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

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based on P. Chankowski, A. Dedes, S. Jäger, JR and P. Tanedo, Comput. Phys. Commun. 181:2180, 2010.

- Sources of the CP and flavor violation in the MSSM
- SUSY_FLAVOR library
  - input parameters and input conventions
  - hadronic variables
  - available physical observables
- Example of SUSY_FLAVOR application: leptonic B decays
- Comparison with other flavor codes and plans for future development: resummation of chirally enhanced effects, new observables
- Summary

1. Sources of the CP and flavor violation in the MSSM

Flavor and CP violation in the SM:

- relatively simple - determined by the 3 angles and phase of the CKM matrix (also QCD strong phase?)
- neutral currents flavor conserving at the tree level.

Enough to generate very rich phenomenology!

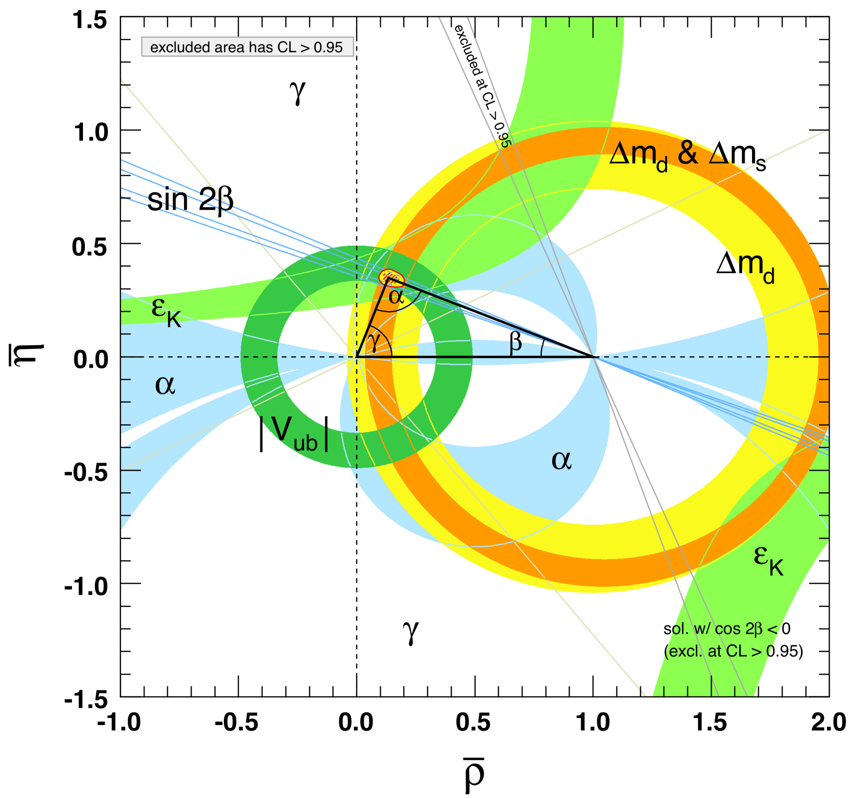
General MSSM much more complicated:

- SM flavor violating couplings replicated in new SUSY vertices
- numerous new sources of CP and flavor violation in the SUSY soft breaking sector.
- in general tree level FCNC present in supersymmetric vertices

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

General MSSM: potentially very difficult technical problem - how to disentangle effects of interfering flavor and CP violation sources in each process?

Experiment: SM flavor violation seems to explain current measurements within experimental bounds! Standard test: "unitarity triangle" gives remarkable consistency (plot from PDG review)



Supersymmetric flavor violating terms should be small. How small?

- Charged lepton sector - very strong constraints (neutrino sector?).
- Kaon sector ($1 \leftrightarrow 2$ transitions) - relative off-diagonal soft terms ("mass insertions") of the order of 10^{-3} or less.
- B meson sector ($1, 2 \leftrightarrow 3$ transitions) - constraints more relaxed.

More experiments and data coming, tools needed for efficient analysis!

Calculations of each process usually straightforward (at least at 1-loop SUSY level) but tedious, often higher order effects have to be included.

Numerous analyses by many authors, not easy to combine due to different conventions, model assumptions etc. Few available public codes restricted to "Minimal Flavor Violation" (MFV) scenario, where CKM elements remain the only source of flavour violation also in MSSM.

