Supersymmetry in b-quarks physics

Łucja Sławianowska
Institute of Theoretical Physics
Warsaw University
slawian@fuw.edu.pl

Based on:

A.J.Buras, P.H.Chankowski, J.Rosiek and Ł.Sławianowska, hep-ph/0107048, *Nucl. Phys.* **B619** (2001), 434.

A.J.Buras, P.H.Chankowski, J.Rosiek and Ł.Sławianowska, hep-ph/0207241, *Phys. Lett.* **B546** (2002), 96-107.

A.J.Buras, P.H.Chankowski, J.Rosiek and Ł.Sławianowska, hep-ph/0210145.

Motivation

Before the advent of LHC and linear colliders, which will enable us to probe energies much above the electroweak scale directly, rare processes are the first place where virtual effects of new particles - can most likely be detected.

They are intensively studied in numerous experiments (BaBar, BELLE, Tevatron).

b-quarks physics is good place to search supersymmetric effects.

I will concentrate on $B^0_{s,d} \to \mu^+\mu^-$ decay and $B^0_{s,d}$-$\bar{B}^0_{s,d}$ mixing.

FV (flavour violation) and CPV (CP violation) - possibilities in supersymmetry

- V_{CKM} matrix is the only one source. The enchancement of FV (compared to the Standard Model) is due to new virtual particles in loops.

- New sources (except V_{CKM} matrix) of FV (and/or CPV) - in sfermion mass matrices ($u \to \widetilde{U}_L, \widetilde{U}_R$)

$$\mathcal{M}_D^2 = \left[\begin{array}{cc} \left(\mathcal{M}_D^2\right)_{LL} & \left(\mathcal{M}_D^2\right)_{LR} \\ \left(\mathcal{M}_D^2\right)_{RL} & \left(\mathcal{M}_D^2\right)_{RR} \end{array} \right],$$

$\left(\mathcal{M}_D^2\right)_{XY}$ $X, Y = L, R \to 3 \times 3$ complex matrices.

Can we distinguish (experimentally) between this two possibilities?

The models with V_{CKM} as the only source of FV and CPV

- What are the predictions for $B^0_{s,d} \to \mu^+\mu^-$ and $B^0_{s,d}$-$\bar{B}^0_{s,d}$ mass difference?

- Do experimental data (for $B^0_{s,d} \to \mu^+\mu^-$ and $B^0_{s,d}$-$\bar{B}^0_{s,d}$) impose any constraints on the supersymmetric parameters space?

- What is the value of V_{td} (needed to calculate the branching ratio of $B^0_{s,d} \to \mu^+\mu^-$, and other interesting rare processes)

Wolfenstein parametrization

$$V_{CKM} = \left[\begin{array}{ccc} 1-\lambda^2/2 & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\varrho - i\eta) & \lambda^2/2 & 1 \end{array} \right]$$

From tree-level processes:
$\lambda \approx 0.222 \pm 0.0018$
$A \approx 0.83 \pm 0.06$
$0.27 \lesssim \sqrt{\bar{\rho}^2 + \bar{\eta}^2} \lesssim 0.46$ ($|V_{ub}|/|V_{cb}| = 0.08 \pm 0.02$).

Further constrains on $\bar{\rho}$ and $\bar{\eta}$: $\bar{\rho}$ and $\bar{\eta}$ from measurements ΔM_d (B_d^0-$\bar{B}_d^0$ masses differences) and of the ε_K (CP violation in the neutral kaon system).

Allows to overconstrain $\bar{\rho}$ and $\bar{\eta}$ and test the assumption of minimal flavour violation and CP violation.

ΔM_d and ε_K loop induced $\Rightarrow$ new physics can contribute to the values of $\bar{\rho}$ and $\bar{\eta}$.

Rare processes description by H_{eff}

General strategy e.g. for $\Delta F = 2$

To compute $\Delta M_{s,d}$ ($B^0_{s,d}$-$\bar{B}^0_{s,d}$) and ε_K (K^0-$\bar{K}^0$) integrate out from the theory all the states with masses $\gtrsim M_W$ and construct the effective Hamiltonian of the form

$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F^2 M_W^2}{16\pi^2} \sum_X \lambda^X_{\mathrm{CKM}} C_X \mathcal{O}_X$$

$\mathcal{O}_X$ - local four-quark operators (different Lorentz structures: $X =$VLL, VRR, VLR, SLL, SRR, SLR, TL, and TR)
$\lambda^X_{\mathrm{CKM}} C_X$ - Wilson coefficients.

