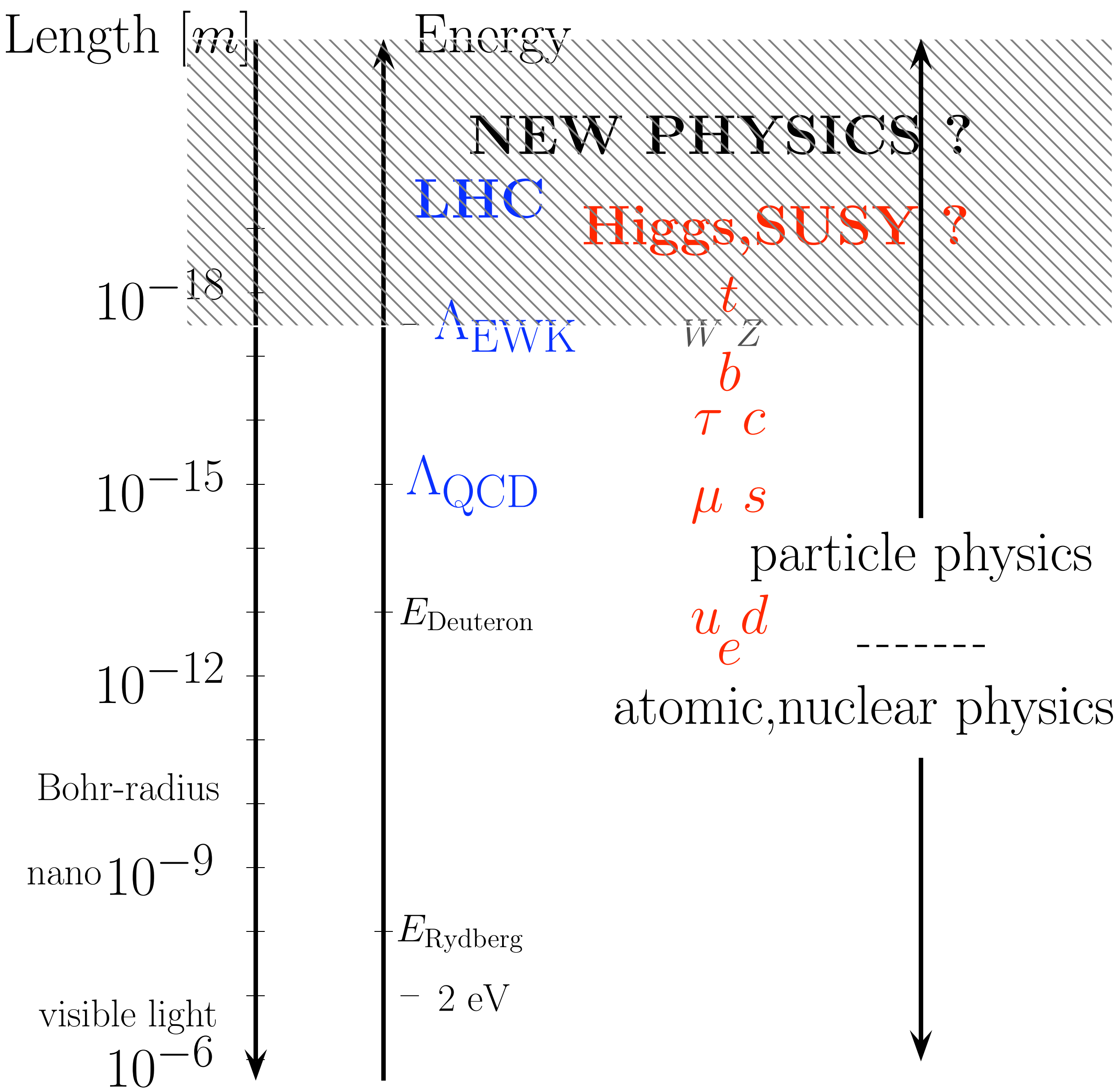
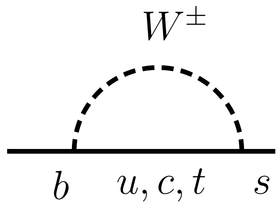
lecture 2: Exploring the Borders of the SM with Flavor