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2. SUSY_FLAVOR library

Currently available programs for FCNC calculations

- CPsuperH (Lee, Carena, Ellis, Pilaftsis, Wagner, arXiv:0712.2360), restricted to MFV.
- SuperIso (Mahmoudi, arXiv:0808.3144), restricted to MFV.
- SusyBSG (Degrassi, Gambino, Slavich, arXiv:0712.3265) MFV and Br($B \to s\gamma$) only, but two loop SUSY corrections.
- SUSY_FLAVOR (Rosiek, Chankowski, Dedes, Jäger, Tanedo, arXiv:1003.4260).

Other codes calculating some flavor observables (MFV version): MasterCode, Micromegas, SPHeno.

Only SUSY_FLAVOR designed to work with general R-parity conserving MSSM.

SUSY_FLAVOR assumptions:

- Calculations done in the general R-parity conserving MSSM (including so called "non-holomorphic" trilinear A terms).
- Input parameters can be set in the SLHA2 convention
- SUSY_FLAVOR version 1: only 1-loop SUSY and EW corrections , resummation of chirally enhanced higher orders planned for version 2.
- 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 v1.02 contains approximately 16000 lines of code and $\sim$400 subroutines.

Output: currently 18 physical observables in lepton and quark sectors, new ones are being added. Based on series of papers on MSSM flavor physics - 13 publications of 10 authors from 1996 till 2010. Apart from SUSY_FLAVOR authors, also A. Buras, T. Ewerth, S. Pokorski, C. Savoy, Ł. Sławianowska.

Calculations in SUSY_FLAVOR pass through the following steps:

1. Parameter Initialization (conventions of hep-ph/9511250 or SLHA2)
2. Calculation of the tree level physical masses and mixing matrices of all MSSM particles
3. 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 eigenstate basis, "mass insertion approximation" **not used**.
4. Implementation of QCD running from SUSY/EW to low energy scale, evaluation of hadronic matrix elements.
5. Evaluation and printing of physical observables.

The program runs fairly quickly ($\lesssim$ 1 sec for 1 MSSM parameter point on standard PC computer).

SUSY_FLAVOR input parameters.

- Standard SM parameters, i.e. $\alpha_{em}, \alpha_s(M_Z), M_Z$, physical charged lepton masses, running quark masses at given scale, CKM parameters (no neutrino masses and U_{PMNS} yet).
- CP-odd Higgs mass M_A, $\tan\beta$, μ parameter and gaugino masses M_1, M_2, M_3 (μ, M_1, M_2 complex in general).
- General form of sfermion soft terms:

$$
\begin{aligned}
- & \ (M_Q^2)^{IJ} Q_{Li}^{I*} Q_{Li}^J - (M_D^2)^{IJ} D_R^{I*} D_R^J - (M_U^2)^{IJ} U_R^{I*} U_R^J \\
- & \ (M_L^2)^{IJ} L_{Li}^{I*} L_{Li}^J - (M_E^2)^{IJ} E_R^{I*} E_R^J \\
+ & \ \epsilon_{ij} (A_d^{IJ} H_i^1 Q_{Lj}^I D_R^J + A_u^{IJ} H_i^2 Q_{Lj}^I U_R^J + A_l^{IJ} H_i^1 L_{Lj}^I E_R^J + \text{H.c.})
\end{aligned}
$$

  $M_Q^2, M_U^2, M_D^2, M_L^2, M_E^2$ 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:

$$
\epsilon_{ij} (A_d'^{IJ} H_i^{2\star} Q_{Lj}^I D_R^J + A_u'^{IJ} H_i^{1\star} Q_{Lj}^I U_R^J + (A_l'^{IJ} H_i^{2\star} L_{Lj}^I E_R^J + \text{H.c.})
$$

SUSY_FLAVOR input conventions.

- Internal conventions based on JR paper on MSSM Feynman Rules, (hep-ph/9511250) - SUSY_FLAVOR project started well before SLHA!
- MSSM parameters convention user selectable - in agreement with hep-ph/9511250 or (default) with the SLHA2. Easy to translate - minor differences, few signs and transpositions in soft terms.
- soft parameters can be given directly, as dimensionful soft mass matrices and A terms (SLHA2 default), or as dimensionless "mass insertions". Example (capital Δ dimensionful, small δ dimensionless):

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

- Input can be set inside master program or read from SLHA2-structured input file.

