# FLAVOR VIOLATION

# IN SUSY

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

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* Known matter comes in 3 generations $i, j = 1, 2, 3$.

$$\mathcal{L} \supset \bar{Q}_i i \not{D} Q_i - \bar{Q}_i (Y_u)_{ij} \langle h^C \rangle U_j - \bar{Q}_i (Y_d)_{ij} \langle h \rangle D_j \qquad \langle h \rangle \simeq 174 \text{ GeV}$$

* 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 $t$)

$$\mathcal{A}_{\mathrm{SM}}(b \to q) \sim V_{tb}V_{tq}^* \cdot (m_t^2 - m_c^2)/m_W^2 \qquad \text{and CKM !}$$

* $\mathcal{A}_{\mathrm{NP}}(b \to q) \sim f \cdot (m_{\tilde{t}}^2 - m_{\tilde{c}}^2)/\Lambda_{NP}^2 \qquad f = \tilde{V}\tilde{V}^\dagger$: NP flavor mixing

* Data from, e.g., meson mixing: $|\mathcal{A}_{\mathrm{NP}}| \lesssim |\mathcal{A}_{\mathrm{SM}}|$ imply:

(we assume as in SM $\mathcal{O}(1)$ 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 $\qquad \to$ rare decays, arg $(B_s - \bar{B}_s)$.

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

<span style="color:red">Minimal Flavor Violation (MFV)</span>

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 !

$$W_{MSSM} = QY_uH_uU + QY_dH_dD + LY_eH_dE + \mu H_dH_u$$

* SUSY-breaking with MFV-generational structure:

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

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

$$\tilde{m}_U^2 = \tilde{m}^2(a_2 \mathbf{1} + b_5 Y_u^\dagger Y_u)$$

$$\tilde{m}_D^2 = \tilde{m}^2(a_3 \mathbf{1} + b_6 Y_d^\dagger Y_d)$$
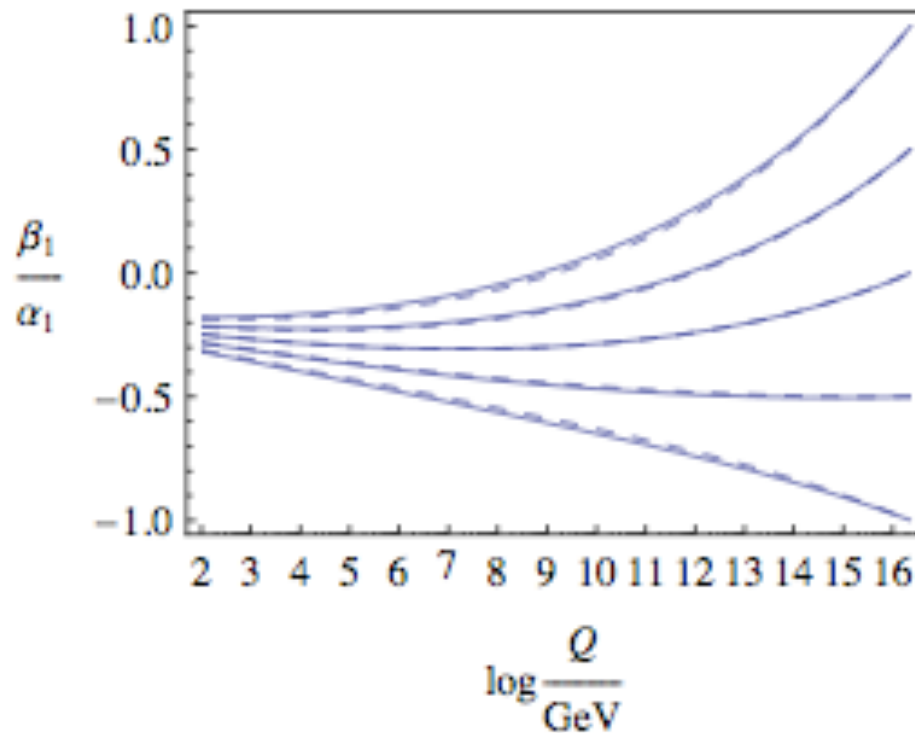
$$A_u = A(a_4 \mathbf{1} + b_7 Y_d Y_d^\dagger) Y_u$$

