A natural route to near-flavour-conservation in SUSY: the Minimal Flavour Violating MSSM

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Outline

- **Introduction:** impact of FCNC processes on generic SUSY corrections
  $\Rightarrow$ New-Physics 'flavour problem'
- **Approach 1:** use exp. info to constrain the general MSSM
  (general = with completely *free* soft terms)
- **Approach 2:** implement a natural "near-flavour-conservation" mechanism within the MSSM $\Rightarrow$ MFV-MSSM
  - Application to meson mixings and discussion

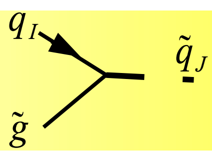
General parameterization of FCNC in SUSY

The "rotation" that makes quark masses diagonal *does not need* to diagonalize squark masses as well

⇒ In the CKM basis for quarks the squark mass matrices are still *off-diagonal* in flavour (and 'chirality')

<u>Then for squarks one chooses between:</u>

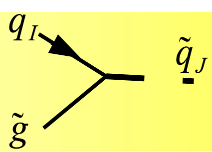
❶ **mass eigenstates** $M_I \, \delta_{IJ}$



$\propto Z_{IJ}$

Propagators *diagonal* ⇒ exact calculations
However, many parameters: M_J , Z_{IJ}

❷ **flavour eigenstates** M_{IJ}



$\propto \delta_{IJ}$

Propagators perturbatively diagonalized through "Mass Insertions"

Mass Matrices **Interactions**

Mass Insertion Approx

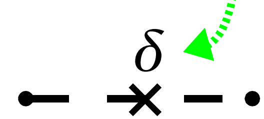
$$M \equiv \begin{pmatrix} M_{11} & \Delta_{12}^{LL} & \cdots \\ \Delta_{21}^{LL} & M_{22} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \simeq \bar{M}\,\mathbf{1} + \begin{pmatrix} 0 & \delta_{12}^{LL} & \cdots \\ \delta_{21}^{LL} & 0 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

SUSY source of FCNC's

squark propagator (flavor basis + MIA) $\simeq$

diagonal

+



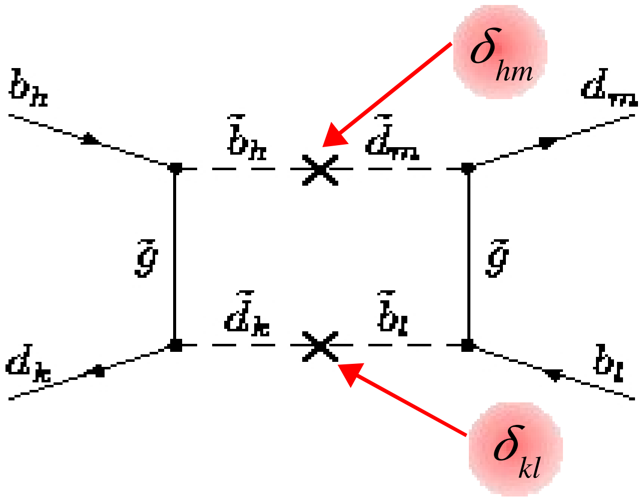
NON-diag.: Mass Insertion

D.Guadagnoli, SUSY 2007, July 26 – August 1, 2007

Naïve assessment of SUSY effects

Example: $\Delta F = 2$ case

$$\text{SUSY corrections} \sim \left(\frac{\delta}{M_{\rm SUSY}}\right)^2 \times f\,(\text{SUSY mass ratios})$$



Since mixing measurements check (within errors) with the SM, one has roughly:

$$|\text{ SUSY corrections }| \;\leq\; \sqrt{\sigma^2_{\rm exp} + \sigma^2_{\rm th}}$$

$\sigma_{\rm th}$ > 10 % (!)

Sensitivity to O(%) deviations from SM demands **steady improvement** on the non-pert. error

bounds on δ
(or rather, on $\delta/M_{\rm SUSY}$)

Analysing FCNCs in SUSY

The SUSY (and NP in general) flavour problem

a) assuming $M_{\text{SUSY}} \sim O(\mathit{300}\ \text{GeV})$ [if we want it to stabilize the ~~EW~~ scale]

$\Longrightarrow\ |\delta| < 10^{-2} \div 10^{-3}$

in absence of a symmetry principle (e.g. GIM-like mechanism) such small numbers are ugly

Let us write the down quark mass matrix, in the basis with diagonal interaction terms (the equivalent of the MIA basis) [values in GeV]

$$\left[\hat{m}_d\right]_{\text{MIA basis}} \equiv \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} \cdot V^{+}_{\text{CKM}} = \begin{pmatrix} 6.8\times10^{-3} & -1.6\times10^{-3} & (5.2+2.3\,i)10^{-5} \\ 2.3\times10^{-2} & 9.7\times10^{-2} & -4.2\times10^{-3} \\ (0.9+1.4\,i)\times10^{-2} & 1.8\times10^{-1} & 4.3 \end{pmatrix}$$

(does this matrix "look better" ?)

b) assuming $|\delta| \sim O(\mathit{1})$

$\Longrightarrow\ M_{\text{SUSY}} \gg O(\text{TeV})$

back to "Separation-of-Scales" Problems

Theoretical approaches to SUSY flavour effects

❶ **Constrain the 'general' MSSM**
(with completely free soft terms)

<u>not easy</u> without simplifying assumptions:
bulkiness of the parameter space

Take the δ bounds "as they come"
(from measured FCNCs)
and study allowed effects on still-to-measure quantities (*e.g.* $A_{CP}\,[B_s \to \psi \phi]$, ...)

