The SUSY_FLAVOR code

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work with J. Rosiek, P. Chankowski, S. Jager and P. Tanedo, arXiv:1003.4260

1. Introduction
   - Flavor Changing sources and CP-violation in MSSM
   - An example : Kaon mixing in MSSM
2. The SUSY_FLAVOR code
   - Currently available programs for FCNC calculations
   - What does SUSY_FLAVOR do ?
   - Main features of SUSY_FLAVOR
   - Structure of the code
   - Future directions
3. Example I : $B_s \to \mu^+\mu^-$
   - A typical result with SUSY_FLAVOR
4. Example II : CP-asymmetries
   - Typical predictions with SUSY_FLAVOR
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In general, in MSSM one cannot simultaneously diagonalize the mass matrices of the SM fermions and their SUSY partners. This mismatch leads to Flavour Changing vertices even at tree level e.g.,

A Tree level FC vertex

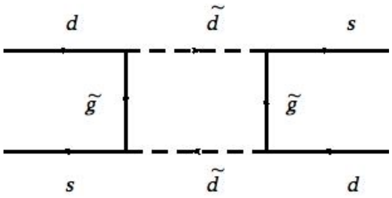
$$\tilde{g}^A - \tilde{q}^i_\alpha - q^I_\beta \text{ vertex : } i g_3 \sqrt{2}\, Y^A_{\alpha\beta} \left(-Z^{Ii}_D P_L + Z^{(I+3)i}_D P_R\right)$$

Furthermore, even if all FCNCs in MSSM arise from the superpotential Yukawa couplings (Minimal Flavor Violation) there are new parameters that are in general complex i.e, a new source of CP-violation. These new couplings ,

CPV-phases

$$\text{Arg}(\mu, A, M_{1,2}, \delta_{IJ})$$

result generically in large contributions to lepton and neutron EDMs.



J. F. Donoghue, H. P. Nilles and D. Wyler, 1983

$$\sum_i \frac{Z_D^{di} Z_D^{*si}}{k^2 - M_i^2} \times \sum_j \frac{Z_D^{dj} Z_D^{*sj}}{k^2 - M_j^2}$$

If squark square masses differ from some common value M^2_{squark} by small 'mass insertions' ΔM_i^2

$$\left(\frac{1}{k^2 - M^2_{squark}}\right)^2 \left(\sum_i Z_D^{di} Z_D^{*si} \Delta M_i^2\right)^2$$

Bounds from Δm_K

$$\left|\sum_i Z_D^{di} Z_D^{*si} \frac{\Delta M_i^2}{M_{squark}^2}\right| \lesssim 10^{-3} \times (M_{squark}/100\ \mathrm{GeV})$$

- squark mass splitting 1 : 1000
- off diagonal elements of Z_D's are less than 10^{-3}
- squarks of 1st and 2nd gen are heavier than 100 TeV
- nearly degenerate squarks

Bounds from Δm_K in Super-CKM basis

$$|\delta_{D\,LL}^{12}| \quad , \quad |\delta_{D\,RR}^{12}| \lesssim 10^{-3} \times (M_{squark}/100\ \mathrm{GeV})$$

There is, however, plenty of room in $b \to s$ transitions where constraints like the above are relaxed. These calculations, although straightforward, are quite involved due to :

- many FCNC vertices and parameters
- many diagrams
- there is tan β-enhancement of B-observables that, sometimes, require even two loop SUSY calculations

If SUSY particles are about to reveal themselves, a combined analysis of observables is necessary to pin down a unique parameter space

Tools are needed!

FCNC related programs :

- CPsuperH
  J. S. Lee, M. Carena, J. Ellis, A. Pilaftsis and C. E. M. Wagner, 0712.2360, restricted to MFV
- SuperIso
  F. Mahmoudi, 0808.3144, restricted to MFV
- SusyBSG
  G. Degrassi, P. Gambino and P. Slavich, 0712.3265 MFV and $\mathrm{Br}(B \to s\gamma)$ but two loop SUSY corrections.
- hep-ph/9604387
  F. Gabbiani, E. Gabrielli, A. Masiero and L. Silvestrini General MSSM based on Mass Insertion Approximation (MIA).
- SUSY_FLAVOR
  J. Rosiek, P. H. Chankowski, A. Dedes, S. Jäger and P. Tanedo, 1003.4260

SUSY_FLAVOR is a Fortran 77 program that calculates important leptonic, semi-leptonic and CP-violating low-energy observables in the general R-parity conserving MSSM.

