MEASURING FLAVOR MIXING WITH MINIMAL FLAVOR VIOLATION AT THE LHC

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Flavor and CP violation within the Standard Model

quark masses from Yukawa-Higgs coupling

$$\bar{Q} Y_u \langle h^C \rangle U, \quad \bar{Q} Y_d \langle h \rangle D \qquad \langle h \rangle \simeq 174 \text{ GeV}$$

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

3 generations $=$ 10 parameter in flavor $\&$ CP sector: 6 masses, 3 angles and 1 phase in CKM-matrix unitary, complex, hierarchical

$|V_{us}| = 0.2257(21), \quad |V_{cb}| = 41.6 \pm 0.6 \cdot 10^{-3}, \quad |V_{ub}| = 4.31 \pm 0.3 \cdot 10^{-3}$

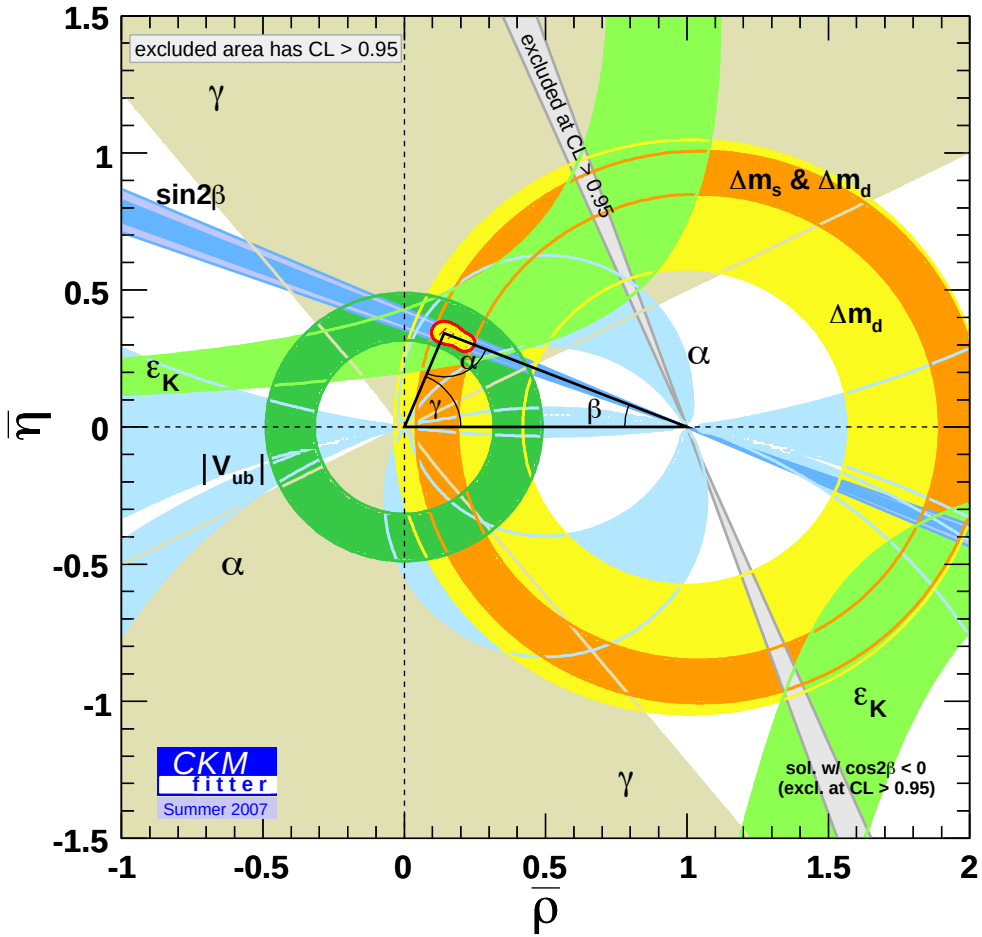
$\beta(\text{measured}) = (21.23^{+1.03}_{-0.99})^\circ$

-third generation is decoupled from the first two

-CP phase is order one

Testing the Standard Model with Flavor and CP

the unitarity triangle $V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$



-fit consistent; contains tree and loop processes of B,K-mesons

New Physics in rare Processes, Where is it ?