Exploring Physics at Highest Energies

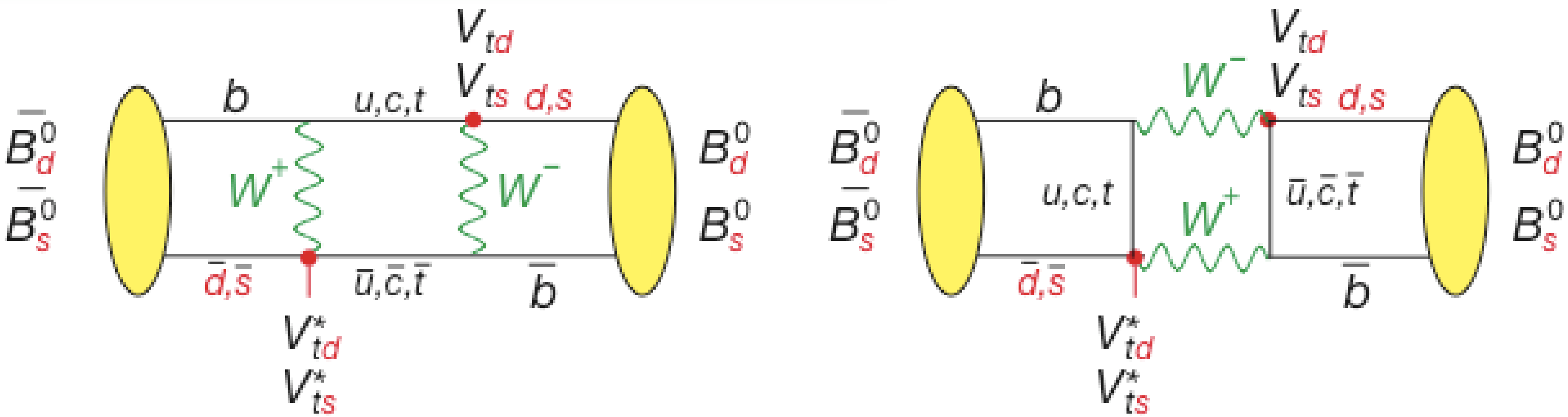


Testing the SM with FCNCs

In SM neutral currents conserve flavor. However, charged currents induce FCNCs through quantum loops.



The upper figure shows an FCNC with flavor number changing in units of one, $\Delta f = 1$, as in decays, meson mixing has $\Delta f = 2$.



Testing the SM with FCNCs

Different sectors and different couplings presently probed:

$s \to d$: $K^0 - \bar{K}^0$, $K \to \pi\nu\bar{\nu}$

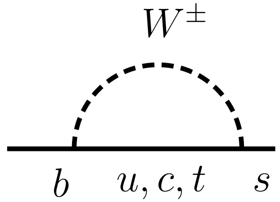
$c \to u$: $D^0 - \bar{D}^0$ (first data on FCNC in up-sector)

$b \to d$: $B^0 - \bar{B}^0$, $B \to \rho\gamma$, $b \to d\gamma$ ($B \to \pi ll$ close)

$b \to s$: $B_s - \bar{B}_s$, $b \to s\gamma$, $B \to K_s\pi^0\gamma$, $b \to sll$, $B \to K^{(*)}ll$ (precision, angular observables starting), $B_s \to \mu\mu$ (bound improving)

$t \to c, u$: not observed

Lets discuss a generic SM FCNC $b \to s$ amplitude



$$\mathcal{A}(b \to s)_{\rm SM} = V_{ub}V_{us}^* A_u + V_{cb}V_{cs}^* A_c + V_{tb}V_{ts}^* A_t$$

quantum loop effect induced by the weak interaction.

$A_q = A(m_q^2/m_W^2)$.

with CKM unitarity $VV^\dagger = 1$, specifically $\sum_i V_{ib}V_{is}^* = 0$:

$$\mathcal{A}(b \to s)_{\rm SM} = V_{tb}V_{ts}^*(A_t - A_c) + V_{ub}V_{us}^*(A_u - A_c)$$

$\mathcal{A}$ would vanish if *i* there wouldn't be a non-trivial CKM matrix, that is, one that allows for changes between different generations, and *ii* for identical up-type quark masses.

