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The MSSM Higgs sector & $\Delta M_{B_{d,s}}$ for large tanβ

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Motivation and generalities

- Exact SUSY → The quark-Higgs couplings are those of a 2HDM-II :

$$\mathcal{L}_{Yuk} = -\,\bar{d}_R^I\,\mathbf{Y}_d^{IJ}\,H_d\cdot Q_L^J + \bar{u}_R^I\,\mathbf{Y}_u^{IJ}\,H_u\cdot Q_L^J + h.c.$$

- When the Higgses acquire their VEV's :

Quark-Higgs vertices : $-\,\bar{d}_R^I\,\mathbf{Y}_d^{IJ}\,h_d^{0*}\,d_L^J - \bar{u}_R^I\,\mathbf{Y}_u^{IJ}\,h_u^{0}\,u_L^J + h.c.$

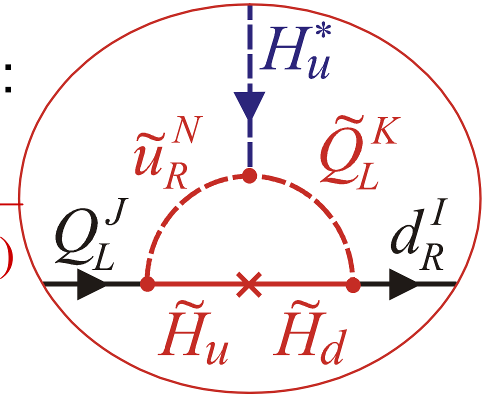
Quark mass terms : $h_d^{0*} \to v_d$, $h_u^{0} \to v_u$

} aligned

$\Rightarrow$ The quark – neutral Higgs vertices are flavour blind

Motivation and generalities

- Soft SUSY-breaking → 2HDM-III structure at loop-level :



$$\mathcal{L}_{Yuk}^{eff} \supset -\bar{d}_R^I \left[\mathbf{Y}_d H_d + \varepsilon_Y \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u H_u^c \right]^{IJ} \cdot Q_L^J$$

(MFV)

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Quark-Higgs vertices : $-\bar{d}_R^I \left[\mathbf{Y}_d h_d^{0*} + \varepsilon_Y \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u h_u^{0*} \right]^{IJ} d_L^J$

Quark mass terms : $h_d^{0*} \downarrow v_d$, $h_u^{0*} \downarrow v_u$

} disaligned!

⇒ Higgs-mediated FCNC for large tanβ $\equiv t_\beta = v_u / v_d$: [Babu, Kolda '99]

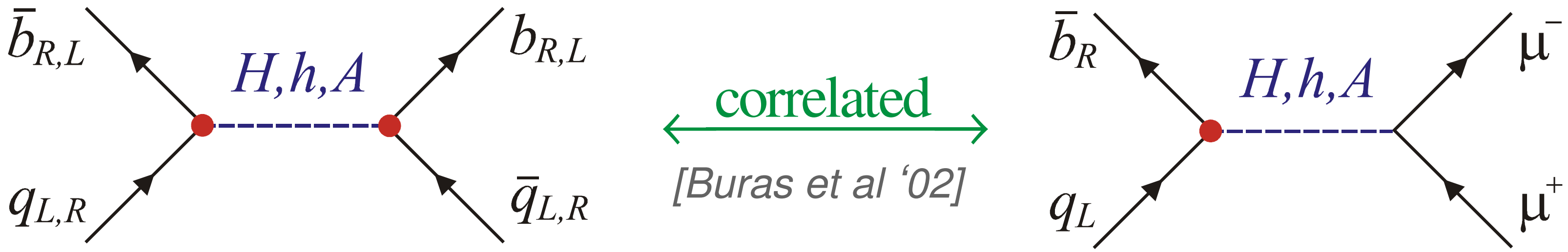
$$\mathcal{L}_{FCNC}^{Higgs} = \kappa^{IJ} \bar{d}_R^I d_L^J \left[c_\beta h_u^{0*} - s_\beta h_d^{0*} \right] + \kappa^{JI*} \bar{d}_L^I d_R^J \left[c_\beta h_u^0 - s_\beta h_d^0 \right]$$

(in quark mass eigenstate basis) $\kappa^{IJ} \sim \varepsilon_Y t_\beta^2 m_I / v$

Motivation and generalities

Rich phenomenology, especially in B physics!

