FLAVOR VIOLATION
IN SUSY

Recent opportunities for collider searches and $b$-physics.

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* Known matter comes in 3 generations \( i, j = 1, 2, 3 \).

\[
\mathcal{L} \supset \bar{Q}_i \mathbb{D} Q_i - \bar{Q}_i (Y_u)_{ij} \langle h^C \rangle U_j - \bar{Q}_i (Y_d)_{ij} \langle h \rangle D_j \quad \langle h \rangle \simeq 174 \text{ GeV}
\]

* Quarks mix and change flavor.

\[
V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \simeq \begin{pmatrix}
1 & \lambda & \lambda^3 \\
-\lambda & 1 & \lambda^2 \\
-\lambda^3 & -\lambda^2 & 1
\end{pmatrix}; \quad \lambda \simeq 0.22
\]

The third generation is decoupled from the first two!

* Today, masses and mixings are known input (still improving).

* Quark Yukawas are hierarchical \( m_u/m_t \sim 10^{-5} \) (this is a puzzle).
Why haven’t we seen NP in FCNC yet?

* FCNCs are suppressed in SM by mixing, loop (and GIM for external c oder t)
  \[ A_{SM}(b \rightarrow q) \sim V_{tb}V_{tq}^* \cdot \frac{(m_t^2 - m_c^2)}{m_W^2} \quad \text{and CKM}! \]

* \[ A_{NP}(b \rightarrow q) \sim f \cdot \frac{(m_t^2 - m_c^2)}{\Lambda_{NP}^2} \quad f = \tilde{V}\tilde{V}^\dagger: \text{NP flavor mixing} \]

* Data from, e.g., meson mixing: |\[ A_{NP} \]| \leq |\[ A_{SM} \]| imply:
  (we assume as in SM \( O(1) \) mass splitting)

A) \( f \sim 1 \): NP not connected to electroweak scale \( \Lambda_{NP} \gg \sqrt{s_{LHC}} \).

B) \( f \lesssim 1 \): largish contributions cancel; not every relevant observable measured yet \( \rightarrow \) rare decays, arg \( (B_s - \bar{B}_s) \).

C) \( f \sim f_{SM} + \epsilon \) and \( f_{SM} = \lambda^n \): suppression similar to SM. With \( \epsilon = 0 \):

Minimal Flavor Violation (MFV)

Chivukula, Georgi ’87; d’Ambrosio et al ’02  non-symmetry based definitions: Ali,London ’99; Buras² ’00
What does MFV imply for SUSY? Simplification!

* The superpotential \((N = 1, \text{unbroken R-parity})\) is MFV!

\[ W_{MSSM} = QY_u H_u U + QY_d H_d D + LY_e H_d E + \mu H_d H_u \]

* SUSY-breaking with MFV-generational structure:

\[ \tilde{Q}^\dagger \tilde{m}^2_Q \tilde{Q} + \tilde{U}^\dagger \tilde{m}^2_U \tilde{U} + \tilde{D}^\dagger \tilde{m}^2_D \tilde{D} + (A_u \tilde{Q} H_u \tilde{U}^* + A_d \tilde{Q} H_d \tilde{D}^* + h.c.) \]

\[
\begin{align*}
\tilde{m}^2_Q &= \tilde{m}^2(a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \\
\tilde{m}^2_U &= \tilde{m}^2(a_2 \mathbf{1} + b_5 Y_u^\dagger Y_u) \\
\tilde{m}^2_D &= \tilde{m}^2(a_3 \mathbf{1} + b_6 Y_d^\dagger Y_d) \\
A_u &= A(a_4 \mathbf{1} + b_7 Y_d Y_d^\dagger) Y_u \\
A_d &= A(a_5 \mathbf{1} + b_8 Y_u Y_u^\dagger) Y_d
\end{align*}
\]

D'Ambrosio et al '02

\(b_i \equiv 0: \text{SUSY breaking is flavor blind}\)
left: SPS2 (middle curve: $b_i(M_{GUT} = 0)$ Paradisi et al 0805.3989

right: AMSB Allanach et al 0902.4880

For low $\tan \beta$, mAMSB becomes exactly flavor blind in the QIR-fixed point limit of $Y_t$ 0902.4880.
* Highly degenerate squarks of 1st and 2nd generation:
\[ \Delta m/m_0 \sim \frac{\lambda^2}{2}; \quad \Delta m < 1 \text{ GeV} \]

