SUSY_FLAVOR: a computational tool for FCNC and CP-violating processes in the MSSM

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Plan of the talk:

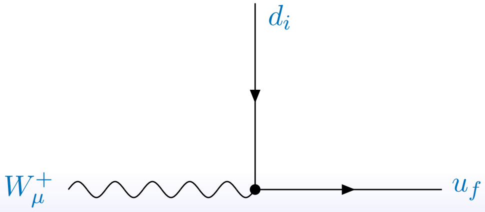
- Sources of the CP and flavor violation in the MSSM
- Tool for analysis: SUSY_FLAVOR library
  - input parameters
  - hadronic variables
  - available physical observables
  - output format
- Example of SUSY_FLAVOR application: leptonic B decays
- SUSY_FLAVOR limitations and plans for future development
- Conclusions

CP and flavor violation sources in the MSSM

Flavor and CP violation in the SM:

- relatively simple - determined by the 3 angles and phase of the CKM matrix present in $W^{\pm}$ vertices (charged currents only)
- neutral currents flavor conserving at the tree level.

Enough to generate very rich phenomenology!



$$-\frac{ie}{\sqrt{2}s_W}V_{fi}^{CKM}\gamma_\mu P_L$$

MSSM much more complicated. Several classes of parameters:

1. Higgs sector: $\tan\beta$ and CP-odd Higgs mass M_A.
2. MSSM spectrum, i.e. SUSY particles masses.
3. SM flavor parameters: Yukawa couplings and the CKM matrix.
4. New sources of flavor and CP violation in the sfermion and gaugino sectors.

General MSSM: 105 free parameters, most connected with flavor and CP violation (more if R-parity not conserved or non-holomorphic soft terms present).

New flavor sources: potentially very large effects, orders of magnitude larger than SM predictions.

Squark mass matrices in the super-CKM basis (sfermions and fermions rotated together to get diagonal Yukawa couplings):

$$\begin{pmatrix} (M^2_{\tilde{U}})_{LL} + \hat{m}_u^2 - \frac{\cos 2\beta(M_Z^2 - 4M_W^2)}{6} & -\frac{v_1}{\sqrt{2}} A_U - \frac{v_2}{\sqrt{2}} A'_U - \cot\beta \mu \hat{m}_u \\ -\frac{v_1}{\sqrt{2}} A_U^\dagger - \frac{v_2}{\sqrt{2}} A_U^{'\dagger} - \cot\beta \mu^\star \hat{m}_u & (M^2_{\tilde{U}})_{RR} + \hat{m}_u^2 + \frac{2\cos 2\beta(M_Z^2 - M_W^2)}{3} \end{pmatrix}$$

$$\begin{pmatrix} (M^2_{\tilde{D}})_{LL} + \hat{m}_d^2 - \frac{\cos 2\beta(M_Z^2 + 2M_W^2)}{6} & \frac{v_2}{\sqrt{2}} A_D - \frac{v_1}{\sqrt{2}} A'_D - \tan\beta \mu \hat{m}_d \\ \frac{v_2}{\sqrt{2}} A_D^\dagger - \frac{v_1}{\sqrt{2}} A_D^{'\dagger} - \tan\beta \mu^\star \hat{m}_d & (M^2_{\tilde{D}})_{RR} + \hat{m}_d^2 - \frac{\cos 2\beta(M_Z^2 - M_W^2)}{3} \end{pmatrix}$$

$(M^2_{\tilde{D}})_{LL}, (M^2_{\tilde{D}})_{RR}, (M^2_{\tilde{U}})_{RR}$ are 3×3 hermitian matrices, A_U, A_D (also A'_U, A'_D) general 3×3 complex matrices.

$(M^2_{\tilde{U}})_{LL}$ is related to $(M^2_{\tilde{D}})_{LL}$ via $SU(2)$ relation $(M^2_{\tilde{U}})_{LL} = K(M^2_{\tilde{D}})_{LL}K^\dagger$

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All measurements confirm SM predictions within errors or at worst differ by few (2-3) σ.

How small must be supersymmetric flavor violating terms?