Interesting signature within MFV : $q = d, s$



$\Delta M_{s(d)}$ decreased (unaffected) — $\mathcal{B}(B_q \to \mu^+\mu^-)$ increased

- Clean (same dependence on F_{B_q} and V_{tq} in both observables)
- ΔM_q : a priori leading contribution from $\bar{b}_R q_L \bar{b}_R q_L$ $(\propto m_b^2)$.
  Vanishes if tree-level Higgs propagation [Babu, Kolda '99]
- Correlation obtained from $\bar{b}_R q_L \bar{b}_L q_R$ $(\propto m_b m_q)$

Look at all (sub-)leading contributions before concluding!

Outline

I. $\Delta M_{d,s}$ *anatomy*

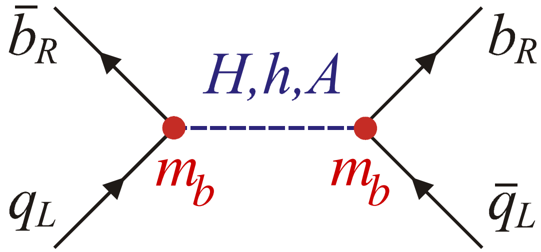
II. SUSY corrections to the Higgs potential

III. $\Delta M_{d,s}$ *versus* $B_{d,s} \to \mu^+ \mu^-$ *and* $B^\pm \to \tau^\pm \nu$

I. $\Delta M_{d,s}$ anatomy

Why the cancellation?

$\Delta M_q^{(m_b^2)} \propto$



$= 0$

[Babu, Kolda '99]

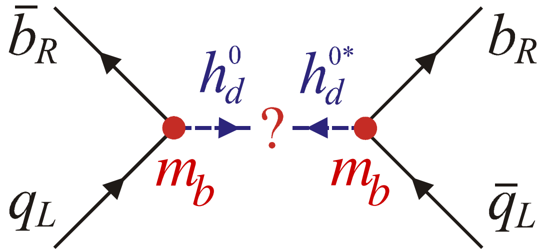
Sparticle masses $\gg$ Higgs masses $\Rightarrow$ effective 2HDM :

- $$V^{(0)} = m_1^2 H_d^\dagger H_d + m_2^2 H_u^\dagger H_u + B\mu\{H_u \cdot H_d + h.c.\}$$
  $$+ \frac{\tilde{g}^2}{8}\left[\left(H_d^\dagger H_d\right) - \left(H_u^\dagger H_u\right)\right]^2 + \frac{g^2}{2}\left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right)$$
- $$\mathcal{L}_{\bar{b}\to\bar{q}}^{Higgs} = \kappa^{bq}\bar{b}_R q_L\left[c_\beta h_u^{0*} - s_\beta h_d^{0*}\right] + \kappa^{qb*}\bar{b}_L q_R\left[c_\beta h_u^0 - s_\beta h_d^0\right]$$

After SSB, for $\tan\beta \to \infty$ (i.e., $v_d \to 0$), the theory is invariant under

$$U(1)_{PQ}:\ \ \mathcal{Q}(H_d) = \mathcal{Q}(d_R^I) = 1,\ \ \mathcal{Q}(other) = 0$$

Why the cancellation?

$\Delta M_q^{(m_b^2)} \propto$ 

$\Delta \mathcal{Q} = 2 \Rightarrow = 0$ (LO in 1/tanβ)

Sparticle masses $\gg$ Higgs masses $\Rightarrow$ effective 2HDM :

- $V^{(0)} = m_1^2 H_d^\dagger H_d + m_2^2 H_u^\dagger H_u + B\mu\{\cancel{H_u H_d} + h.c.\}$
  $+\frac{\tilde{g}^2}{8}\left[\left(H_d^\dagger H_d\right) - \left(H_u^\dagger H_u\right)\right]^2 + \frac{g^2}{2}\left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right)$

$m_{12}^2 = s_\beta c_\beta M_A^2$, tanβ-suppressed for fixed M_A

- $\mathcal{L}_{\bar{b}\to\bar{q}}^{Higgs} = \kappa^{bq} \bar{b}_R q_L \left[\cancel{c_\beta h_u^{0*}} - s_\beta h_d^{0*}\right] + \kappa^{qb*} \bar{b}_L q_R \left[\cancel{c_\beta h_u^0} - s_\beta h_d^0\right]$

After SSB, for tanβ $\to \infty$ (i.e., $v_d \to 0$), the theory is invariant under