$$A_d = A(a_5 \mathbf{1} + b_8 Y_u Y_u^\dagger) Y_d$$

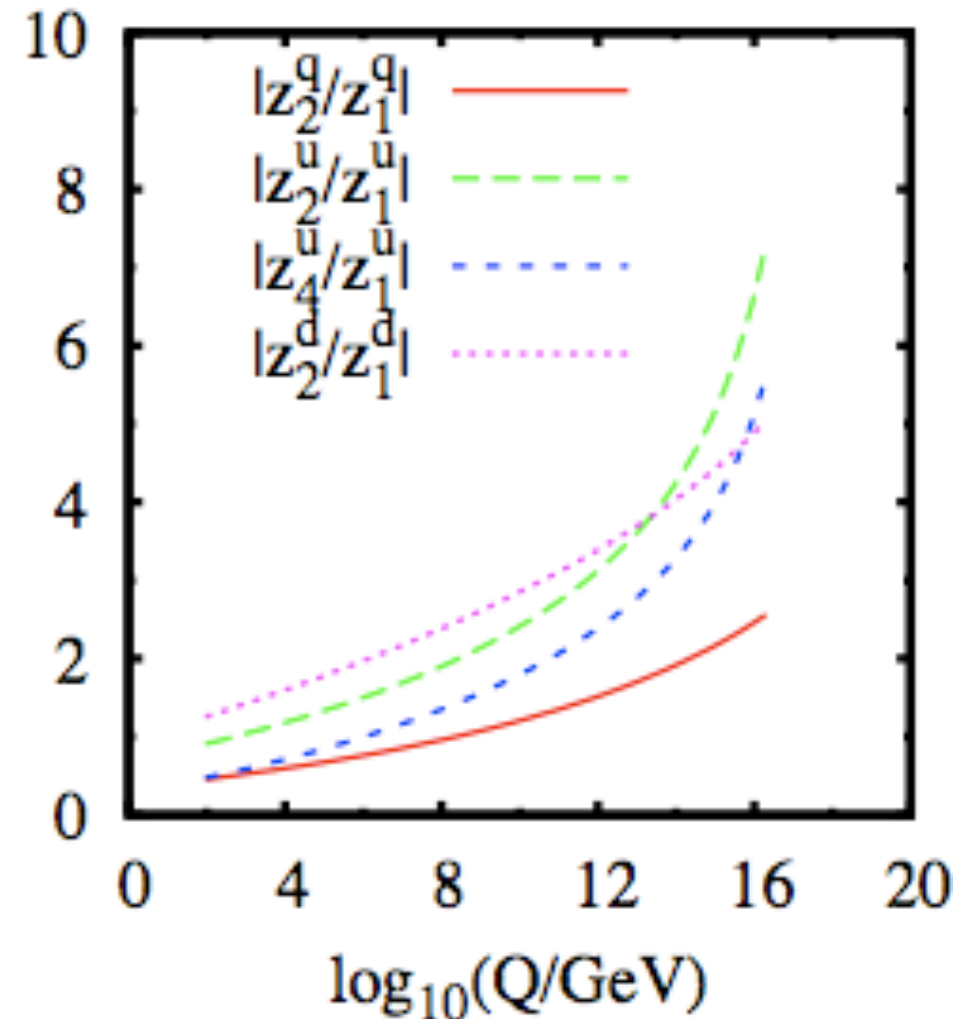D'Ambrosio et al '02      $b_i \equiv 0$: SUSY breaking is flavor blind

left: SPS2 (middle curve: $b_i(M_{GUT} = 0)$ Paradisi et al 0805.3989

right: AMSB Allanach et al 0902.4880



(e) SPS4

For low $\tan\beta$, mAMSB becomes exactly flavor blind in the QIR-fixed point limit of $Y_t$ 0902.4880 .