Flavor Changing Neutral Currents

$$\mathcal{A}(b \to s)_{\rm SM} = \underbrace{V_{tb}V_{ts}^*}_{\lambda^2}(A_t - A_c) + \underbrace{V_{ub}V_{us}^*}_{\lambda^4}(A_u - A_c)$$

amplitude is dominated by first term because of lesser CKM suppression and because the GIM (Glashow Iliopoulos Maiani) suppression inactive for tops $\frac{m_t^2 - m_c^2}{m_W^2} \sim \mathcal{O}(1)$, whereas $\frac{m_u^2 - m_c^2}{m_W^2} \ll 1$.

We probe top properties with rare b-decays despite of $m_t \gg m_b$.

The general features hold for any FCNC in the SM:

Flavor Changing Neutral Currents in SM

i FCNCs are induced by the weak interaction thru loops.
ii FCNCs require $V \neq 1$.
iii FCNCs vanish for degenerate intermediate quarks. Since mass splitting among up-quarks is larger than for down quarks, GIM suppression is larger with external up-type than down-type quarks.

$\mathcal{B}(b \to s\gamma) = 3 \cdot 10^{-4}$ $(E_\gamma > 1.6$ GeV)

$\mathcal{B}(b \to sl^+l^-) = 4 \cdot 10^{-6}$ $(m_{ll}^2 < 0.04$ GeV^2)

SM: $\mathcal{B}(t \to cg) \sim 10^{-10}$, $\mathcal{B}(t \to c\gamma) \sim 10^{-12}$, $\mathcal{B}(t \to cZ) \sim 10^{-13}$, $\mathcal{B}(t \to ch) \lesssim 10^{-13}$ Eilam, Hewett, Soni '91/99

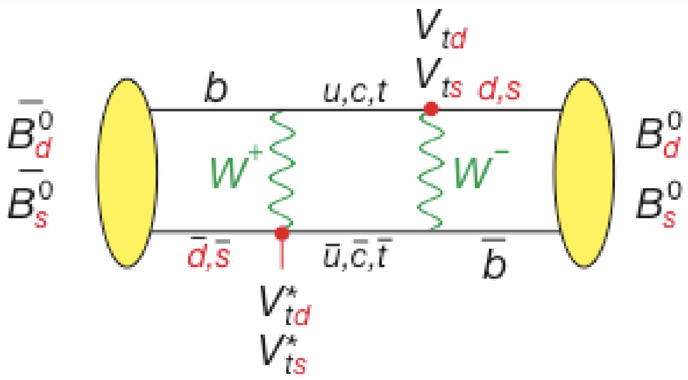
Flavor Changing Neutral Currents in SM

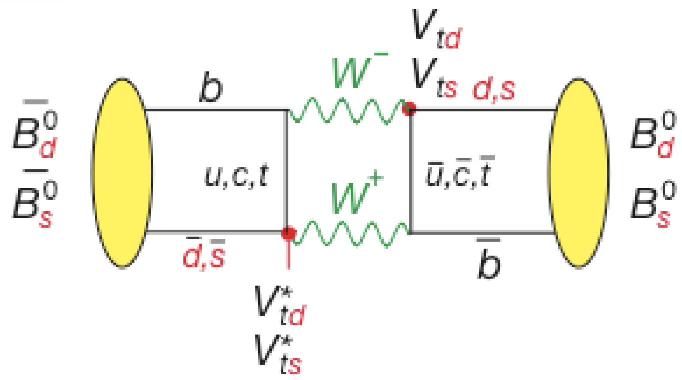
We see that 3 mechanisms suppress FCNCs in SM: CKM, GIM and absence at tree level. New physics, which doesnt need to share these features, competes with small SM background!

FCNCs feel physics in the loops from energies much higher than the ones actually involved in the real process.

They are very useful to look for new physics, in fact, we already now a lot about new physics from FCNCs!

Probing Physics at Highest Energies with Flavor





$$\mathcal{A}(B_d^0 \to \bar{B}_d^0)_{\rm SM} \propto \frac{g^4}{16\pi^2}(V_{td}V_{tb}^*)^2 \frac{\langle \bar{B}_d^0|(\bar{b}_L\gamma_\mu d_L)(\bar{b}_L\gamma^\mu d_L)|B_d^0\rangle}{m_W^2} S(m_t^2/m_W^2)$$

$$\mathcal{A}(B_d^0 \to \bar{B}_d^0)_{\rm NP} \propto \frac{\langle \bar{B}_d^0|(\bar{b}\Gamma d)(\bar{b}\Gamma' d)|B_d^0\rangle}{\Lambda_{\rm NP}^2} \qquad (tree)$$

$$\mathcal{A}(B_d^0 \to \bar{B}_d^0)_{\rm NP} \propto \frac{g^4}{16\pi^2}\frac{\langle \bar{B}_d^0|(\bar{b}\Gamma d)(\bar{b}\Gamma' d)|B_d^0\rangle}{\Lambda_{\rm NP}^2} \qquad (weak\ \ loop)$$

where we allowed for generic new physics at the energies $\Lambda_{\rm NP}$, either at tree level, or thru weak loops, as, e.g., in the MSSM.