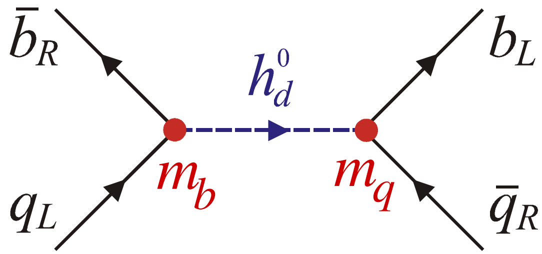
$$U(1)_{PQ}: \ \mathcal{Q}(H_d) = \mathcal{Q}(d_R^I) = 1, \ \ \mathcal{Q}(other) = 0$$

What are the leading contributions?

Look at all contributions with *1 suppression factor*

What are the leading contributions?

A/ *Chirality flipped contribution* ("LR")



$$\Delta Q = 0 \quad \Rightarrow \quad \Delta M_q^{LR} \propto \frac{m_b \boxed{m_q}}{v^2} \quad \text{decreases } \Delta M_s$$

[Buras, Chankowski, Rosiek, Sławianowska '01]

What are the leading contributions?

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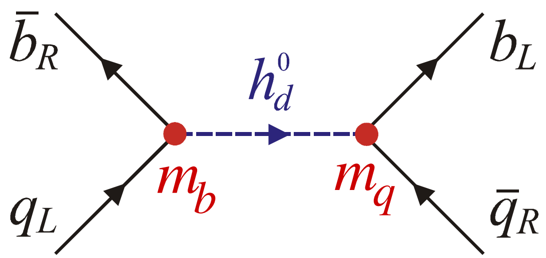
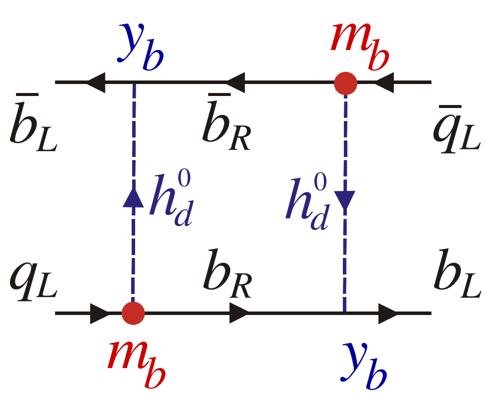


$$\Delta Q = 0 \quad \Rightarrow \quad \Delta M_q^{LR} \propto \frac{m_b \boxed{m_q}}{v^2}$$

decreases ΔM_s

[Buras, Chankowski, Rosiek, Sławianowska '01]

B/ *Weak scale loop contribution*

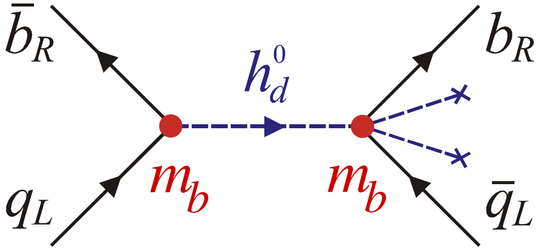


$$\Delta Q = 0 \quad \Rightarrow \quad \Delta M_q^{WS} \propto \frac{m_b^2}{v^2} \times \boxed{\frac{y_b^2}{16\pi^2}}$$

increases $\Delta M_{d,s}$, but numerically small

What are the leading contributions?

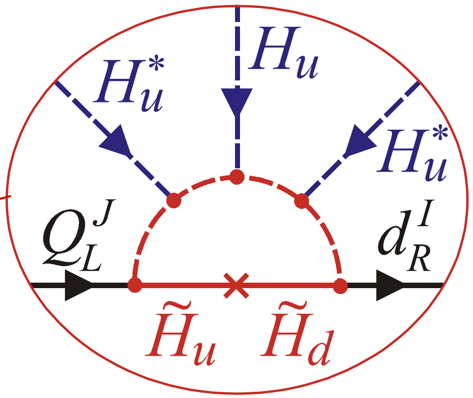
C/ *Higher-dimension operator contribution*



$$\Delta Q = 2 \quad \Rightarrow \quad \Delta M_q^{\mathrm{d6}} \propto \frac{m_b^2}{v^2} \times \boxed{\frac{v^2}{M_{SUSY}^2}}$$

What are the leading contributions?

Type of Higgs-FCNC resulting from HD operators?



