Theoretical Physics Seminar

7th April 2011

Selected Aspects of Flavour and Supersymmetry

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Outline

I. Looking for New Physics… The flavour problem

II. Formulation within the MSSM

Adopt a soft-breaking universality ansatz
and study the « left-over dangerousness ». Two scenarios:

III. Higgs-mediated FCNC for large tanβ

IV. Imprints of large θ_ν on (s)quark mixings in GUTs

I. Looking for New Physics…
The flavour problem

The SM flavour sector is peculiar

All flavour breakings and CP violation are contained in the Yukawa matrices

$$\mathcal{L}_Y = \bar{d}_R^I \, \mathbf{Y}_d^{IJ} Q^J \cdot H^c - \bar{u}_R^I \, \mathbf{Y}_u^{IJ} Q^J \cdot H + \bar{e}_R^I \, \mathbf{Y}_e^{IJ} L^J \cdot H^c + h.c.$$

$$Q^J = \begin{pmatrix} u_L^J \\ d_L^J \end{pmatrix}, \quad L^J = \begin{pmatrix} \nu_L^J \\ e_L^J \end{pmatrix}, \quad H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}, \quad H^c = \begin{pmatrix} h^{0*} \\ -h^- \end{pmatrix}$$

Flavour symmetry $U(3)^5$
of the gauge sector :

$$q^I \to \mathbf{V}_q^{IJ} q^J, \qquad q = Q, u_R, d_R, L, e_R$$

The flavour basis can be chosen such that

$$\mathcal{L}_Y = \bar{d}_R^I \, \hat{\mathbf{Y}}_d^I Q^I \cdot H^c - \bar{u}_R^I \, \hat{\mathbf{Y}}_u^I \, \mathbf{V}_{CKM}^{IJ} Q^J \cdot H + \bar{e}_R^I \, \hat{\mathbf{Y}}_e^I L^I \cdot H^c + h.c.$$

4 parameters

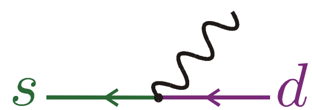
In Wolfenstein parametrisation :

only source of CP violation in the SM

$$\mathbf{V}_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho+i\eta)^* \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O\left(\lambda^4\right)$$

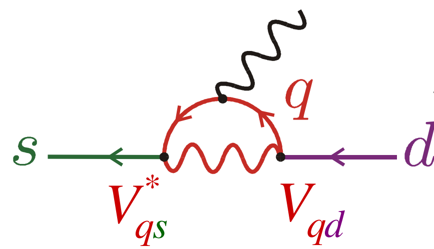
+ Suppression of FCNC :

- No FCNC at tree-level



$= 0$

- GIM suppression at 1 loop
  (not always eff.: $m_u \ll m_c \ll m_t$)