Probing Physics at Highest Energies with Flavor

$B_d^0 - \bar{B}_d^0$ oscillation data ok with SM: $\mathcal{A}(B_d^0 \to \bar{B}_d^0)_{\rm NP} \lesssim \mathcal{A}(B_d^0 \to \bar{B}_d^0)_{\rm SM}$

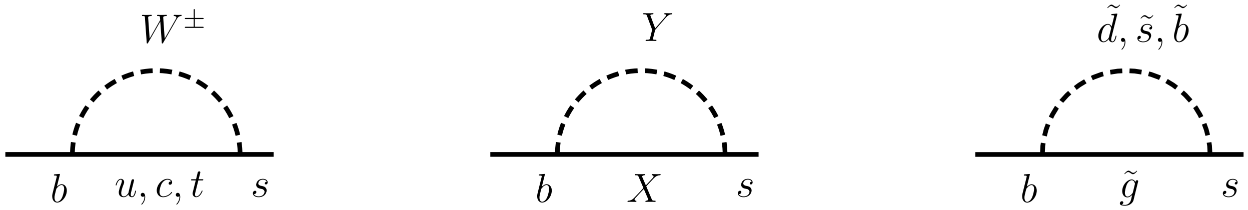
$\Lambda_{\rm NP} \gtrsim 4\pi m_W/(g^2|V_{td}|) \sim \mathcal{O}(250)$ TeV (tree level)

$\Lambda_{\rm NP} \gtrsim m_W/|V_{td}| \sim\mathcal{O}\ (10)$ TeV (weak loop)

In either case, the connection with the electroweak scale is lost!

	$K^0\bar{K}^0$	$D^0\bar{D}^0$	$B_d^0\bar{B}_d^0$	$B_s^0\bar{B}_s^0$
$\Lambda_{\rm NP}$ [TeV]	$2 \cdot 10^5$	$5 \cdot 10^3$	$2 \cdot 10^3$	$3 \cdot 10^2$

Table 1: The lower bounds on the scale of new physics from FCNC mixing data in TeV for arbitrary new physics at 95 % C.L.



The absence of O(1) New Physics observations in FCNC-processes implies that physics at theTeV-scale has non-generic flavor properties.

In particular, suppression mechanisms of similar power as CKM and GIM, which are built-in in the SM, need to be at work.

SM has global symmetry G_F for $Y_{u,d,l} = 0$:

$$G_F = U(3)^5 \to U(1)_B \times U(1)_L \times U(1)_Y$$

A model is termed minimally flavor violating (MFV), if, as in the SM, all flavor symmetry breaking is induced by the Yukawa matrices.

Example: Flavor in SUSY

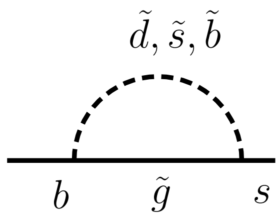
$*$ The superpotential ($N = 1$, unbroken R-parity) is MFV:

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

$*$ 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:

$$\mathcal{L}_{soft} = -\tilde{Q}^\dagger_{Li} (\tilde{m}^2_Q)_{ij} \tilde{Q}_{Lj} + \ldots$$

This is ruled out by FCNC data for TeV-scale SUSY partners.



* The off-diagonal squark mass terms ”mass insertions” $\delta_{ij}^{Q} = (\tilde{m}_Q^2)_{ij}/\tilde{m}^2_{ave}\,, i \neq j$, induce FCNCs, and are constrained by data.

