(Heavy) Flavor Physics - Theory

* Flavor Physics: about, status
* Beyond-the-SM Flavor: concepts, constraints, predictions; susy
* Direct and indirect tests at hadron colliders

Gudrun Hiller, Dortmund
The Standard Model of Particle Physics

renormalizable quantum field theory + local symmetry

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{em} \]

\[ \mathcal{L}_{SM} = -\frac{1}{4} F^2 + \bar{\psi}i\not{D}\psi + \frac{1}{2}(D\Phi)^2 - \left( \bar{\psi}Y\Phi\psi \right) + \mu^2\Phi^2 - \lambda\Phi^4 \]  

\( \psi \): fermions (quarks and leptons)

\( F_{\mu\nu} \): gauge bosons \( g, \gamma, Z, W \)

\( \Phi \): Higgs boson (not observed to date)

Known fundamental matter comes in generations \( \psi \rightarrow \psi_i, \ i = 1, 2, 3. \)

Flavor physics = investigations on generational structure of fermions (and partners)
fields in representations under the SM group $SU(3)_C \times SU(2)_L \times U(1)_Y$

Higgs: $\Phi(1, 2, 1/2)$

quarks: $Q_L(3, 2, 1/6)_i, D_R(3, 1, -1/3)_i, U_R(3, 1, 2/3)_i$

leptons: $L_L(1, 2, -1/2)_i, E_R(1, 1, -1)_i$

L: doublet, R:singlet under $SU(2)_L$

\[
\mathcal{L}_{\text{SM}} = \sum_{\psi=Q,U,D,L,E} \bar{\psi}_i \mathcal{D} \psi_i \\
- \bar{Q}_{Li} (Y_u)_{ij} \Phi^C U_{Rj} - \bar{Q}_{Li} (Y_d)_{ij} \Phi D_{Rj} - \bar{L}_{Li} (Y_e)_{ij} \Phi E_{Rj} \\
+ \mathcal{L}_{\text{higgs}} + \mathcal{L}_{\text{gauge}}
\]

$Y_u, Y_d, Y_e$: Yukawa matrices ($3 \times 3$, complex). After diagonalization, there are $6 + 3$ Dirac masses and 4 parameters in the quark mixing matrix $V_{CKM} \equiv V$ left. These are the only sources of flavor in the SM.
Mismatch between gauge and mass basis allows quarks to mix and change flavor. This happens only thru charged (weak) currents, with strength $V_{ij} = V_{ui}d_j$. Wolfenstein parameter $\lambda \simeq 0.22$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & +\lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & +A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

With 3 generations there are 10 param. in quark flavor & CP sector: 6 masses, 3 angles and 1 phase in CKM-matrix unitary, complex, hierarchical, known with accuracy: $|V_{us}| = 0.225$ (permille), $|V_{cb}| = 42 \cdot 10^{-3}$ (percent), $|V_{ub}| = 4 \cdot 10^{-3}$ (ten percent), $\sin 2\beta$(measured) = 0.67 (percent)

PS: enormous progress from $B$-factories over past decade. PPS: still improving precision.
* The third generation is decoupled from the first two.
* The CP violating phase is order one.
* SM quark flavor violation is entirely described by 10 parameters.
* With these parameters better and better known, one can look for (even small) deviations from SM/CKM-induced flavor and CP violat.

The unitarity triangle

\[ V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0 \]

\[ \sum_j V_{ji}V_{jk}^* = \delta_{ik} \]

the next unitarity triangle

\[ V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \]
Flavor Changing Neutral Currents

generic SM $b \rightarrow s$ amplitude

quantum loop effect $\mathcal{A}(b \rightarrow s) = V_{ub} V_{us}^* A_u + V_{cb} V_{cs}^* A_c + V_{tb} V_{ts}^* A_t$

with unitarity $VV^\dagger = 1$:

$\mathcal{A}(b \rightarrow s) = V_{tb} V_{ts}^*(A_t - A_c) + V_{ub} V_{us}^*(A_u - A_c) = V_{tb} V_{ts}^*(A_t - A_c) + \mathcal{O}(\lambda^4)$

