Flavor at the LHC Era

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What is flavor physics?

**Flavor physics**

Interactions that distinguish between the fermion generations

- Interaction basis:
  - Flavor physics \(\neq\) Gauge interactions, Higgs self-interactions
  - Flavor physics = Yukawa interactions

- Flavor parameters:
  - Fermion masses
  - Mixing parameters (angles and phases)

- Mathematically:
  - Interactions that break the global \([SU(3)]^5\) symmetry
  - “Flavor Violation”
Motivation

Why is flavor physics interesting?

- Flavor physics is sensitive to new physics at $\Lambda_{NP} \gg E_{\text{experiment}}$
- The New Physics flavor puzzle:
  If there is NP at the TeV scale, why are FCNC so small?
- The Standard Model flavor puzzle:
  Why are the flavor parameters small and hierarchical?
  Why are the neutrino flavor parameters different?
- The puzzle of the baryon asymmetry:
  Flavor suppression kills KM baryogenesis
  Flavor matters in leptogenesis
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From BABAR/BELLE to ATLAS/CMS

The B-factories...

- Clarified the picture of CP violation
  \[ \rightarrow \text{The KM mechanism dominates CPV in meson decays} \]

- Constrained extensions of the Standard Model
  \[ \rightarrow \text{Challenges for model builders} \]

- Deepened the NP flavor puzzle
  \[ \rightarrow \text{FCNC are small in } s \rightarrow d, c \rightarrow u, b \rightarrow d \text{ and } b \rightarrow s \]
**From BABAR/BELLE to ATLAS/CMS**

The B-factories...

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- Constrained extensions of the Standard Model
  \[\Rightarrow\] Challenges for model builders

- Deepened the NP flavor puzzle
  \[\Rightarrow\] FCNC are small in \(s \rightarrow d, c \rightarrow u, b \rightarrow d\) and \(b \rightarrow s\)

ATLAS/CMS will, hopefully, observe NP at \(\Lambda_{NP} \lesssim TeV\) and...

- Measure new flavor parameters

- Teach us about how the NP flavor puzzle is (not) solved

- Probe NP at \(\Lambda_{NP} \gg TeV\)
Plan of Talk

1. From flavor@GeV to NP@TeV
   - The new physics flavor puzzle
   - The supersymmetric flavor puzzle
     - Lessons from $\Delta m_D$

2. Minimal flavor violation (MFV)

3. From NP@TeV to flavor
   - An example: Extra vector-like down quarks
   - Testing MFV at the LHC
Flavor at the LHC era

From flavor@GeV to NP@TeV
Learning from flavor about NP

• In the past, flavor at low scale led to discoveries of or constraints on new physics at much higher scales
  – $\varepsilon_K \neq 0 \implies$ Third generation
  – $\Gamma(K_L \rightarrow \mu\mu) \ll \Gamma(K \rightarrow \mu\nu) \implies$ Charm
  – $\Delta m_K \implies m_c \sim 1.5 \text{ GeV}$
  – $\Delta m_B \implies m_t \gg m_W$

• At present, flavor precision measurements show no deviations from the SM
  – Pose the new physics flavor puzzle
  – Constrain specific models
The NP flavor puzzle

New Physics

- The effects of new physics at a high energy scale $\Lambda_{\text{NP}}$ can be presented as higher dimension operators.

- For example, we expect the following dimension-six operators:

$$\frac{z_{sd}}{\Lambda_{\text{NP}}^2} (\overline{d}_L \gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\text{NP}}^2} (\overline{c}_L \gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\text{NP}}^2} (\overline{d}_L \gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\text{NP}}^2} (\overline{s}_L \gamma_\mu b_L)^2$$

- New contribution to neutral meson mixing, e.g.

$$\frac{\Delta m_B}{m_B} \sim \frac{z_{bd}}{3} \left( \frac{f_B}{\Lambda_{\text{NP}}} \right)^2$$

- Generic flavor structure $\equiv z_{ij} \sim 1$ or, perhaps, loop – factor.
The NP flavor puzzle

High Scale?