- Charged lepton sector - very strong constraints (more relaxed for neutrinos).
- Kaon sector ($1 \leftrightarrow 2$ down generation transitions) - relative off-diagonal soft terms ("mass insertions") of the order of 10^{-3} or less for $M_{SUSY} \sim 1$ TeV.
- B meson sector ($1, 2 \leftrightarrow 3$ down generation transitions) - constraints more relaxed in the past but getting strong with new experiments - B-factories and LHCb
- up sector - DD mixing, top decays - constraint still much weaker.

Common simplifying assumption: no extra flavor violation in sfermion sector, all governed by CKM matrix only - $\rightarrow$ so called "Minimal Flavor Violation" (MFV) models.

Realistic alternative: flavor violation terms large but effects suppressed by heavy SUSY spectrum? Much more complicated for analysis, often higher order effects have to be included!.

More experiments and data coming constantly - tools needed for efficient analysis, not only within MFV models.

Solution for non-flavor experts, experimentalists: ready publicly available "libraries".

SUSY_FLAVOR library

Available public "flavor codes" for FCNC calculations mostly restricted to MFV scenario. Examples:

- CPsuperH
- SuperIso
- SusyBSG

Some flavor observables (MFV version) calculated also by: MasterCode, SPHeno, Micromegas.

Exception: SUSY_FLAVOR (currently version v2.5) designed to work with general R-parity conserving MSSM, all possible flavor violating terms in the sfermion sector allowed.

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SUSY_FLAVOR assumptions:

- Calculations done in the general R-parity conserving MSSM (including so called "non-holomorphic" trilinear A terms, like $QUH_D^\star$ etc.).
- Input parameters set at the SUSY scale in the SLHA2 convention
- chirally enhanced higher order corrections resummed to all orders, also for non-MFV case
- QCD corrections and hadronic matrix elements treated mostly on the basis calculations done in the frame of SM; hadronic related quantities documented and user accessible, for future updates.
- Program written in FORTRAN 77; SUSY_FLAVOR v2.0 contains approximately 15000 lines of code and ∼600 subroutines.

Based on series of papers on MSSM flavor physics - 16 publications of 15 authors, 1996–2014.

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SUSY_FLAVOR v2.5 capabilities: over 30 observables in lepton and quark sectors

Observable	Experiment
$\Delta F = 1$	
$\mathrm{Br}(\mu \to e\gamma)$	$< 5.7 \times 10^{-13}$
$\mathrm{Br}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$
$\mathrm{Br}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$
$\mathrm{Br}(K_L \to \pi^0\nu\nu)$	$< 6.7 \times 10^{-8}$
$\mathrm{Br}(K^+ \to \pi^+\nu\nu)$	$17.3^{+11.5}_{-10.5} \times 10^{-11}$
$\mathrm{Br}(B_d \to ee)$	$< 1.13 \times 10^{-7}$
$\mathrm{Br}(B_d \to \mu\mu)$	$< 7.4 \times 10^{-10}$
$\mathrm{Br}(B_d \to \tau\tau)$	$< 4.1 \times 10^{-3}$
$\mathrm{Br}(B_d \to \mu e)$	$< 3.7 \times 10^{-9}$
$\mathrm{Br}(B_s \to ee)$	$< 7.0 \times 10^{-5}$
$\mathrm{Br}(B_s \to \mu\mu)$	$(2.9 \pm 0.7) \times 10^{-9}$
$\mathrm{Br}(B_s \to \tau\tau)$	$--$
$\mathrm{Br}(B_s \to \mu e)$	$< 1.4 \times 10^{-8}$
$\mathrm{Br}(B_s \to \tau e)$	$< 2.8 \times 10^{-5}$
$\mathrm{Br}(B_s \to \mu\tau)$	$< 2.2 \times 10^{-5}$
$\mathrm{Br}(B^+ \to \tau^+\nu)$	$(1.14 \pm 0.27) \times 10^{-4}$
$\frac{\mathrm{Br}(B \to D\tau\nu)}{\mathrm{Br}(B \to Dl\nu)}$	$(0.440 \pm 0.058 \pm 0.042)$
$\frac{\mathrm{Br}(B \to D^\star\tau\nu)}{\mathrm{Br}(B \to D^\star l\nu)}$	$(0.332 \pm 0.024 \pm 0.018)$
$\mathrm{Br}(B \to X_s\gamma)$	$(3.52 \pm 0.25) \times 10^{-4}$
$\mathrm{Br}(t \to ch, uh)$	$< 5.6 \times 10^{-3}$