	$\sqrt{\lvert\Re(\delta_{12}^d)^2_{LL}\rvert}$		$\sqrt{\lvert\Im(\delta_{12}^d)^2_{LL}\rvert}$	
x	TREE	NLO	TREE	NLO
0.3	1.4×10^{-2}	2.2×10^{-2}	1.8×10^{-3}	2.9×10^{-3}
1.0	3.0×10^{-2}	4.6×10^{-2}	3.9×10^{-3}	6.1×10^{-3}
4.0	7.0×10^{-2}	1.1×10^{-1}	9.2×10^{-3}	1.4×10^{-2}
	$\sqrt{\lvert\Re(\delta_{12}^d)_{LL}(\delta_{12}^d)_{RR}\rvert}$		$\sqrt{\lvert\Im(\delta_{12}^d)_{LL}(\delta_{12}^d)_{RR}\rvert}$	
x	TREE	NLO	TREE	NLO
0.3	1.8×10^{-3}	8.6×10^{-4}	2.3×10^{-4}	1.1×10^{-4}
1.0	2.0×10^{-3}	9.6×10^{-4}	2.6×10^{-4}	1.3×10^{-4}
4.0	2.8×10^{-3}	1.3×10^{-3}	3.7×10^{-4}	1.8×10^{-4}
	$\sqrt{\lvert\Re(\delta_{12}^d)^2_{LR}\rvert}$		$\sqrt{\lvert\Im(\delta_{12}^d)^2_{LR}\rvert}$	
x	TREE	NLO	TREE	NLO
0.3	3.1×10^{-3}	2.6×10^{-3}	4.1×10^{-4}	3.4×10^{-4}
1.0	3.4×10^{-3}	2.8×10^{-3}	4.6×10^{-4}	3.7×10^{-4}
4.0	4.9×10^{-3}	3.9×10^{-3}	6.5×10^{-4}	5.2×10^{-4}

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

e.g., 0711.2903

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

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

$Y_u = \mathrm{diag}(y_u, y_c, y_t), \qquad Y_d = V \cdot \mathrm{diag}(y_d, y_s, y_b)$ (up mass basis)

Controlled departure from flavor-blind SUSY breaking:
e.g., s-top – s-charm mixing: $(\tilde{m}_Q^2)_{23}/\tilde{m}^2 \sim y_b^2 V_{cb} V_{tb}^* \sim 10^{-5} \tan\beta^2$

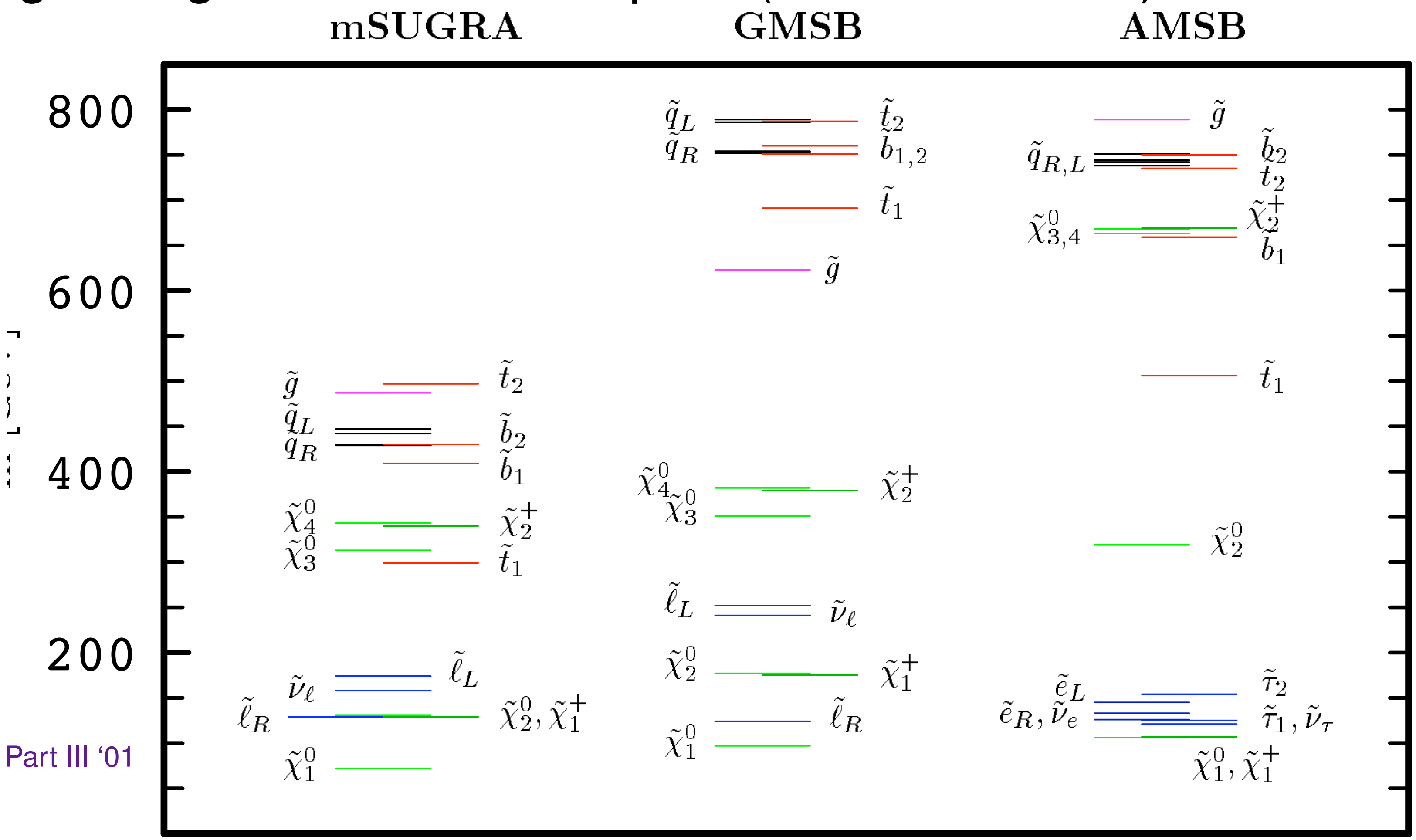
* $\mathcal{O}(1)$ deviations possible in MFV-MSSM from SM in rare processes if $\tan\beta$ is large. $\tan\beta = < H_u > / < H_d >$