Parton-level form factors calculated by SUSY_FLAVOR v.1.02

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

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

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

Currently in preparation also : $llll$ box (e.g. $\mu \to eee$ decay), $ll\gamma$ penguin (e.g. $\mu \to e\gamma$, $\tau \to \mu\gamma, e\gamma$ decays, $g-2$ anomaly).

Combinations of Wilson coefficients calculated already by SUSY_FLAVOR allow to calculate many more processes then currently implemented - e.g. $B \to Xll$, various asymmetries, hadronic decays etc. Lot of room for future development.

Hadronic parameters in SUSY_FLAVOR.

Imported from SM analyses - SUSY corrections hopefully small.

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

$B_1^{\mathrm{VLL}}(\mu_K)$	bk(1) $= 0.61$
$B_1^{\mathrm{SLL}}(\mu_K)$	bk(2) $= 0.76$
$B_2^{\mathrm{SLL}}(\mu_K)$	bk(3) $= 0.51$
$B_1^{\mathrm{LR}}(\mu_K)$	bk(4) $= 0.96$
$B_2^{\mathrm{LR}}(\mu_K)$	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}^{VLL}	bk_sm $= 0.724$
η_{cc}	eta_cc $= 1.44$
η_{ct}	eta_ct $= 0.47$
η_{tt}	eta_tt $= 0.57$

All hadronic variables documented in the manual published in Comp. Phys. Commun. (or SUSY_FLAVOR web page) and papers cited inside.

SUSY_FLAVOR **output**: list of observables calculated in v1.02 and their currently measured values or 95% C.L bounds.

Observable	Experiment
$\Delta F = 0$	
$\|d_e\|$(ecm)	$< 1.6 \times 10^{-27}$
$\|d_\mu\|$(ecm)	$< 2.8 \times 10^{-19}$
$\|d_\tau\|$(ecm)	$< 1.1 \times 10^{-17}$
$\|d_n\|$(ecm)	$< 2.9 \times 10^{-26}$
$\Delta F = 1$	
Br($K_L \to \pi^0 \nu\nu$)	$< 6.7 \times 10^{-8}$
Br($K^+ \to \pi^+ \nu\nu$)	$17.3^{+11.5}_{-10.5} \times 10^{-11}$
Br($B_d \to ee$)	$< 1.13 \times 10^{-7}$
Br($B_d \to \mu\mu$)	$< 1.8 \times 10^{-8}$
Br($B_d \to \tau\tau$)	$< 4.1 \times 10^{-3}$
Br($B_s \to ee$)	$< 7.0 \times 10^{-5}$
Br($B_s \to \mu\mu$)	$< 5.8 \times 10^{-8}$
Br($B_s \to \tau\tau$)	$--$
Br($B \to X_s \gamma$)	$(3.52 \pm 0.25) \times 10^{-4}$
$\Delta F = 2$	
$\|\epsilon_K\|$	$(2.229 \pm 0.010) \times 10^{-3}$
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}

SUSY_FLAVOR limitations

No resummation of leading higher order chirally enhanced corrections. Version 1.0 works in the regime of not too high $\tan\beta \lesssim 20 - 30$ and in the absence of very large trilinear A terms. For small $\tan\beta$ Higgs penguins small and thus not included (available but switched off). First thing to improve for version 2.0!

Further problems in hadronic sector:

1. size of SUSY corrections to QCD-related quantities not fully controlled (quality of SM import?).
2. not all new results could be accommodated by updating variables - new forms of contributions can appear (e.g. QCD corrections to $b \to s\gamma$ decay not updated in SUSY_FLAVOR with newest results).

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.