$$\overset{m_q = \text{cst}}{\sim} \sum_{q=u,c,t} V_{qs}^* V_{qd} = 0$$

- Strong CKM hierarchy : $\lambda \equiv \sin\theta_C \simeq 0.23$

These two features do not survive in most SM extensions

The SM flavour success

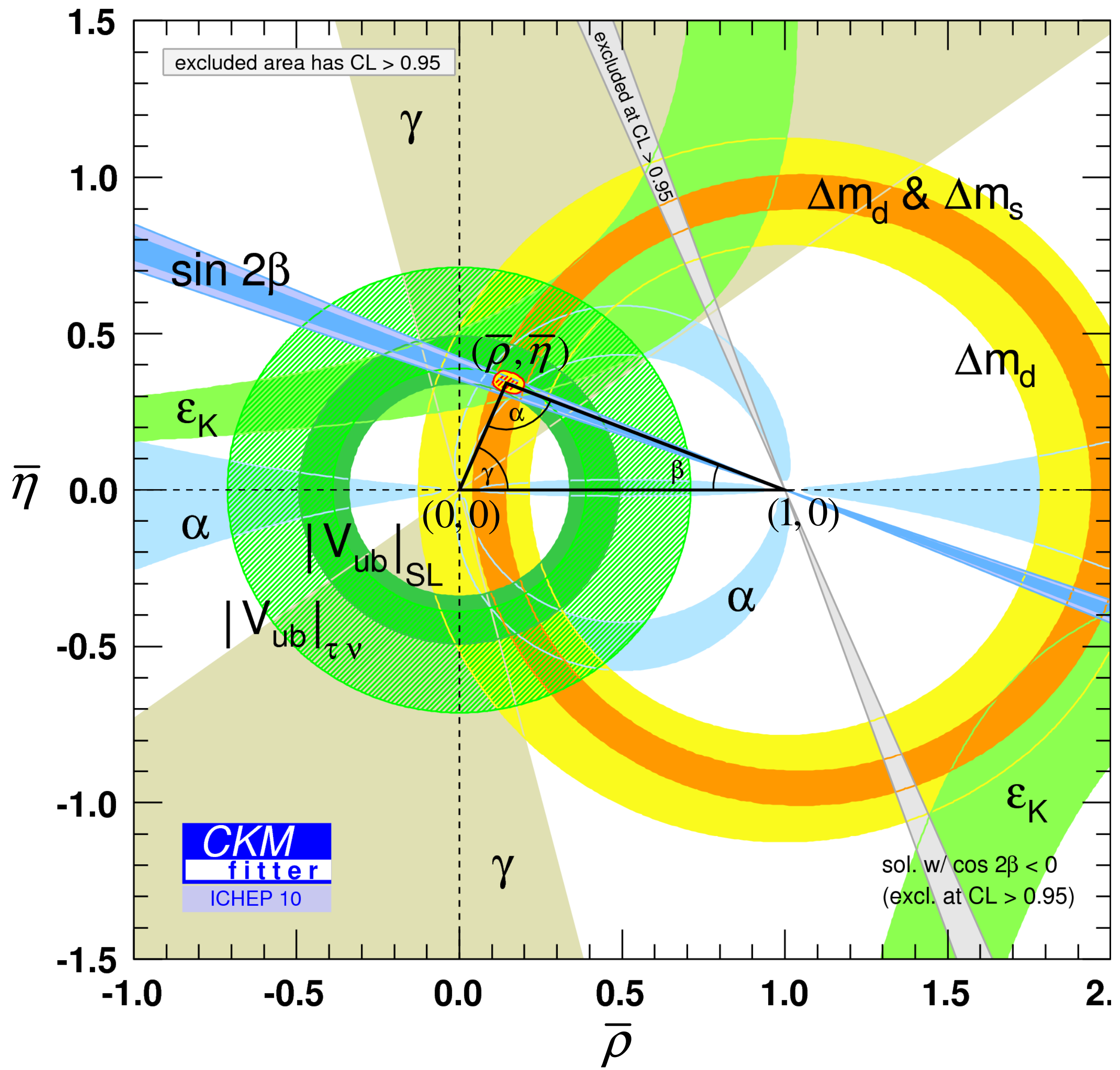
…and New Physics
flavour problem
if at the TeV scale

$$\bar{\rho} \equiv \rho\left(1-\tfrac{1}{2}\lambda^2\right)$$

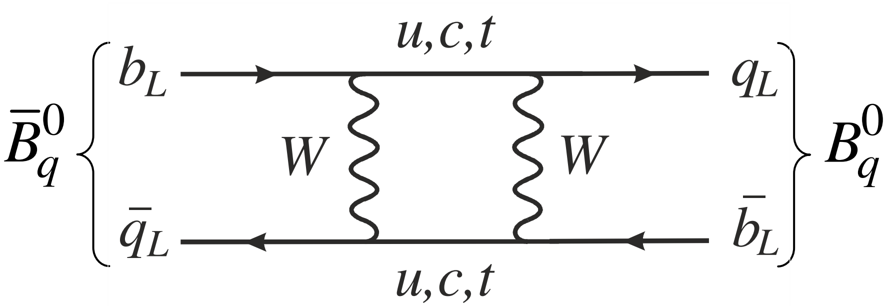
$$\bar{\eta} \equiv \eta\left(1-\tfrac{1}{2}\lambda^2\right)$$

$$(\lambda = 0.2257 \pm 0.0010)$$

$$(A = 0.814 \pm 0.022)$$



A possible deviation?



$(q = d, s)$

- Dispersive part (t) $\rightarrow M_{12}^{B_q}$
- Absorptive part (c,u) $\rightarrow \Gamma_{12}^{B_q}$

3 physical quantities: $\left|M_{12}^{B_q}\right| \simeq \frac{1}{2}\Delta M_q, \quad \left|\Gamma_{12}^{B_q}\right|, \quad \phi_q \equiv \arg\left(-M_{12}^{B_q} / \Gamma_{12}^{B_q}\right)$

Like-sign dimuon charge asymmetry $a_{fs} = \dfrac{N^{++} - N^{--}}{N^{++} + N^{--}}$ *:*

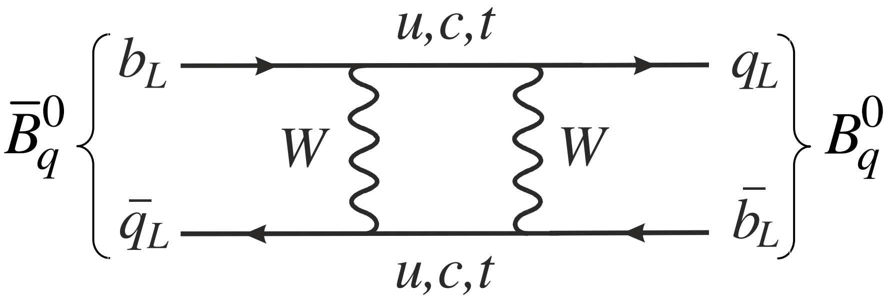
$$a_{fs}^{CDF+D0} = (-8.5 \pm 2.8) \cdot 10^{-3} = (0.506 \pm 0.043)\, a_{fs}^{d} + (0.494 \pm 0.043)\, a_{fs}^{s}$$ [D0+CDF '10]

$$a_{fs}^{SM} = (-0.20 \pm 0.03) \cdot 10^{-3}$$ $\rightarrow 2.9\sigma$ discrepancy [Lenz,Nierste '06/'11]

$$a_{fs}^{q} = \sin\phi_q \left|\Gamma_{12}^{B_q}\right| / \left|M_{12}^{B_q}\right|$$