Observable	Experiment
$\Delta F = 0$	
$\lvert d_e \rvert$(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)	$< 2.9 \times 10^{-26}$
$\Delta F = 1$	
$\mathrm{Br}(K_L \to \pi^0 \nu\nu)$	$< 6.7 \times 10^{-8}$
$\mathrm{Br}(K^+ \to \pi^+ \nu\nu)$	$17.3^{+11.5}_{-10.5} \times 10^{-11}$
$\mathrm{Br}(B_d \to ee)$	$< 1.13 \times 10^{-7}$
$\mathrm{Br}(B_d \to \mu\mu)$	$< 1.8 \times 10^{-8}$
$\mathrm{Br}(B_d \to \tau\tau)$	$< 4.1 \times 10^{-3}$
$\mathrm{Br}(B_s \to ee)$	$< 7.0 \times 10^{-5}$
$\mathrm{Br}(B_s \to \mu\mu)$	$< 5.8 \times 10^{-8}$
$\mathrm{Br}(B_s \to \tau\tau)$	$--$
$\mathrm{Br}(B \to X_s\gamma)$	$(3.52 \pm 0.25) \times 10^{-4}$
$\Delta F = 2$	
$\lvert \epsilon_K \rvert$	$(2.229 \pm 0.010) \times 10^{-3}$
ΔM_K	$(5.292 \pm 0.009) \times 10^{-3}\ \mathrm{ps}^{-1}$
ΔM_D	$(2.37^{+0.66}_{-0.71}) \times 10^{-2}\ \mathrm{ps}^{-1}$
ΔM_{B_d}	$(0.507 \pm 0.005)\ \mathrm{ps}^{-1}$
ΔM_{B_s}	$(17.77 \pm 0.12)\ \mathrm{ps}^{-1}$

Table: List of observables calculated by SUSY_FLAVOR and their currently measured values or 95% C.L bounds.

Main features of SUSY_FLAVOR

- the calculation does not rely on the "Mass Insertion Approximation (MIA)" expansion. Complex "mass insertions" of the form,

$$\delta^{IJ}_{QXY} = \frac{(M^2_Q)^{IJ}_{XY}}{\sqrt{(M^2_Q)^I_{XX}(M^2_Q)^J_{YY}}} \quad ,$$

  are inputs in SUSY_FLAVOR

- additional "non-holomorphic" terms are included

$$A'^{IJ}_d H^{2\star}_i Q^I_i D^J + A'^{IJ}_u H^{1\star}_i Q^I_i U^J + \mathrm{H.c.} \ ,$$

  L. J. Hall and L. Randall, 1990

- As an intermediate step, parton-level form factors for quark and lepton 2-, 3- and 4-point Green functions are calculated.

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
$ddll$	$H_i^0\bar{u}u$, $A_i^0\bar{u}u$	
$dd\nu\nu$		

Table: One loop parton level diagrams implemented in SUSY_FLAVOR.

M. Misiak, S. Pokorski and J. Rosiek, 1997,
S. Pokorski, J. Rosiek and C. A. Savoy, 1999
A. J. Buras, P. H. Chankowski, J. Rosiek and L. Slawianowska,2001,2003
A. J. Buras, T. Ewerth, S. Jager and J. Rosiek, 2004
A. Dedes, J. Rosiek and P. Tanedo, 2008.

- The program runs fairly quickly (∼1 sec for 1 param point).