* GIM suppression inactive $\frac{m_t^2 - m_c^2}{m_W^2} \sim \mathcal{O}(1)$

* direct CP violation $b \rightarrow s$ small: $|\mathcal{A}(b \rightarrow s)| = |\mathcal{A}(\bar{b} \rightarrow \bar{s})||(1 + \mathcal{O}(\lambda^2))$

* $c \rightarrow u$, top FCNCs: GIM and CKM suppressed in SM.
Exploring Physics at Highest Energies

Length [m]

10^{-18} –
10^{-15} –
10^{-12} –
10^{-9} –
10^{-6} –
–
–
–
–
–
–
nano
visible light

Energy

NEW PHYSICS ?

LHC

Higgs, SUSY ?

\Lambda_{EWK}

\Lambda_{QCD}

E_{Deuteron}

E_{Rydberg}

2 eV

particle physics

atomic, nuclear physics

(Heavy) Flavor Theory

Cern, June 2009

Slide 7
Modulo "hints" all flavor changing data† are currently ok with the SM within uncertainties.

(but no explanation for flavor/hierarchies in masses and mixing)

What is the flavor structure of the electroweak physics beyond the SM?

†Not every relevant observable is measured or measured with sufficient accuracy.
Flavor Violation beyond the SM

\[ A_{SM}(b \rightarrow q) \sim V_{tb} V_{tq}^* \cdot \frac{g^2}{16\pi^2} \cdot \frac{(m_t^2 - m_c^2)}{m_W^2} \]

\[ A_{NP}(b \rightarrow q) \sim f_{bq} \cdot \text{(loop or tree)} \cdot \frac{(m_t^2 - m_c^2)}{\Lambda^2} \]

\[ f_{AB} = \tilde{\nu}_{iA} \tilde{\nu}_{Bi}^\dagger: \text{New Physics flavor mixing} \quad \Lambda: \text{scale of NP} \]

* Data on FCNC suggest that – if \( \Lambda \sim \sqrt{s_{LHC}} \sim \Lambda_{EWK} \) – it is very natural that the suppression of flavor changing transitions is similar to the one in the SM

\[ f \sim f_{SM} + \epsilon \text{ and } f_{SM} = \lambda^n, \lambda \sim \sin \Theta_C \sim 0.2. \]

* Flavor suppression as in the SM (\( \epsilon = 0 \)):

**Minimal Flavor Violation (MFV)**

Chivukula, Georgi ‘87; d’Ambrosio et al ‘02 non-symmetry based definitions: Ali, London ‘99; Buras\(^2\) ‘00
The superpotential ($N = 1$, unbroken R-parity) is MFV:

$$W_{MSSM} = Q_L Y_u H_u U_R + Q_L Y_d H_d D_R + L_L Y_e H_d E_R + \mu H_d H_u$$

Without further input there can be arbitrarily large and CP-violating intergenerational mixing among the scalar partners of the SM fermions from the SUSY breaking:

$$\mathcal{L}_{soft} = -\tilde{Q}^i_L (\tilde{m}_Q^2)_{ij} \tilde{Q}_L j + \ldots$$

This is ruled out by FCNC data for TeV-scale SUSY partners.
The off-diagonal squark mass terms "mass insertions" 
\[ \delta_{ij}^Q = \frac{(\tilde{m}_Q^2)_{ij}}{\tilde{m}_{\text{ave}}}, i \neq j, \]
induce FCNCs, and are constrained by data.

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\[ \sqrt{\Re(\delta_{12}^d)^2_{LL}}, \sqrt{\Re(\delta_{12}^d)^2_{LR}}, \sqrt{\Im(\delta_{12}^d)^2_{LL}}, \sqrt{\Im(\delta_{12}^d)^2_{LR}} \]

Table 1: Maximum allowed values for \( |\Re(\delta_{12}^d)_{AB}| \) and \( |\Im(\delta_{12}^d)_{AB}| \), with \( A, B = (L, R) \) for an average squark mass \( m_\tilde{q} = 500 \text{ GeV} \) and for different values of \( x = m_\tilde{q}^2/m_{\tilde{Q}}^2 \). The bounds are given at tree level in the effective Hamiltonian and at e.g., 0711.2903 NLO in QCD corrections as explained in the text. For different values of \( m_\tilde{q} \) the bounds scale roughly as \( m_\tilde{q}/500 \text{ GeV} \).
MFV Flavor in SUSY