Observable	Experiment
$\Delta F = 0$	
$\frac{1}{2}(g-2)_e$	$(1159652188.4 \pm 4.3) \times 10^{-12}$
$\frac{1}{2}(g-2)_\mu$	$(11659208.7 \pm 8.7) \times 10^{-10}$
$\frac{1}{2}(g-2)_\tau$	$< 1.1 \times 10^{-3}$
$\lvert d_e\rvert$(ecm)	$< 1.6 \times 10^{-27}$
$\lvert d_\mu\rvert$(ecm)	$< 2.8 \times 10^{-19}$
$\lvert d_\tau\rvert$(ecm)	$< 1.1 \times 10^{-17}$
$\lvert d_n\rvert$(ecm)	$< 2.9 \times 10^{-26}$
$\Delta F = 2$	
$\lvert\epsilon_K\rvert$	$(2.229 \pm 0.010) \times 10^{-3}$
ΔM_K	$(5.292 \pm 0.009) \times 10^{-3}$ ps^{-1}
ΔM_D	$(2.37^{+0.66}_{-0.71}) \times 10^{-2}$ ps^{-1}
ΔM_{B_d}	(0.507 ± 0.005) ps^{-1}
ΔM_{B_s}	(17.77 ± 0.12) ps^{-1}

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Calculations in SUSY_FLAVOR pass through the following steps:

1. Parameter initialization (default: SLHA2 conventions)
2. Calculation of the tree level physical masses and mixing matrices of all MSSM particles
3. Resummation of leading chirally enhanced corrections, calculation of bare and renormalized Yukawa couplings and CKM elements
4. Calculation of Wilson coefficients at the SUSY/EW scale (2-, 3- and 4-point Green functions expanded in the basis of appropriate effective operators. All calculations done in mass eigenstates basis, “mass insertion approximation” not used.
5. Implementation of QCD running from SUSY/EW to low energy scale, evaluation of hadronic matrix elements.
6. Evaluation and printing of physical observables.

Fast code: ($\ll$1 sec for 1 MSSM parameter point on standard PC).

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SUSY_FLAVOR input parameters

- SM parameters in gauge and fermion sectors (no neutrino masses and U_{PMNS} yet).
- Higgs parameters M_A, $\tan\beta$, μ parameter, gaugino masses M_1, M_2, M_3 (μ, M_1, M_2 complex in general).
- Sfermion soft terms in the super-CKM basis:

$$
\begin{aligned}
- & \quad Q_L^\dagger M_Q^2 Q_L - D_R^\dagger M_D^2 D_R - U_R^\dagger M_U^2 U_R - L_L^\dagger M_L^2 L_L - E_R^\dagger M_E^2 E_R \\
+ & \quad A_d H_d Q_L D_R + A_u H_u Q_L U_R + A_l H_d L_L E_R + \mathrm{H.c.})
\end{aligned}
$$

  $M_Q^2, M_U^2, M_D^2, M_L^2, M_E^2$ are hermitian and A_d, A_u, A_l general complex 3×3 matrices.

- 'Non-holomorphic' trilinear terms A_d', A_u', A_l', again general complex:

$$
A_d^{'} H_u^\star Q_L D_R + A_u^{'} H_d^\star Q_L U_R + A_l^{'} H_u^\star L_L E_R + \mathrm{H.c.}
$$

SUSY_FLAVOR input conventions

- Internal code conventions based on JR paper on MSSM Feynman Rules, (Phys.Rev D41 (1990), hep-ph/9511250) - SUSY_FLAVOR project started well before SLHA!
- MSSM default parameter convention follows SLHA2 (conventions of hep-ph/9511250 allowed as an user selected option).
- soft parameters can be given as dimensionful soft mass matrices and A terms (SLHA2 default), or as dimensionless "mass insertions":

$$(M_Q^2)_{LL} = \begin{pmatrix} m_{Q1}^2 & \Delta_{QLL}^{12} & \Delta_{QLL}^{13} \\ \Delta_{QLL}^{21} & m_{Q2}^2 & \Delta_{QLL}^{23} \\ \Delta_{QLL}^{31} & \Delta_{QLL}^{32} & m_{Q3}^2 \end{pmatrix} \qquad \delta_{QLL}^{IJ} = \frac{\Delta_{QLL}^{IJ}}{\sqrt{m_{QI}^2 \, m_{QJ}^2}}$$