3. Example of SUSY_FLAVOR application: leptonic B decays

LHC has first chance to measure leptonic $B \to l^+ l^-$ decay, very rare in the SM (prediction first calculated by Buchalla and Buras). Winter 2008 experimental status :

Channel	Expt.	Bound (90% CL)	SM Prediction
$B_s^0 \to \mu^+\mu^-$	CDF II	$< 4.7 \times 10^{-8}$	$(4.8 \pm 1.3) \times 10^{-9}$
$B_d^0 \to \mu^+\mu^-$	CDF II	$< 1.5 \times 10^{-8}$	$(1.4 \pm 0.4) \times 10^{-10}$
$B_s^0 \to \mu^+ e^-$	CDF	$< 6.1 \times 10^{-6}$	≈ 0
$B_d^0 \to \mu^+ e^-$	BABAR	$< 9.2 \times 10^{-8}$	≈ 0

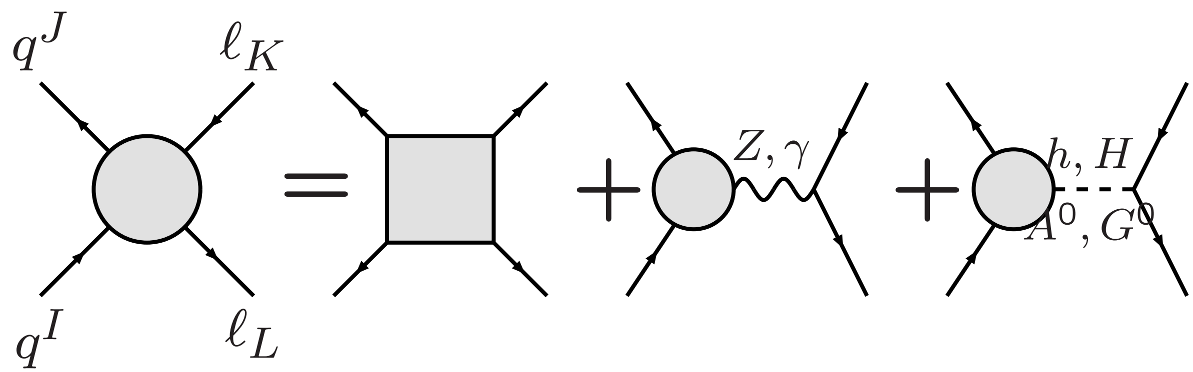
LHCb will be able to probe $B_s^0 \to \mu^+\mu^-$ down to the SM prediction at 3σ (5σ) significance with 2 (6) fb^{-1} of data, or after about 1 (3) year.

ATLAS and CMS will be able to reconstruct the $B_s^0 \to \mu^+\mu^-$ signal with significance of 3σ after ≈ 30 fb^{-1}

In MSSM for large values of $\tan\beta$ Higgs penguin contribution dominates. In MFV scenario:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \approx 5 \cdot 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{300\text{ GeV}}{M_A}\right)^4 ,$$

Low(er) $\tan\beta$ regime - gauge penguins and box diagrams with contributions from squark flavor violating terms have to be included.



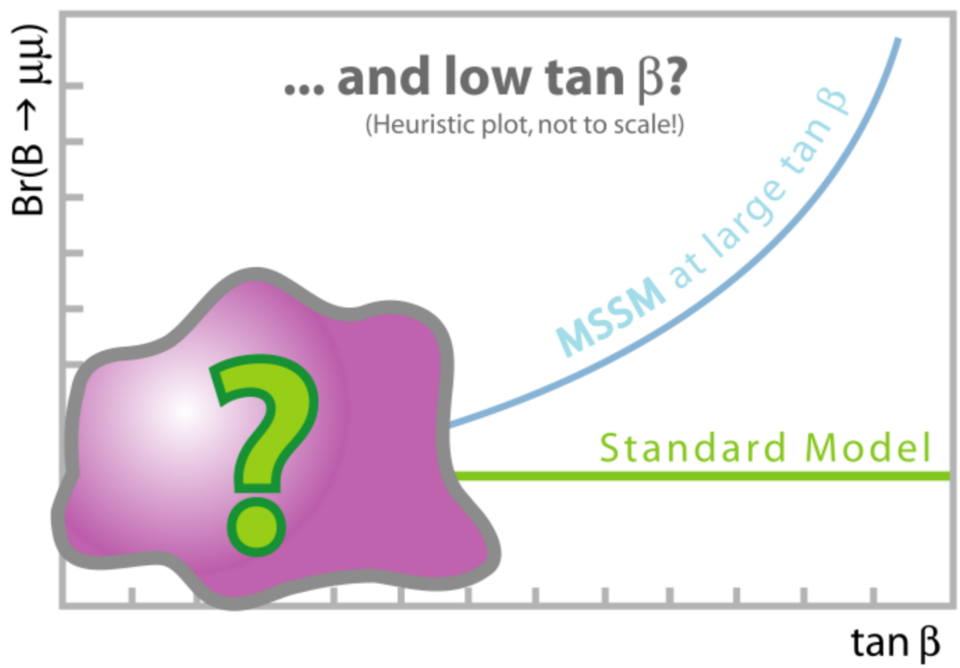
General formulae rather complicated - details in Dedes, JR, Tanedo, arXiv: 0812.4320 [hep-ph].