* 3rd generation decoupled (via \( V_{CKM} \)).
Huge non-MFV effects thru non-CKM CP-phases: 8 asymmetries in angular distribution $\Gamma(q^2, \Theta_l, \Theta_K, \varphi)$ in $B \rightarrow (K^* \rightarrow K\pi)\mu^+\mu^-$

4 CP-asys CP-odd: untagged $\bar{B}_s, B_s \rightarrow (\Phi \rightarrow KK)\mu^+\mu^-$  

Three CP-asy's are $T_N$-odd and can be $\mathcal{O}(1)$ with NP

Figs. from 0805.2525

Other recent works on angular analyses [hep-ph]: Bobeth et al 0709.4174, Egede et al 0807.2589, Altmannshofer et al 0811.1214
Predictive $\mathcal{O}(1)$ effects within MFV models if $\tan \beta$ largish. Many works

Here, AMSB ($m_{3/2} = 40$ TeV) Figs from Allanach et al 0902.4880

Analytical expressions for the full flavor structure, that is, $a_i$, $b_j$ or $(\delta^q)_{ij}$, within mAMSB 0902.4880.
Measuring MFV Mixing at Colliders

* In MFV, mixing between third and other generations is suppressed:

\[
\tilde{m}_Q^2 = \tilde{m}^2 (a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger)
\]

\[
(\tilde{m}_Q^2)_{23}/\tilde{m}^2 \sim \lambda_b^2 V_{cb} V_{tb}^* \sim 10^{-5} \tan \beta^2
\]

* Such a tiny coupling can indeed be probed! \text{GH,Nir '08} requirement: \( \tilde{t} \rightarrow c\chi^0 \) dominant decay & sufficiently suppressed rate.

* Then, stop lifetime \( \tau_{\tilde{t}} \sim \text{ps} \left( \frac{m_{\tilde{t}}}{100 \text{ GeV}} \right) \left( \frac{0.03}{\Delta m/m_{\tilde{t}}} \right)^2 \left( \frac{10^{-5}}{Y} \right)^2 \) is long

\[
\Delta m = m_{\tilde{t}} - m_{\chi^0}, \ Y_{\text{MFV}} \sim \lambda_b^2 V_{cb}, \text{ and yields a macroscopic decay length! \ trick: measure lifetime instead of branching ratio}
\]

* This is a counterexample to the lore that colliders determine only masses, and mixings are measured in low energy experiments.
Tevatron Light Stop Searches in $\tilde{t} \rightarrow c\tilde{\chi}_1^0$

Fig from D0, 0803.2263 [hep-ex]
* \( \Delta m > m_b \) opens up tree level 4-body decays \( \tilde{t} \rightarrow b\chi^0l\nu \).

\[
\frac{\Gamma(\tilde{t} \rightarrow b\chi^0l\nu)}{\Gamma(\tilde{t} \rightarrow c\chi^0)} \approx \frac{g^6|V_{tb}|^2}{2(4\pi)^4} \frac{(\Delta m - m_b)^8}{[Y(\Delta m)]^2 m_W^4 m_{\chi}^2} \]

solid curve: \( \beta\gamma\tau_{\tilde{t}} > 0.1 m_m \); dashed: \( Y_{min} \) alignment; horizontal solid line \( Y \approx \lambda_c \) anarchy + extended R-symm. [Fig:GH,Nir ’08]

light stop ingredient of EWK baryogenesis; supports coannihilation of relic density; stop NLSP in hypercharged anomaly mediation

Dermisek et al’07, or large A-terms.
The LHC will explore for the first time the scale of electroweak symmetry breaking. What are the flavor quantum numbers of new particles/SM partners?

Already strong constraints: Either TeV-BSM accidentally small in measured $K, D, B$-observables, or there is an organizing principle such as MFV; or, we haven’t looked good enough at relevant observables yet $\rightarrow$ LHC(b), super flavor factories.

Flavor has implications and opportunities for collider searches. The stop decay length measurement is just one new idea.

If MFV is confirmed, the origin of flavor is most likely unrelated to the TeV-scale.