$$\Delta m_s^{\rm SM} \sim \quad (V_{tb}^* V_{ts})^2 \times \frac{g^4}{16\pi^2} \quad \times \frac{(\bar{b}\Gamma s)(\bar{b}\Gamma' s)}{m_W^2}$$

$$\Delta m_s^{\rm NP} \sim \quad \text{flavor} \quad \times \text{loop/tree} \times \frac{(\bar{b}\Gamma s)(\bar{b}\Gamma' s)}{\Lambda^2}$$

	New Physics from loops	tree level New Physics
$B_s - \bar{B}_s$	$\Lambda \gtrsim m_W/\lvert V_{ts}\rvert \sim O(2-3)$ TeV	$\Lambda \gtrsim 4\pi m_W/\lvert V_{ts}\rvert \sim O(30)$ TeV
$B_d - \bar{B}_d$	$\Lambda \gtrsim m_W/\lvert V_{td}\rvert \sim O(10-15)$ TeV	$\Lambda \gtrsim 4\pi m_W/\lvert V_{td}\rvert \sim O(100)$ TeV
"SM" flavor	$\Lambda \gtrsim m_W \sim O(100)$ GeV	$\Lambda \gtrsim 4\pi m_W \sim O(1)$ TeV

Is the absence of NP signals in FCNCs an accident (we havent looked at the right observables yet) , or is there a symmetry behind?

Minimal Flavor Violation

flavor and CP in SM: $-\mathcal{L}_Y = \bar{Q} Y_U h^C U + \bar{Q} Y_D h D + \bar{L} Y_E h E + h.c.$

flavor symmetry: $U(3)^5 \xrightarrow{Y} U(1)_B \times U(1)_L \times U(1)_Y$

non-abelian quark part: $G_F \equiv SU(3)_Q \times SU(3)_D \times SU(3)_U$

Yukawas are spurions of G_F: $Y_D(3, \bar{3}, 1)$, $Y_U(3, 1, \bar{3})$

Minimal Flavor Violation (MFV)= Y_D, Y_U are the only spurions of flavor G_F breaking Chivukula, Georgi '87; d'Ambrosio et al '02

MFV is property of the Standard Model.

MFV: potential organizing principle for New Physics

non-symmetry based definitions: Ali,London '99; Buras^2 '00

Solutions to the NP Flavor Puzzle

unless flavor is "as in the SM": $\Lambda_{NP} \gg \sqrt{s_{LHC}} \sim \Lambda_{EWKSB}$

model-independent solutions: MFV and variants:

NMFV Agashe et al '05; Feldmann, Mannel '06

hierarchical wave functions Davidson et al '07; previously: Nelson,Strassler "suppressing flavor anarchy" '00

solutions within SUSY:

alignement+flavor symmetry Nir, Seiberg '93

decoupling "effective SUSY" (first 2 generation squarks heavy) Cohen, Kaplan, Nelson '96

extended R-symmetry (A-terms and Majorana masses vanish) Kribs, Poppitz, Weiner '07

What does MFV imply for SUSY? Simplification !

superpotential (unbroken R-parity):

$$W_{MSSM} = Q Y_u H_u U + Q Y_d H_d D + L Y_e H_d E + \mu H_d H_u$$ MFV !

SUSY-breaking constrained by MFV:

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

$$\tilde{m}_Q^2 = \tilde{m}^2 (a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger)$$
$$\tilde{m}_U^2 = \tilde{m}^2 (a_2 \mathbf{1} + b_5 Y_u^\dagger Y_u + c_1 Y_u^\dagger Y_d Y_d^\dagger Y_u)$$
$$A_u = A (a_4 \mathbf{1} + b_7 Y_d Y_d^\dagger) Y_u$$ etc D'Ambrosio et al '02

predictions:

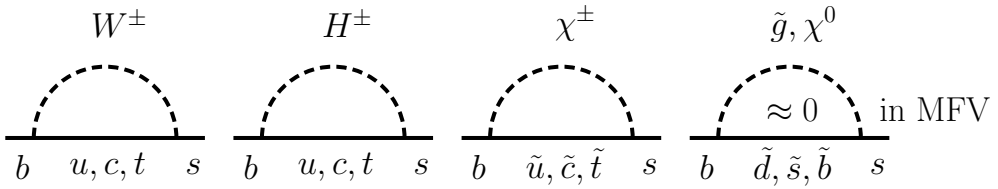
- 3rd generation decoupled (via V_{CKM})
- highly degenerate squarks of 1st and 2nd generation:

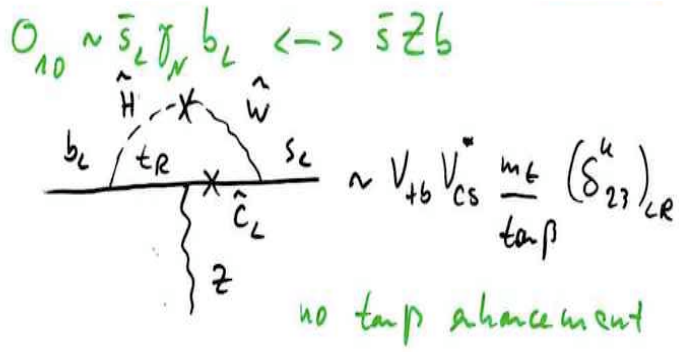
$\Delta m / m_0 \sim \lambda_c^2 / 2$; $\Delta m < 1$ GeV GH,Schmaltz '01

-squark spectrum is 10+2 (8+4 for large $\tan\beta$)

Testing Minimal Flavor Violation: 1. loops

FCNC quantum loops:





constraints from K,D,B-physics “penguins”, meson-mixing

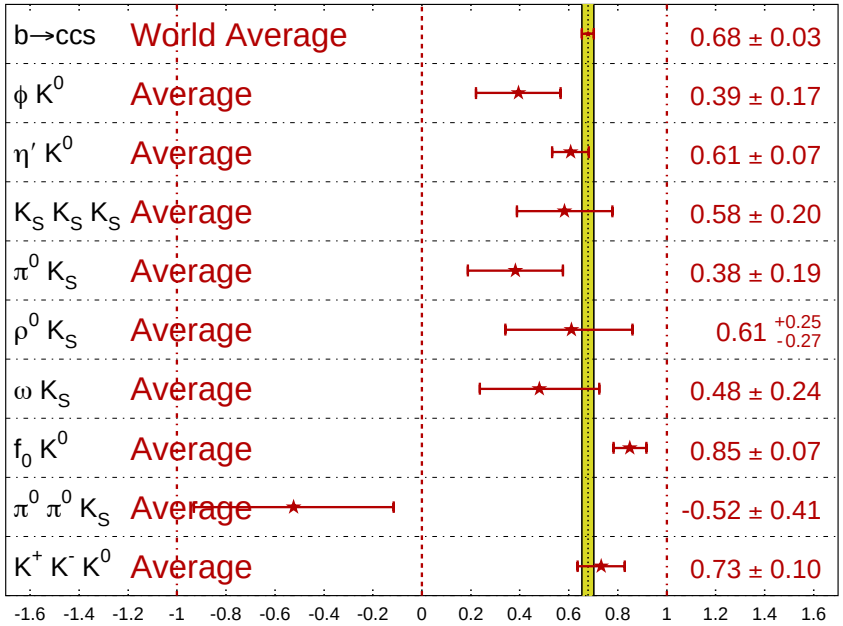
potentially huge effects if flavor is not minimally broken.

ongoing tests at B-factories and Tevatron; extended searches at LHC

Challenges for Minimal Flavor Violation

$$\sin(2\beta^{\rm eff}) \equiv \sin(2\phi_1^{\rm eff})$$

HFAG
LP 2007
PRELIMINARY



$$\eta_{CP} \sin 2\beta(\underbrace{(\bar{s}s)K_S}_{FCNC}) = \sin 2\beta(\underbrace{(\bar{c}c)K_S}_{tree}) + |\underbrace{\frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*}}_{0.02}| \cdot \#(hadronic)$$

non-CKM CP-phases, right-handed currents, CKM-links broken,

e.g., $\mathcal{B}(B_d \to \mu\mu)/\mathcal{B}(B_s \to \mu\mu) \neq |f_{B_d}V_{td}|^2/|f_{B_s}V_{ts}|^2$;

$B \to K^{(*)}ll$ CP observables in angular analysis Bobeth,GH,Piranishvili 0805.2525