Calculations in SUSY_FLAVOR pass through the following steps:

1. Parameter Initialization (hep-ph/9511250 or SLHA2)
2. Calculation of the physical masses and mixing angles
3. Calculation of Wilson coefficients at the SUSY scale
4. Implementation of hadronic matrix elements

SUSY_FLAVOR contains 15000 code lines and 40 subroutines

Sample Output

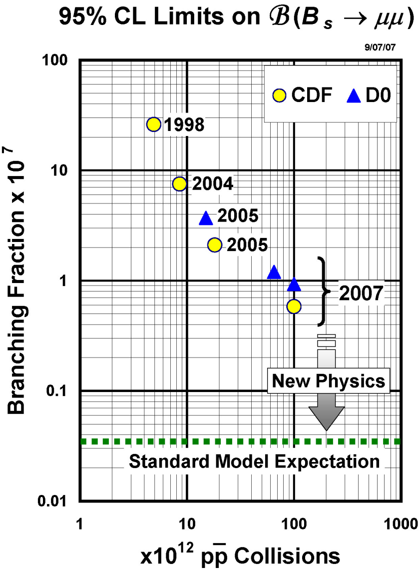
```
Electric dipole moments:
Electron EDM            = 4.7256E-25
Muon EDM                = 9.7726E-23
Tau EDM                 = 1.6425E-21
Neutron EDM             = 5.9331E-24

Neutrino K decays:
BR(K_L^0 -> pi^0 vv)    = 2.8555E-11
BR(K^+ -> pi^+ vv)      = 7.3932E-11

Leptonic B decays:
BR(B_d -> mu^+ mu^-)    = 1.2012E-10
BR(B_s -> mu^+ mu^-)    = 4.7395E-09

B -> X_s photon decay:
BR(B -> X_s gamma)      = 2.5756E-04

KK mixing:
eps_K                   = 2.3366E-03
Delta m_K               = 2.4362E-15

DD mixing:
Delta m_D               = 1.6656E-17
```

```
BB mixing:
Delta m_B_d = 3.6999E-13
Delta m_B_s = 1.3242E-11
```

SUSY_FLAVOR library is an open project. We wish to :

- add more observables in the B-meson system, like the CP asymmetries in $B\bar{B}$ meson mixing and in $B \to X_s\gamma$ decay, as well as observables associated with $B \to Kl^+l^-$ decay.
- 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 moments, $(g-2)_l$
- 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.
- add full resummation of leading large $\tan\beta$ effects beyond the MFV scenario.

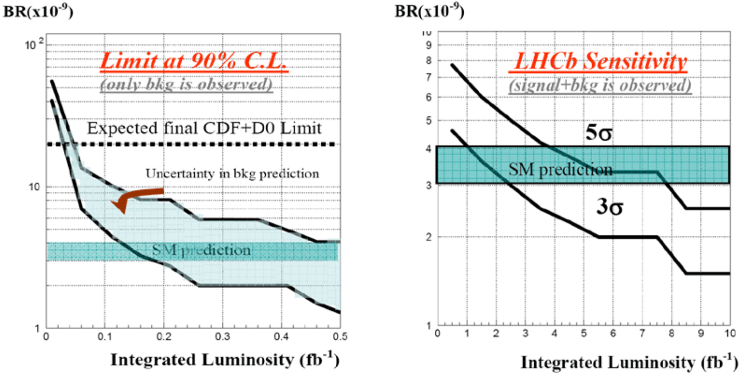
Example I



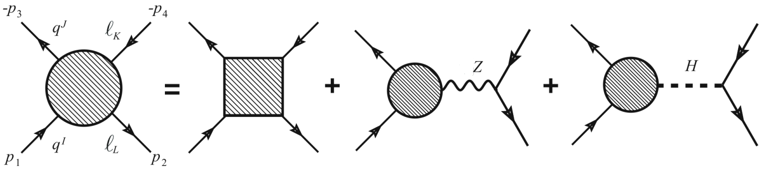
A history of the Tevatron data set. Courtesy of the CDF B-physics group.