(MFV)

$$\mathcal{L}_{Yuk}^{eff} \supset -\bar{d}_R^I \left[\mathbf{Y}_d H_d + \varepsilon_Y \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u H_u^c + \frac{1}{M_{SUSY}^2} \varepsilon_{6d} \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u \mathbf{Y}_u^\dagger \mathbf{Y}_u \left(H_u^\dagger H_u \right) H_u^c \right]^{IJ} \cdot Q_L^J$$

Quark-Higgs int. : $- \bar{d}_R^I \left[\mathbf{Y}_d h_d^{0*} + \varepsilon_{Y,6d} \mathbf{Y}_d \ldots \mathbf{Y}_u h_u^{0*} + \frac{v_u^2}{M_{SUSY}^2} \varepsilon_{6d} \mathbf{Y}_d \ldots \mathbf{Y}_u h_u^0 \right]^{IJ} d_L^J$

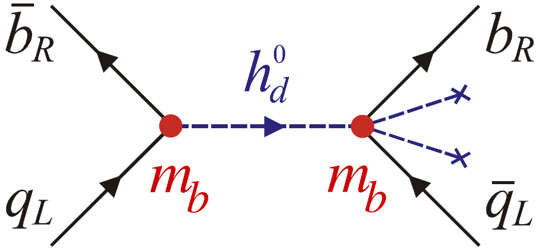
Quark mass terms : $h_d^{0*} \to v_d$, $h_u^{0*} \to v_u$, $h_u^0 \to v_u$

The only tanβ-enhanced effect in Higgs-FCNC comes from the modification of the rotation of the quark interaction eigenstates

$$\Rightarrow \quad \mathcal{L}_{\bar{b} \to \bar{q}}^{Higgs} = -(\kappa + \delta\kappa)^{bq} \underbrace{\bar{b}_R q_L h_d^{0*}}_{\text{PQ-conserving}} - (\kappa + \delta\kappa)^{qb*} \bar{b}_L q_R h_d^0 + \underbrace{O(1/t_\beta)}_{\supset \text{ loop not compensated by a large } \tan\beta \text{ factor}}$$

What are the leading contributions?

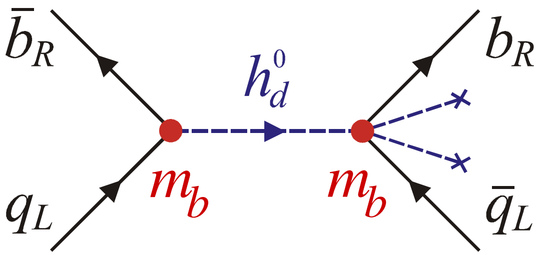
C/ Higher-dimension operator contribution



$$\Delta Q = 2 \quad \Rightarrow \quad \Delta M_q^{\mathrm{d6}} \propto \frac{m_b^2}{v^2} \times \boxed{\frac{v^2}{M_{SUSY}^2}} \qquad small!$$

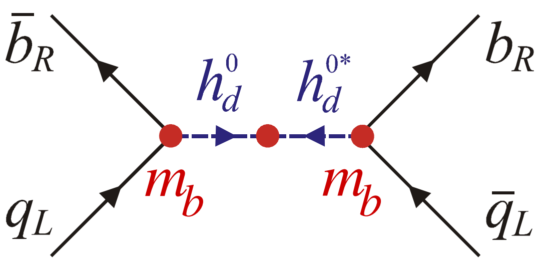
What are the leading contributions?

C/ *Higher-dimension operator contribution*



$$\Delta Q = 2 \quad \Rightarrow \quad \Delta M_q^{\mathrm{d6}} \propto \frac{m_b^2}{v^2} \times \boxed{\frac{v^2}{M_{SUSY}^2}} \qquad small!$$

D/ *Corrections to Higgs masses/mixings* ("RR")



$$\Delta Q = 2 \quad \Rightarrow \quad \Delta M_q^{RR} \propto \frac{m_b^2}{v^2} \times \boxed{\text{SUSY loop in Higgs potential}}$$

Corrections to the Higgs sector have already been extensively studied. However, contradictory statements about their effects on $B-\overline{B}$ mixing are found in the literature. We thus go through them again in part II.