Some (further) Standard Model tests with b-physics

	experiment	SM	comments
$a_{CP}(b \to s\gamma)$	$0.4 \pm 3.6\,\%$	$0.42 \pm 0.17\,\%$ hep-ph/0312260	CPX in $bs\gamma, g$
$a_{CP}(b \to d/s\gamma)$	-0.110 ± 0.116 BaBar'05	10^{-9} hep-ph/0312260	MFV test
$S_{K_S\pi^0\gamma}$	0.00 ± 0.28 Belle/BaBar'05	$-2m_s/m_b$	V+A FCNCs
spin $\Lambda_b \to \Lambda\gamma$	–	$\sim m_s/m_b$ GH,Kagan '00; '07	V+A FCNCs
$\mathcal{B}(B \to X_s g)$	$< 9\%$ CLEO'97	$5.0 \pm 1.0 \cdot 10^{-3}$	NP in bsg
TDCPA $b \to s\bar{s}s$	$S_{avg} = 0.53 \pm 0.05$	$\sin 2\beta + \Delta S$	CPX
$\mathcal{B}(B \to X_s \bar{\mu}\mu)$	$4.3 \pm 1.2 \cdot 10^{-6}$	$4.3 \pm 0.7 \cdot 10^{-6}$	q^2-spectra
$a_{CP}(B \to X_s \bar{\ell}\ell)$	-0.22 ± 0.26	-0.2 ± 0.2 % hep-ph/9812267	CPX
$A_{FB}^{CP}(B \to K^* \bar{\ell}\ell)$	–	$\lesssim 10^{-3}$ Buchalla,GH,Isidori'00	CPX in bsZ
R_K $\mu\mu$ vs. ee	1.06 ± 0.48 BaBar'05	$1 + \mathcal{O}(m_\mu^2/m_b^2)$ GH,Krüger 03	non-SM Higgs
$\mathcal{B}(B \to K\nu\bar{\nu})$	$< 3.6 \cdot 10^{-5}$ Belle'05	$3.8^{+1.2}_{-0.6} \cdot 10^{-6}$	$O(10)$ from SM
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$< 4.7 \cdot 10^{-8}$ CDF'07	$3.2 \pm 1.5 \cdot 10^{-9}$	$O(15)$ from SM
$\mathcal{B}(B_s \to \tau^+\tau^-)$	$< \mathcal{O}(5\%)$	$7.2 \pm 1.1 \cdot 10^{-7}$	$O(10^5)$ from SM
$\mathcal{B}(B_d \to \tau^+\tau^-)$	$< 3.4 \cdot 10^{-3}$ BaBar'05	$2.1 \pm 0.3 \cdot 10^{-8}$	$O(10^5)$ from SM
$R_{\ell\ell}$ (Bd vs. Bs)	–	$\lvert V_{td}/V_{ts} f_{Bd}/f_{Bs}\rvert^2$	LHC-MFV test
ang a$B \to K\ell\bar{\ell}$	$O(1)$ BaBar,Belle	% Bobeth,GH,Piranishvili 07	new Higgses

MFV/Flavor collider so far

SUSY FCNC rates can be sizeable $\mathcal{O}(10\%)$ Hurth, Porod '03

$\mathcal{B}(\tilde{t}_{1,2} \to \tilde{\chi}^+ b) \sim 50\%$ and $\mathcal{B}(\tilde{u} \to \tilde{\chi}^+ b) \sim 13\%$

Problem for squark mass determination from edges in cascades (such analyses assume implicitly MFV, i.e., $\tilde{m}_1^2 = \tilde{m}_2^2 \neq \tilde{m}_3^2$ and FCNC$= 0$).

Flavored di-squark-production $pp \to \tilde{q}\tilde{q}' X$ Klasen et al '05, '07, Rainwater '05

Study with 2 down-quark singlets show that there is discriminating power between MFV or not Grossmann, Nir, Thaler, Volansky, Zupan '07

Charged-Higgs-production with or without flavor $pp \to H^+ X$, $pp \to H^+ + jet + X$ Diaz-Cruz,He,Yuan; Dittmaier,GH,Plehn,Spannowsky '07

slepton mass splitting Nomura et al'07; Feng et al '07 secondary vertex from $\tilde{t}$ GH,Nir'08

