \mathcal{L}_{kin} - V(Y_u, Y_d, H) + \\
(\lambda_u \bar{Q}_L H \Psi_{uR} + \lambda_u' \bar{\Psi}_u Y_u \Psi_{uR} + M_u \bar{\Psi}_u U_R + \\
\lambda_d \bar{Q}_L H \Psi_{dR} + \lambda_d' \bar{\Psi}_d Y_d \Psi_{dR} + M_d \bar{\Psi}_d D_R + h.c. ) ,
$$
Yukawas:

\[ y_u = \frac{\lambda_u M_u}{\chi_u Y_u^\dagger} \]  \( \langle Y \rangle \gg M \)

\[ y_d = \frac{\lambda_d M_d}{\chi_d Y_d^\dagger} \]  \( \langle Y^\dagger \rangle \ll M \)

\[ y_t \sim \lambda_u \]

\[ \langle Y^\dagger \rangle \ll M \]
Yukawas:

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y_u = \frac{\lambda_u M_u}{\lambda_u Y_u^\dagger}
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Inverted hierarchy!

Flavor physics can appear at the TeV scale.
Yukawas:

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\[ y_d = \frac{\lambda_d M_d}{\lambda_d Y_d} \]

\[ \langle Y \rangle \gg M \]
\[ y_t \sim \lambda_u \]
\[ \langle Y^\dagger \rangle \ll M \]

Inverted hierarchy!
Flavor physics can appear at the TeV scale.

Exotic fermions:

\[ m'_{u,d} \sim \lambda'_{u,d} \langle Y_{u,d} \rangle \]

Flavon couplings highly suppressed

\[ \sim \frac{M}{Y^i + \delta Y^i} v \bar{q}_i q_i \approx \left(1 - y^i \frac{\delta Y^i}{M}\right) m_q \bar{q}_i q_i \]
Remarks:

- Only two flavor violating structures as SM,

\[ Y_d = \hat{Y}_d \quad \quad Y_u = \hat{Y}_d V \]

However NOT MFV.
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- Only two flavor violating structures as SM,

\[ Y_d = \hat{Y}_d \quad Y_u = \hat{Y}_d V \]

However NOT MFV.

- Potential:
  
  With two flavon fields no renormalizable potential.
  
  Possible to construct potential with high cut-off.
  
  Adding several flavons: More flavor violating structures but still enough flavor suppression.

- Trivial extension to lepton. Different gaugings.
Phenomenology
Modified SM Couplings

\[ \mathcal{L}_{yuk} = \lambda_u \overline{Q}_L \hat{H} \Psi_{uR} + \lambda'_u \overline{\Psi}_u Y_u \Psi_{uR} + M_u \overline{\Psi}_u U_R + \ldots \]

After EWSB the mass eigenstates are

\[
\begin{pmatrix}
  u_R^i \\
  u_L^i
\end{pmatrix} =
\begin{pmatrix}
  c_{uR_i} & -s_{uR_i} \\
  s_{uR_i} & c_{uR_i}
\end{pmatrix}
\begin{pmatrix}
  U_R^i \\
  \Psi_{uR}^i
\end{pmatrix},
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\]

Natural parametrization

\[
x_i \equiv \frac{M_u}{m_{u_i}},
\]

\[
y_i \equiv \frac{\lambda_u v}{\sqrt{2} m_{u_i}},
\]

\[
s_{u_{Li}} = \sqrt{\frac{y_i^2 - 1}{x_i^2 y_i^2 - 1}}
\]

\[
s_{u_{Ri}} = \sqrt{\frac{x_i^2 - 1}{x_i^2 y_i^2 - 1}}
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Modified SM Couplings

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                                       \Psi_{uR} \end{pmatrix},
\]

\[
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    u_L^i
\end{pmatrix} = \begin{pmatrix} c_{u_{L_i}} & -s_{u_{L_i}} \\
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                                       \Psi_{u} \end{pmatrix},
\]