❷ **Maybe FCNC effects in SUSY are small, because already those in the SM are.**

i.e. low-energy flavour breaking "building blocks" are <u>the same</u> in the SM and in the MSSM

<u>Naturalness</u> of "near-flavour-conservation" in SUSY: **MFV-MSSM**

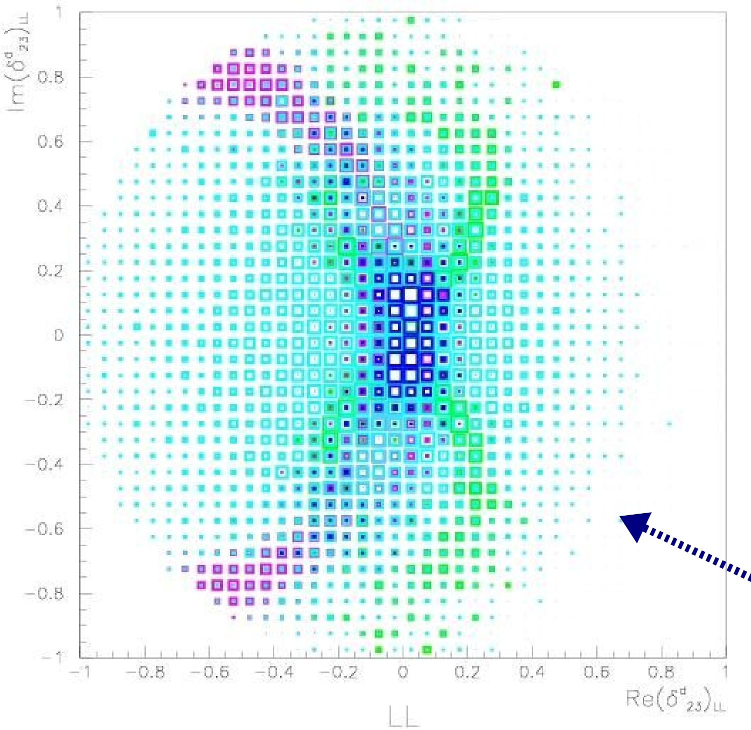
Hall & Randall

D'Ambrosio *et al.*

❶

Constrain the general MSSM

Example: constraints from $b \to s$ FCNCs



y-axis: $Im[(\delta^{23})_{XY}]$

x-axis: $Re[(\delta^{23})_{XY}]$

Constraints

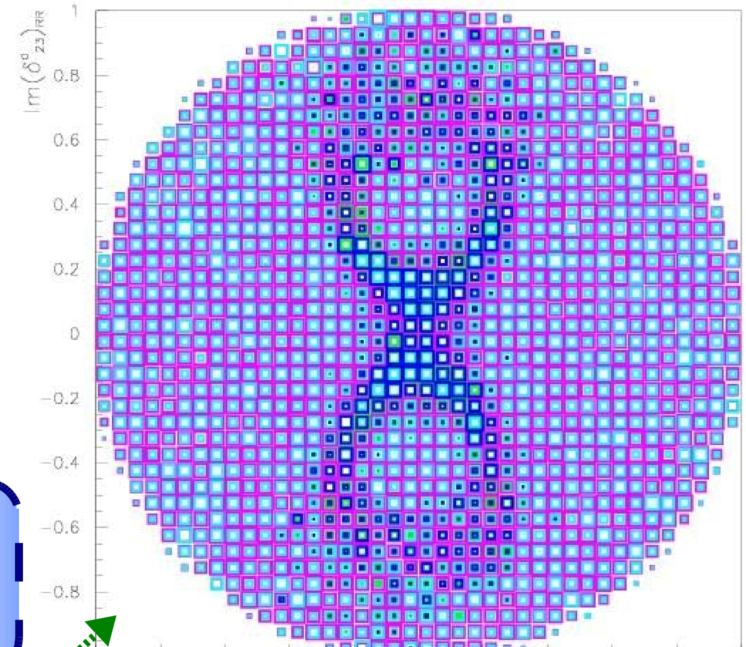
- green box = Δm_s
- magenta box = $b \to s\ \gamma$
- cyan box = $b \to s\ l^+ l^-$
- blue box = all