- For \( z_{ij} \sim 1 \),

\[
\Lambda_{NP} \gtrsim \begin{cases} 
1 \times 10^4 \text{ TeV} & \epsilon_K \\
1 \times 10^3 \text{ TeV} & \Delta m_K \\
9 \times 10^2 \text{ TeV} & \Delta m_D \\
4 \times 10^2 \text{ TeV} & \Delta m_B \\
7 \times 10^1 \text{ TeV} & \Delta m_{B_s} 
\end{cases}
\]

Did we misinterpret the fine tuning problem and the dark matter puzzle?
The NP flavor puzzle

Small (hierachical?) flavor parameters?

- For $\Lambda_{\text{NP}} \sim 1 \, \text{TeV}$,

\[
\text{Im}(z_{sd}) \lesssim 6 \times 10^{-9} \\
z_{sd} \lesssim 8 \times 10^{-7} \\
z_{cu} \lesssim 1 \times 10^{-6} \\
z_{bd} \lesssim 6 \times 10^{-6} \\
z_{bs} \lesssim 2 \times 10^{-4}
\]

$\Rightarrow$ The flavor structure of NP@TeV must be highly non-generic

How? Why? = The NP flavor puzzle
The NP Flavor Puzzle

How does the SM do it?

• $\Lambda_{\text{SM}} \sim m_W$, 

\[
\begin{align*}
\mathcal{I}m(z_{sd}^{\text{SM}}) &\sim \alpha_2^2 y_t^2 |V_{td}V_{ts}|^2 \sim 1 \times 10^{-10} \\
\bar{z}_{sd}^{\text{SM}} &\sim \alpha_2^2 y_c^2 |V_{cd}V_{cs}|^2 \sim 5 \times 10^{-9} \\
\bar{z}_{bd}^{\text{SM}} &\sim \alpha_2^2 y_t^2 |V_{td}V_{tb}|^2 \sim 7 \times 10^{-8} \\
\bar{z}_{bs}^{\text{SM}} &\sim \alpha_2^2 y_t^2 |V_{ts}V_{tb}|^2 \sim 2 \times 10^{-6}
\end{align*}
\]

---

Does the NP know the SM Yukawa couplings?
The $\Delta m_K$ challenge for Supersymmetry

Take, for example, the contribution from the first two generations of squark doublets to $K - \bar{K}$ mixing:

\[
\begin{align*}
\frac{\Delta m_K}{m_K} &= B_K \eta_K g(m_{\tilde{g}}^2/m_{\tilde{d}}^2) \frac{\alpha_s^2}{108} \frac{f_K^2}{m_{\tilde{d}}^2} \frac{(\Delta m_{\tilde{d}}^2)^2}{m_{\tilde{d}}^4} (K_{21}^d K_{11}^d)^2 \\
\Delta m_K &\sim 7.0 \times 10^{-15} \implies \frac{Tev}{m_{\tilde{d}}} \times \frac{\Delta m_{\tilde{d}}^2}{m_{\tilde{d}}^2} \times K_{21}^d \leq 0.01
\end{align*}
\]
How can Supersymmetry do it?

The $K - \bar{K}$ mixing constraint:

$$\frac{T eV}{m_{\tilde{d}}} \times \frac{\Delta m_{\tilde{d}}^2}{m_{\tilde{d}}^2} \times K_{21}^d \leq 0.01$$

- **Solutions:**
  - Heaviness: $m_{\tilde{d}} \gg 1 \text{ TeV}$
  - Degeneracy: $\Delta m_{\tilde{d}}^2 \ll m_{\tilde{d}}^2$
  - Alignment: $K_{21}^d \ll 1$
The SUSY Flavor Puzzle

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  - Degeneracy: $\Delta m_{\tilde{d}}^2 \ll m_{\tilde{d}}^2$
  - Alignment: $K_{21}^d \ll 1$
  - Split Supersymmetry
  - Gauge-mediation
  - Horizontal symmetries
$D^0 - \bar{D}^0$ mixing, experimentally

Recent exciting experimental results from BABAR and BELLE:

- $y \equiv \Delta \Gamma_D / 2\Gamma \sim 10^{-2}$
  - Consistent with SM
  - Large SU(3) breaking from phase space effects