* MFV implies squark flavor-mixing given by quark-Yukawa matrices

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

etc.

\[ Y_u = \text{diag}(y_u, y_c, y_t), \quad Y_d = V \cdot \text{diag}(y_d, y_s, y_b) \] (up mass basis)

Controlled departure from flavor-blind SUSY breaking.

* $\mathcal{O}(1)$ deviations possible in MFV-MSSM from SM in rare processes if $\tan \beta$ is large.

* Anomaly mediation, gauge mediation and CMSSM/mSUGRA (by construction) are MFV.

* MFV coefficients also induced by RG-evolution.
* Highly degenerate squarks of 1st and 2nd generation:
\[ \Delta m/m_0 \sim \lambda^2_c/2; \quad \Delta m < 1 \text{ GeV} \]
* 3rd generation decoupled (via CKM).
Predictive $\mathcal{O}(1)$ effects within MFV models if $\tan \beta$ largish. Many works

Here, AMSB ($m_{3/2} = 40$ TeV)

Analytical expressions for the full flavor structure, that is, $a_i$, $b_j$ or $(\delta^q)_{ij}$, within mAMSB 0902.4880.
The larger the departure from MFV, the larger the potential NP effects due to larger mixing and/or mass splitting between generations.

Existing flavor data leave large room for strong non-MFV signals to show up in branching ratios, decay shapes, angular distributions and CP-asymmetries. Esp.: $B_s$-mixing, $D^0$-mixing, $B \to K^{(*)}\ell\ell$, photon helicity in $b \to q\gamma_{L,R}$, and in

$$R_{\mu\mu} = \frac{B(B_s \to \mu^+\mu^-)}{B(B_d \to \mu^+\mu^-)}$$

$$R_{\mu\mu}^{SM,MFV} = \frac{m_{B_s} f_{B_s}^2 \tau_{B_s}}{m_{B_d} f_{B_d}^2 \tau_{B_d}} r_{ps} \times \frac{|V_{ts}|^2}{|V_{td}|^2}.$$
Testing Quark Flavor Violation at Colliders

- indirectly: $b$ physics
- directly: (s)top physics
add \( A = \gamma, g, Z, h^0, \ldots \). That’s an =”A”-penguin.

construction of weak low energy effective theory valid \( \mu \leq \mu_W = \Lambda \)

\[
\mathcal{L}_{\text{eff}} = \sum_i C_i(\mu) \frac{O_i(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{p^4}{\Lambda^4}\right)
\]

\( O_i \): dim 6 operators out of light degrees of freedom originate from penguins and boxes

\( C_i \): Wilson coefficients: contain info on high scales \( \gtrsim \mu_W \) e.g., hep-ph/9806471

\( C_i(m_W) \): matching of effective onto full theory. RG-running

\( C_i \): known up to NNLO in SM for QCD, and NLO for EWK corr.
$b \rightarrow s\gamma, \ b \rightarrow sll$ Decays

Diagrams in SM

\[ \mathcal{H}_{\text{eff}} = -4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum C_i(\mu) O_i(\mu) \]

Dipole operators

\[ O_7 \propto \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu} \]

\[ O_8 \propto \bar{s}_L \sigma_{\mu\nu} b_R G^{\mu\nu} \]

4-Fermi operators

\[ O_9 \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell) \]

\[ O_{10} \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \gamma_5 \ell) \]

NP in Wilson coefficients

\[ C_i = C_i^{SM} + C_i^{NP} \]

Model-independent analysis: $B r$'s, $A_{CP}, A_{FB} = f(C_i) \rightarrow \text{fit!}$

hep-ph/9408213
FCNC Photon Couplings Model-independently

dipole operators $O_7 \propto \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ "flipped" $O'_7 \propto \bar{s}_R \sigma_{\mu\nu} b_L F^{\mu\nu}$