Minimal flavour violation $\Rightarrow$ factorization of the Wilson coefficients into λ^X_{CKM} which depends only on the CKM matrix elements and C_X (real numbers).

Two distinctive possibilities (at the level of H_{eff}):

- truly minimal models: as in the SM, only $C_{\rm VLL}$ is non-negligible and $C_{\rm VLL}$ for $B^0_{s,d}$-$\bar{B}^0_{s,d}$ and K^0-$\bar{K}^0$ mixing are all equal (universal value of $C_{\rm VLL}$).

- models in which more C_X are non-negligible and/or are non-universal.

The MSSM can be of either type, depending on the ratio $v_2/v_1 \equiv \tan\beta$ of the vacuum expectation values of the two Higgs boson doublets.

Neutral mesons mixing: V_{CKM} as an only source of FV and CPV

$$\begin{aligned}
\Delta M_d &= \frac{G_F^2 M_W^2}{16\pi^2} M_{B_d} \eta_B \hat{B}_{B_d} F_{B_d}^2 |V_{tb}^* V_{td}|^2 |F^d| \\
&\propto \hat{B}_{B_d} F_{B_d}^2 |(1-\bar{\rho}) - i\bar{\eta}|^2 |F^d| \\
\Delta M_s &= \frac{G_F^2 M_W^2}{16\pi^2} M_{B_s} \eta_B \hat{B}_{B_s} F_{B_s}^2 |V_{tb}^* V_{ts}|^2 |F^s| \\
&\propto \hat{B}_{B_s} F_{B_s}^2 F^s
\end{aligned} \tag{1}$$

$$\bar{\eta} \left[(1-\bar{\rho}) A^2 \eta_2 F^\varepsilon + P_c \right] A^2 \hat{B}_K = 0.204$$

F^ε, F^d and F^s depend on the Wilson coefficients C_X, QCD RG running and matrix elements of the operators $\mathcal{O}_X$ for $X \neq$ VLL.
Concrete model (MSSM) $\Rightarrow$ F^ε, F^d and F^s - calculable functions of (supersymmetric) parameters.
Experiment: $\varepsilon_K = 2.28 \times 10^{-3}$, $M_d = 0.496/\mathrm{ps}$, $\Delta M_s > 15/\mathrm{ps}$.

$\eta_2 = 0.57$, $\eta_B = 0.55$, $P_c = 0.30 \pm 0.05$,
$\hat{B}_K \approx 0.85 \pm 0.15$,
$\hat{B}_{B_d} F^2_{B_d} \approx (230 \pm 40 \text{ MeV})^2$,
$\hat{B}_{B_s} F^2_{B_s} \approx (265 \pm 40 \text{ MeV})^2$.

Two classes of models (both with V_{CKM} only):

- dominance of $C_{\mathrm{VLL}} \Rightarrow F^\varepsilon = F^d = F^s$ (in the SM $F^\varepsilon = F^d = F^s = F_{\mathrm{SM}} \approx 2.38 \pm 0.11$)
- contributions from all operators $\Rightarrow F^\varepsilon \neq F^d \neq F^s$

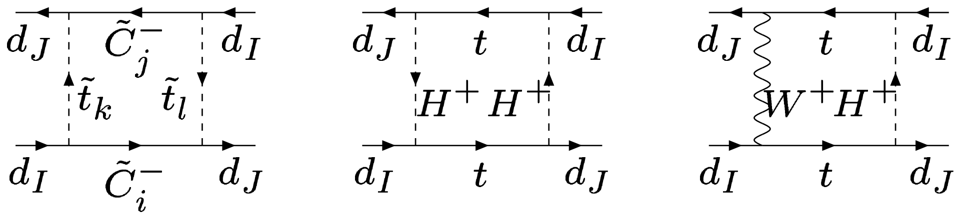
Constraints on new physics model from the measured $B^0_{d,s}$-$\bar{B}^0_{d,s}$:

$$0.52 \left(\frac{\Delta M_s}{15/\mathrm{ps}} \right) < \left| \frac{F^s}{F_{\mathrm{SM}}} \right| < 1.29 \left(\frac{\Delta M_s}{15/\mathrm{ps}} \right)$$