$\Rightarrow$ *New Physics phases in* $B_s - \bar{B}_s$ *and* $B - \bar{B}$ *mixings?*

A possible deviation?



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Angular analysis of tagged $B_s \rightarrow J/\psi\,\phi$ decays:

CDF+D0 $\quad -2\beta_s^{\mathrm{eff}} = \left(-0.83_{-0.36}^{+0.30}\right) \cup \left(-2.31_{-0.30}^{+0.36}\right)$ *[HFAG '10]*

SM $\quad -2\beta_s^{SM} \simeq -0.04 \quad \rightarrow 2.3\sigma$ discrepancy

$$-2\beta_s^{\mathrm{eff}} = -2\,\cancel{\beta_s^{SM}} + \phi_s^{NP} \simeq \cancel{\phi_s^{SM}} + \phi_s^{NP} = \phi_s$$

Supports large ϕ_s

II. Formulation within the MSSM

Reminder

	Particles	Sparticles
Spin 1	*gauge bosons* $G^a_\mu,\ W^i_\mu,\ B_\mu,$	
Spin 1/2	*quarks and leptons* (× 3 gen) $Q^j = (u^j_L, d^j_L),\ u^j_R,\ d^j_R$ $L = (\nu_L, e_L),\ e_R$	*gauginos* $\tilde{G}^a,\ \boxed{\tilde{W}^i,\ \tilde{B}}$ *higgsinos* $\boxed{\tilde{H}_u,\ \tilde{H}_d}$ *SSB* *charginos* $\tilde{\chi}^{\pm}_{1,2}$ *neutralinos* $\tilde{\chi}^0_{1,2,3,4}$
Spin 0	*2 higgs doublets* $H_u = (h^+_u, h^0_u)$ $H_d = (h^{0*}_d, -h^-_d)$	*squarks and sleptons* (× 3 gen) $\tilde{Q}^j = (\tilde{u}^j_L, \tilde{d}^j_L),\ \tilde{u}^j_R,\ \tilde{d}^j_R$ $\tilde{L} = (\tilde{\nu}_L, \tilde{e}_L),\ \tilde{e}_R$

The number of particles has to be doubled + 2 higgs-doublets instead of one

The MSSM flavour sector

SUSY-conserving part :

(R-parity assumed)

- 1 new source of CP violation : $\arg\mu$
- New occurences of the Yukawa matrices

SUSY-breaking part :

Many new sources of flavour and CP violation!

$$\mathcal{L}_{SB} \supset -\frac{1}{2}\left(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{G}\tilde{G} \right) + h.c.$$

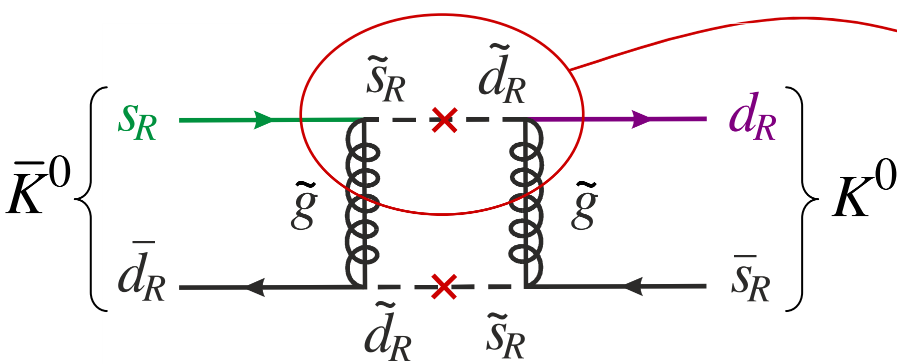
$$-\tilde{Q}^{*I} (\tilde{\mathbf{m}}^2_Q)^{IJ} \tilde{Q}^J - \tilde{d}^{*I}_R (\tilde{\mathbf{m}}^2_d)^{IJ} \tilde{d}^J_R - \tilde{u}^{*I}_R (\tilde{\mathbf{m}}^2_u)^{IJ} \tilde{u}^J_R - \tilde{L}^{*I} (\tilde{\mathbf{m}}^2_L)^{IJ} \tilde{L}^J - \tilde{e}^{*I}_R (\tilde{\mathbf{m}}^2_e)^{IJ} \tilde{e}^J_R$$