- green ring: $Br(B \to X_s \gamma) \sim |C_7|^2 + |C'_7|^2 \sim |C'_7^{SM}|^2$
- red cross: time-dependent CP-asymmetry $B \to (K^{*0} \to K_S^{0} \pi^{0}) \gamma$
- blue area: $Br(B \to X_s ll)$ data favor sign($C_7$) to be SM like.
• Penguin bounds: \((at \mu \simeq m_b, assuming no BSM operators)\)

\[ bsZ : |C_{10}| \lesssim (1-2)|C_{10}|_{SM}, \quad bs\gamma : C_7 \simeq C_{7SM}, \quad bsg : |C_8| \lesssim 5|C_8|_{SM}. \]

• Todays best bound on MSSM Higgs-penguins from Tevatron

\[ \mathcal{B}(B_s \to \mu^+\mu^-) \]

• \(b \to d\) beginning to be probed, MFV-link with \(b \to s\)

to come: CP-phases and helicity.

• Tools in penguin-physics:

multi-observable analyses and fits and SM-null tests.
How to calculate $A(B \to K^*\mu\mu)$

1. choose model, such as SM, MSSM etc. This is your "full" theory.

2. Calculate the low energy effects "Wilson coefficitents" of this full theory within a "generalized Fermi-theory", the effective theory, $H_{eff}$.

3. Take the matrix element $A(B \to K^*\mu\mu) = \langle K^*\mu\mu|H_{eff}|B \rangle$. This needs input from non-pertubative QCD: form factors etc.

In full QCD, there are 7 form factors in $B \to K^*$: $A_0, A_1, A_2, V, T_1, T_2, T_3$. see, e.g., ABHH,hep-ph/9910221

This simplifies for low dilepton mass to just 2: $\xi_\perp, \xi_\parallel$. e.g., BFS hep-ph/0412400

4. Work out your observables/distributions.

5. Employ cuts: Remove huge BGD from $B \to V_{cc}K^* \to \mu\muK^*$;

$V_{cc} = J/\Psi, \Psi', ..$ by cuts in dilepton invariant mass.

(Heavy) Flavor Theory

Cern, June 2009
$d^2\Gamma/dq^2 d\cos \Theta$; note: $\cos \Theta (\bar{B}l^+) = -\cos \Theta (\bar{B}l^-)$

$A_{FB}: \#$ forward - $\#$ backward $\ell^+$ in dilepton CMS w.r.t. $\bar{B}$ (CP-odd)

$$A_{FB}(\hat{s}) \equiv \int d\cos \Theta \text{sign}(\cos \Theta) \frac{d\Gamma}{d\hat{s}d\cos \Theta} \sim -\text{Re} \left[ C_{10}^* (C_{7}^{\text{eff}} + \beta(\hat{s})C_{9}^{\text{eff}}) \right]$$
There is no unique rigorous framework available to describe exclusive $b \rightarrow sll$ decays in the whole kinematically accessible range. Theoretically preferred region: low dilepton mass below $J/\Psi$ (QCDF); low recoil region also calculable. **CUTS are important!**

Whole $q^2$-region tests the SM; different regions are sensitive to different New Physics.  blue: SM; green: no zero at lo $q^2 \rightarrow signC_7$; red/pink: sign $A_{FB}$ at hi $q^2 \rightarrow signC_{10}$
Early data can help a lot – already sign determination useful:

BaBar: $A_{FB}^{high q^2} = 0.76^{+0.52}_{-0.32} \pm 0.07$  

Belle measurement of similar quality 0410006, 0603018; $|C_{10}^{NP}| - \Phi_{10}$ plot from 0805.2525 uses sign $A_{FB}^{high q^2}$ is SM-like (blue: $A_{FB}$ constraint; black allowed)
Full Angular Analysis in $B \rightarrow V(\rightarrow PP)\mu\mu$

full angular analysis \textit{hep-ph/9907386}

$$d\Gamma^4 \sim J dq^2 d \cos \Theta_l d \cos \Theta_{K^*} d\Phi; \quad J = \sum_{i=1}^{9} J_i(q^2) f(\Theta_l, \Theta_{K^*}, \Phi)$$

$$\Gamma \sim J_1 - J_2/3, \quad A_{FB} \sim J_6, \quad A_{T}^{(2)} \sim J_3 \textit{hep-ph/0502060}$$