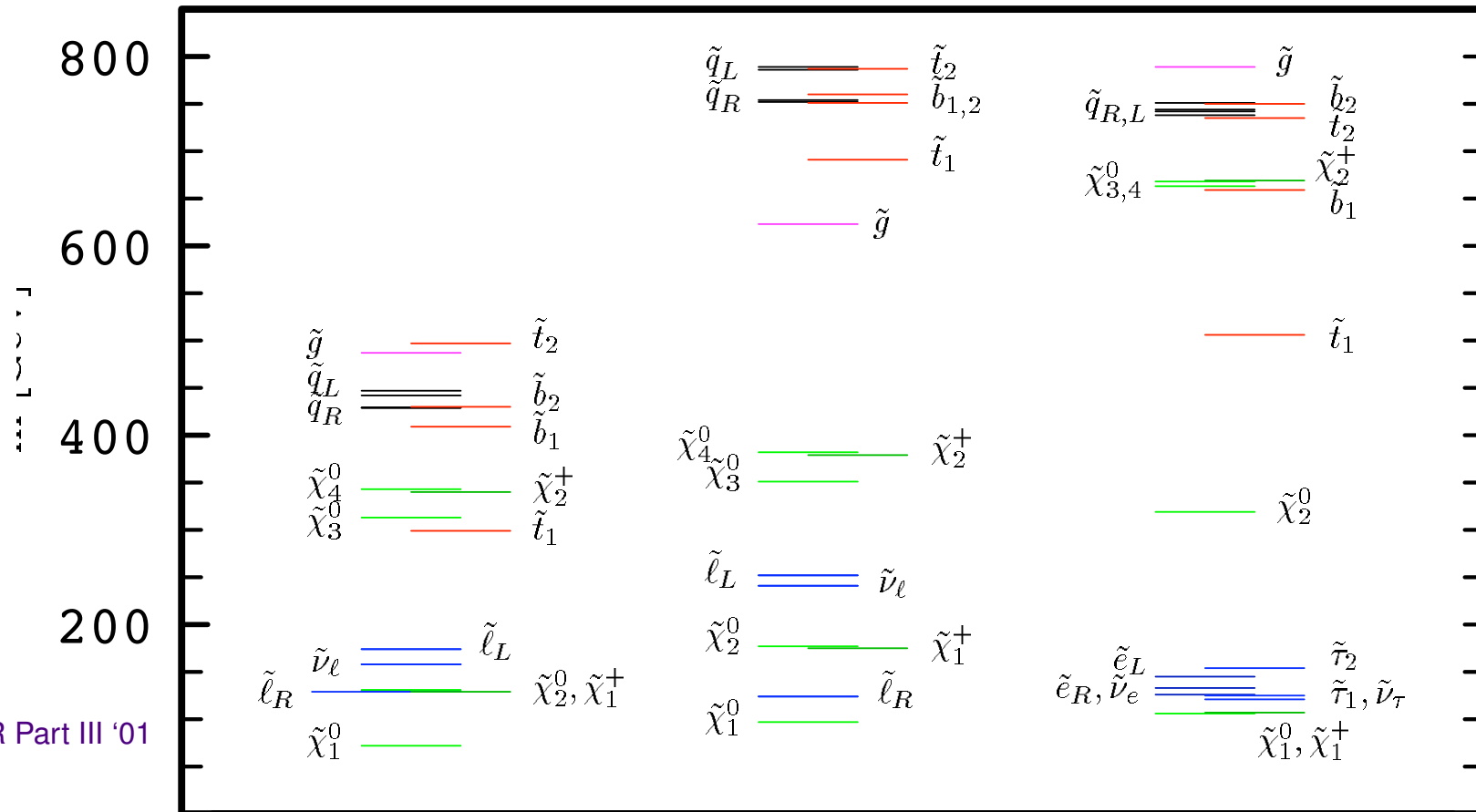# MFV Predictions for the MSSM

\* Highly degenerate squarks of 1st and 2nd generation:

$$\Delta m/m_0 \sim \lambda_c^2/2; \qquad \Delta m < 1 \text{ GeV}$$
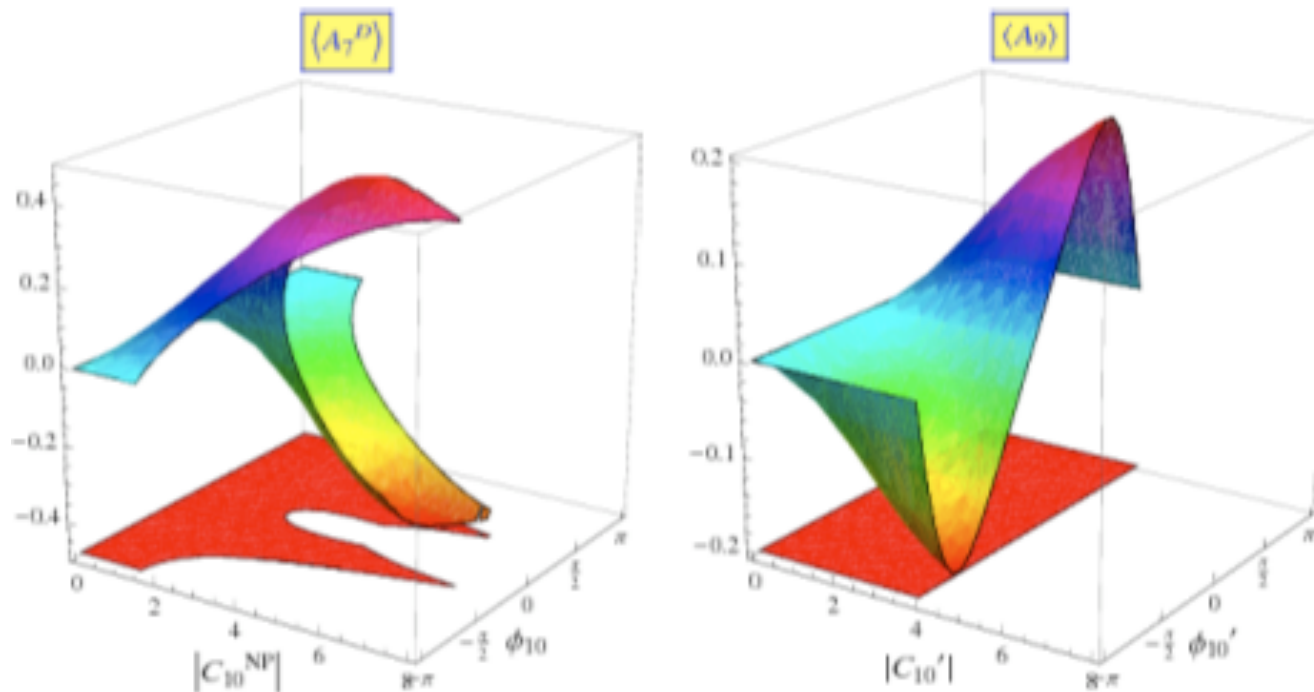
\* 3rd generation decoupled (via $V_{CKM}$).

# Testing SUSY Flavor with FCNC-Loops: CP

∗ Huge non-MFV effects thru non-CKM CP-phases: 8 asymmetries in angular distribution $\Gamma(q^2, \Theta_l, \Theta_K, \varphi)$ in $B \to (K^* \to K\pi)\mu^+\mu^-$

4 CP-asys CP-odd: untagged $\bar{B}_s, B_s \to (\Phi \to KK)\mu^+\mu^-$ <span style="color:purple">Bobeth et al 0805.2525</span>