- $x \equiv \Delta m_D / \Gamma \gg y$
  - Consistent with SM

- No evidence for CPV
  - No hint for NP

For our purposes, the most significant new result:

$$\Delta m_D / m_D \lesssim 2 \times 10^{-14}$$
The $\Delta m_D$ challenge for Supersymmetry

Take, for example, the contribution from the first two generations of squark doublets to $D - \bar{D}$ mixing:

\[
\Delta m_D = B_D \eta_D g (m_{\tilde{g}}^2/m_u^2) \frac{\alpha_s^2}{108} \frac{f_D^2}{m_{\tilde{u}}^2} \frac{(\Delta m_{\tilde{u}}^2)^2}{m_{\tilde{u}}^4} (K_{21}^u K_{11}^{u*})^2
\]

\[
\frac{\Delta m_D}{m_D} \lesssim 2.0 \times 10^{-14} \implies \frac{TeV}{m_{\tilde{u}}} \times \frac{\Delta m_{\tilde{u}}^2}{m_{\tilde{u}}^2} \times K_{21}^u \lesssim 0.1
\]
\[ \Delta m_K \text{ and } \Delta m_D \]

For the first two generation squark doublets:

- \[ m_{\tilde{u}}^2 = m_{\tilde{d}}^2 [\text{to } \mathcal{O}(m_Z^2)] \]
- \[ \Delta m_{\tilde{u}}^2 = \Delta m_{\tilde{d}}^2 [\text{to } \mathcal{O}(m_c^2)] \]
- \[ \sin \theta_u - \sin \theta_d = \sin \theta_C [\text{to } \mathcal{O}(m_c^2/m_q^2)] \]
- \[ K - \bar{K} \text{ mixing gives} \]
  \[ \frac{\text{TeV}}{m_{\tilde{q}}} \times \frac{\Delta m_{\tilde{q}}^2}{m_{\tilde{q}}^2} \times \sin \theta_d \leq 0.01 \]
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Can it be purely alignment?

1. Assume observability at the LHC: $m_{\tilde{q}} \lesssim 1 \text{ TeV}$;

2. Assume no degeneracy: $\Delta m_{\tilde{q}}^2 / m_{\tilde{q}}^2 \sim 1$;

3. For alignment alone to do the job: $\sin \theta_u \leq 0.10$, $\sin \theta_d \leq 0.01$

But this is inconsistent with $\sin \theta_u - \sin \theta_d = 0.23$

If the first two squark doublets are within reach of the LHC, they must be quasi-degenerate
Can it be purely alignment?

1. Assume observability at the LHC: $m_{\tilde{q}} \lesssim 1 \text{ TeV}$;
2. Assume no degeneracy: $\Delta m^2_{\tilde{q}} / m^2_{\tilde{q}} \sim 1$;
3. For alignment alone to do the job: $\sin \theta_u \leq 0.10$, $\sin \theta_d \leq 0.01$

But this is inconsistent with $\sin \theta_u - \sin \theta_d = 0.23$

If the first two squark doublets are within reach of the LHC, they must be quasi-degenerate

- Gauge mediation (GMSB)?
- RGE?
Minimal Flavor Violation
Minimal Flavor Violation (MFV)

**Definition**

A class of models where the NP flavor puzzle is solved

- **The idea:** The only sources of flavor violation are the SM Yukawa interactions

- **A rigorous definition:** $Y_U(3,1,\bar{3}), Y_D(3,\bar{3},1)$ are the only spurions that break $G_q = SU(3)_Q \times SU(3)_D \times SU(3)_U$

- **A consequence:** All flavor physics depends on
  \[
  \lambda_D = \text{diag}(y_d, y_s, y_b), \quad \lambda_U = \text{diag}(y_u, y_c, y_t), \quad V_{\text{CKM}}
  \]

- **Example:** Consider the operator $\frac{z_{sd}}{\Lambda_{\text{NP}}^2}(\bar{s}_L \gamma_\mu d_L)^2$:
  With MFV, $z_{sd} \propto y_c^4 (V_{cd}^* V_{cs})^2$

- **A specific model:** SUSY with gauge-mediated breaking
  \[
  \Delta m_q^2 / m_q^2 \sim y_c^2, \quad K_{21}^d K_{22}^d = V_{cd}^* V_{cs}
  \]
Minimal Flavor Violation (MFV)