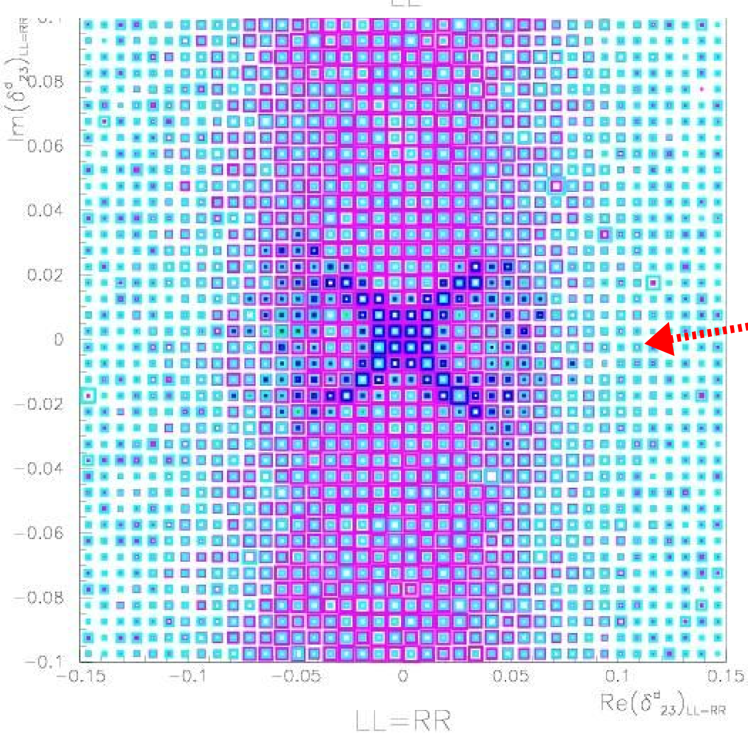
LL only, tan β=3 ⇩ $[-0.15,+0.15] + i\,[-0.25,0.25]$

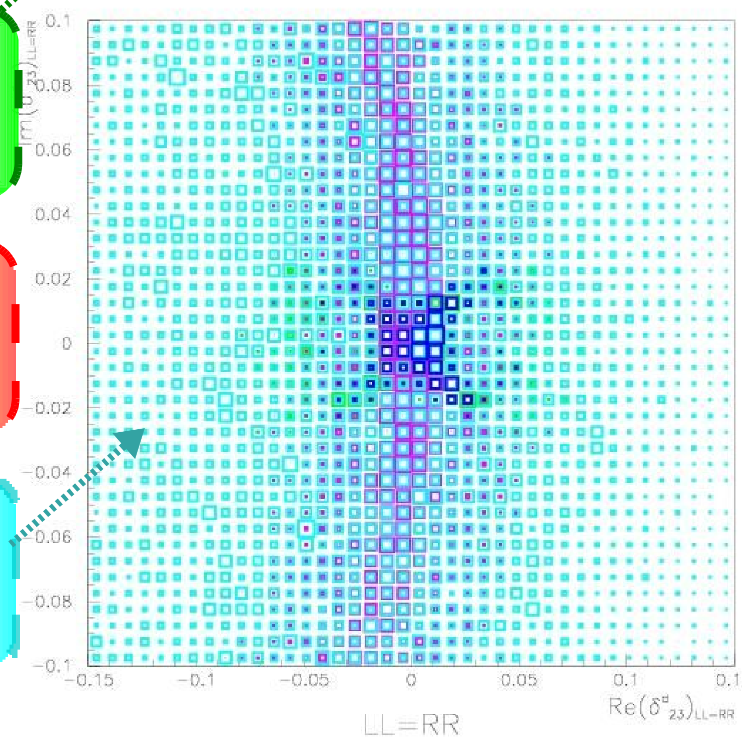
RR only, tan β=3 ⇩ $[-0.4,+0.4] + i\,[-0.9,0.9]$

LL=RR, tan β=3 ⇩ $[-0.05,+0.05] + i\,[-0.03,0.03]$

LL=RR, tan β=10 ⇩ $[-0.03,+0.03] + i\,[-0.02,0.02]$



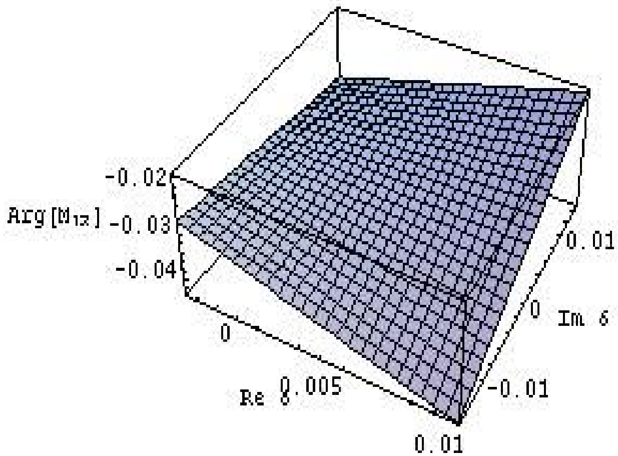




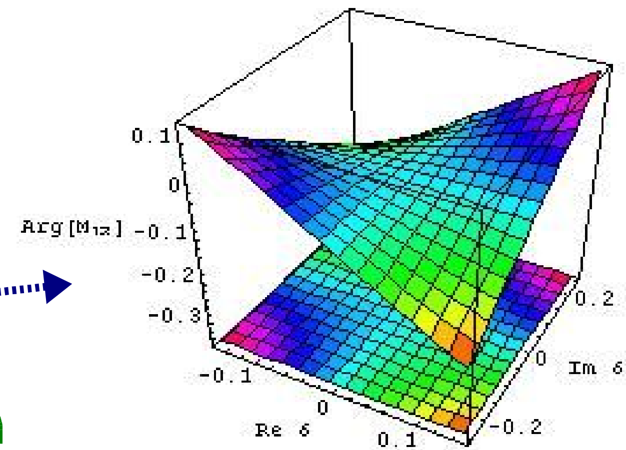
Implication on the B_s – mixing phase

✔ In the SM one has $Arg\, M_{12}^{SM} \equiv Arg\{\langle B_s | H_{eff,\,SM}^{\Delta B,\,S=2} | \bar{B}_s \rangle\} = -2\lambda^2\eta \simeq -0.04$

☞ What is the allowed range for $Arg\, M_{12}^{MSSM}$ with the previous limits on the δ's ?