II. SUSY corrections to the Higgs potential

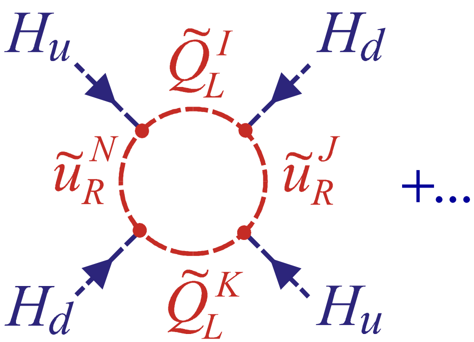
Matching MSSM → 2HDM

V has the most general structure compatible with gauge symmetry :

- $$V^{(1)} = m_{11}^2 H_d^\dagger H_d + m_{22}^2 H_u^\dagger H_u + \left\{ m_{12}^2 H_u \cdot H_d + h.c. \right\}$$
$$+\frac{\lambda_1}{2}\left(H_d^\dagger H_d\right)^2 + \frac{\lambda_2}{2}\left(H_u^\dagger H_u\right)^2 + \lambda_3 \left(H_u^\dagger H_u\right)\left(H_d^\dagger H_d\right) + \lambda_4 \left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right)$$
$$+\left\{ \frac{\lambda_5}{2}\left(H_u \cdot H_d\right)^2 - \lambda_6 \left(H_d^\dagger H_d\right)\left(H_u \cdot H_d\right) - \lambda_7 \left(H_u^\dagger H_u\right)\left(H_u \cdot H_d\right) + h.c. \right\}$$

Ex: (MFV)
$$\lambda_5 = -\frac{3y_t^4}{8\pi^2}\frac{a_t^2 \mu^2}{M_{\tilde{t}_R}^4} L_1\left(M_{\tilde{t}_L}^2 / M_{\tilde{t}_R}^2\right) + \ldots$$

$$L_1(x) = \frac{-1}{(1-x)^2} - \frac{(1+x)\ln x}{2(1-x)^3}$$



Note: many refs! *[Haber, Hempfling '93][Carena, Espinosa, Quirós, Wagner '95]…*

We keep arbitrary flavour and CP structures, and propose a definition for tanβ in the effective 2HDM better suited to the large tanβ regime.

WF renormalization and definition of tanβ

$$\mathcal{L}_{Kin} = Z^r_{uu}\partial_\mu H_u^\dagger \partial^\mu H_u + Z^r_{dd}\partial_\mu H_d^\dagger \partial^\mu H_d - \left\{ Z_{ud}\partial_\mu H_u \cdot \partial^\mu H_d + h.c. \right\}$$

$$\begin{pmatrix} H_u^{'} \\ -H_d^{c'} \end{pmatrix} = \begin{pmatrix} 1+(\delta Z^r_{uu} + i\delta H^r_{uu})/2 & (\delta Z^*_{ud} + i\delta H^*_{ud})/2 \\ (\delta Z_{ud} + i\delta H_{ud})/2 & 1+(\delta Z^r_{dd} + i\delta H^r_{dd})/2 \end{pmatrix} \begin{pmatrix} H_u \\ -H_d^c \end{pmatrix}$$

arbitrary

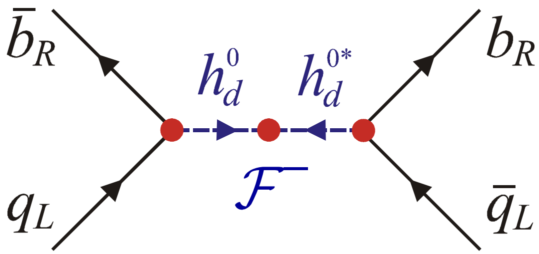
m_1^2, m_2^2 are renormalized such that the fields in the effective 2HDM (before redef.) stay at the minimum of the potential $\Rightarrow v_{i,eff} = Z_{WF,ij} \cdot v_{j,tree}$

We exploit the freedom to change the Higgs basis to

- keep the vevs real and positive
- prevent tanβ from getting tanβ-enhanced corrections !

$$\begin{pmatrix} v_{u,eff} \\ v_{d,eff} \end{pmatrix} = \begin{pmatrix} 1+\delta Z^r_{uu}/2 + i\, t_\beta^{-1}\, \delta Z^i_{ud} & \delta Z^*_{ud} \\ 0 & 1+\delta Z^r_{dd}/2 \end{pmatrix} \begin{pmatrix} v_{u,tree} \\ v_{d,tree} \end{pmatrix}$$