∗ Three CP-asy's are $T_N$-odd and can be $\mathcal{O}(1)$ with NP <span style="color:purple">Figs. from 0805.2525</span>
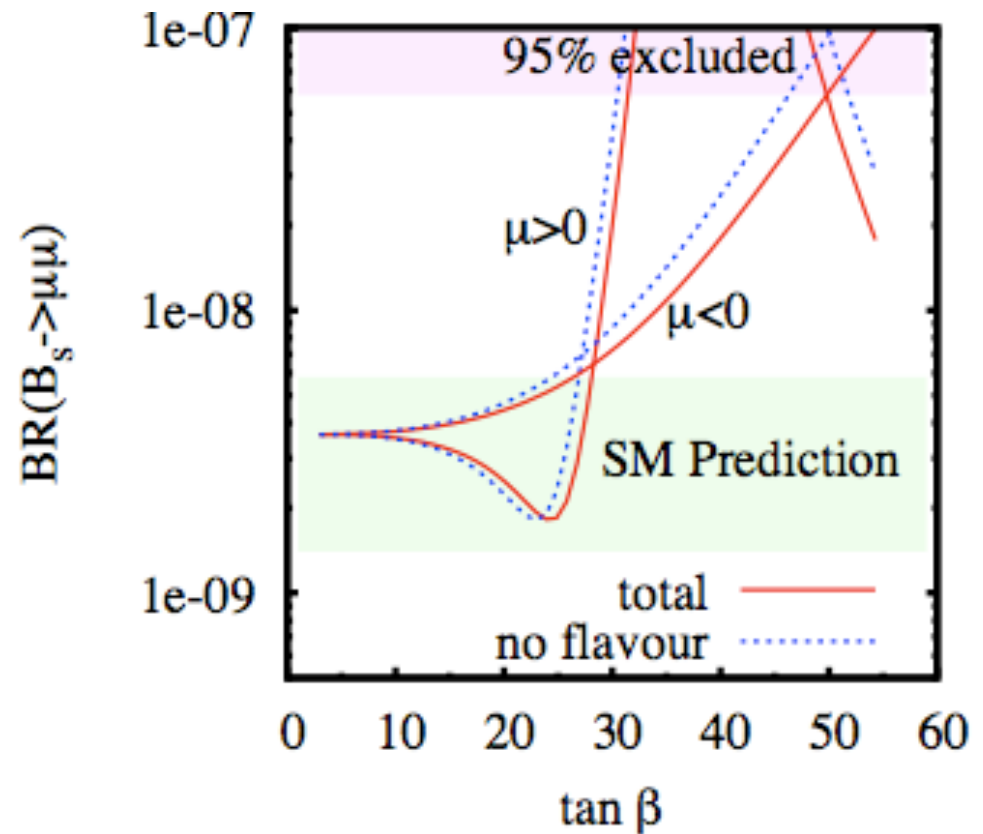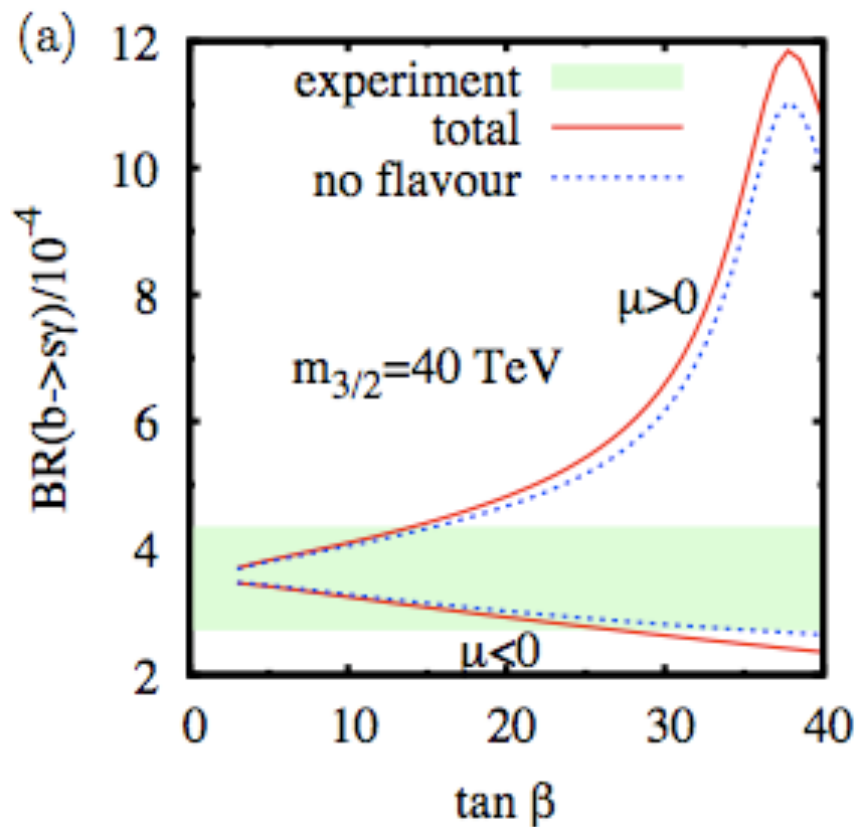