Natural parametrization

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x_i \equiv \frac{M_u}{m_{u_i}}, \quad y_i \equiv \frac{\lambda_u v}{\sqrt{2} m_{u_i}},
\]

\[
s_{u_{Li}} = \sqrt{\frac{y_i^2 - 1}{x_i^2 y_i^2 - 1}} \quad s_{u_{Ri}} = \sqrt{\frac{x_i^2 - 1}{x_i^2 y_i^2 - 1}}
\]

Decoupling:

\[ x_i \rightarrow \infty \quad \text{or} \quad y_i \rightarrow 1 \]
Right handed fermions mix with exotic with equal charges so their couplings are the same as in the SM.
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**SM left-handed doublets mix with singlets. The couplings are modified.**

**Charged currents:**

\[
\bar{u}_L (c_{uL} V c_{dL}) \gamma^\mu d_L + \bar{u}_L (c_{uL} V s_{dL}) \gamma^\mu d'_L \\
+ \bar{u}'_L (s_{uL} V c_{dL}) \gamma^\mu d_L + \bar{u}'_L (s_{uL} V s_{dL}) \gamma^\mu d'_L
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+ \bar{u}'_L (s_{u_L} V c_{d_L}) \gamma^\mu d_L + \bar{u}'_L (s_{u_L} V s_{d_L}) \gamma^\mu d'_L
\]

**Neutral currents:**

\[
\bar{u}_L (T^u_3 c_{u_L}^2 - s_w^2 Q_u) \gamma^\mu u_L + \bar{u}_L (T^u_3 c_{u_L} s_{u_L}) \gamma^\mu u'_L \\
+ \bar{u}'_L (T^u_3 s_{u_L} c_{u_L}) \gamma^\mu u_L + \bar{u}'_L (T^u_3 s_{u_L}^2 - s_w^2 Q_u) \gamma^\mu u'_L + (u \rightarrow d),
\]

**Higgs Couplings:**

\[
\frac{1}{\sqrt{2}} \lambda_u h \left[ -\bar{t}_L c_{u_L} s_{u_R} t_R + \bar{t}_L c_{u_L} c_{u_R} t'_R - \bar{t'}_L s_{u_L} s_{u_R} t_R + \bar{t'}_L s_{u_L} c_{u_R} t'_R \right] + (u \rightarrow d) + \text{h.c.}
\]
Δ\text{Down Sector}

- $Z\rightarrow bb$

\[
\frac{\delta g_{Z\rightarrow b\bar{b}}}{g_{Z\rightarrow b\bar{b}}} = s_{dL3}^2
\]

\[
\frac{\delta \Gamma_{Zb\bar{b}}}{\Gamma_{Zb\bar{b}}} = -s_{dL3}^2 \frac{2 + 4s_w^2 Q_d}{1 + 4s_w^2 Q_d + 8s_w^4 Q_d^2} \approx -2.3 s_{dL3}^2
\]

\[
s_{dL3} \sim \frac{m_b}{M_d}
\]

$s_{dL3} < .04$
Down Sector

• $Z \rightarrow b \bar{b}$

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\]

\[
s_{dL3} \sim \frac{m_b}{M_d}
\]

$s_{dL3} < .04$

• Direct bounds

$m_{b'} > 268 \text{GeV}$ or $< 100 \text{GeV}$ [$b' \rightarrow Zb$, BR = 1]

$m_{b'} > 385 \text{GeV}$ [$b' \rightarrow Wt$, BR = 1]