Corrections to Higgs masses and mixings



$$\mathcal{F}^- = \frac{s^2_{\alpha-\beta}}{M_H^2} + \frac{c^2_{\alpha-\beta}}{M_h^2} - \frac{1}{M_A^2} \simeq \left(-\lambda_5 + \lambda_7^2/\lambda_2\right)\frac{v^2}{M_A^4} \neq 0$$

+ Higgs WF renormalization in the effective FCNC vertices

Earlier approaches

[Parry '06] : Corrections to $\alpha, \beta, M_{h,H,A}$ using the FeynHiggs package

[Freitas, Gasser, Haisch '07] : $\delta\mathcal{F}^- \propto \frac{M_h^2}{M_H^2 - M_h^2}\varepsilon_{GP}$ This pole singularity is not present in our result

There are many cancellations at play. These are built in in the effective Lagrangian approach. The non-vanishing of $\mathcal{F}^-$ originates from the PQ-violating couplings λ_5 and λ_7 for large tanβ.

III. $\Delta M_{d,s}$ versus $B_{d,s} \to \mu^+\mu^-$ and $B^\pm \to \tau^\pm \nu$

Final formula

$$X = \frac{(\varepsilon_Y 16\pi^2)^2}{(1+\tilde{\varepsilon}_3 \tan\beta)^2 (1+\varepsilon_0 \tan\beta)^2} \frac{m_t^4}{M_W^2 M_A^2} \left[\frac{\tan\beta}{50}\right]^4 \quad \begin{cases} |V_{ts}| = 0.041;\ F_{B_s} = 0.24\,GeV \\ |V_{td}| = 0.0086;\ F_{B_d} = 0.20\,GeV \end{cases}$$

$$(\Delta M - \Delta M^{SM})_{\{s,d\}} = \begin{Bmatrix} -14\,ps^{-1} \\ \sim 0\,ps^{-1} \end{Bmatrix} X \left[\frac{m_s}{0.06\,GeV}\right]\left[\frac{m_b}{3\,GeV}\right]\left[\frac{P_2^{LR}}{2.56}\right]$$

$$+ \begin{Bmatrix} +4.4\,ps^{-1} \\ +0.13\,ps^{-1} \end{Bmatrix} X \frac{M_W^2(-\lambda_5 + \lambda_7^2/\lambda_2)(16\pi^2)}{M_A^2} \left[\frac{m_b}{3\,GeV}\right]^2 \left[\frac{P_1^{SLL}}{-1.06}\right]$$

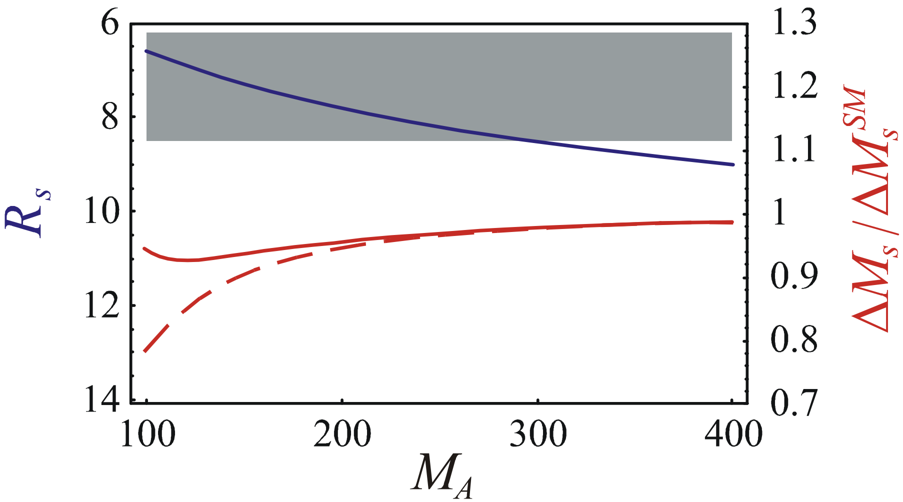
Typically: $M_{\tilde{q}} = \mu = a_{t,b} \Rightarrow \sim \frac{(y_t^4 + y_b^4)}{2} \frac{M_W^2}{M_A^2}$