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

- Splitting: Highly degenerate squarks of 1st and 2nd generation:

$\Delta m/m_0 \sim \lambda_c^2/2; \qquad \Delta m < 1$ GeV

- Mixing: 3rd generation decoupled (via CKM, $\sim \lambda^2$).



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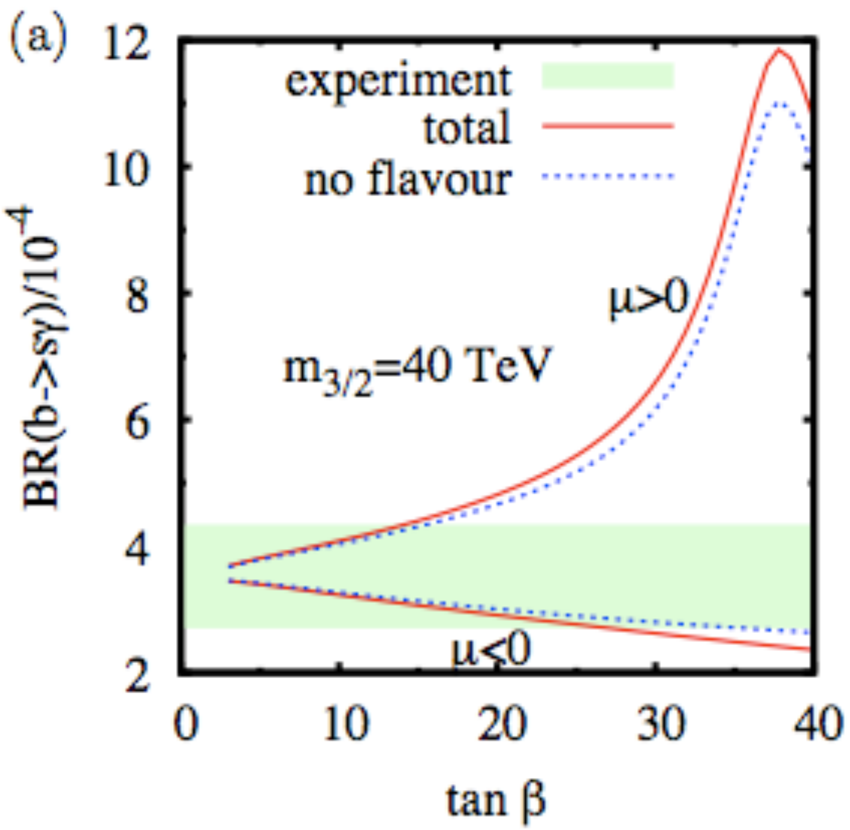
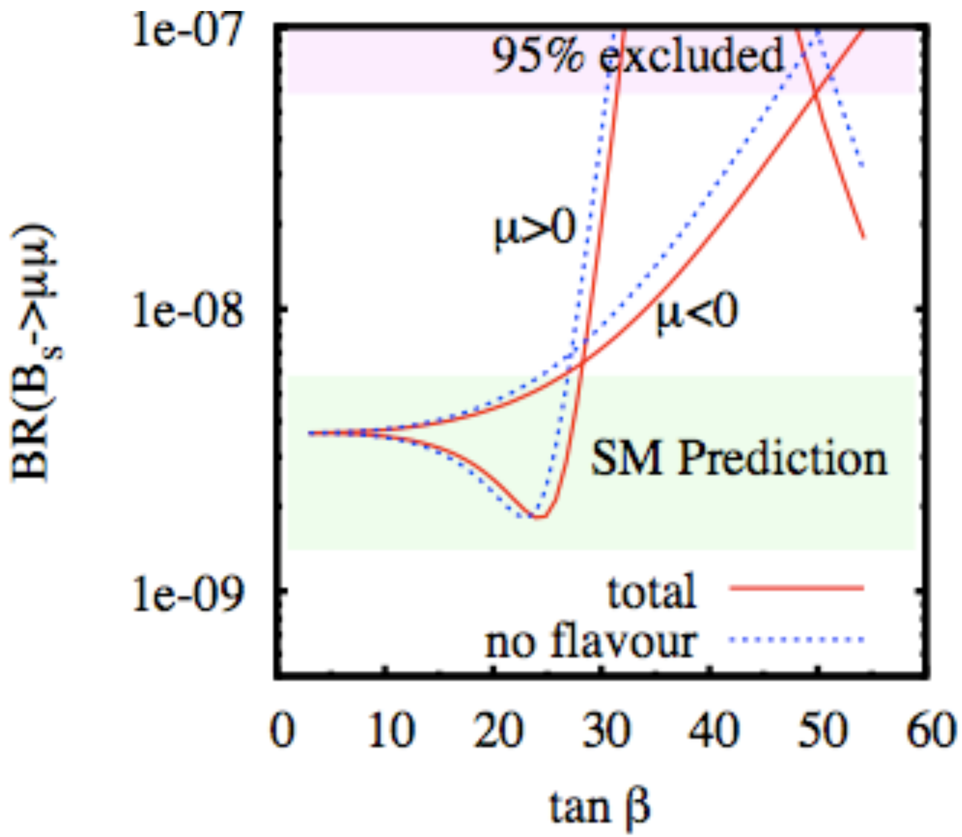
Predictivity and large Effects in FCNC Loops

* Predictive $\mathcal{O}(1)$ effects within MFV models if $\tan\beta$ largish.





* Different decays are complementary

Summary BSM Flavor

$*$ FCNCs are sensitive to BSM because they are small in SM.

$*$ Observables with very small or vanishing SM value are called null tests. Often CP-asymmetries, e.g., small CPX in $b \to s$,

$$\mathcal{A}(b \to s)_{\mathrm{SM}} = \underbrace{V_{tb}V_{ts}^*}_{\lambda^2}(A_t - A_c) + \underbrace{V_{ub}V_{us}^*}_{\lambda^4}(A_u - A_c)$$

or employ $V - A$ nature of flavor change in SM ($\to$ polarization studies).

$*$ MFV: limiting case in model space; suppresses FCNCs in BSM; predicitive; as SM, doesnt explain origin of flavor.

$*$ Question for LHC era: Is the TeV scale MFV or non MFV?

$*$ The larger the departure from MFV, the larger the potential NP effects due to larger mixing and/or mass splitting between gen'tions.

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

$$R_{\mu\mu} = \frac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_d \to \mu^+\mu^-)}, \qquad R_{\mu\mu}^{\mathrm{SM,MFV}} = \frac{m_{B_s} f_{B_s}^2 \tau_{B_s}}{m_{B_d} f_{B_d}^2 \tau_{B_d}} r_{\mathrm{ps}} \times \frac{|V_{ts}|^2}{|V_{td}|^2}.$$