$$+ \tilde{d}^{*I}_R \mathbf{A}^{IJ}_d \tilde{Q}^J \cdot H_d - \tilde{u}^{*I}_R \mathbf{A}^{IJ}_u \tilde{Q}^J \cdot H_u + \tilde{e}^{*I}_R \mathbf{A}^{IJ}_e \tilde{L}^J \cdot H_d + h.c$$

d–squark mass matrix in sCKM basis :

$$\begin{pmatrix} \overbrace{\mathbf{V}_{d_L}\tilde{\mathbf{m}}_Q^2\mathbf{V}_{d_L}^\dagger + (v_d\hat{\mathbf{Y}}_d^\dagger)(v_d\hat{\mathbf{Y}}_d) + xM_Z^2\mathbf{1}}^{\left(\mathbf{M}^2_{\tilde{d}}\right)_{LL}} & \overbrace{\mathbf{V}_{d_L}(v_d\mathbf{A}_d^\dagger)\mathbf{V}_{d_R}^\dagger - \mu\tan\beta(v_d\hat{\mathbf{Y}}_d^\dagger)}^{\left(\mathbf{M}^2_{\tilde{d}}\right)_{LR}} \\ \mathbf{V}_{d_R}(v_d\mathbf{A}_d)\mathbf{V}_{d_L}^\dagger - \mu^*\tan\beta(v_d\hat{\mathbf{Y}}_d) & \underbrace{\mathbf{V}_{d_R}\tilde{\mathbf{m}}_d^2\mathbf{V}_{d_R}^\dagger + (v_d\hat{\mathbf{Y}}_d)(v_d\hat{\mathbf{Y}}_d^\dagger) + yM_Z^2\mathbf{1}}_{\left(\mathbf{M}^2_{\tilde{d}}\right)_{RR}} \end{pmatrix}$$

Typical contribution to FCNC :



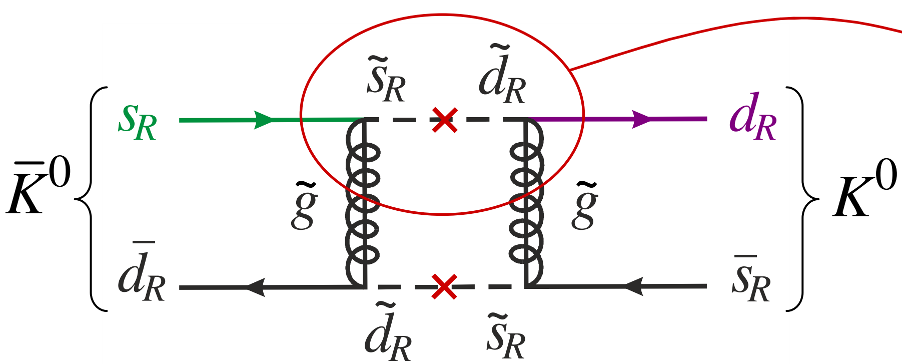
$$\propto \sum_{k=1}^{6} Z^*_{k\,s_R}\, P(\tilde{m}_k^2)\, Z_{k\,d_R}$$

FCNC still loop- and GIM-suppressed,
but flavour-couplings a priori not suppressed anymore

d–squark mass matrix in sCKM basis :

$$\begin{pmatrix} \overbrace{\mathbf{V}_{d_L}\tilde{\mathbf{m}}_Q^2\mathbf{V}_{d_L}^\dagger + (v_d\hat{\mathbf{Y}}_d^\dagger)(v_d\hat{\mathbf{Y}}_d) + xM_Z^2\mathbf{1}}^{\left(\mathbf{M}^2_{\tilde d}\right)_{LL}} & \overbrace{\mathbf{V}_{d_L}(v_d\mathbf{A}_d^\dagger)\mathbf{V}_{d_R}^\dagger - \mu\tan\beta(v_d\hat{\mathbf{Y}}_d^\dagger)}^{\left(\mathbf{M}^2_{\tilde d}\right)_{LR}} \\ \mathbf{V}_{d_R}(v_d\mathbf{A}_d)\mathbf{V}_{d_L}^\dagger - \mu^*\tan\beta(v_d\hat{\mathbf{Y}}_d) & \underbrace{\mathbf{V}_{d_R}\tilde{\mathbf{m}}_d^2\mathbf{V}_{d_R}^\dagger + (v_d\hat{\mathbf{Y}}_d)(v_d\hat{\mathbf{Y}}_d^\dagger) + yM_Z^2\mathbf{1}}_{\left(\mathbf{M}^2_{\tilde d}\right)_{RR}} \end{pmatrix}$$