Current exp bound : 5.8×10^{-8}

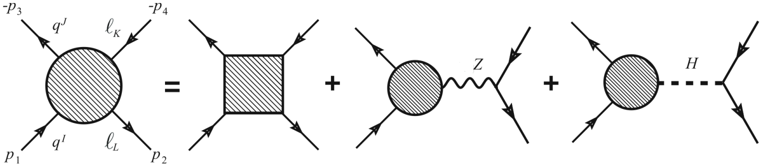
SM prediction : $(4.8 \pm 1.3) \times 10^{-9}$



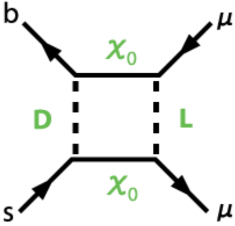
Source: arXiv:0710.5056

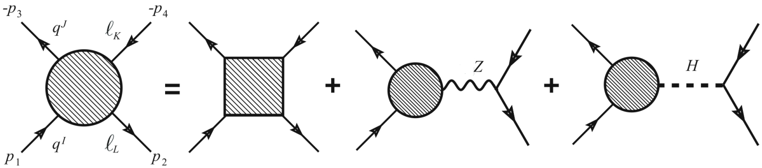


-p3
-p4
qJ
ℓK
qI
ℓL
p1
p2
=
+
Z
+
H



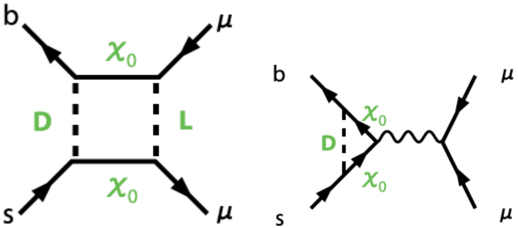
e.g.,





$-p_3$
q^J
ℓ_K
$-p_4$
p_1
q^I
ℓ_L
p_2
=
+
Z
+
H

e.g.,



b
μ
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χ_0
s
μ
b
μ
χ_0
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χ_0
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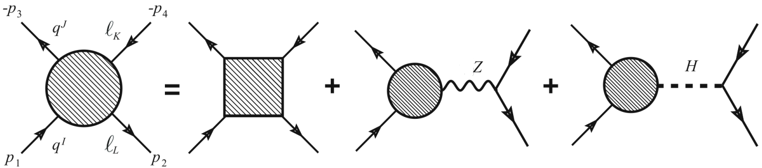
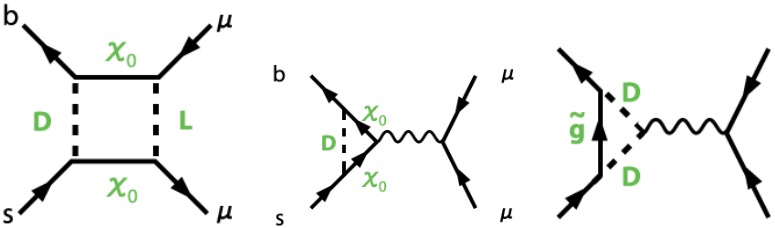
μ


$-p_3$
q^J
ℓ_K
$-p_4$
p_1
q^I
ℓ_L
p_2
=
+
Z
+
H

e.g.,


b
μ
χ_0
D
L
χ_0
s
μ
b
χ_0
D
χ_0
s
μ
μ
D
$\tilde{g}$
D

There are 10 effective operators for the amplitude : $b \to s\,\ell\,\ell'$

$$\mathcal{H}_{\rm eff} = \sum_{X,Y=L,R} \left(C^V_{XY}\,\mathcal{O}^V_{XY} \;+\; C^S_{XY}\,\mathcal{O}^S_{XY} \;+\; C^T_{XY}\,\mathcal{O}^T_{X} \right)$$

$$\begin{aligned} \mathcal{O}^V_{XY} &= \bar{b}\gamma^\mu P_X s \;\otimes\; \bar{\ell}\gamma_\mu P_Y \ell' \\ \mathcal{O}^S_{XY} &= \bar{b} P_X s \;\otimes\; \bar{\ell} P_Y \ell' \\ \mathcal{O}^T_{X} &= \bar{b}\sigma^{\mu\nu} P_X s \;\otimes\; \bar{\ell}\sigma_{\mu\nu} P_Y \ell' \end{aligned}$$