Simplified expression ($m_\mu/M_{B_q} \to 0$):

$$\mathcal{B}(B_q^0 \to \mu^- \mu^+) \approx \frac{\tau_{B_q} M_{B_q}}{8\pi} \left(|F_S|^2 \; + \; |F_P + 2\, m_\mu \, F_A|^2 \right)$$

where formfactors F_S, F_P, F_A are given by SUSY loops.

MFV models - branching ratio enhanced comparing to SM. What in general MSSM?



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Two possible scenarios:

1. $\tan\beta \gtrsim 10$, Higgs penguin domination $|F_S| \approx |F_P| \gg 2m_\ell|F_A|$ due to $\tan^2\beta$ enhancement. Thoroughly investigated in the literature, mostly in the MFV limit. Full branching ratio enhanced.

2. $\tan\beta \lesssim 10$, comparable box and Z-penguin contributions, Higgs penguins small. Either an enhancement or a suppression of the branching ratios is possible depending on the choice of MSSM parameters.

Suppression below the SM prediction also possible! Requires a cancellation between various terms. Important from the point of view of Tevatron and LHC searches!

SUSY_FLAVOR a great tool for numerical scan searching for cancellation regions, using multiprocess analysis (more details and analytical results in arXiv : 0812.4320 [hep-ph]).

Numerical setup.

Multi-dimensional scan over the following MSSM parameters:

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 $A_{\tilde{\tau}} = M_{\tilde{\ell}}$.

Most relevant parameters chosen for scan, other do not lead to significant variations of the $\mathcal{B}(B^0_s \to \mu^+\mu^-)$.

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Many variables - constraints from other processes necessary to get meaningful results.

We use constraints on observables calculated by SUSY_FLAVOR and bounds on direct SUSY searches (additionally LEP data for the Higgs mass bound, $m_h \geq 92.8 - 114$ GeV depending on the value of $\sin^2(\alpha - \beta)$).

Quantity	Current Measurement	Experimental Error
$m_{\chi_1^0}$	> 46 GeV	
$m_{\chi_1^\pm}$	> 94 GeV	
$m_{\tilde{b}}$	> 89 GeV	
$m_{\tilde{t}}$	> 95.7 GeV	
m_h	> 92.8 GeV	
$\lvert\epsilon_K\rvert$	$2.232 \cdot 10^{-3}$	$0.007 \cdot 10^{-3}$
$\lvert\Delta M_K\rvert$	$3.483 \cdot 10^{-15}$	$0.006 \cdot 10^{-15}$
$\lvert\Delta M_D\rvert$	$< 0.46 \cdot 10^{-13}$	
ΔM_{B_d}	$3.337 \cdot 10^{-13}$ GeV	$0.033 \cdot 10^{-13}$ GeV
ΔM_{B_s}	$116.96 \cdot 10^{-13}$ GeV	$0.79 \cdot 10^{-13}$ GeV
$\mathrm{Br}(B \to X_s \gamma)$	$3.34 \cdot 10^{-4}$	$0.38 \cdot 10^{-4}$
$\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu})$	$< 1.5 \cdot 10^{-10}$	
$\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})$	$1.5 \cdot 10^{-10}$	$1.3 \cdot 10^{-10}$
Electron EDM	$< 0.07 \cdot 10^{-26}$	
Neutron EDM	$< 0.63 \cdot 10^{-25}$	