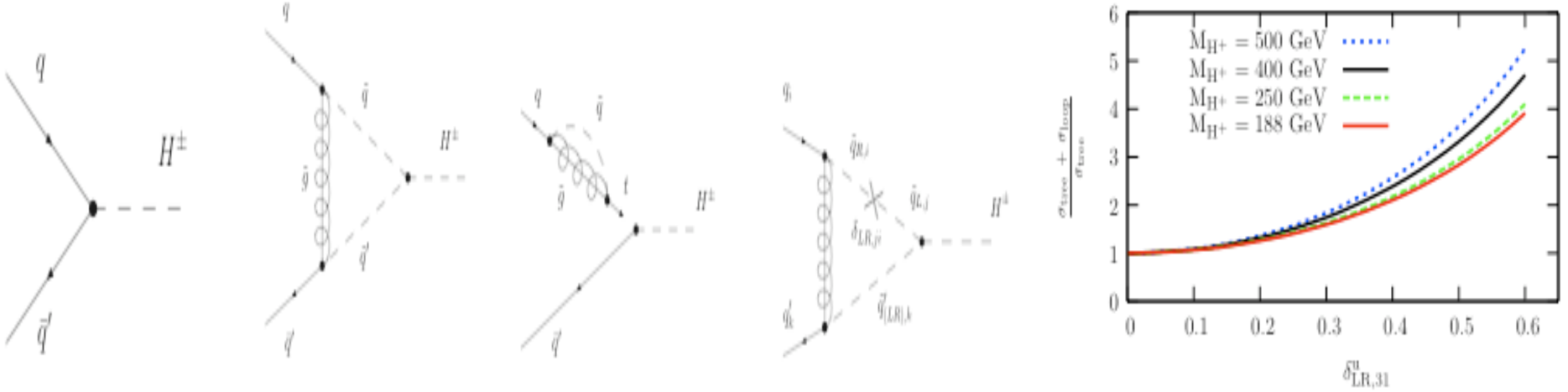
Testing Minimal Flavor Violation: 2. direct at the LHC

potentially huge effects if flavor is not minimally broken.

MFV-null test: if we see signal in particular reaction, MFV (or MSSM) must be broken:

Charged-Higgs-production with or without flavor $pp \to H^+ X$,

$pp \to H^+ + jet + X$ Diaz-Cruz,He,Yuan; Dittmaier,GH,Plehn,Spannowsky '07

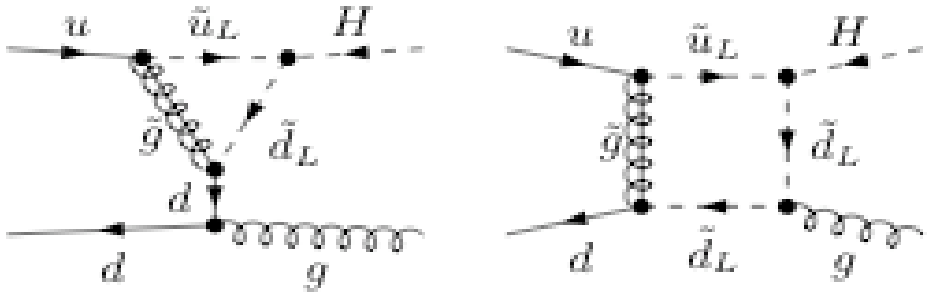


sensitive to flavor mixing essentially unconstrained by K,D,B-physics

Charged-Higgs plus jet $qg \to q' H^+$

idea: avoid chiral suppression by extra gauge boson, e.g., $\bar{Q}\gamma_\mu Q H_u D^\mu H_u^C$.

D-term contribution from $H^+\tilde{q}\tilde{q}'$ finite in chiral limit and MFV.



$\sigma_{pp->H^+j}$	2HDM	MFV D-term only	MFV with $m_q \neq 0$	beyond MFV
$\tan\beta = 3$	$2.5 \cdot 10^{-1} fb$	$6.7 \cdot 10^{-4} fb$	$\simeq \sigma_{2HDM}$	$14.3 fb$

O(30) enhancement over MFV (small/moderate $\tan\beta$)

Measuring MFV Mixing at the LHC

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

$$\tilde{m}_Q^2 = \tilde{m}^2(a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \qquad (\tilde{m}_Q^2)_{23} = \tilde{m}^2 b_2 \lambda_b^2 V_{cb} V_{tb}^*$$

There is an opportunity to measure the mixing because it is so small: measure lifetime instead of branching ratio GH,Nir '08

This is a counterexample to the lore that colliders determine only masses and mixing are measured in low energy experiments

requirement: $\tilde{t} \to c\chi^0$ dominant decay & sufficiently suppressed rate