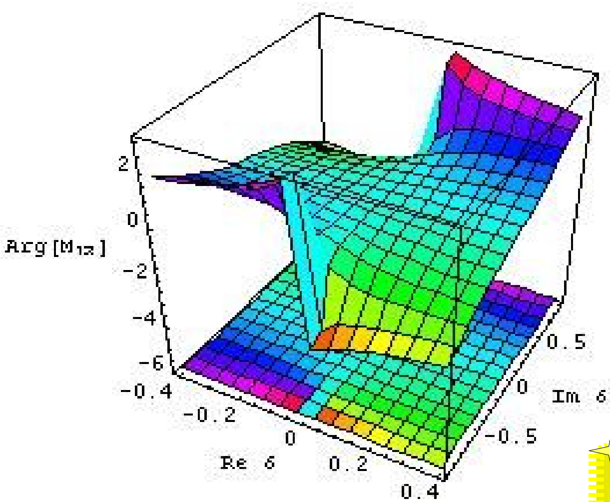


LR only, $\tan\beta=3$
no sizable deviations
from the SM

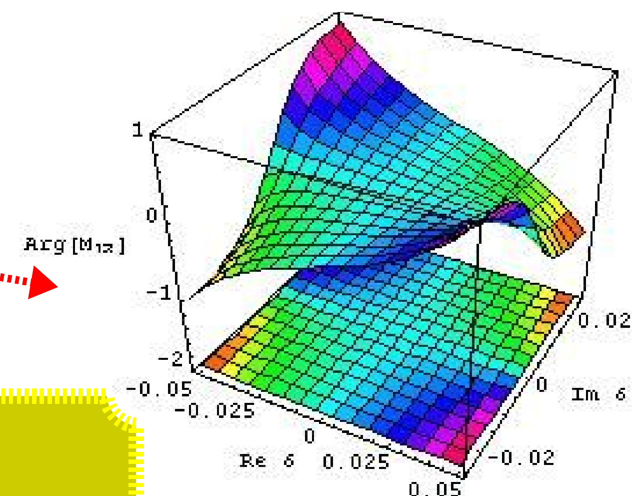


LL only, $\tan\beta=3$
$\sim 10 \times$ SM value are allowed

RR only, $\tan\beta=3$
$\sim 100 \times$ SM value are easy to get
(but RR is still mildly constrained...)



LL=RR, $\tan\beta=3$
$\sim 100 \times$ SM value are again easy
(yet LL=RR is severely constrained!)



The CP asymmetry in $B_s \to \psi\phi$
will provide a truly fantastic probe!

❷

Minimal Flavour Violation in the MSSM

Minimal Flavour Violation (MFV)

MFV:
In the SM, FCNC are small, because of the GIM mechanism.
Can extensions of the SM incorporate a *similar* mechanism of near-flavour-(and CP)-conservation?

Controversial issue on how to define MFV

❶ **'pragmatic' definition, Buras *et al.*, *'00*:**
in terms of allowed effective operators + explicit occurrence of the CKM

❷ **EFT definition, D'Ambrosio *et al.*, *'02*:** in terms of the SM Yukawa couplings

Def. ❶ does not produce a consistent low-energy limit for the MSSM, even at low tan β

Altmannshofer, Buras, D.G., '07

- In fact, in extensions of the SM one has (by def.) **new**, a priori unrelated sources of flavour (and CP) violation.
- MFV can then only be defined as a 'symmetry requirement' for such **new** sources
- The set of allowed operators and FV structures is an **outcome** of such requirement

MFV 'principle'

☞ the SM Yukawa couplings are the *only* structures responsible for low-energy flavour and CP violation

⇒ every new source of flavour violation must be expressed as function of the SM Yukawa couplings

Example: soft mass term for 'left-handed' squarks

$$L_{\text{soft}} = -(m_Q^{IJ})^2 \left((\tilde{u}_L^I)^* \tilde{u}_L^J + (\tilde{d}_L^I)^* \tilde{d}_L^J \right) + \ldots$$

a priori new source of flavour violation

FC effects are <u>*naturally small*</u>: intuitively $\delta = O(1) \times f(\text{CKM})$

MFV expansion

$$[m_Q^2]^T = \overline{m}^2 \left(a_1 \mathbf{1} + b_1 K^+ Y_u^2 K + b_2 Y_d^2 + O(Y_u^2 Y_d^2) \right)$$

squark mass scale and **expansion coefficients** **free parameters after the MFV expansion**

Strategy

☞ After expansions, mass scales are only a few. Then:

① Fix them to scenarios

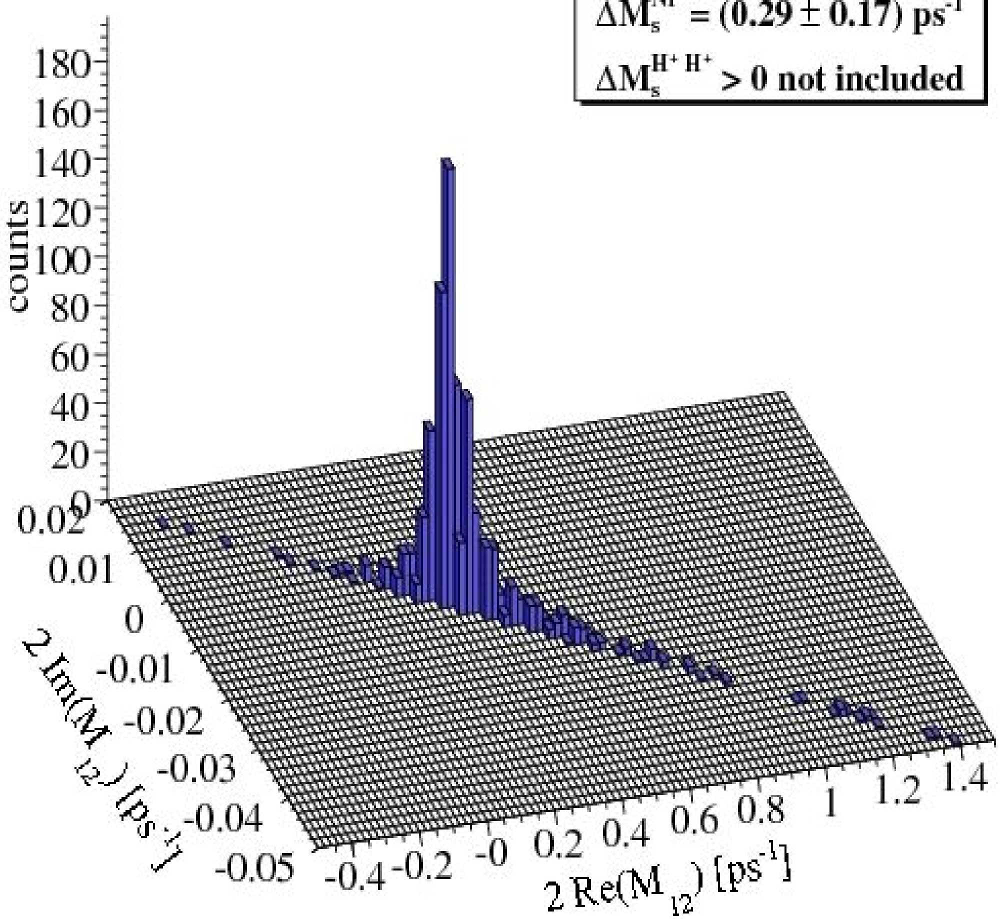
② Extract just the expansion coefficients (12 indep. parameters)

⇒ Dramatic increase in the predictivity and testability of the model

$\Delta F = 2$ example
for mass scales
chosen as

$\overline{m}$	=	200 GeV	(squark scale)
M_g	=	500 GeV	(gluino mass)
$M_{1,2}$	=	$(100, 500)$ GeV	(U(1)×SU(2) gaugino masses)
μ	=	1000 GeV	(μ-parameter)

$\overline{B}_s - B_s$ amplitude



Comments

- Distributions of values, due to the extraction of the expansion parameters, are quite *narrow*
- Corrections are *naturally small*
- Corrections are *dominantly positive*. Signature of the MFV-MSSM at low tan β

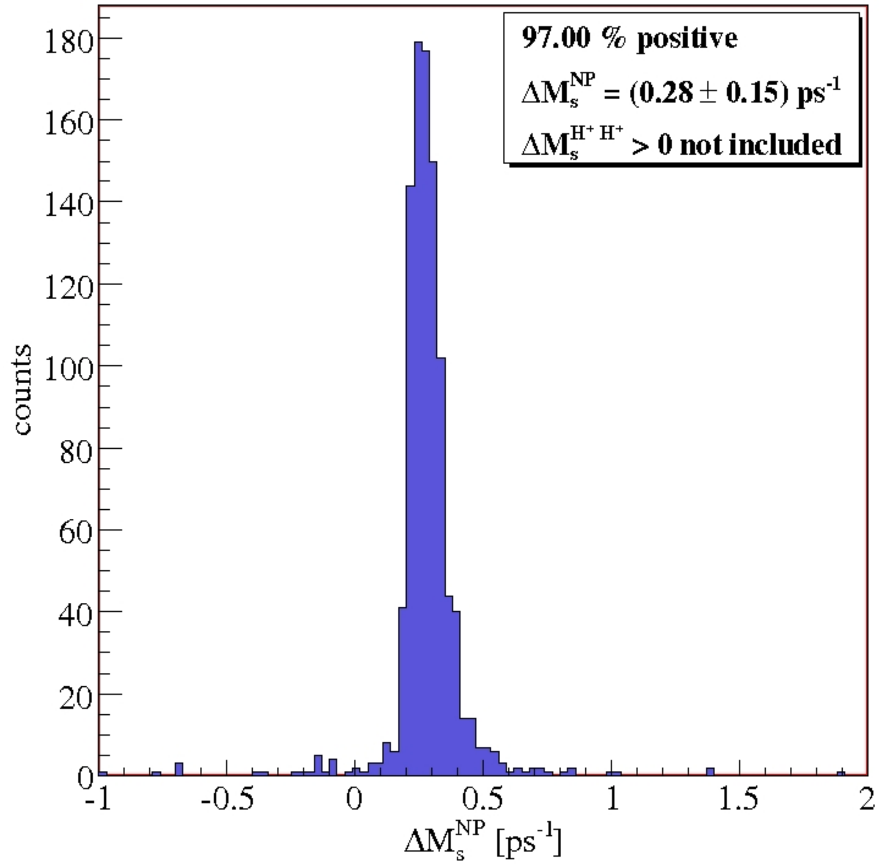
Due to MFV,
the mixing phase is
aligned with the SM value