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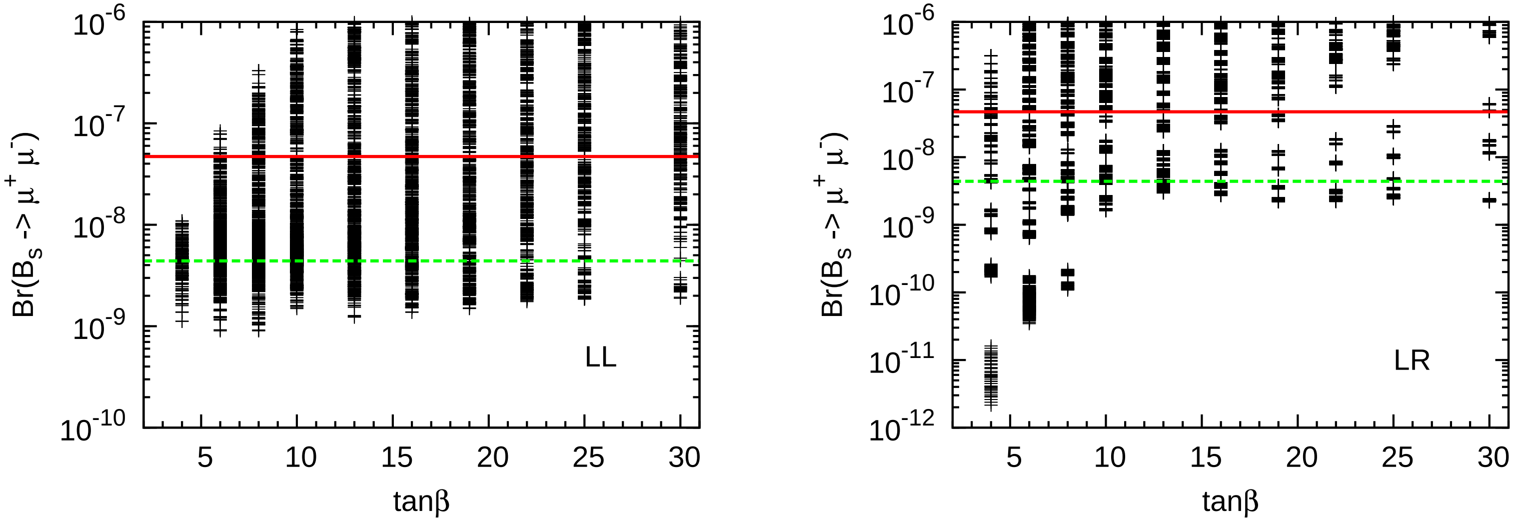
Scan results, $\mathcal{B}(B_s \to \mu^+\mu^-)$ versus $\tan\beta$ (red line: CDF limit, green line: SM prediction):



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

1. The upper CDF bound can be attained with very low values of $\tan\beta$.

2. Values below the SM predictions possible! Varying $\delta^{23}_{d\,LL}$ one can reach minimal $\mathcal{B}(B^0_s \to \mu^+\mu^-)_{min} \approx 10^{-9}$. Strong cancellation region around $\delta^{23}_{d\,LR} \approx -0.01$ and $\tan\beta \lesssim 10$ where $\mathcal{B}(B^0_s \to \mu^+\mu^-)_{min} \approx 10^{-12}$, 3 orders below the SM prediction - effectively unobservable at the LHC!