Typical contribution to FCNC :



$$\propto \sum_{k=1}^{6} Z^*_{k\,s_R} P(\tilde{m}_k^2)\, Z_{k\,d_R}$$

$$\propto \left(\delta^d_{sd}\right)_{RR} + O\left((\delta^d)^2\right)$$

A posteriori : define mass insertions

$$\left(\delta^d_{IJ}\right)_{MN} \equiv \frac{1}{\tilde{m}^2}\left(\mathbf{M}^2_{\tilde d}\right)^{IJ}_{MN} \qquad (M, N = L, R)$$

The MSSM flavour problem

q	IJ	$\left(\delta^q_{IJ}\right)_{LL,RR}$	$\sqrt{\left(\delta^q_{IJ}\right)_{LL}\left(\delta^q_{IJ}\right)_{RR}}$	$\left(\delta^q_{IJ}\right)_{LR}$
d	12	0.03	0.002	2×10^{-4}
d	13	0.2	0.07	0.08
d	23	0.6	0.2	0.01
u	12	0.1	0.008	0.02

[Gabbiani et al. '96]
[Masiero, Vempati, Vives '07]
[Ciuchini et al. '07]
[Artuso et al. '08]
[Isidori, Nir, Perez '10]
...

$\tilde{m} = 1 TeV$

$m^2_{\tilde{g}} / \tilde{m}^2 = 1$

If sparticle masses are $\lesssim$ a few TeV, most of the MI must be tiny, that is,
- either the sfermions must be quasi degenerate
- or they must be quasi aligned with fermions

(or a combination of both mechanisms).

Problem : origin of this structure!

Origin of SUSY breaking?

The soft-breaking terms are the footprints of the SUSY-breaking mechanism.

If the mediation of SUSY breaking to the MSSM is flavour blind (e.g., GMSB), the soft terms will obey universality conditions of the type

$$\tilde{\mathbf{m}}_Q^2, \tilde{\mathbf{m}}_d^2, \tilde{\mathbf{m}}_u^2, \tilde{\mathbf{m}}_L^2, \tilde{\mathbf{m}}_e^2 \propto \mathbf{1}, \quad \mathbf{A}_u \propto \mathbf{Y}_u, \quad \mathbf{A}_d \propto \mathbf{Y}_d, \quad \mathbf{A}_e \propto \mathbf{Y}_e$$

This is usually considered as safe from the point of view of flavour violating effects.

In this talk : study « left-over dangerousness »

We take the soft-breaking universality ansatz as zeroth order approximation. Sizeable flavour violating effects could still be produced via the impact of large parameters. Two known examples: $\tan\beta$, neutrino mixing angles.

Can such effects account for large phases in $B_{s,d} - \overline{B}_{s,d}$ mixings?

Two scenarios

1. *Higgs-mediated FCNC for large tanβ*

$$\frac{m_t}{m_b} \underset{\text{tree-level}}{=} \frac{y_t v_u}{y_b v_d} \simeq 43 \quad \begin{cases} v_u \sim v_d, \; y_t \gg y_b \\ \boxed{v_u \gg v_d, \; y_t \sim y_b} \end{cases}$$

$\tan\beta \equiv v_u / v_d \sim 40-50$ allows
the unification of top and bottom Yukawa couplings

MSSM with large $\tan\beta$:
the large $\tan\beta$ factor compensates for the loop suppression in Higgs-mediated FCNC

2. *Imprints of large θ_ν on (s)quark mixings in GUTs*

$$\frac{m_\tau}{m_b} \underset{\text{EW scale}}{=} \frac{y_\tau}{y_b} \underset{\text{GUT scale}}{\sim} 1 \longrightarrow \boxed{\mathbf{Y}_d = \mathbf{Y}_e^T}$$

ex : minimal SU(5)

The large neutrino mixing angles can induce significant quark-squark misalignments.
Specific scenario : SUSY SO(10) model proposed by Chang, Masiero, Murayama

III. Higgs-mediated FCNC for large tanβ

Main idea

SUSY imposes a 2HDM-II structure for the Yukawa interactions:

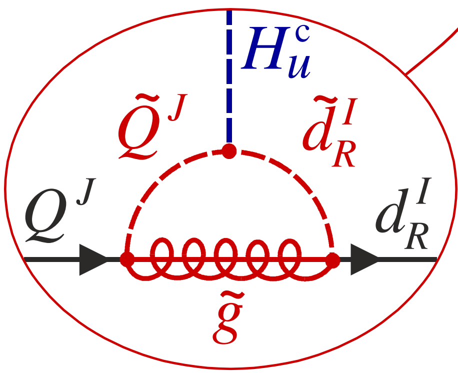
$$\mathcal{L}_Y^{quarks} = \bar{u}_R^I \mathbf{Y}_u^{IJ} H_u \cdot Q^J$$
$$- \bar{d}_R^I \mathbf{Y}_d^{IJ} H_d \cdot Q^J + h.c.$$