Our Model

$m_{b'} > 385 \text{GeV}$ allowed

$45 \text{GeV} < m_{b'} < 385 \text{GeV}$ model dependent
Up Sector

- Oblique corrections

\[
S = -16\pi \Pi'_{3Y}(0), \\
T = \frac{4\pi}{s_w^2 c_w^2 M_Z^2} [\Pi_{11}(0) - \Pi_{33}(0)], \\
U = 16\pi [\Pi'_{11}(0) - \Pi'_{33}(0)]
\]

\[
T = \frac{48\pi}{s_w^2 c_w^2 M_Z^2} [2s_{uL3}^2 \Pi_{LL}(m_t, m_b, 0) + 2s_{uL3}^2 \Pi_{LL}(m_{t'}, m_b, 0) + (1 - c_{uL3}^4) \Pi_{LL}(m_t, m_t, 0) - s_{uL3}^4 \Pi_{LL}(m_{t'}, m_{t'}, 0) - 2s_{uL3}^2 c_{uL3}^2 \Pi_{LL}(m_t, m_{t'}, 0)]
\]

\[
T = \frac{3 s_{uL3}^2 m_t^2}{8\pi s_w^2 c_w^2 M_Z^2} \left[ c_{uL3}^2 \left( \frac{m_{t'}^2}{m_t^2} \log \left( \frac{m_{t'}^2}{m_t^2} \right) - 1 \right) + \frac{s_{uL3}^2}{2} \left( \frac{m_{t'}^2}{m_t^2} - 1 \right) \right].
\]

\[
S \approx 0 \quad U \approx 0
\]
Heavy Higgs

A heavy Higgs can be naturally accommodated

Correction to $T$ is always positive while contribution to $S$ is always negligible.
• $V_{tb}$

$$V_{CKM} = c_{u_L} \cdot V \cdot c_{d_L}$$

Tevatron

$$V_{tb} \approx c_{u_{L3}} > 0.77$$

(single top production)

• $b \rightarrow s\gamma$

$$A_{b \rightarrow s\gamma} = f(m_t) + s_{u_{L3}}^2 (f(m_{t'}) - f(m_t))$$

(always bigger than SM)

• Direct bounds

$$m_{t'} > 335 \text{ GeV}$$

allowed

$$45 \text{ GeV} < m_{t'} < 335 \text{ GeV}$$

model dependent
Examples

We choose models with order 1 couplings. Always consistent with flavor bounds. Details of the spectrum model dependent but structure robust.
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We choose models with order 1 couplings. Always consistent with flavor bounds. Details of the spectrum model dependent but structure robust.

- $\text{SU}(3)_{QL} \otimes \text{U}(3)_{UR} \otimes \text{U}(3)_{DR}$

<table>
<thead>
<tr>
<th>$M_u$ (GeV)</th>
<th>$M_d$ (GeV)</th>
<th>$\lambda_u$</th>
<th>$\lambda'_u$</th>
<th>$\lambda_d$</th>
<th>$\lambda'_d$</th>
<th>$g_Q$</th>
<th>$g_U$</th>
<th>$g_D$</th>
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<tbody>
<tr>
<td>350</td>
<td>100</td>
<td>1.1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>0.3</td>
<td>1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

$Y_u \approx \text{Diag} \left( 1 \cdot 10^5, \ 2 \cdot 10^2, \ 3 \cdot 10^{-1} \right) \cdot V \ \text{TeV}$,

$Y_d \approx \text{Diag} \left( 6 \cdot 10^3, \ 4 \cdot 10^2, \ 7 \right) \ \text{TeV}$. 
\[
\frac{\delta R_b}{R_b} = -1.0 \cdot 10^{-3},
\]
\[
S = 0.00, \ T = 0.15, \ U = 0.01,
\]
\[
V_{tb} = 0.97.
\]

\text{spin}_{1/2} : .4, 1.8, 90 \ TeV

\text{spin}_{1} : .29, 1.9, 3.9, 80 \ TeV
Effective 4-Fermi operators from flavor gauge boson,

\[
Q_{1}^{q_{i}q_{j}} = \bar{q}_{jL}^{\alpha}\gamma_{\mu}q_{iL}^{\alpha}\bar{q}_{jL}^{\beta}\gamma_{\mu}q_{iL}^{\beta},
\]

\[
\tilde{Q}_{1}^{q_{i}q_{j}} = \bar{q}_{jR}^{\alpha}\gamma_{\mu}q_{iR}^{\alpha}\bar{q}_{jR}^{\beta}\gamma_{\mu}q_{iR}^{\beta},
\]