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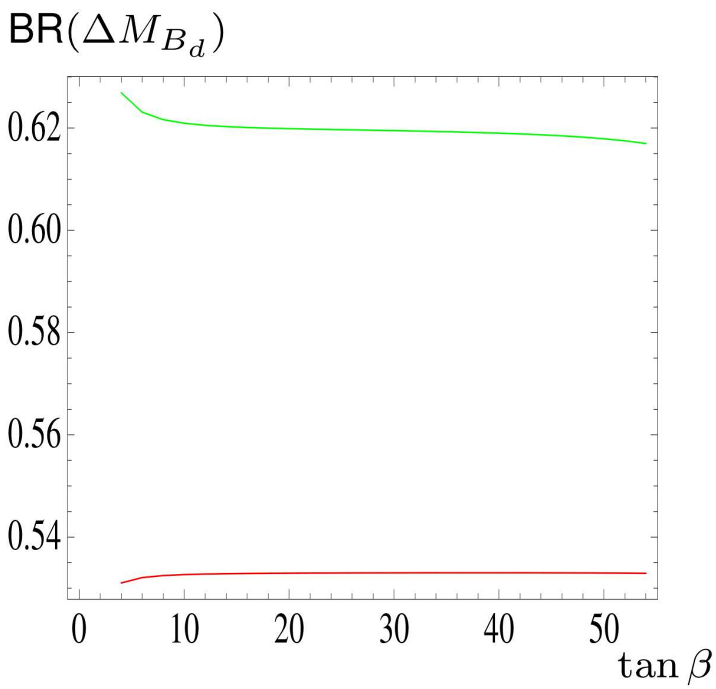
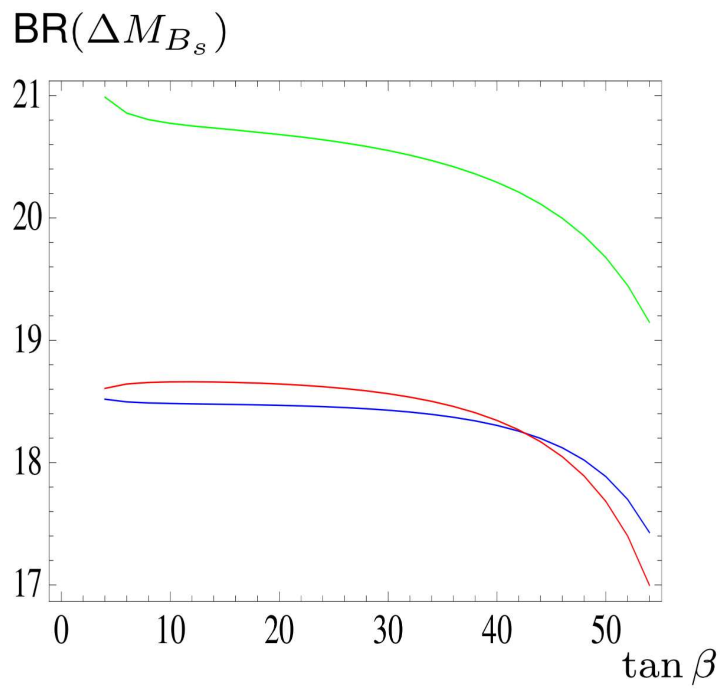
4. Comparison with other flavor codes and future plans

Comparison possible only in MFV scenario - usually reasonable agreement. Example (plots courtesy of W. Porod):



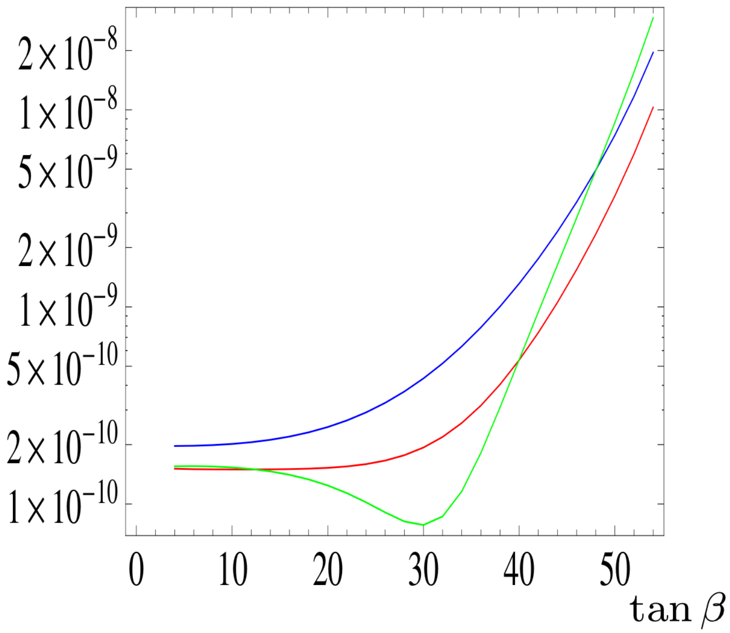


$m_b(m_b) = 4.2$ GeV, $m_t = 172.9$ GeV, $m_0 = 400$ GeV, $M_{1/2} = 300$ GeV, $A_0 = 0$, $\mu > 0$