<span style="color:purple">Other recent works on angular analyses [hep-ph]: Bobeth et al 0709.4174, Egede et al 0807.2589, Altmannshofer et al 0811.1214</span>

* Predictive $\mathcal{O}(1)$ effects within MFV models if $\tan\beta$ largish. <sub>many works</sub>

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



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 ! <small>GH,Nir '08</small> requirement:
$\tilde{t} \to c\chi^0$ dominant decay & sufficiently suppressed rate.

✳ Then, stop lifetime $\tau_{\tilde{t}} \sim$ 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 ! <small>trick: measure lifetime instead of branching ratio</small>

✳ This is a counterexample to the lore that colliders determine only masses, and mixings are measured in low energy experiments.

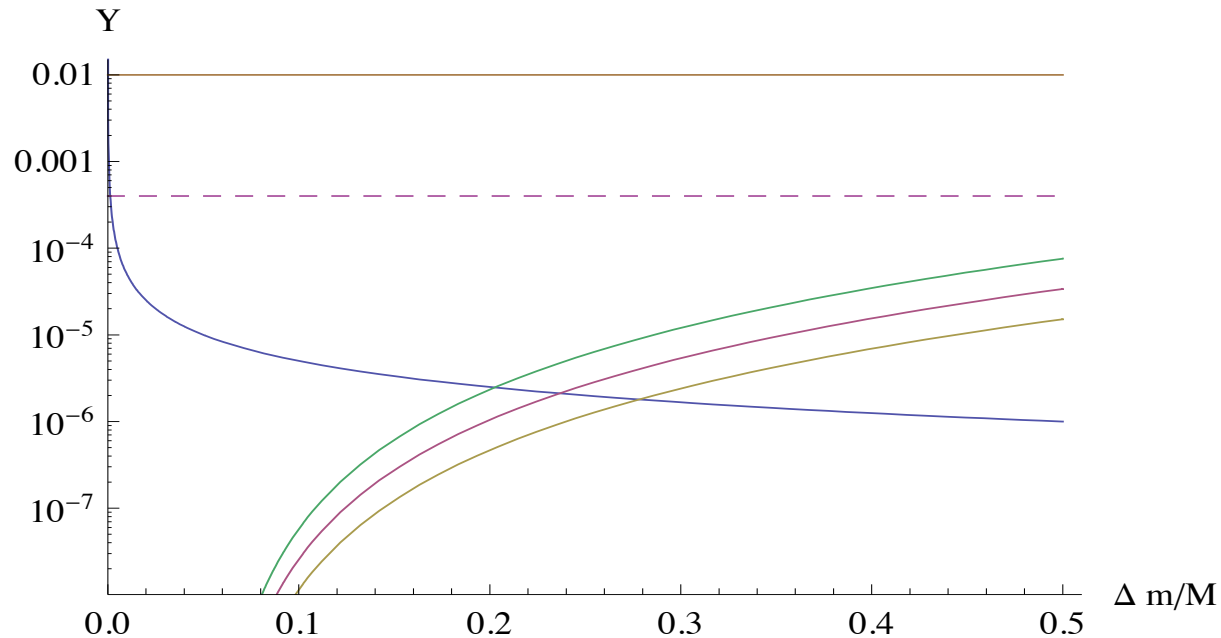# Tevatron Light Stop Searches in $\tilde{t} \to c\tilde{\chi}_1^0$