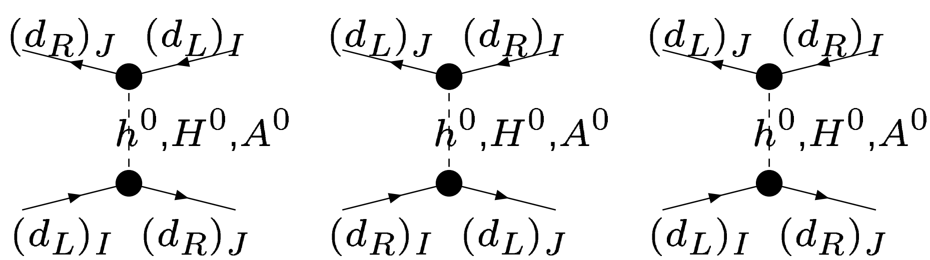
(at present $\Delta M_s > 15/\mathrm{ps} \rightarrow F^s$ is bounded only from below), and much weaker bound from ΔM_d:
$1.04 \lesssim \sqrt{\left| \frac{F^d}{F_{\mathrm{SM}}} \right|} |1 - \bar{\rho} - i\bar{\eta}| \lesssim 1.69$.

F^ε, F^d, F^s in supersymmetry

- $2 \lesssim \tan\beta \lesssim 20$: dominant contributions from box diagram, $\Rightarrow F^\varepsilon = F^d = F^s$



- large $\tan\beta$, ~ 50: substantial loop induced FV couplings of H_0, h_0, A_0
  Combine to give:



formally 2-loop, but very large effects even for heavy sparticles $\Rightarrow$ dominance of double penguin, $F^\varepsilon = F^d = F_{SM}$, F^s negative, $F^s < F_{SM}$.

Calculation of FV Higgs vertices with charginos and stops

Naively: compute the triangle diagram
Resummation of large $\tan\beta$ correction - effective lagrangian approach :

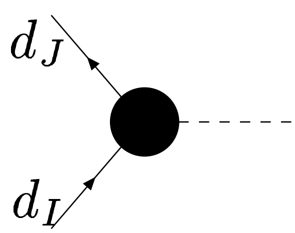
- integrate out heavy sparticles before electroweak symmetry breaking

- 2-Higgs doublet model with H^d and H^u couplings to up and down-type quarks simultaneously

- couplings of the neutral Higgs bosons to down-type quarks:

$$\left[X^S_{LR}\right] = \frac{g\overline{m}_{d_I}\tan^2\beta\epsilon_Y y_t^2}{2M_W(1+\tilde{\epsilon}_J\tan\beta)^2} V_0^{*3J} V_0^{3I} \begin{cases} -\cos\alpha & H_0 \\ -i & A_0 \end{cases}$$

$$\epsilon_Y \sim A_t$$



$$\sim A_t \tan^2\beta$$

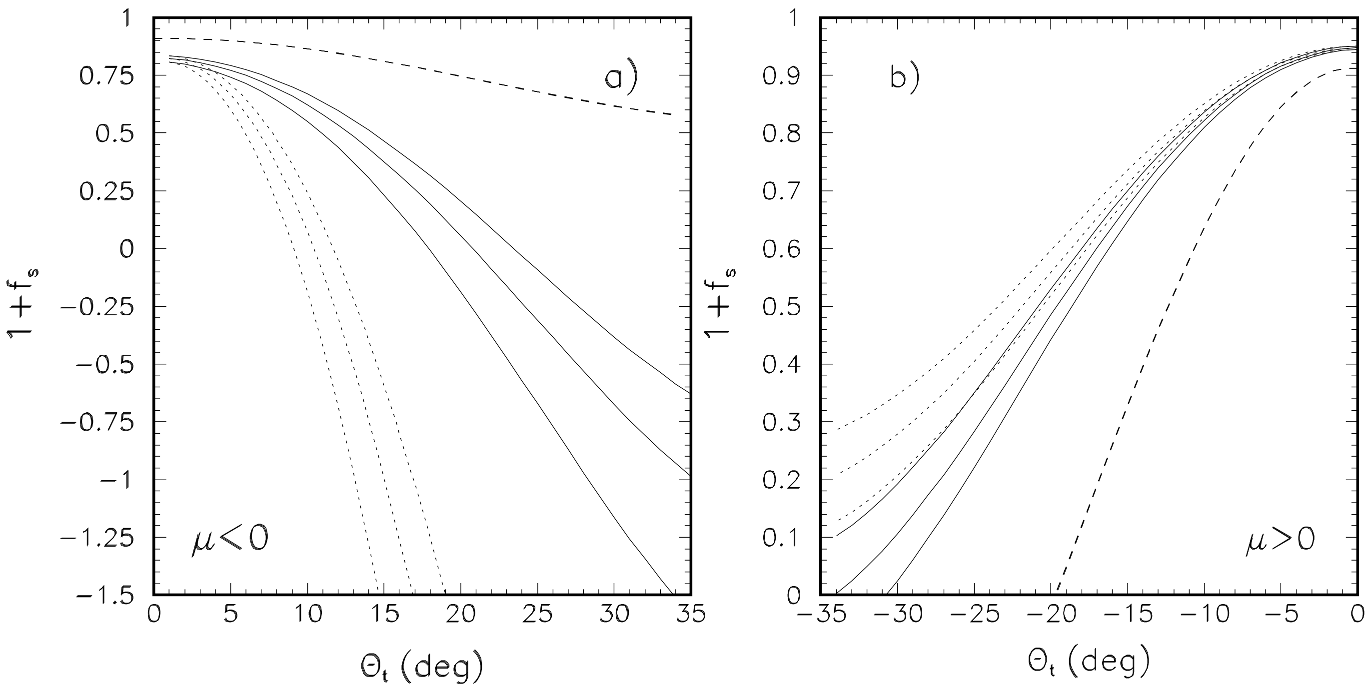
More accurate approach: decouple heavy sparticles after electroweak symmetry breaking $\Rightarrow$ sometimes big differences.