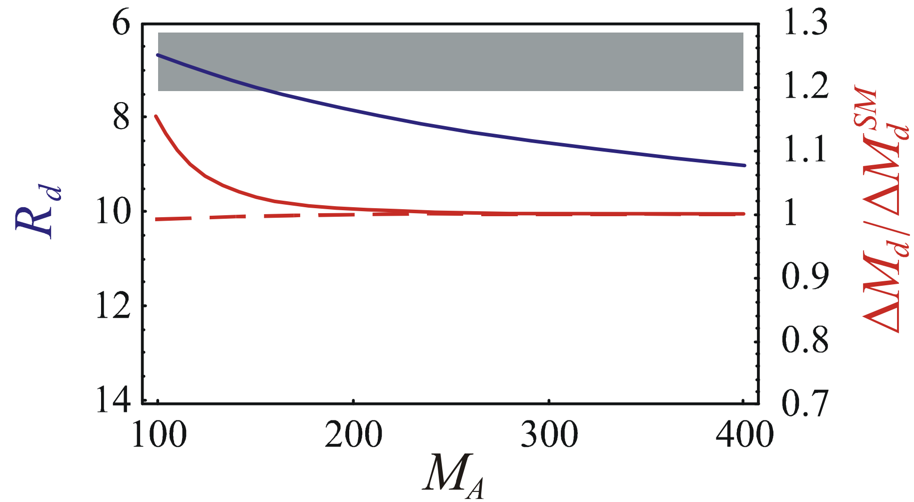
(Moderate) effect for small M_A .

Correlation to $B_q \to \mu^+\mu^-$

$$\mathcal{B}(B_{\{s,d\}} \to \mu^+\mu^-) = \left\{ \begin{matrix} 3.9\cdot 10^{-5} \\ 1.2\cdot 10^{-6} \end{matrix} \right\} X \frac{M_W^2}{M_A^2} \left[\frac{\tan\beta}{50} \right]^2$$

[Babu, Kolda ‘99]
[Chankowski, Sławianowska ‘01]
[Bobeth et al ‘01] [Huang et al ‘01]
[Buras et al ‘02][Isidori, Retico ‘01]
...





Plain: $\Delta M_q = \Delta M_q^{SM+LR+RR}$

Dashed: $\Delta M_q = \Delta M_q^{SM+LR}$

$$R_q \equiv \log_{10}\left[\mathcal{B}\left(B_q \to \mu^+\mu^-\right) \Big/ \Delta M_q (ps^{-1}) \right]$$

$\tan\beta = 40;\ M_{\tilde{q}} = M_2 = 1TeV$

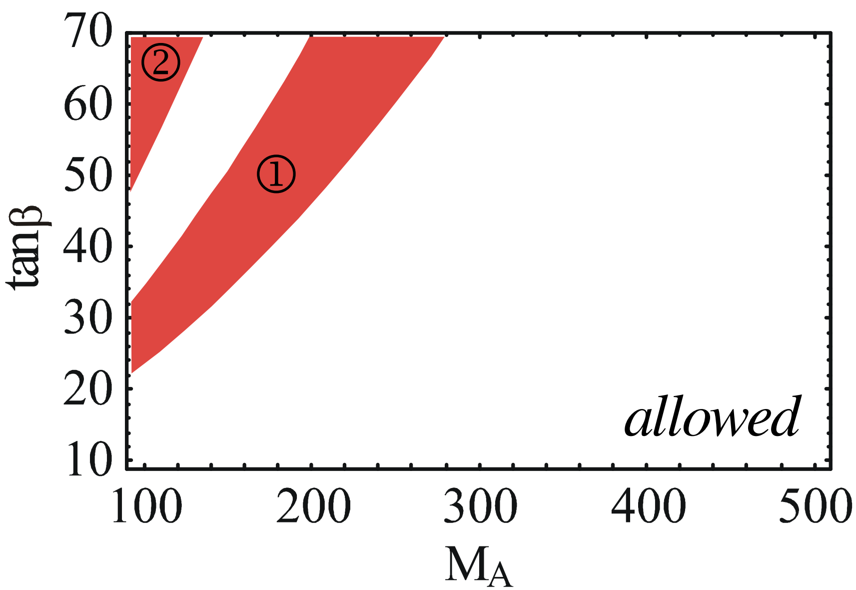
$a_{t,b} = 2TeV;\ \mu = M_{\tilde{g}} = 1.5TeV$