\[
Q_{5}^{q_{i}q_{j}} = \bar{q}_{jR}^{\alpha}q_{iL}^{\beta}\bar{q}_{jL}^{\beta}q_{iR}^{\alpha}.
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>( C_{K}^{1} )</th>
<th>Re (in GeV(^{-2}))</th>
<th>Im (in GeV(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \tilde{C}_{K}^{1} )</td>
<td>(-7 \cdot 10^{-15})</td>
<td>(-8 \cdot 10^{-20})</td>
</tr>
<tr>
<td></td>
<td>( C_{K}^{5} )</td>
<td>(-1 \cdot 10^{-16})</td>
<td>(-1 \cdot 10^{-21})</td>
</tr>
<tr>
<td></td>
<td>( \tilde{C}_{K}^{5} )</td>
<td>(-4 \cdot 10^{-15})</td>
<td>(-4 \cdot 10^{-20})</td>
</tr>
<tr>
<td></td>
<td>( C_{D}^{1} )</td>
<td>(-3 \cdot 10^{-20})</td>
<td>(-3 \cdot 10^{-23})</td>
</tr>
<tr>
<td></td>
<td>( \tilde{C}_{D}^{1} )</td>
<td>(-3 \cdot 10^{-25})</td>
<td>(-4 \cdot 10^{-28})</td>
</tr>
<tr>
<td></td>
<td>( C_{D}^{5} )</td>
<td>(-4 \cdot 10^{-22})</td>
<td>(-4 \cdot 10^{-25})</td>
</tr>
<tr>
<td></td>
<td>( C_{B_{d}}^{1} )</td>
<td>(2 \cdot 10^{-16})</td>
<td>(2 \cdot 10^{-16})</td>
</tr>
<tr>
<td></td>
<td>( \tilde{C}<em>{B</em>{d}}^{1} )</td>
<td>(1 \cdot 10^{-21})</td>
<td>(1 \cdot 10^{-21})</td>
</tr>
<tr>
<td></td>
<td>( C_{B_{d}}^{5} )</td>
<td>(2 \cdot 10^{-18})</td>
<td>(2 \cdot 10^{-18})</td>
</tr>
<tr>
<td></td>
<td>( C_{B_{s}}^{1} )</td>
<td>(3 \cdot 10^{-13})</td>
<td>(-4 \cdot 10^{-13})</td>
</tr>
<tr>
<td></td>
<td>( \tilde{C}<em>{B</em>{s}}^{1} )</td>
<td>(5 \cdot 10^{-16})</td>
<td>(-6 \cdot 10^{-16})</td>
</tr>
<tr>
<td></td>
<td>( C_{B_{s}}^{5} )</td>
<td>(5 \cdot 10^{-14})</td>
<td>(-6 \cdot 10^{-14})</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Bounds</th>
<th>( C_{K}^{1} )</th>
<th>Re (in GeV(^{-2}))</th>
<th>Im (in GeV(^{-2}))</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>( \tilde{C}_{K}^{1} )</td>
<td>([-9.6, 9.6] \cdot 10^{-13})</td>
<td>([-4.4, 2.8] \cdot 10^{-15})</td>
</tr>
<tr>
<td></td>
<td>( C_{K}^{5} )</td>
<td>([-9.6, 9.6] \cdot 10^{-13})</td>
<td>([-4.4, 2.8] \cdot 10^{-15})</td>
</tr>
<tr>
<td></td>
<td>( \tilde{C}_{K}^{5} )</td>
<td>([-1.0, 1.0] \cdot 10^{-14})</td>
<td>([-5.2, 2.9] \cdot 10^{-17})</td>
</tr>
</tbody>
</table>