$B \rightarrow K(*)l\bar{l}$ CP observables in angular analysis Bobeth,GH,Piranishvili 0805.2525

CP-asymmetries $A_i \propto J_i - \bar{J}_i$: SM: all doubly Cabbibo-suppressed

$A_3, A_9$ vanish in SM by helicity conservation: sens. to RH currents $A_3, A_9, (A_6)$ can be extracted from single-diff distribution in $\Phi(\Theta_l)$

$A_7, A_8, A_9$: T-odd: no strong phase suppression; O(1) with NP

$A_5, A_6, A_8, A_9$: CP-odd: can be extracted without tagging from $\Gamma + \bar{\Gamma}$

Difference between $B_d \rightarrow K^*$ and $B_s \rightarrow \Phi$ probes predom. $B_s$ mixing ($\Delta \Gamma_s$ and phase); $A_5,6,8,9$ without flavor-tagging and time-integrated!

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Angular Distribution

For $\bar{B} = (b\bar{q})$ decays:

$$J(q^2, \theta_l, \theta_{K^*}, \phi) = J_1^q \sin^2 \theta_{K^*} + J_1^q \cos^2 \theta_{K^*} + (J_2^q \sin^2 \theta_{K^*} + J_2^q \cos^2 \theta_{K^*}) \cos 2\theta_l$$
$$+ J_3^q \sin^2 \theta_{K^*} \sin^2 \theta_l \cos 2\phi + J_4^q \sin 2\theta_{K^*} \sin 2\theta_l \cos \phi + J_5^q \sin 2\theta_{K^*} \sin \theta_l \cos \phi$$
$$+ J_6^q \sin^2 \theta_{K^*} \cos \theta_l + J_7^q \sin 2\theta_{K^*} \sin \theta_l \sin \phi$$
$$+ J_8^q \sin 2\theta_{K^*} \sin 2\theta_l \sin \phi + J_9^q \sin^2 \theta_{K^*} \sin^2 \theta_l \sin 2\phi,$$  \hspace{1cm} (2.3)

$J_i = J_i(q^2), q = p_{l^+} + p_{l^-}; J_i$ are functions of transversity amplitudes.

$\Theta_l$: angle between $l^-$ and $\bar{B}$ in dilepton CMS (warning: different conventions in literature)

$\Theta_{K^*}$: angle between $K$ and $\bar{B}$ in $K^*$-cms

$\Phi$: angle between normals of the $K\pi$ and $l^+l^-$ plane

For CP-conjugate $B$ decays: $J_{1,2,3,4,7} \rightarrow \bar{J}_{1,2,3,4,7}, J_{5,6,8,9} \rightarrow -\bar{J}_{5,6,8,9}$
Here, what is meant by T is the naive T transformation, not time-reversal! Under naive T, the momenta and spins of all particles are flipped, but the initial and final states are not interchanged.

$\varphi_W$: weak, CP-violating phase; $\varphi_S$: strong, CP-conserving phase

T-even CP asymmetries: $\propto \sin \varphi_W \sin \varphi_S$: small if QCD gives us only small strong phases despite a possible O(1) NP phase.

PS: this is exactly what happens at low dilepton mass in $B \to K^{(*)}ll$ decays where QCDF predicts small $\varphi_S$

T-odd CP asymmetries: $\propto \sin \varphi_W \cos \varphi_S$ maximal for vanishing strong phase
Both $A_7$ and $A_6$ are sensitive to Z-penguins ($\sim C_{10}$)
\( A_7, A_8, A_9 \) are T-odd and can be order one with NP

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\( \mathcal{B}(B_s \rightarrow \mu \mu) \) < \( 1.4 \cdot 10^{-8} \) < \( 6.3 \cdot 10^{-9} \) < \( 1.3 \cdot 10^{-8} \) SM
$A_7, A_8, A_9$ are T-odd and can be order one with NP