Two “driver programs” attached to SUSY_FLAVOR distribution:

- susy_flavor_file.f - compact example how to run SUSY_FLAVOR starting from SLHA2-compatible input file with default name susy_flavor.in. Simplest and convenient for most users - can accept directly input files produced by other SUSY generators.
- susy_flavor_prog.f - more sophisticated example how to initialize directly parameters in loops inside the main program. Useful for fast scanning over MSSM parameters, does not require heavy hard disk access.

Resummation of chirally enhanced effects in SUSY_FLAVOR

"Chirally enhanced" - limit of large $\tan\beta$ or large soft LR mixing terms.

Example - correction to quark Yukawa-mass relation. Tree level:

$$L^{(0)}_{Hq} = Y_u H_u q u + Y_d H_d q d \to \frac{v_u Y_u}{\sqrt{2}} \bar{u} u + \frac{v_d Y_d}{\sqrt{2}} \bar{d} d \equiv m_u \bar{u} u + m_d \bar{d} d$$

With radiative corrections:

$$\begin{aligned} L^{(1)}_{Hq} &= (Y_u + \Delta Y_u) H_u q u + (Y_d + \Delta Y_d) H_d q d + \Delta Y'_u H^\star_d q u + \Delta Y'_d H^\star_u q d \\ &\to \frac{v_u Y_u}{\sqrt{2}} \left(1 + \frac{\Delta Y_u}{Y_u} + \frac{v_d}{v_u} \frac{\Delta Y'_u}{Y_u}\right) \bar{u} u + \frac{v_d Y_d}{\sqrt{2}} \left(1 + \frac{\Delta Y_d}{Y_d} + \frac{v_u}{v_d} \frac{\Delta Y'_d}{Y_d}\right) \bar{d} d \end{aligned}$$

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$\Delta Y_X/Y_X$ are typically of the order of typical EW correction, $\sim$few %.

But correction $\Delta Y'_d$ multiplied by potentially large factor $\frac{v_u}{v_d} = \tan\beta$, $\Delta Y'_b \tan\beta \sim \mathcal{O}(Y_b)$ possible for $\tan\beta \sim 50$!

$$Y_b \approx \frac{m_b\sqrt{2}}{v_b(1 + \frac{\Delta Y'_b}{Y_b}\tan\beta)} \equiv \frac{m_b\sqrt{2}}{v_b(1 + \epsilon_b \tan\beta)}$$

General MSSM: interesting problem of (finite) renormalization of flavor quantities - interplay of CKM and sfermion flavor violation sources (Crivellin, Hofer, JR 2011).

Resummation features implemented in SUSY_FLAVOR:

- Finite renormalization of quark and lepton masses and CKM matrix (i.e. relation between "bare" parameters of the Lagrangian and measured physical quark masses and CKM elements).
- Analytical expressions can be used in the "decoupling limit" $v \ll M_{SUSY}$ (usually good approximation); iterative (numerical) calculations used in general case.
- Formulae for the effective gluino, chargino, neutralino and Higgs vertices given in terms of physical masses, renormalized Yukawa couplings and CKM matrix.
- SUSY and Higgs loops calculated in terms of resummed vertices - higher order corrections automatically accounted for.

Safety output - size of chiral radiative corrections. Example:

Corrections to lepton Yukawa couplings:	10.4%	10.4%	10.5%
Corrections to down-quark Yukawa couplings:	20.4%	20.8%	36.2%
Corrections to up-quark Yukawa couplings:	0.8%	1.2%	1.1%
Corrections to CKM matrix elements:	0.0%	0.0%	20.6%
	0.0%	0.0%	13.1%
	8.6%	13.3%	0.0%

Corrections large, $\gtrsim \mathcal{O}(1)$ - output unreliable, parameter point to be rejected?

Left for user decision: size of chiral corrections printed in output file, user-defined filters can be applied.