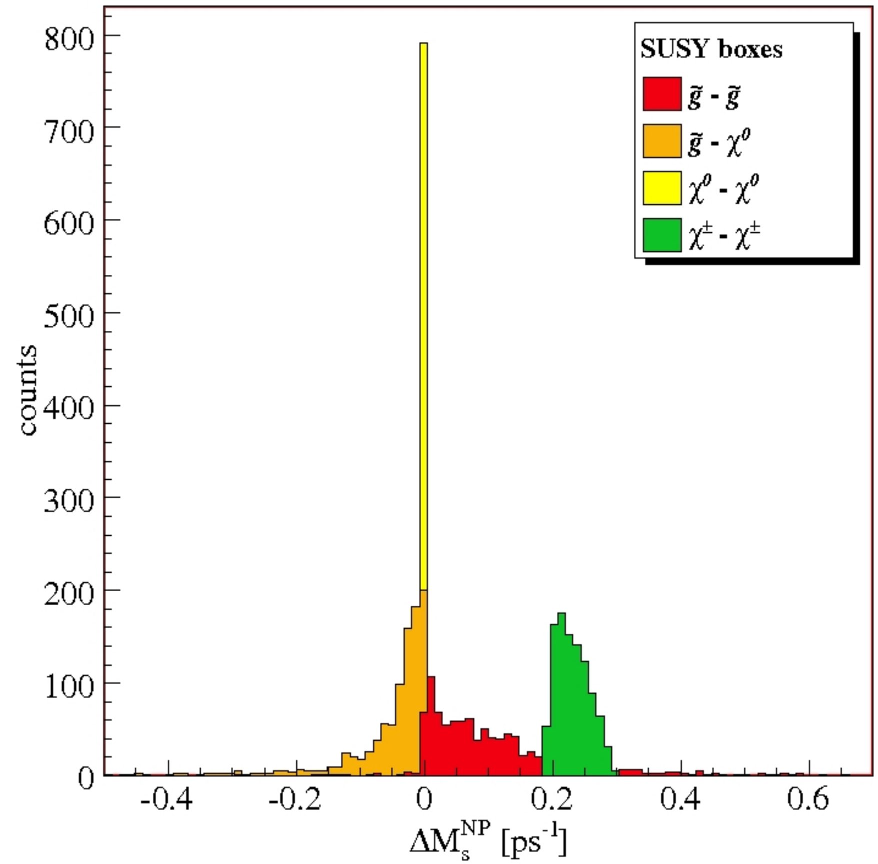
Large μ scenario

Notes

- When μ is large, LR entries in the squark mass matrices become relevant, even for low tan β.
- They manifest dominantly in gluino contributions, which become competitive with chargino's.