The operator $\mathcal{O}^T_X$ does not contribute to $\mathcal{B}(B_s \to \mu^+\mu^-)$

We focus on lepton flavour conserving $B_s \to \mu^+\mu^-$. The squared amplitude goes approximately like :

$$|\mathcal{M}|^2 \approx 2M_{B_s}^2 \left(|F_S|^2 \; + \; |F_P + 2\, m_\ell\, F_A|^2\right) \; ,$$

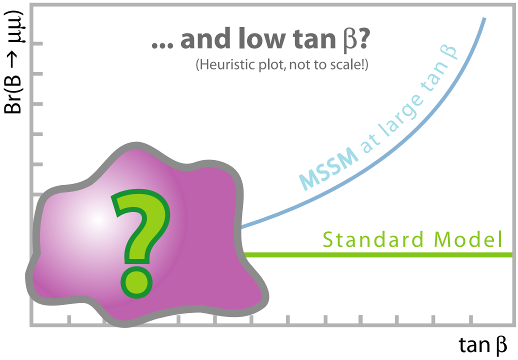
with the various form-factors being :

$$\begin{aligned}
F_S &= \frac{i}{4} \frac{M_{B_s}^2 f_{B_s}}{m_b + m_s} \left(C_{LL}^S + C_{LR}^S - C_{RR}^S - C_{RL}^S\right) , \\
F_P &= \frac{i}{4} \frac{M_{B_s}^2 f_{B_s}}{m_b + m_s} \left(-C_{LL}^S + C_{LR}^S - C_{RR}^S + C_{RL}^S\right) , \\
F_A &= -\frac{i}{4} f_{B_s} \left(-C_{LL}^V + C_{LR}^V - C_{RR}^V + C_{RL}^V\right) .
\end{aligned}$$

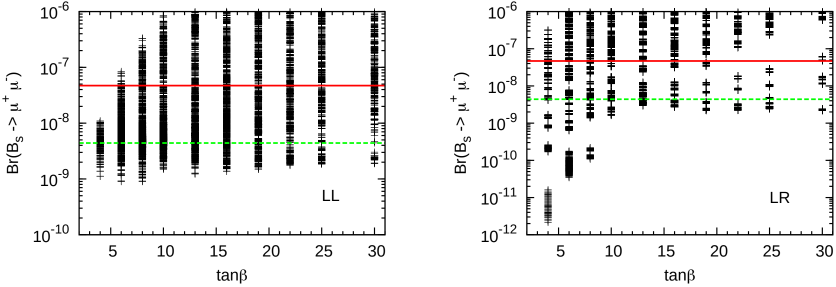
Cancellation of the SM contribution is, in principle, possible : it must be $F_A \approx 0$. Thus $\tan\beta$ must be low since only then $F_{S,P} \approx 0$

A typical result with SUSY_FLAVOR

The aim is to calculate all possible SUSY contributions to $\mathrm{Br}(B_s \to \mu^+\mu^-)$ at low $\tan\beta$ ($\lesssim 30$) and thus to complete the picture.

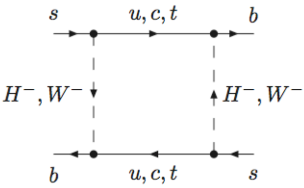


Consistency with other FCNC observables and collider mass constraints were checked.