Main idea

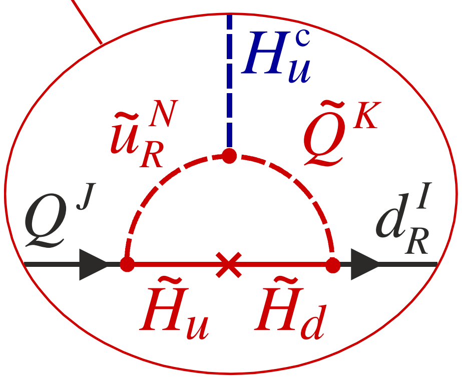
Soft SUSY breaking → 2HDM-III structure at loop level:

(sparticle masses ≫ Higgs masses)

$$\mathcal{L}_Y^{quarks} = \bar{u}_R^I \left[\mathbf{Y}_u H_u + \boldsymbol{\delta}\mathbf{Y}_u H_d^c \right]^{IJ} \cdot Q^J$$
$$- \bar{d}_R^I \left[\mathbf{Y}_d H_d + \left(\varepsilon_0 \mathbf{Y}_d + \varepsilon_Y \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u \right) H_u^c \right]^{IJ} \cdot Q^J + h.c.$$



$\propto \mu^* / M_3$



$\propto \mathbf{A}_u^{*NK} / \mu$

New flavour structure, not aligned with $\mathbf{Y}_d$

Dimension-4 effective operators ⇒ the corrections are non-decoupling

Main idea

Soft SUSY breaking → 2HDM-III structure at loop level: (sparticle masses $\gg$ Higgs masses)

$$\mathcal{L}_Y^{quarks} = \bar{u}_R^I \left[\mathbf{Y}_u H_u + \boldsymbol{\delta}\mathbf{Y}_u H_d^c \right]^{IJ} \cdot Q^J$$

$$- \bar{d}_R^I \left[\mathbf{Y}_d \underset{\downarrow\, v_d}{H_d} + \left(\varepsilon_0 \mathbf{Y}_d + \varepsilon_Y \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u \right) \underset{\downarrow\, v_u}{H_u^c} \right]^{IJ} \cdot Q^J + h.c.$$

After SSB: v_d v_u $\Rightarrow$ $\boxed{\tan\beta\text{-enhancement}}$

The corrected d-quark mass matrix must be rediagonalized.

Doing so, the misalignment of quark mass terms and quark-Higgs vertices implies:

- $O(1)$ corrections to H^+ vertices
- Higgs-mediated FCNC with coupling $\kappa^{IJ} \sim \left(m^I / v \right) \varepsilon_Y V_{tI}^* V_{tJ} (\tan\beta)^2$:

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

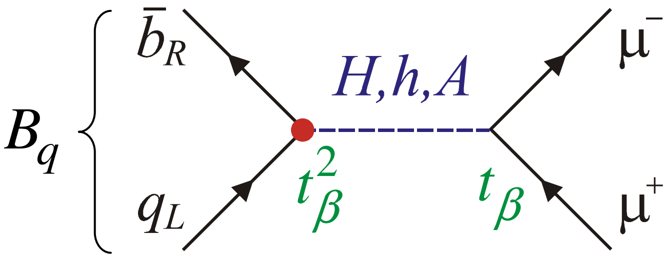
[Babu,Kolda '99]

$(c_\beta \equiv \cos\beta, etc)$

Distinctive phenomenology

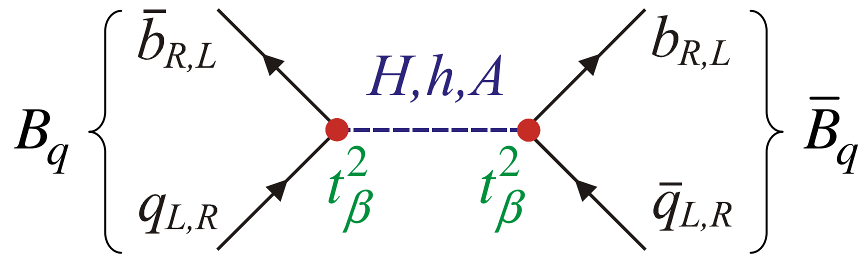
Higgs couplings still proportional to m^I $\Rightarrow$ look at B physics (note: also K physics)

$\boxed{B_{s,d} \to \mu^+\mu^-}$



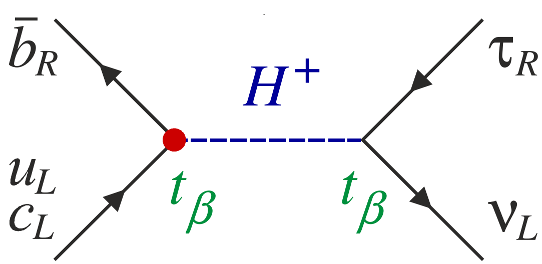
$\mathcal{B}(B_q \to \mu^+\mu^-)$ increased