Example with (GeV):
$m = 300$
$M_g = 300$
$M_{1,2} = (100,500)$
$\mu = 1000$





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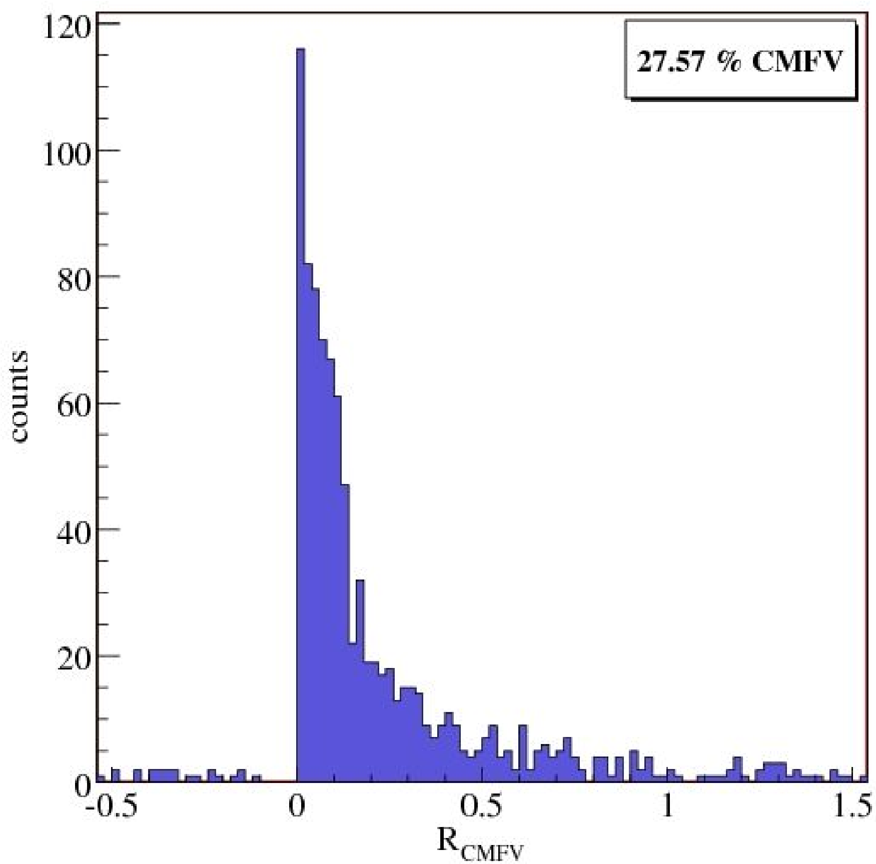
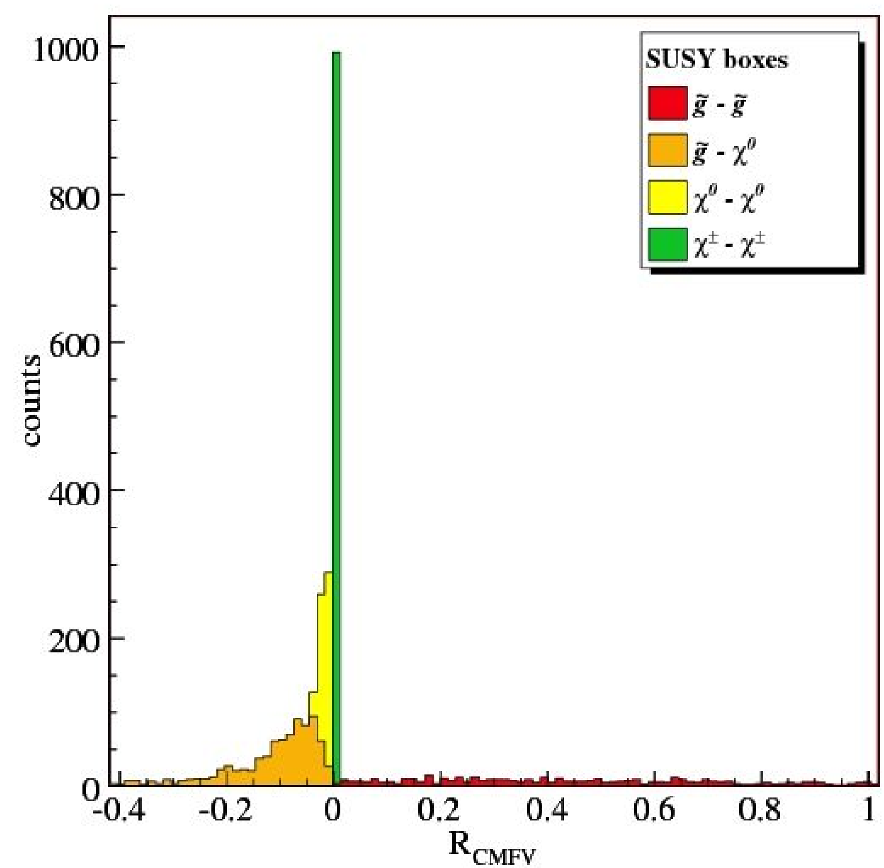
Test of ‘constrained’ MFV (CMFV) within the MSSM

The case of Q_1 -dominated MFV (so-called CMFV) can be tested by looking at the ratio

$$R_{CMFV} \equiv \frac{\text{contrib. to operators other than } Q_1}{\text{contrib. to } Q_1}$$