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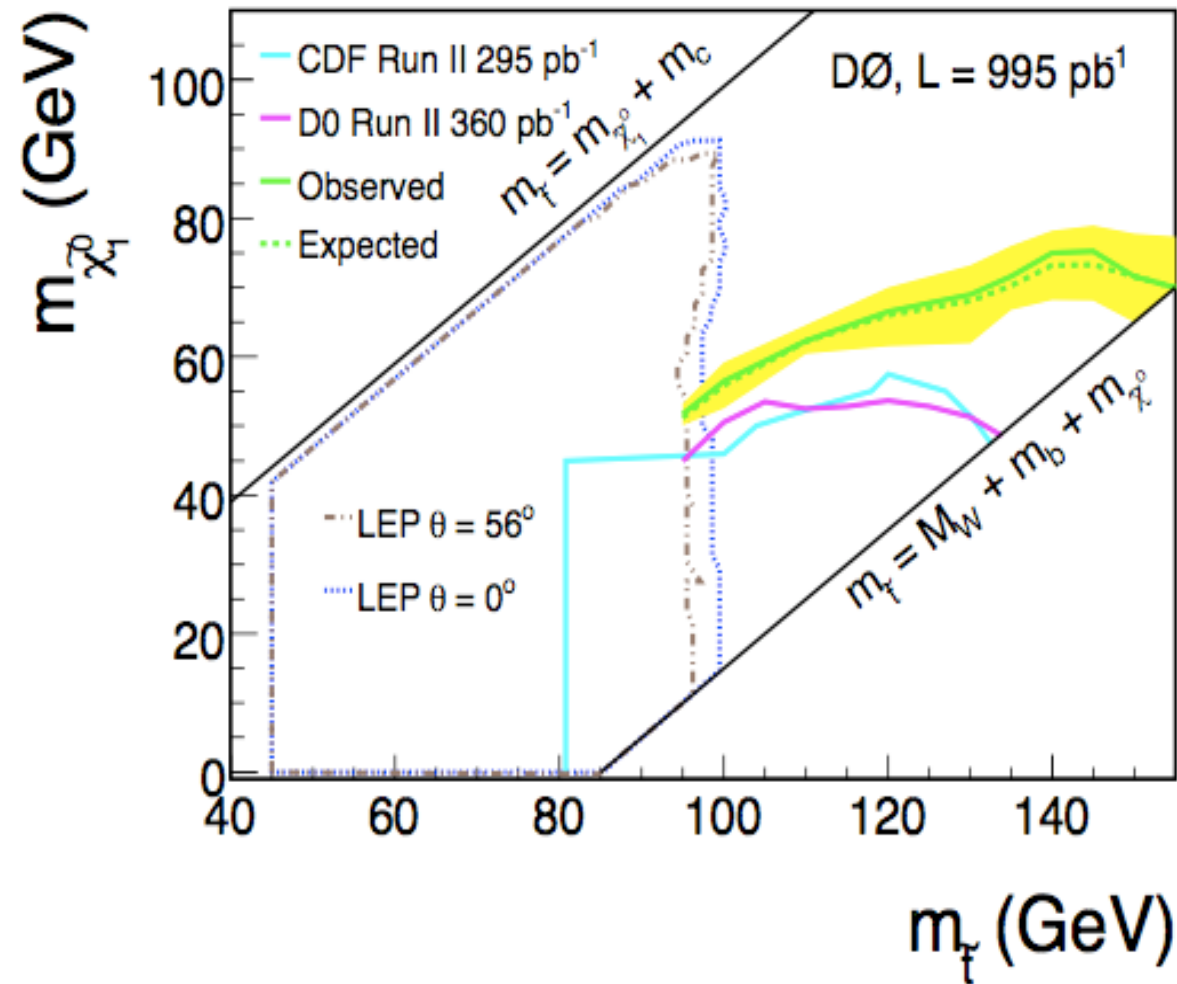
$* \; \Delta m > m_b$ opens up tree level 4-body decays $\tilde{t} \to b\chi^0 l\nu$.

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

solid curve: $\beta\gamma\tau_{\tilde{t}} > 0.1mm$; dashed: $Y_{min}$ alignement; 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.

# Summary

- 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 havent 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.