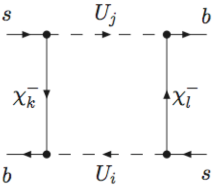


A. Dedes, J. Rosiek and P. Tanedo, Phys. Rev. D **79** (2009) 055006 [arXiv:0812.4320 [hep-ph]].

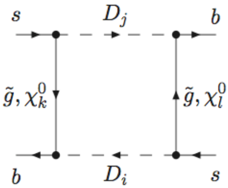
Example II



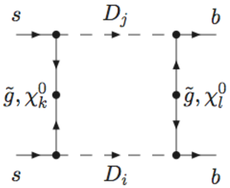
(A): W and charged Higgs exchanges



(B): chargino exchange

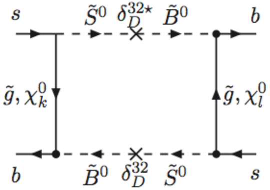


(C): neutralino and gluino exchanges



(D): neutralino and gluino exchanges

$(\mathrm{C}) \equiv$



$+ \quad \mathcal{O}((\delta_D^{IJ})^3)$

We choose a MSSM parameter point not applicable in MIA i.e.,

$$
\begin{aligned}
M_{\tilde{q}_{1,2}} &= 1000, \quad M_{\tilde{t}_L} = 400, \quad M_{\tilde{t}_R, b_R} = 200, \quad A_{t,b} = 0, \\
M_{\tilde{g}} &= 600, \quad M_2 = 200, \quad M_1 = \frac{3}{5} M_2, \\
\tan\beta &= 10, \quad M_A = 1000, \quad \mu = 200, \\
\delta_D^{23} &\in [-1 \div +1] .
\end{aligned}
$$

Constraints

We allow for an observable to be within 2σ from its experimental value and a theoretical uncertainty of 50%. In what follows we checked that every single input point passes the experimental measurements coming from

$$\Delta F = 0 : \mathrm{n-EDM}, \mathrm{e-EDM}$$

$$\Delta F = 1 : B \to s\gamma \ , \ B_{s,d} \to \mu^+\mu^- \ , \ K^+ \to \pi^+\nu\bar{\nu}$$

$$\Delta F = 2 : \Delta M_{B_d} \ , \ \Delta M_{B_s} \ , \ \Delta M_D \ , \ \Delta M_K \ , \ \epsilon_K \ , \ S_{\psi K_S} \ .$$

and of course direct collider searches.

Observables :

$$M_{12}^q = |M_{12}^q|_{\rm SM}\ C_{B_q}\ e^{i\phi_q}\ ,$$

$$\Delta M_q = C_{B_q}\ (\Delta M_q)_{\rm SM}\ , \quad q = s, d\ ,$$

$$S_{\psi K_S} = \sin(\phi_d)\ ,$$

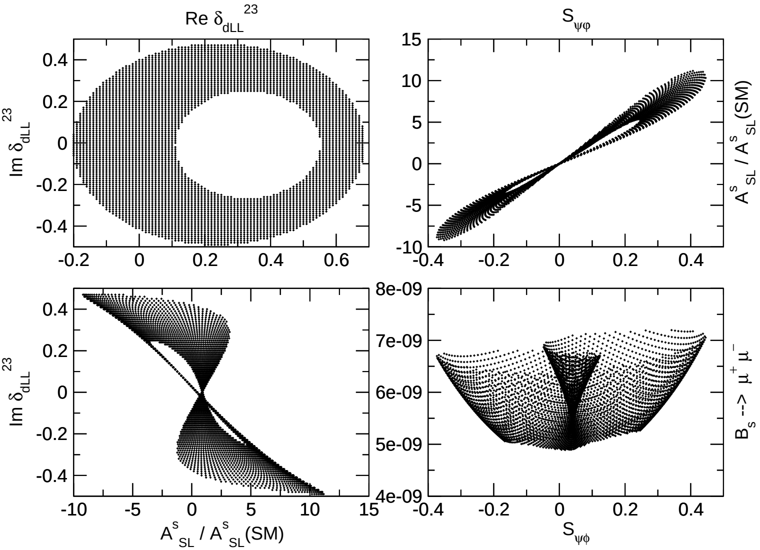
$$S_{\psi\phi} = -\sin(\phi_s)\ , \quad \text{unconstrained}$$

$$A_{\rm SL}^s = -\left|{\rm Re}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right)^{\rm SM}\right| \frac{1}{C_{B_s}}\ S_{\psi\phi}\ , \quad \text{unconstrained}$$

[see previous talk by U. Nierste]