Parton-level form factors in SUSY_FLAVOR v2.5

Available set of quark and lepton 2-, 3- and 4-point Green functions:

Box	Penguin	Self energy
$dddd$	$Z\bar{d}d$, $\gamma\bar{d}d$, $g\bar{d}d$	d-quark
$uuuu$	$H_i^0\bar{d}d$, $A_i^0\bar{d}d$	u-quark
$ddll$	$H_i^0\bar{u}u$, $A_i^0\bar{u}u$, $g\bar{u}u$	charged lepton l
$dd\nu\nu$	$\gamma\bar{l}l$	

where e.g. $dddd$ denote all flavor combinations $d^I d^J d^K d^L$ etc.

More soon: $llll$ box ($\mu \to eee$ decay), $\bar{u}u\gamma$ triangle ($t \to c\gamma$ decay) etc.

Wilson coefficients programmed already in SUSY_FLAVOR allow to calculate more observables then implemented - e.g. $B \to K l^+ l^-$, various asymmetries etc.

Required: proper dressing in QCD corrections and hadronic matrix elements. Lot of room for future development.

Hadronic parameters in SUSY_FLAVOR.

Imported from SM analyses - SUSY corrections hopefully small.

FORTRAN "common blocks" (global variables) store user accessible hadronic and QCD-related quantities, which can be modified when new results become available.

All hadronic variables documented in the manual (arXiv or SUSY_FLAVOR web page) and papers cited inside.

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Example - neutral $\bar{K}K$ mixing:

`common/meson_data/dmk,amk,epsk,fk,dmd,amd,fd,amb(2),dmb(2),gam_b(2),fb(2)`

M_K^{exp}	amk $= 0.497672$
ΔM_K^{exp}	dmk $= 3.49 \cdot 10^{-15}$
ε_K^{exp}	epsk $= 2.26 \cdot 10^{-3}$
f_K	fk $= 0.1598$

`common/bx_4q/bk(5),bd(5),bb(2,5),amu_k,amu_d,amu_b`

$B_1^{\rm VLL}(\mu_K)$	bk(1) $= 0.61$
$B_1^{\rm SLL}(\mu_K)$	bk(2) $= 0.76$
$B_2^{\rm SLL}(\mu_K)$	bk(3) $= 0.51$
$B_1^{\rm LR}(\mu_K)$	bk(4) $= 0.96$
$B_2^{\rm LR}(\mu_K)$	bk(5) $= 1.30$
Renormalization scale μ_K	amu_k $= 2$

`common/sm_4q/eta_cc,eta_ct,eta_tt,eta_b,bk_sm,bd_sm,bb_sm(2)`

$B_{SM}^{\rm VLL}$	bk_sm $= 0.724$
η_{cc}	eta_cc $= 1.44$
η_{ct}	eta_ct $= 0.47$
η_{tt}	eta_tt $= 0.57$

Hadronic quantities easy to update by users - extra SLHA2-like "`Block SFLAV_HADRON`" available in the `susy_flavor.in` input file:

```
(.........)
Block SFLAV_HADRON                      # hadronic and QCD-related input
    1    0.1598e0                       # f_K
(.........)
    5    0.75e0                         # B_K for SM contribution to KKbar
    6    1.44e0                         # eta_cc in KK mixing (SM)
    7    0.47e0                         # eta_cc in KK mixing (SM)
    8    0.57e0                         # eta_cc in KK mixing (SM)
    9    2.e0                           # scale for B_K (non-SM)
    10   0.61e0                         # B_K for VLL (non-SM)
    11   0.76e0                         # B_K for SLL1
    12   0.51e0                         # B_K for SLL2
    13   0.96e0                         # B_K for LR1
    14   1.30e0                         # B_K for LR2
(..........)
    42   0.497614e0                     # K0 mass (experimental value)
    43   3.483e-15                      # Delta mK (experimental value)
    44   2.229e-3                       # eps_K (experimental value)
(..........)
```

similarly for D, B, lepton physics.