$\boxed{\Delta M_{s,d}}$ $(q = d, s)$



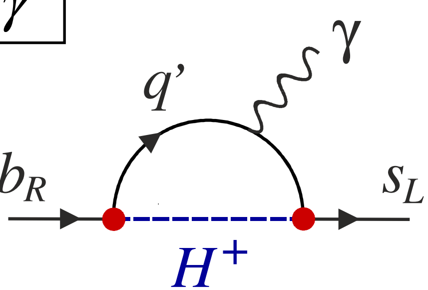
$\Delta M_{s(d)}$ decreased (unaffected)

$\boxed{B^+ \to \tau^+\nu,\ B \to D\tau^+\nu, \ldots}$



$\mathcal{B}(B \to \tau\nu)$ decreased

$\boxed{B \to X_s\gamma}$

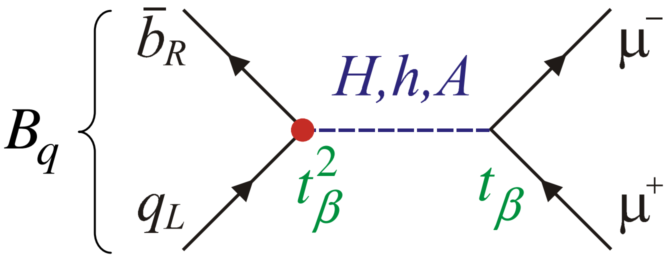


Positive contribution,
but $\tilde{\chi}$ − squark loops interfere

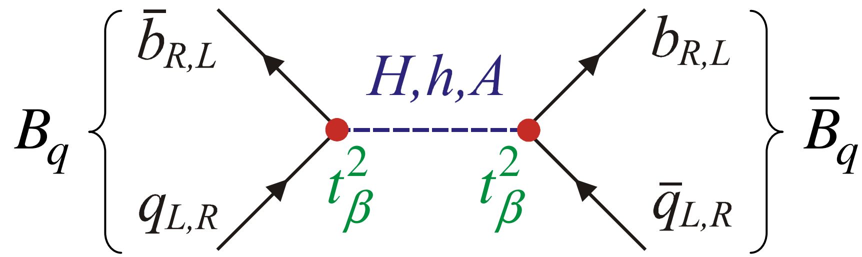
Distinctive phenomenology

Higgs couplings still proportional to m^I $\Rightarrow$ look at B physics (note: also K physics)

$\boxed{B_{s,d} \to \mu^+ \mu^-}$ $\boxed{\Delta M_{s,d}}$ $(q = d, s)$



correlated $\longleftrightarrow$



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

$\Delta M_{s(d)}$ decreased (unaffected)

- Clean: same dependence on F_{B_q} and V_{tq} in both observables *[Buras et al. '02]*
- Superficially leading contribution $\Delta M_q^{(m_b^2)} = 0$, correlation obtained for $\Delta M_q^{(m_q m_b)}$

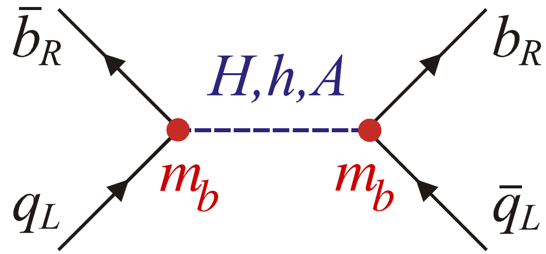
Look at all (sub-)leading contributions before concluding!

New contributions to $\phi_{s,d}$?

[Gorbahn,Jäger,Nierste,S.T. '09]

Why the cancellation?

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



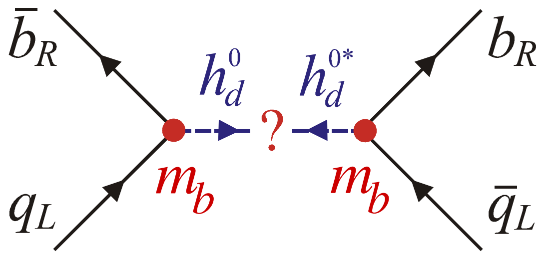
$= 0$

[Babu,Kolda '99]

The amplitude is ruled by

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

Why the cancellation?

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

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

The amplitude is ruled by

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

$B\mu = s_\beta c_\beta M_A^2$,
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

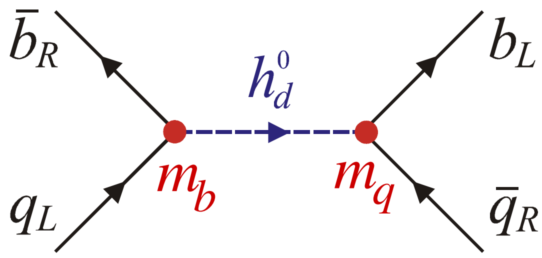
$$U(1)_{PQ}: \;\; \mathcal{Q}(H_d) = \mathcal{Q}(d_R^I) = 1, \;\; \mathcal{Q}(other) = 0$$

What are the leading contributions?