**MFV predictions: Spectra**

- \( y_u, y_d, y_s, y_c \ll 1 \)

\[ \Rightarrow \text{There is an approximate } [SU(2)]^3_q \text{ symmetry in Nature} \]

Spectra of new particles may exhibit 3 or 2 + 1 degeneracy

Indeed, in GMSB models, the first two squark generations of each sector are quasi-degenerate
MFV predictions: Mixing

- The only source of mixing – the CKM matrix:

\[
V_{\text{CKM}}^{\text{LHC}} = \begin{pmatrix}
1 & 0.2 & 0 \\
-0.2 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[\Rightarrow\] There is an approximate \([U(1)]^3\) symmetry in each sector

New particles will decay to either 3rd generation or non-3rd generation quarks but not to both
Apologies to BABAR and BELLE

- The CKM matrix a-la ATLAS/CMS:

\[ V_{\text{CKM}} = \begin{pmatrix} 1 & 0.2 & 0 \\ -0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]
Minimal Flavor Violation (MFV)

Apologies to BABAR and BELLE

- The CKM matrix a-la ATLAS/CMS:
  \[ V_{\text{CKM}} = \begin{pmatrix} 
  1 & 0.2 & 0 \\
  -0.2 & 1 & 0 \\
  0 & 0 & 1 
  \end{pmatrix} \]

- The CKM matrix a-la BABAR/BELLE:
  \[ V_{\text{CKM}} = \begin{pmatrix} 
  0.97383 \pm 0.00024 & 0.2272 \pm 0.0010 & (3.96 \pm 0.09) \times 10^{-3} \\
  0.2271 \pm 0.0010 & 0.97296 \pm 0.00024 & (4.221^{+0.010}_{-0.080}) \times 10^{-2} \\
  (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (4.161^{+0.012}_{-0.078}) \times 10^{-2} & 0.999100^{+0.000034}_{-0.000004} 
  \end{pmatrix} \]
Extra vector-like down quarks
The framework

- Imagine that the LHC discovers vector-like down quarks
  \( B'_L(3, 1)_{-1/3} + B'_R(3, 1)_{-1/3} \)

- If MFV applies \( \Rightarrow B'_L, B'_R \) have well-defined transformation properties under \( G_q = SU(3)_Q \times SU(3)_D \times SU(3)_U \)

- If they couple to SM fields \( \Rightarrow \) The smallest \( G_q \) representation is triplet

- We consider \( SU(3)_Q \times SU(3)_D \)-triplets

- The leading decay modes:
  \[ \Gamma(B'_i \rightarrow Wq_j) \approx 2\Gamma(B'_i \rightarrow Zq_j) \approx 2\Gamma(B'_i \rightarrow hq_j) \]
### The MFV models

<table>
<thead>
<tr>
<th>$B'_L$</th>
<th>$B'_R$</th>
<th>Spectrum</th>
<th>Couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3, 1)</td>
<td>(1, 3)</td>
<td>hierarchical $(\tilde{Y}_D)$</td>
<td>hierarchical + diagonal $(\tilde{Y}_D)$</td>
</tr>
<tr>
<td>(1, 3)</td>
<td>(1, 3)</td>
<td>degenerate $(\mathbf{1})$</td>
<td>hierarchical + diagonal $(\tilde{Y}_D)$</td>
</tr>
<tr>
<td>(1, 3)</td>
<td>(3, 1)</td>
<td>hierarchical $(\tilde{Y}_D)$</td>
<td>semi-universal + diagonal $(\mathbf{1})$</td>
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</tr>
</tbody>
</table>

- $\tilde{Y}_D = \text{diag}(y_d, y_s, xy_b)$, \( \mathbf{1} = \text{diag}(1, 1, x) \)
Extra vector-like down quarks

Measuring flavor at the LHC

The LHC can, in principle, provide us with

1. The spectrum
2. production cross-sections
3. Some capability of heavy flavor tagging
4. Some information on decay widths
Testing MFV at the LHC

ATLAS/CMS can exclude MFV if any of the following is violated:

• In events where the $B$’s are pair-produced
  \[
  \frac{\Gamma(B'\bar{B}' \to X q_l q_3)}{\Gamma(B'\bar{B}' \to X q_l q_l) + \Gamma(B'\bar{B}' \to X q_3 q_3)} \lesssim 10^{-3}
  \]

• A non-degenerate $B'$ decays to either $q_3$’s or $q_l$’s but not to both

• For $2+1$ spectrum, $2 \to X q_l$ and $1 \to X q_3$

ATLAS/CMS can support MFV if they can establish

• Three-fold or two-fold degeneracy

• Two-fold degeneracy and no final $q_3$’s
Conclusions

- The consistency of flavor precision measurements at $E_{\text{exp}} \sim GeV$ with the SM poses a problem to NP at $\Lambda_{\text{NP}} \sim TeV$

- If new particles are discovered, new flavor parameters will be measured

- The parameters of interest: $M$, $\text{BR}(\rightarrow f_3, f_l)$, $\sigma_{\text{prod}}$

- Solutions to the new physics flavor problem can then be tested

- In particular, MFV can, in principle, be excluded

- Spectrum (degeneracies?) and flavor decomposition (alignment?) will teach us about NP at $\Lambda_{\text{NP}} \gg TeV$
Flavor parameters of squark doublets

\[ \tilde{M}_{UL}^2 = \tilde{m}_{Q_L}^2 + \left( \frac{1}{2} - \frac{2}{3} s_W^2 \right) m_Z^2 \cos 2\beta + M_u M_u^\dagger \]

\[ \tilde{M}_{DL}^2 = \tilde{m}_{Q_L}^2 - \left( \frac{1}{2} - \frac{1}{3} s_W^2 \right) m_Z^2 \cos 2\beta + M_d M_d^\dagger \]

Symmetries:

- \( \tilde{m}_{Q_L}^2 \) breaks supersymmetry and \( G_q \) but conserves \( SU(2)_L \)
- The terms \( \propto m_Z^2 \) break susy and \( SU(2)_L \) but conserve \( G_q \)
- The terms \( \propto M_q M_q^\dagger \) break \( SU(2)_L \) and \( G_q \) but conserve susy

Consequences:

- Ignoring \( m_Z^2 \) we have \( m_{\tilde{u}}^2 = m_{\tilde{d}}^2 \)
- Ignoring \( m_c^2 \) we have \( \Delta m_{\tilde{u}}^2 = \Delta m_{\tilde{d}}^2 \) and \( K^u K^{d\dagger} = V_{CKM} \)
Minimal Flavor Violation (MFV)

Definition

- In the absence of Yukawa interactions, $Y_D = Y_U = Y_E = 0$, the SM acquires a large global symmetry:
  $$G_{\text{global}} = U(3)_Q \times U(3)_D \times U(3)_U \times U(3)_L \times U(3)_E$$

- In the absence of $Y_D, Y_U$, the SM quark sector has a
  $$G_q = SU(3)_Q \times SU(3)_D \times SU(3)_U$$
  global flavor symmetry

- The symmetry would be there in the SM if the Yukawa couplings were fields (spurions) transforming as
  $Y_U(3,1,\bar{3}), \quad Y_D(3,\bar{3},1)$

- MFV: $Y_U$ and $Y_D$ are the only spurions that break $G_q$
Example: $\Delta m_K$

$L_{\text{eff}}$ (SM + nonrenormalizable terms): All terms constructed from SM fields and the Yukawa spurions are formally invariant under $G_q$

- Consider the operator $\frac{z_{sd}}{\Lambda_{\text{NP}}} (s_L \gamma_\mu d_L)^2$
- $s_L(3, 1, 1), \ d_L(3, 1, 1) \implies (s_L \gamma_\mu d_L) \in (8, 1, 1)$
- Must be proportional to $(Y_U Y_U^\dagger)_{21} = y_c^2 V^*_{cd} V_{cs}$
- With MFV, $z_{sd} \propto y_c^4 (V^*_{cd} V_{cs})^2$
- Consistent with the phenomenological constraints

$L_{\text{NP}}$: All terms constructed from SM fields, new fields and the Yukawa spurions are formally invariant under $G_q$