SUSY_FLAVOR output

Output printed to the file `susy_flavor.out` with “SLHA2-like structure” (splitted into blocks). Example - list of $\Delta F = 2$ observables:

```
#           **************************
#           * SUSY_FLAVOR 2.50 output *
#           **************************

(.......)
BLOCK SFLAV_DELTA_F2              # Delta F = 2 processes
    1       2.453913407E-03       # epsilon_K
    2       2.508122147E-15       # Delta m_K (GeV)
    3       1.781110131E-15       # Delta m_D (GeV)
    4       3.414876336E-13       # Delta m_Bd (GeV)
    5       1.159694065E-13       # Re(H_eff_Bd)
    6      -1.253177870E-13       # Im(H_eff_Bd)
    7       1.219476743E-11       # Delta m_Bs (GeV)
    8       6.092519965E-12       # Re(H_eff_Bs)
    9       2.434925491E-13       # Im(H_eff_Bs)
```

Printed in output: MSSM spectrum, chiral corrections size, $\Delta F = 0, 1, 2$ observables

Application example: leptonic B decays

$Br(B_s \to \mu^+\mu^-)$ decay very rare in the SM. Current status:

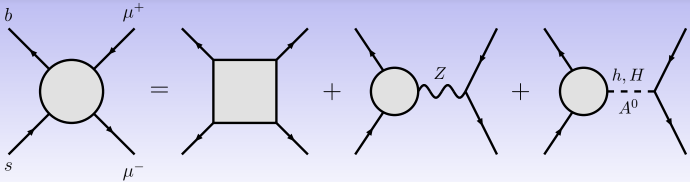
Experimental Bound	SM Prediction
$2.9 \pm 0.7 \times 10^{-9}$	$(3.5 \pm 0.3) \times 10^{-9}$

Very good agreement!

How strong are the constraints on the MSSM parameters?

Popular statement - $Br(B_s \to \mu^+\mu^-)$ kills the low energy/large $\tan\beta$ version of MSSM. Is it true?

Structure of $B_s \to \mu^+\mu^-$ decay in MSSM



Decay rate $Br(B_s \to \mu^+\mu^-)$:

$$\mathcal{B}(B_s^0 \to \mu^-\mu^+) = \frac{\tau_{B_s} M_{B_q} f_{B_s}^2}{4(16\pi^2)^3} \left(|F_S|^2 \;+\; |F_P + 2\, m_\mu\, F_A|^2\right)$$

F_X: (S)calar, (P)seudoscalar and (A)xial formfactors.

SM - only box and Z-penguin contributions to F_A non-negligible.

MSSM - all coefficients important, depending on SUSY spectrum and flavor violating structure.

How significantly $Br(B_s \to \mu^+\mu^-)$ can be modified in the MSSM? Two possible scenarios:

1. *Low* $\tan\beta \lesssim 20-30$*: Box and* Z*-penguin comparable, Higgs penguin small or negligible.* Corrections to the amplitude from all diagrams important. Both enhancement or suppression of the decay rate comparing to SM possible depending on the MSSM parameters.
2. *Large* $\tan\beta \gtrsim 20-30$*: Higgs penguin domination:* $|F_S| \approx |F_P| \gg 2m_\ell|F_A|$. Generic result: strong enhancement of the decay rate, $\sim \tan^6\beta/M_A^4$.

What kind of SUSY spectrum is compatible with current experimental bounds? Is the large $\tan\beta$ scenario still possible?

A. MFV-type models.

Low $\tan\beta$ scenario: Higgs penguins small. SM prediction modified but typically within the current experimental bound - no significant constraints on SUSY spectrum.

High $\tan\beta$ scenario: Higgs penguins strongly enhanced, other contributions negligible.

In this limit, the branching ratio is given approximately by

$$Br\left(B_s \to \mu^+\mu^-\right) \approx \frac{1}{32\pi} \frac{f_{B_s}^2 M_{B_s}^5 m_\mu^2 \tau_{B_s}}{m_A^4 (m_b + m_s)^2 v_1^2} \left[\left| \tilde{Y}_d^{32} \right|^2 + \left| \tilde{Y}_d^{23} \right|^2 \right]$$

$\tilde{Y}_d^{IJ}$ - effective flavor-violating Higgs-down quark Yukawa couplings.

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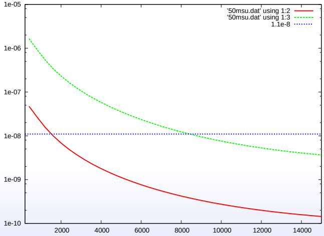
In the rough approximation:

$$Br(B_s \to \mu^+\mu^-) = \mathcal{O}(5) \cdot 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{300}{M_A}\right)^4$$

Y_d^{32}, Y_d^{23} can be suppressed only by heavy SUSY masses.