\[
| C_{D}^{1} | < 7.2 \cdot 10^{-14}
\]
\[
| \tilde{C}_{D}^{1} | < 7.2 \cdot 10^{-14}
\]
\[
| C_{D}^{5} | < 4.8 \cdot 10^{-13}
\]
\[
| C_{B_{d}}^{1} | < 2.3 \cdot 10^{-11}
\]
\[
| \tilde{C}_{B_{d}}^{1} | < 2.3 \cdot 10^{-11}
\]
\[
| C_{B_{d}}^{5} | < 6.0 \cdot 10^{-13}
\]
\[
| C_{B_{s}}^{1} | < 1.1 \cdot 10^{-9}
\]
\[
| \tilde{C}_{B_{s}}^{1} | < 1.1 \cdot 10^{-9}
\]
\[
| C_{B_{s}}^{5} | < 4.5 \cdot 10^{-11}
\]

Safer than MFV!
• \( \text{SU}(3)_{QL} \otimes \text{SU}(3)_{UR} \otimes \text{SU}(3)_{DR} \)

<table>
<thead>
<tr>
<th>( M_u ) (GeV)</th>
<th>( M_d ) (GeV)</th>
<th>( \lambda_u )</th>
<th>( \lambda'_u )</th>
<th>( \lambda_d )</th>
<th>( \lambda'_d )</th>
<th>( g_Q )</th>
<th>( g_U )</th>
<th>( g_D )</th>
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</thead>
<tbody>
<tr>
<td>400</td>
<td>100</td>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\( Y_u \approx \text{Diag}(1 \cdot 10^5, 2 \cdot 10^2, 8 \cdot 10^{-2}) \cdot V \text{ TeV} \),

\( Y_d \approx \text{Diag}(5 \cdot 10^3, 3 \cdot 10^2, 6) \text{ TeV} \),

<table>
<thead>
<tr>
<th>( C^1_K )</th>
<th>( C^1_K )</th>
<th>( C^5_K )</th>
<th>( C^1_D )</th>
<th>( C^1_D )</th>
<th>( C^5_D )</th>
<th>( C^1_{B_d} )</th>
<th>( C^1_{B_d} )</th>
<th>( C^5_{B_d} )</th>
<th>( C^1_{B_s} )</th>
<th>( C^1_{B_s} )</th>
<th>( C^5_{B_s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Re (in GeV}^{-2})</td>
<td>( \text{Im (in GeV}^{-2})</td>
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</tr>
<tr>
<td>( -1 \cdot 10^{-14} )</td>
<td>( -1 \cdot 10^{-19} )</td>
<td>( -2 \cdot 10^{-16} )</td>
<td>( -2 \cdot 10^{-21} )</td>
<td>( -5 \cdot 10^{-15} )</td>
<td>( -6 \cdot 10^{-20} )</td>
<td>( -2 \cdot 10^{-20} )</td>
<td>( -2 \cdot 10^{-23} )</td>
<td>( -2 \cdot 10^{-25} )</td>
<td>( 1 \cdot 10^{-16} )</td>
<td>( 5 \cdot 10^{-16} )</td>
<td>( 9 \cdot 10^{-22} )</td>
</tr>
</tbody>
</table>
\[ \frac{\delta R_b}{R_b} = -1.0 \cdot 10^{-3}, \]
\[ S = 0.00, \quad T = 0.01, \quad U = 0.00, \]
\[ V_{tb} = 1.00. \]

\[ \text{spin}_{\frac{1}{2}} : 0.4, 1.8, 90 \text{ TeV} \]
\[ \text{spin}_{1} : 2.8, 53, 53, 66 \text{ TeV} \]
Signals

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- b’ : Decay in Wt, Zb highly suppressed by small mixing, branching into Hb O(1)

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  \[ t' \rightarrow t\bar{t} \]

- **Flavor gauge boson**: Non-universal lepto-phobic \( Z' \)
  Mostly coupled to third generation.
  Drell-Yan production or gluon fusion.

Wednesday, October 20, 2010
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• So far flavor scale is a free parameter. Possible to link it to the TeV scale in a theory that addresses the hierarchy problem?