Important features of the double penguin contribution to ΔM_s (to ΔM_d neglible, $\propto \frac{m_d}{m_s}$):

- grows as $\tan^4 \beta$,
- $|(F^s)_{DP}|$ (double penguin) can be bigger than $|(F^s)_{SM}|$ and is always negative, $(F^s)_{DP} < (F^s)_{SM}$
- sensitive to the top squarks mixing ($\propto A_t$),
- does not vanish if all the sparticle mass parameters are uniformly scaled up (non-decoupling effect),
- vanishes as the inverse square of the Higgs sector mass scale set by M_A.

Constrains supersymmetric parameters:

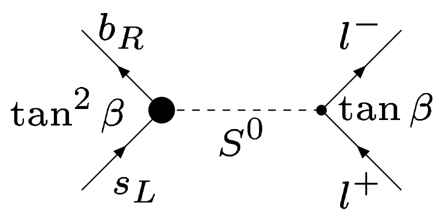
$$0.52\left(\frac{\Delta M_s}{15/\mathrm{ps}}\right) < \left|\frac{F^s}{F_{\mathrm{SM}}}\right| < 1.29\left(\frac{\Delta M_s}{15/\mathrm{ps}}\right)$$



$\frac{F^s}{F_{SM}}$ in the MSSM for $\tan\beta = 50$, $M_{H+} = 200$, $m_{\tilde{g}} = 3M_2$, $M_{\tilde{b}_R} = 800$ GeV and the lighter chargino mass 600 GeV as a function of the stop mixing angle θ_t. In panel a $\mu < 0$ and $M_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{t}_2} = 750$ GeV. In panel b $\mu > 0$ and $M_{\tilde{t}_1} = 500$ GeV, $M_{\tilde{t}_2} = 850$ GeV. Solid lines: complete calculation. Dotted: approximation (effective lagrangian approach) and the dashed: calculation without the resummation of the $\tan\beta$ enhanced terms (naively).

$B^0_{s,d} \to \mu^+\mu^-$ decay

Flavour changing neutral Higgs boson couplings totally dominate the amplitudes of the $B^0_{s,d} \to \mu^+\mu^-$ decays for $\tan\beta \gtrsim 30$.