Fig. from 0805.2525
Angular Analysis in $B \rightarrow Kll$, $l = e \textit{ vs } \mu$

\[
\frac{d\Gamma}{d\cos \Theta_l} = \frac{3}{4} (1 - F_H^l)(1 - \cos^2 \Theta_l) + \frac{F_H^l}{2} + A_{FB}^l \cos \Theta_l
\]

information in $F_H^l$ and $A_{FB}^l$ beyond $d\Gamma/l/dq^2$ (in general: lepton flavor dependence)

$F_H^l$ can be correlated with $R_K = \mathcal{B}(B \rightarrow K\mu\mu)/\mathcal{B}(B \rightarrow K\textit{ee})$

In SM: $R_K - 1$, $F_H^l$ and $A_{FB}^l$ (and $\mathcal{B}(B \rightarrow ll)$) are suppressed by lepton mass.

Probe of Higgs-exchanges, lepto-quarks, R-parity violation etc.

Model-independently w. scalar/tensor couplings (for low $q^2$):

$|A_{FB}^e| < 13\%, \quad |A_{FB}^\mu| < 15\%, \quad R_K - 1 = \mathcal{O}(1), \quad F_H^{e,\mu} < \mathcal{O}(0.5)$
With the rich final state and many orthogonal observables, $b \to qll$ processes are powerful probes of BSM physics. At hadron colliders in particular exclusive decays into muons can be studied. Inclusive decays and those with $l = e$ or invisibles, i.e., $l = \tau$ or $\nu$ are favorable to $e^+e^-$ super flavor machines.

While the $Br$ is observed, and first data on $A_{FB}, R_K$ etc are available, $B \to K^{(*)}ll$ has great potential to test the SM, search for NP and classify it (CP, right-handed currents, Higgs effects,..).

Ideally, measure everything: the full angular distributions, and final states $l = e, \mu, \tau$ and $\nu$ (Z-penguins).

$Br(B \to K^{(*)}\mu\mu)/Br(B \to K^{(*)}ee)$ tests lepton non-universality. Also $b \to d$. 

(Heavy) Flavor Theory

Cern, June 2009
Flavor physics in direct searches at hadron colliders usually means top physics. Further opportunities exist: Lepton flavor violation (sleptons): 0712.0674, 0712.2074, 0802.2582, but also quark flavor physics. The latter is difficult because there is no particle ID; its just top, bottom and all the others. However, some info is possible, e.g., from Higgs production and decay, or squark processes e.g., 0512315, 0708.0940, 0801.1800, if the third generation is involved. These studies are complementary to the ones performed indirectly.

I want to discuss here one idea: the possibility of observing a light, long-lived stop. 0802.0916
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 if \( \tilde{t} \rightarrow c\chi^0 \) is dominant decay & has 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

\( \Delta m = m_{\tilde{t}} - m_{\chi^0} \), \( Y_{\text{MFV}} \sim \lambda_b^2 V_{cb} \), 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]
**Δm > mb** opens up tree level 4-body decays $\tilde{t} \rightarrow b\chi^0 l\nu$.

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

solid curve: $\beta\gamma_{\tilde{t}} > 0.1 mm$; dashed: $Y_{min}$ alignment; horizontal solid line $Y \simeq \lambda c$ 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 $→$ LHC(b), super flavor factories.

Info can be obtained from indirect and direct collider searches. (see stop decay length measurement as one new example for the latter.)
What can we learn from flavor physics?

Find out whether TeV-physics has more flavor violation than the SM.

The observation of non-MFV couplings could point towards the origin of generational mixing and hierarchies, i.e., flavor.


C. Bobeth, G. Hiller and G. Piranishvili, “CP Asymmetries in $\bar{B} \rightarrow \bar{K}^* (\rightarrow \bar{K}\pi) l^+ l^-$ and Untagged $\bar{B}_s, B_s \rightarrow \Phi (\rightarrow K^+ K^-) l^+ l^-$ Decays at NLO,” JHEP 0807, 106 (2008) [arXiv:0805.2525 [hep-ph]].