Observation: it is enough to have either left or right squark sector heavy:



$Br(B_s \to \mu^+\mu^-)$, $Br(B_d \to \mu^+\mu^-)$ plotted as a function of average right sector squarks mass. Left squark sector light, $m_{\tilde{t}_L} \approx m_{\tilde{b}_L} \approx 500 GeV$, $\tan\beta = 50$, $M_A = 200$.

B. General flavor violation.

Both enhancement and **significant suppression** of the $Br(B_s \to \mu^+\mu^-)$ possible - even below the SM prediction!

$$\mathcal{B}(B_s^0 \to \mu^-\mu^+) = \frac{\tau_{B_s} M_{B_q} f_{B_s}^2}{4(16\pi^2)^3} \left(|F_S|^2 \ + \ |F_P + 2\, m_\mu\, F_A|^2\right)$$

Enhancement easy to achieve, can come from any type of contribution (box or penguin). For suppression cancellations required:

$$F_P + 2\, m_\mu\, F_A \approx 0 \qquad \text{and} \qquad F_P \gg F_S \ ,$$

or

$$|F_S| \approx |F_P| \approx |F_A| \approx 0 \ .$$

Both options possible in general MSSM, require a certain amount of fine tuning once constraints on squark mass insertions from other flavor-changing neutral current (FCNC) measurements are imposed.

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SUSY_FLAVOR a great tool for numerical scan and searching for cancellation regions, using multi-process analysis!

Multi-dimensional scan over MSSM parameters Dedes, JR, Tanedo:

Parameter	Symbol	Min	Max	Step
Ratio of Higgs vevs	$\tan\beta$	2	30	varied
CKM phase	γ	0	π	$\pi/25$
CP-odd Higgs mass	M_A	100	500	200
SUSY Higgs mixing	μ	-450	450	300
$SU(2)$ gaugino mass	M_2	100	500	200
Gluino mass	M_3	$3M_2$	$3M_2$	0
SUSY scale (1st & 2nd squark generation)	$M_{\rm SUSY}$	500	1000	500
Slepton Masses	$M_{\tilde{\ell}}$	$M_{\rm SUSY}/3$	$M_{\rm SUSY}/3$	0
Left top squark mass	$M_{\tilde{Q}_L}$	200	500	300
Right bottom squark mass	$M_{\tilde{b}_R}$	200	500	300
Right top squark mass	$M_{\tilde{t}_R}$	150	300	150
Mass insertion	δ^{13}_{dLL}, δ^{23}_{dLL}	-1	1	1/10
Mass insertion	δ^{13}_{dLR}, δ^{23}_{dLR}	-0.1	0.1	1/100

δ^{IJ}_{dLL}, δ^{IJ}_{dLR}, μ and M_2 parameters chosen to be real, the trilinear soft couplings set to $A_t = A_b = M_{\tilde{Q}_L}$ and $A_{\tilde{\tau}} = M_{\tilde{\ell}}$.

J. Rosiek, SUSY_FLAVOR: a computational tool for FCNC and CP-violating processes in the MSSM.

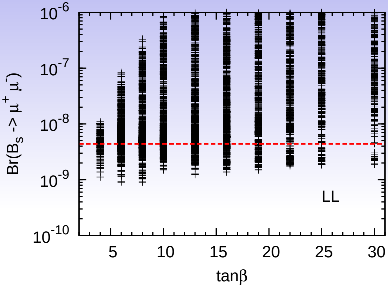
Many variables - constraints from other processes necessary.

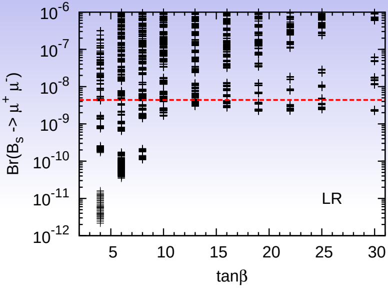
Used for this scan:

- constraints on observables calculated by SUSY_FLAVOR: ϵ_K, ΔM_K, ΔM_D, ΔM_{B_d}, ΔM_{B_s}, $\mathrm{Br}(B \to X_s \gamma)$, $\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu})$, $\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})$, electron EDM, neutron EDM.
- some bounds on direct SUSY searches: $m_{\chi_1^0}$, $m_{\chi_1^\pm}$, $m_{\tilde{b}}$, $m_{\tilde{t}}$, m_h.