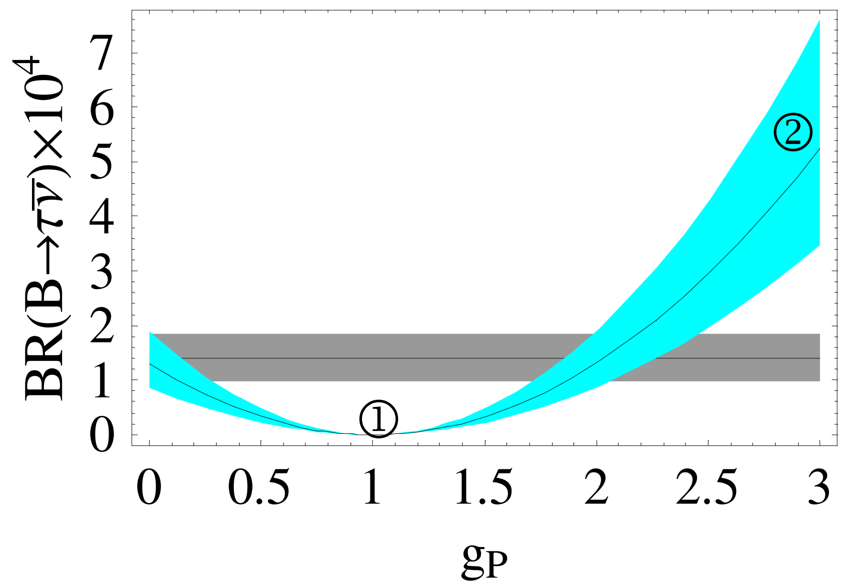
$M_1 = 0.5TeV$

The $B^{\pm} \to \tau^{\pm}\nu$ constraint

$$\mathcal{B}\left(B^{\pm} \to \tau^{\pm}\nu\right) = \mathcal{B}\left(B^{\pm} \to \tau^{\pm}\nu\right)_{SM} \left|1 - g_P\right|^2, \quad g_P \simeq \frac{M_B^2 \tan\beta^2}{M_{H^{\pm}}^2 (1+\varepsilon_0 \tan\beta)}$$

[Hou '93][Akeroyd, Recksiegel '03]…





⇒ The precise measurements of $\Delta M_{d,s}$ are best used as normalizations to avoid the large uncertainties related to V_{tq} and F_{B_q} when using $\mathcal{B}\left(B_s \to \mu^+\mu^-\right)$ and $\mathcal{B}\left(B^{\pm} \to \tau^{\pm}\nu\right)$ to probe the MSSM with large tanβ

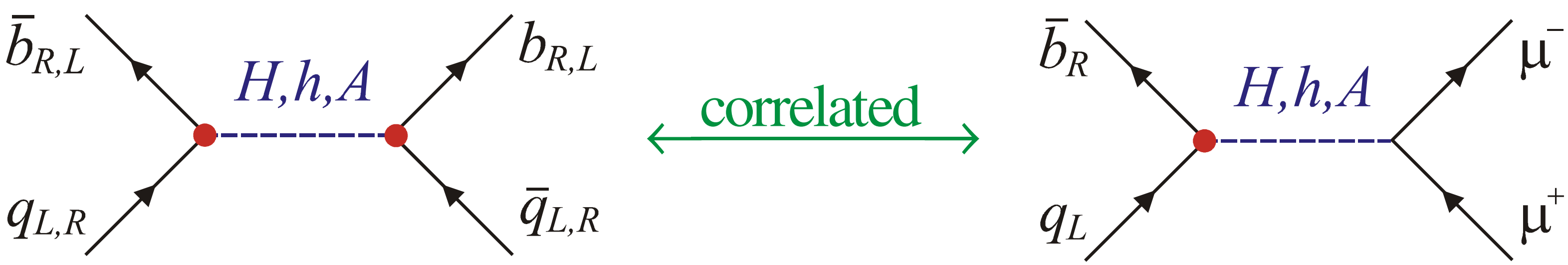
Conclusions

Conclusions

- Systematic investigation of *all leading contributions* to ΔM_q in the MFV-MSSM with large tanβ and heavy sparticles

- No new large effects are found. Still, *corrections to Higgs masses/mixings* can be relevant for *small* M_A (< 200 GeV). They *add* to the SM contribution.

- Correlation to $\mathcal{B}(B_q \to \mu^+\mu^-)$ then becomes :



ΔM_s decreased (but less),
ΔM_d increased

$\mathcal{B}(B_q \to \mu^+\mu^-)$ increased
(as before)

- With all contributions under control: the present experimental bounds on $\mathcal{B}(B_q \to \mu^+\mu^-)$ *excludes a significant decrease* (*increase*) of $\Delta M_s (\Delta M_d)$