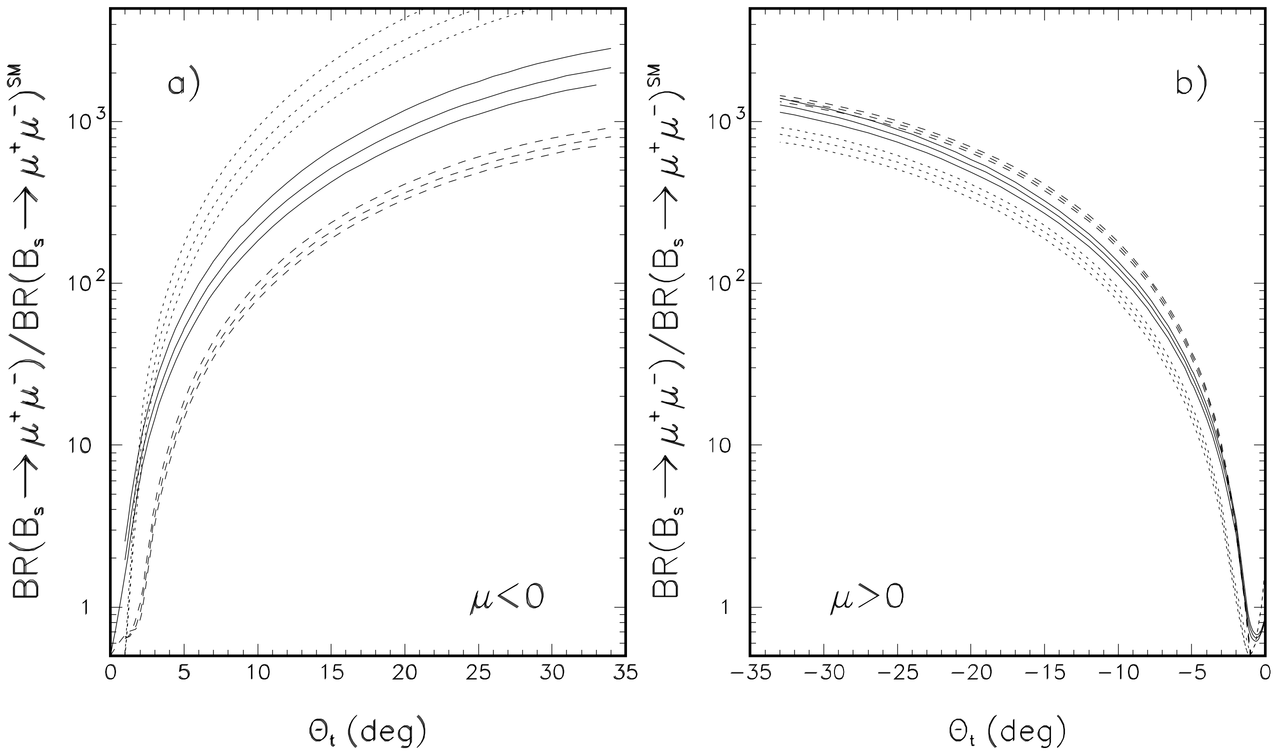
$BR(B^0_{s,d} \to l^+l^-) \approx \frac{\tan\beta^6}{M_A^4}$ - for large $\tan\beta$ possible very large effects!

$BR(B^0_{s,d} \to \mu^+\mu^-) \sim 10^{-6}$

Standard Model prediction:

$$BR(B^0_s \to \mu^+\mu^-) \approx 3.5 \times 10^{-9} \left(\frac{F_{B_s}}{230\ \mathrm{MeV}}\right)^2$$