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

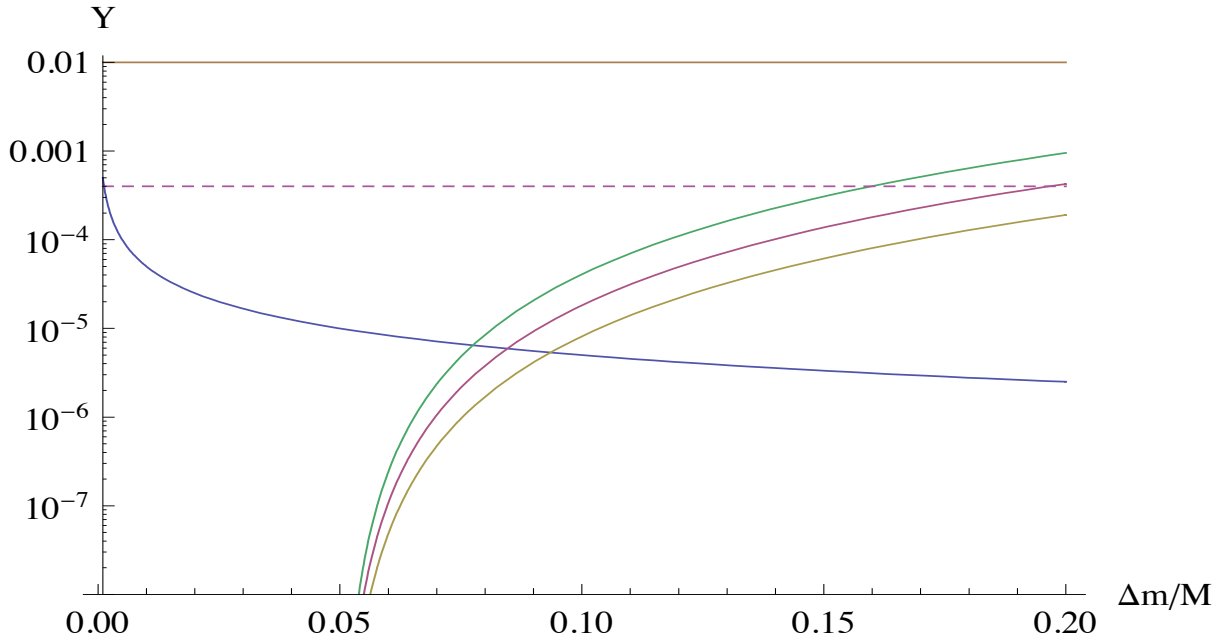
$\Delta m = m_{\tilde{t}} - m_{\chi^0}$; macroscopic decay length (small $Y \sim \lambda_b^2 V_{cb}$)

unique to MFV

$\Delta m > m_b$ opens up tree level 4-body decays $\tilde{t} \to b\chi^0 l\nu$.

$$\frac{\Gamma(\tilde{t}\to b\chi^0 l\nu)}{\Gamma(\tilde{t}\to c\chi^0)} \approx \frac{g^6|V_{tb}|^2}{2} \frac{(\Delta m - m_b)^7}{[Y(\Delta m/M)]^2 M m_W^4 m_{\chi^+}^2}$$

solid curve: $\beta\gamma\tau_{\tilde{t}} > 0.1mm$; dashed: Y_{min} alignement; horizontal solid line $Y \simeq \lambda_c$ anarchy +extended R-symm.GH,Nir '08



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

Dermisek etal'07

Summary

- The flavor structure of the SM is very specific, hence, very predictive. (CKM, CP-violation)
- This flavor breaking could be also realized by symmetry in physics beyond-the-SM “Minimal Flavor Violation “.
- If MFV, this implies certain form of quark-partners spectrum and mixing.
- The LHC can answer these and many other questions; complementary (direct/indirect; quarks & leptons)
- The possibility of a stop decay length measurement shows that ATLAS/CMS could have much more to say about flavor and mixing than usually thought.

back up slides

Charged-Higgs plus Jet $qg \to q' H^+$

discovery of charged-Higgs prod. would signal breakdown of SM and non-standard flavor/Higgssector, including breakdown of MFV.

works for small $\tan\beta$!

Dittmaier,GH,Plehn,Spannowsky '07