Typical predictions with SUSY_FLAVOR

δ_{dLL}^{23}

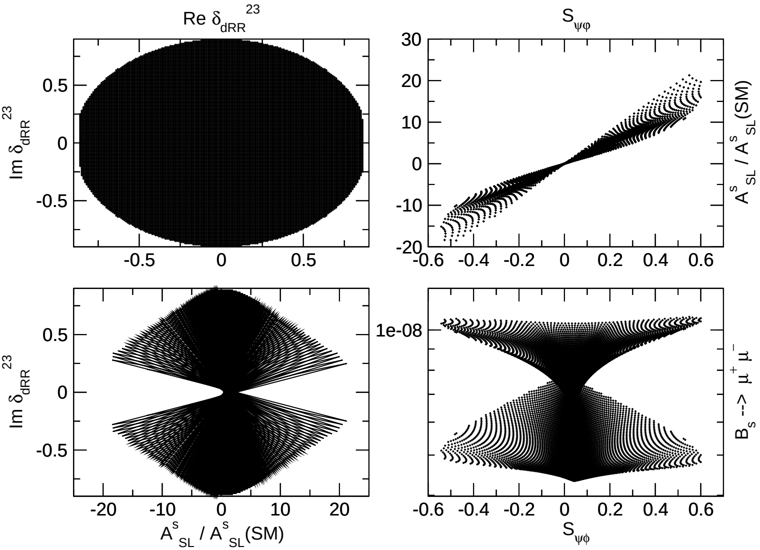


Conclusions

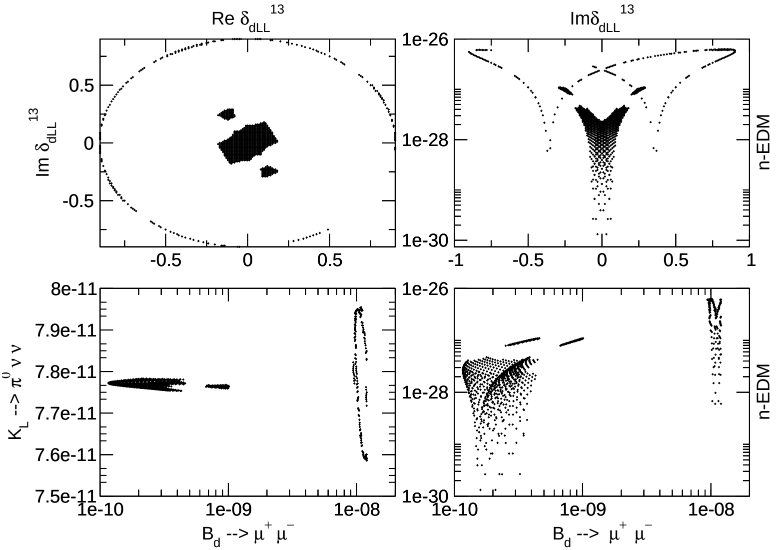
- A tool for calculating FCNC processes in MSSM is presented
- SUSY_FLAVOR calculates interesting FCNC and CP-violating processes not relying on Mass Insertion Approximation method. Two examples were presented in this talk
- SUSY_FLAVOR is a numerical library that calculates 2-, 3-, and 4-point one-loop Green functions in (R-parity conserving) MSSM
- It is interfaced to SLHA2 for comparisons with other calculations
- It is useful both for theorists and experimentalists
- SUSY_FLAVOR code/documentation can be downloaded from :

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

δ^{23}_{dRR}


Re δdRR 23
Im δdRR 23
0.5
0
-0.5
-0.5
0
0.5
Sψφ
30
20
10
0
-10
-20
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
A s SL / A s SL(SM)
Im δdRR 23
0.5
0
-0.5
-20
-10
0
10
20
A s SL / A s SL(SM)
1e-08
Bs --> μ+ μ−
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
Sψφ

δ^{13}_{dLL}


Re δ dLL 13
Im δ dLL 13
0.5
0
-0.5
1e-26
1e-28
1e-30
n-EDM
-1
1
8e-11
7.9e-11
7.8e-11
7.7e-11
7.6e-11
7.5e-11
K L --> π 0 ν ν
1e-10
1e-09
1e-08
B d --> μ + μ −