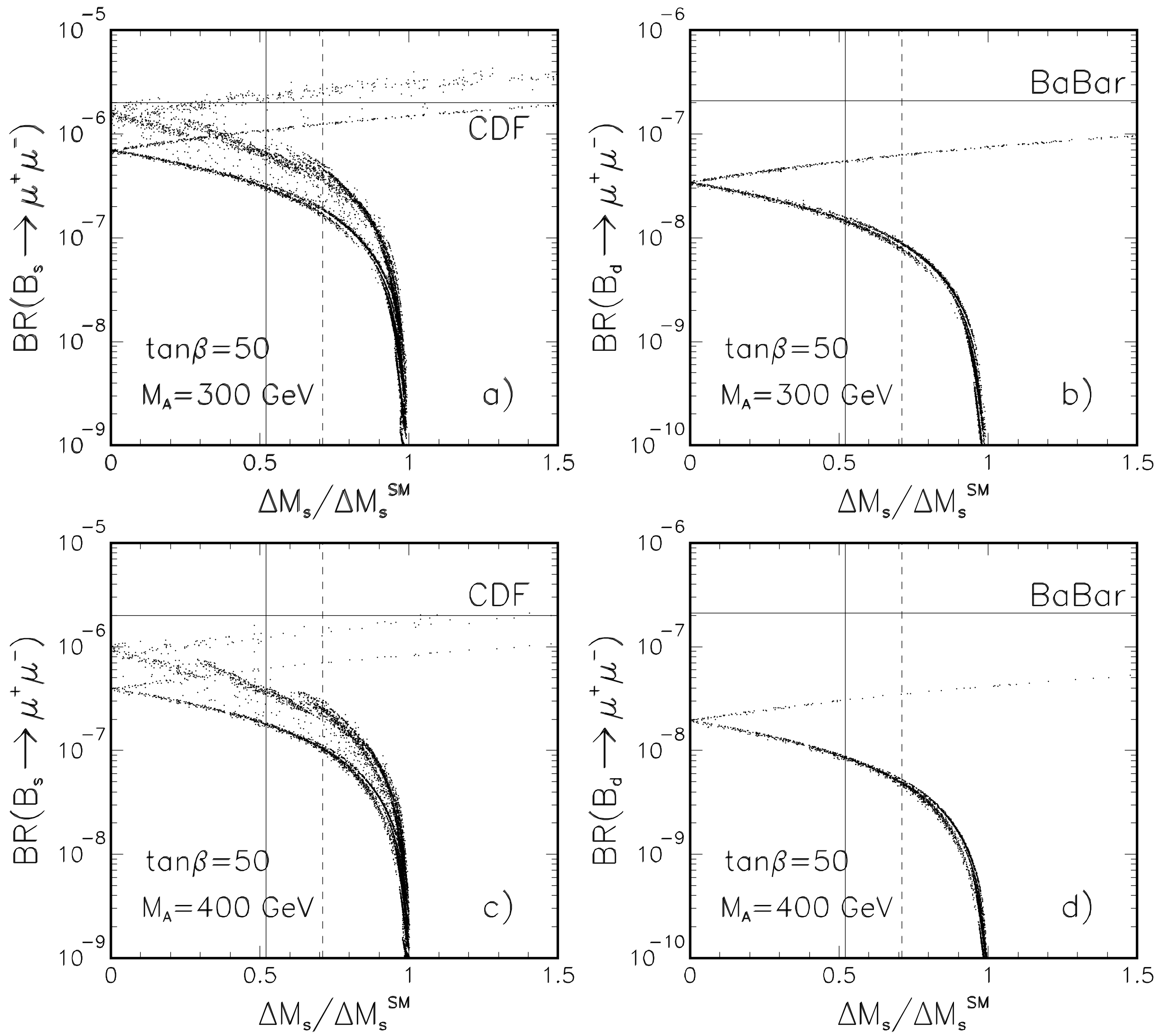
$$BR(B^0_d \to \mu^+\mu^-) \approx 1.4 \times 10^{-10} \left(\frac{F_{B_d}}{200\ \mathrm{MeV}}\right)^2 \left(\frac{|V_{td}|}{0.009}\right)^2$$



The ratio $BR(B_s^0 \to \mu^+\mu^-)/BR(B_s^0 \to \mu^+\mu^-)^{\rm SM}$ in the MSSM for $\tan\beta = 50$, $M_{H+} = 200$, $m_{\tilde{g}} = 3M_2$, $M_{\tilde{b}_R} = 800$ GeV and the lighter chargino mass 600 GeV as a function of the stop mixing angle θ_t. In panel a $\mu < 0$ and $M_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{t}_2} = 750$ GeV. In panel b $\mu > 0$ and $M_{\tilde{t}_1} = 500$ GeV, $M_{\tilde{t}_2} = 850$ GeV. Solid lines: complete calculation. Dotted: effecive lagrangian approach, dashed: without the resummation of the $\tan\beta$ enhanced terms.

Correlation between $BR(B^0_{s,d} \to l^+l^-)$ and $\Delta M_{s,d}$

$$BR(B^0_{s,d} \to l^+l^-) \sim \frac{\tan\beta^6}{M_A^4} \quad \Delta M_s \sim \frac{\tan\beta^4}{M_A^2}$$



Conclusions

- MSSM with V_{CKM} only can be close to the Standard Model (for $\tan\beta < 20$) or be quite different.
- For large $\tan\beta$ double penguins dominate $\Delta M_{s,d}$, $B^0_{s,d} \to \mu^+\mu^-$
- Those efects $\sim A_t$.
- Do not vanish in the limit of very heavy particles.
- Significant correlation $\Delta M_{s,d} \leftrightarrow B^0_{s,d} \to \mu^+\mu^-$ (if we exclude the unlikely case ($|F^s_{DP}| > F_{SM}$) $\Rightarrow$ upper limit on $B^0_d \to \mu^+\mu^-$.
- If V_{CKM} is not the only one source of FV, then there is not such correlation, if $BR(B^0_d \to \mu^+\mu^-) \gtrsim 3 \times 10^{-8} \Rightarrow$ nonmininal FV