J. Rosiek, SUSY_FLAVOR: a computational tool for FCNC and CP-violating processes in the MSSM.

Scan results, $\mathcal{B}(B_s \to \mu^+\mu^-)$ versus $\tan\beta$ (red line: SM prediction):





Left panel: $\delta^{23}_{d\,LL}$ varied, $\delta^{23}_{d\,LR} = 0$, right panel: $\delta^{23}_{d\,LL} = 0$, $\delta^{23}_{d\,LR}$ varied.

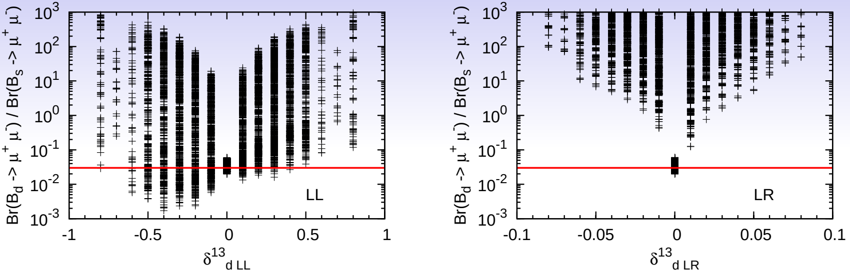
Values above or below the SM predictions possible, for all $\tan\beta$ range!

Varying $\delta^{23}_{d\,LL}$: minimal $\mathcal{B}(B^0_s \to \mu^+\mu^-)_{min} \approx 10^{-9}$.

Varying $\delta^{23}_{d\,LR}$: minimal $\mathcal{B}(B^0_s \to \mu^+\mu^-)_{min} \approx 10^{-12}$, 3 orders below the SM - effectively unobservable at the LHC!

J. Rosiek, SUSY_FLAVOR: a computational tool for FCNC and CP-violating processes in the MSSM.

Another interesting possibility: $Br(B_d \to \mu^+\mu^-)$ can be larger then $Br(B_s \to \mu^+\mu^-)$ (red line - SM prediction)!



Conclusion: result for $B_s \to \mu^+\mu^-$ compatible with experiment possible in MSSM also for not very heavy SUSY spectrum (if we accept fine tuning between new flavor couplings).

SUSY hard to discover, but also very hard to kill by any experiment...

SUSY_FLAVOR limitations

- Resummation of chirally enhanced corrections may became numerically unreliable in extreme cases of very large $\tan\beta$ or trilinear A terms - control output for size of corrections to Yukawa coupling and CKM elements always printed.
- Some new results in QCD calculations could be accommodated only changing code structure, not just updating variables - new forms of contributions (e.g. some QCD corrections to $b \to s\gamma$ decay).
- QCD improvements currently not a priority in SUSY_FLAVOR development - typically few % refinements, flavor violating soft terms can generate effects several orders of magnitude larger than SM predictions.

Plans for future development:

- add observables for new lepton flavor violating processes like $\ell^J \to \ell^K \ell^L \ell^M$, neutrino-related observables, explicit dependence on U_{PMNS} matrix
- add more observables in the B-meson system, e.g. the CP asymmetries in $B\bar{B}$ meson mixing and in $B \to X_s\gamma$ decay, observables associated with $B \to K l^+ l^-$ decay etc. - all SUSY loop formfactors already available, phenomenological formulae to be added.
- include more quantities in the top sector, like $t \to c\gamma, cZ^0, cg$, in order to probe the flavor violation in up-squark mass matrices.
- ...

Conclusions

- SUSY_FLAVOR is able to calculate over 30 FCNC and CP-violating processes, in the general R-parity conserving MSSM
- interfaced to SLHA2 for universality and compatibility to other codes.
- important higher-order effects resummed
- powerful tool for multi-process flavor analyses, as shown for example of $B_s^0 \to \mu^+\mu^-$ decay.
- project under development, new features and processes will be added.
- hopefully useful both for theorists and experimentalists! Code and documentation can be downloaded from:

http://www.fuw.edu.pl/susy_flavor