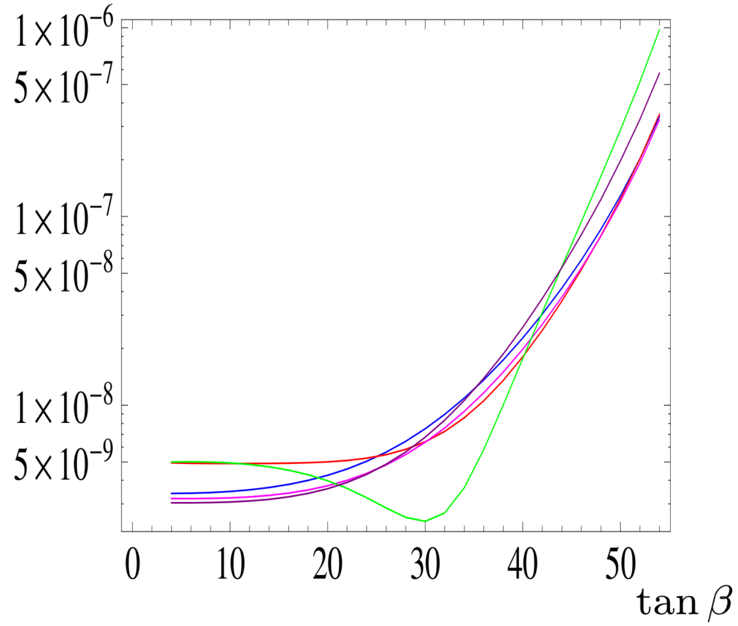
MasterCode , SUSY_FLAVOUR , SPheno

Some deviations exists:

BR($B_d \to \mu^+\mu^-$)



BR($B_s \to \mu^+\mu^-$)



$m_b(m_b) = 4.2$ GeV, $m_t = 172.9$ GeV, $m_0 = 400$ GeV, $M_{1/2} = 300$ GeV, $A_0 = 0$, $\mu > 0$

MasterCode , SUSY_FLAVOUR , SPheno , SuperIso , Micromegas

To be investigated, hopefully differences disappear after including chiral resummation and Higgs penguins(MFV codes do that).

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SUSY_FLAVOR perspectives

Our library is an open project. We wish to:

- add full resummation of leading chirally enhanced effects (large $\tan\beta$ and/or large A terms regime) - most urgent, currently in preparation.
- add observables for lepton flavor violating processes like $\ell^J \to \ell^I \gamma$, $\ell^J \to \ell^K \ell^L \ell^M$, and for the lepton anomalous magnetic momenta $(g-2)_I$ (fairly simple, under way).
- 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 (on the waiting list...).
- include quantities related to FCNCs in the top sector, like $t \to cX$ with $X = \gamma, Z, g, H$, in order to probe the flavor violation in up-squark mass matrices that are (almost) unconstrained to this moment (on the waiting list...).

Urgent improvement: resummation of leading chirally enhanced effects.

SUSY_FLAVOR in principle can resum higher order large $\tan\beta$ terms in MFV scenario (Buras, Chankowski, JR, Sławianowska 2004) - option currently switched off for consistency.

General MSSM - much more difficult problem. Effective resummed SUSY and Higgs vertices published recently: Crivellin, Hofer, JR, arXiv:1103.4272 [hep-ph]. Main points of the paper (see next talk by Andi Crivellin for details):

- Finite renormalization of quark and charged lepton masses and CKM matrix.
- Analytical expressions available in the "decoupling limit" $v/M_{SUSY} \ll 1$ (in most cases very good approximation); iterative calculations required in general case.
- Formulae for the effective resummed gluino, chargino, neutralino and Higgs vertices given in terms of physical masses, renormalized Yukawa couplings and CKM matrix.

Tools for resummation of chiral corrections ready, implementing still technically not trivial:

- Modifications required to big part (actually most) of SUSY_FLAVOR 400+ routines, careful checks needed to avoid introducing bugs.
- Higgs penguins has to be switched back on and also carefully checked.
- Purely numerical problems like numerical stability of iterative mass and CKM renormalization, quality of “unitarization” of mixing matrices etc. also to be checked.

Hopefully done by the end of summer...

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5. Conclusions

- I presented SUSY_FLAVOR, a numerical library for calculating FCNC and CP violating processes in the general R-parity conserving MSSM
- SUSY_FLAVOR v.1 calculates over 18 interesting FCNC and CP-violating processes, not relying on Mass Insertion Approximation.
- Interfaced to SLHA2 for comparisons with other calculations
- Powerful tool for multi-process flavor analyses, as shown in example for $B_s^0 \to \mu^+\mu^-$ decay.
- Project under development, new features and processes will be added soon.
- Hopefully useful both for theorists and experimentalists! Code and documentation can be downloaded from:

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