One can ‘define’ CMFV to hold when, *e.g.* $|R_{CMFV}| < 0.05$



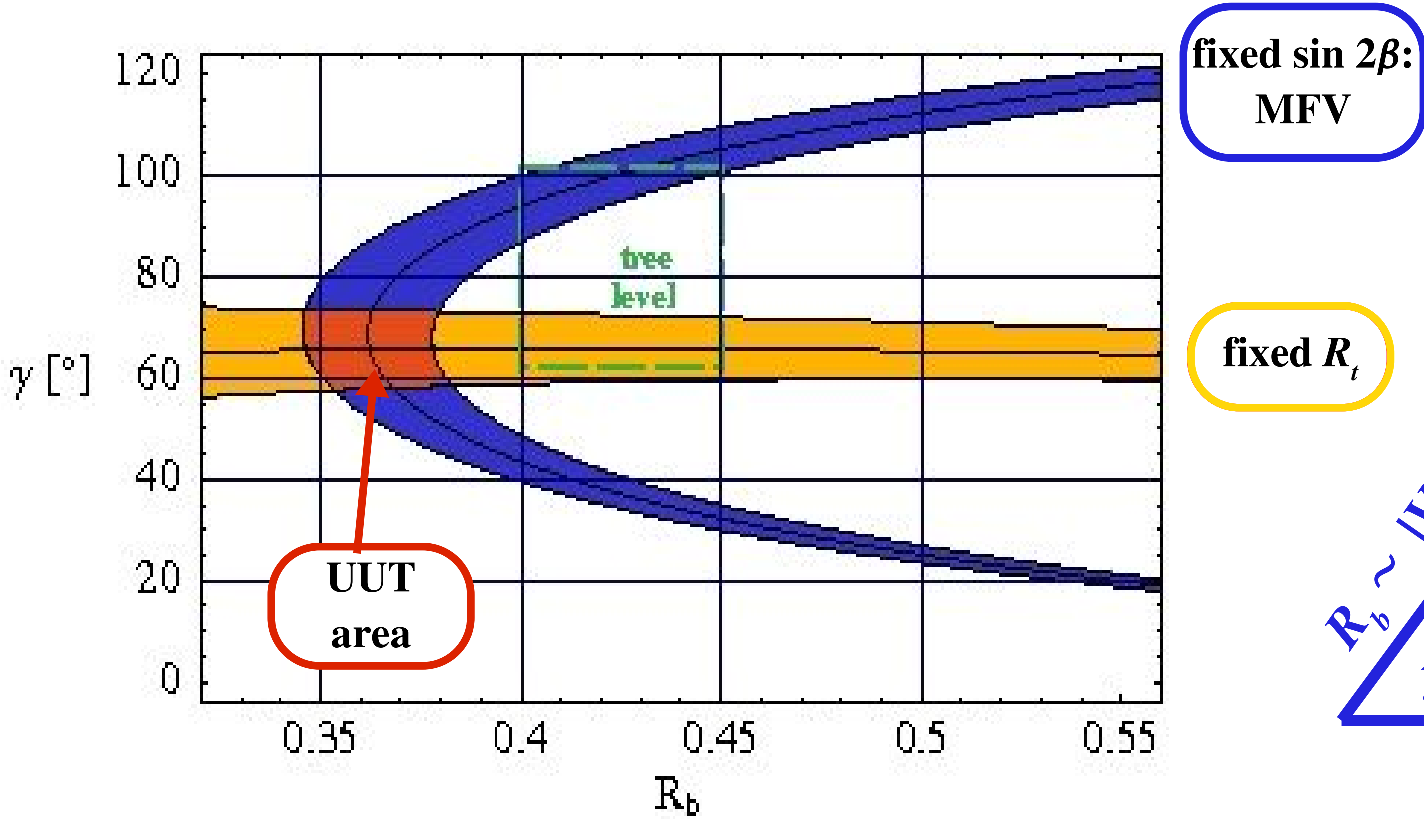


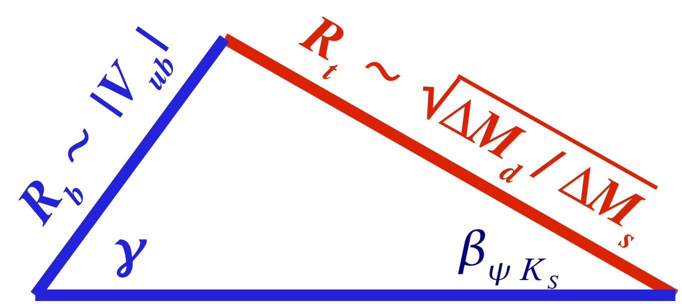
MFV – Unitarity Triangle

☞ The ratio $\Delta M_d / \Delta M_s$, usually included in the analysis of the Universal Unitarity Triangle, is <u>not a good "constant"</u> in generic MFV models

☑ The MFV – Unitarity Triangle can be constructed from

$\sin 2\beta = \sin 2\beta_{\psi K_s}$ and $|V_{ub}|$ and/or γ





Conclusions

- ☑ In the general MSSM, SUSY effects are typically constrained to be **small** (exceptions: ($B_s \to \psi\phi$), ...) after imposing existing exp. input

- ☑ In the MFV-MSSM, SUSY effects are **naturally small**, due to a 'built-in' GIM-like mechanism.

In either case, to resolve such effects,
one needs a better control, O(few %),
of the effective operator matrix elements

Back-up

Contributions to ΔF = 2 (low tan β)

$$\Delta M_s^{MSSM} = \Delta M_s^{SM} + \Delta M_s^{H^+H^+} + \Delta M_s^{\tilde{\chi}^+\tilde{\chi}^+} + \Delta M_s^{\tilde{g}\tilde{g}} + \Delta M_s^{\tilde{g}\tilde{\chi}^0} + \Delta M_s^{\tilde{\chi}^0\tilde{\chi}^0}$$

Higgses

- Depend on $|\mu|, m_{H_u}, m_{H_d}$, through the H± mass
- Do not depend on any other SUSY scale and/or MFV coefficient

charginos

- Depend on $\{\mu, M_2\} \to M_{\tilde{\chi}^\pm}$ $\{\bar{m}, A, \mu\} \to M_{\tilde{u}}$
- Generically important

gluinos

- Depend on $M_3 \to M_{\tilde{g}}$ $\{\bar{m}, A, \mu\} \to M_{\tilde{d}}$
- Important for large μ

neutralino-(gluino)

- Depend on $\{M_1, M_2, M_3\} \to M_{\tilde{\chi}^0}, M_{\tilde{g}}$ $\{\bar{m}, A, \mu\} \to M_{\tilde{d}}$
- Generically unimportant (especially pure neutralino)

Mass scenarios

Fixing mass scales

- Leaving aside Higgses, one has then to fix 6 mass scales: $\bar{m}, A, M_1, M_2, M_3, \mu$

Interesting cases

a) $\bar{m}$ not large and μ small: {charginos are light} → **{chargino dominated}**

b) μ large: {scalar operators become relevant} → **{chargino & gluino dominated}**

Small μ scenario

Notes

- When μ is small, it governs the lightest chargino mass
- Scalar operator contributions from LR entries of the d- squark mass matrix are small, still because μ is small

Example with (GeV):
$m = 300$
$M_g = 300$
$M_{1,2} = (500,500)$
$\mu = 200$