Look at <u>all</u> contributions with $\boxed{\textit{1 suppression factor}}$

What are the leading contributions?

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

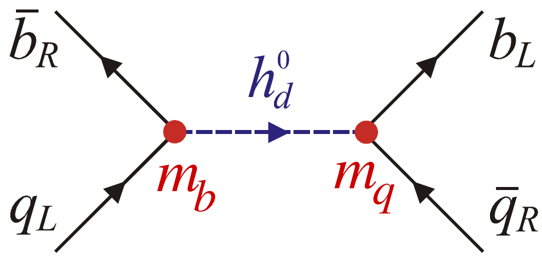


$$\Delta Q = 0 \quad \Rightarrow \quad \Delta M_q^{LR} \propto \frac{m_b \boxed{m_q}}{v^2} \quad \text{decreases } \Delta M_s$$

[Buras,Chankowski, Rosiek,Sławianowska '02]

What are the leading contributions?

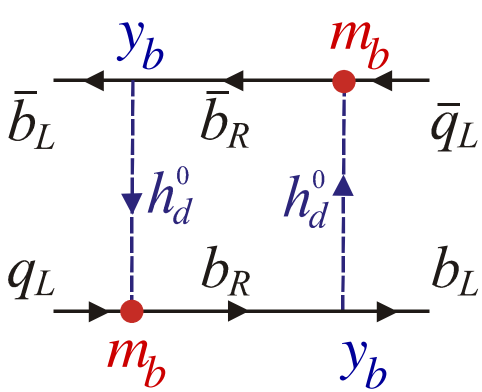
A/ *Chirality-flipped contribution* ("LR")



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

[Buras,Chankowski, Rosiek,Sławianowska '02]

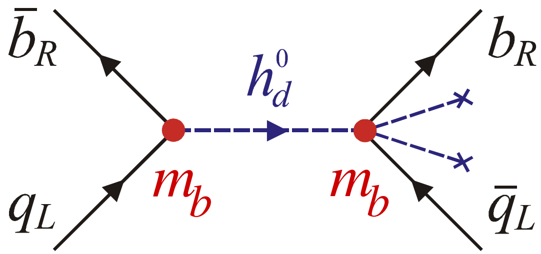
B/ *Weak-scale loop contribution*



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

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

C/ Higher dimension operator contribution



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

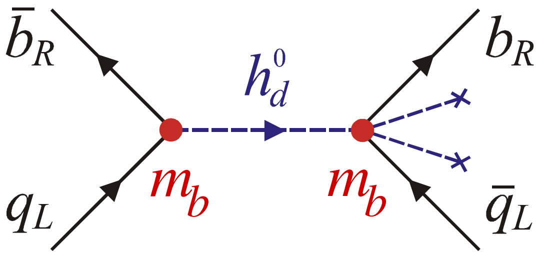
The higher dimension quark-Higgs effective vertices are also loop-suppressed.

Compensate the loop-suppression by a large tanβ factor

→ Only non-negligible effect in rediagonalization of d-quark mass matrix

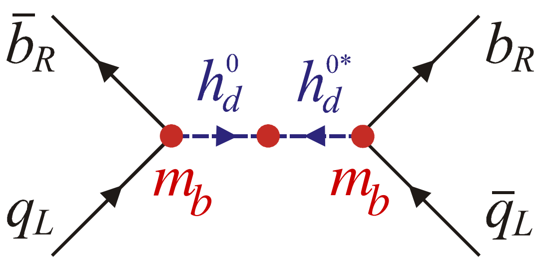
→ Higgs FCNC of the type $\bar{d}_R^I d_L^J h_d^{0*} / \bar{d}_L^I d_R^J h_d^0$ as before, up to 1/tanβ corrections.

C/ *Higher dimension operator contribution*



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

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



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

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 *[Parry '06][Freitas,Gasser,Haisch '07]*

$\Rightarrow$ go through them again

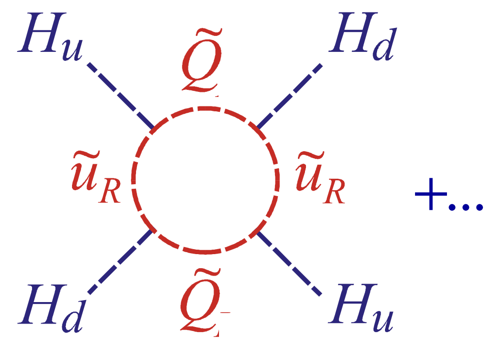
Matching MSSM → 2HDM

At 1-loop, 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: $$\lambda_5 = -\frac{3\left|y_t\right|^4}{8\pi^2} \frac{a_t^2 \mu^2}{M_{\tilde{t}_R}^4} L_1\left(M_{\tilde{t}_L}^2 / M_{\tilde{t}_R}^2\right) + \ldots$$

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

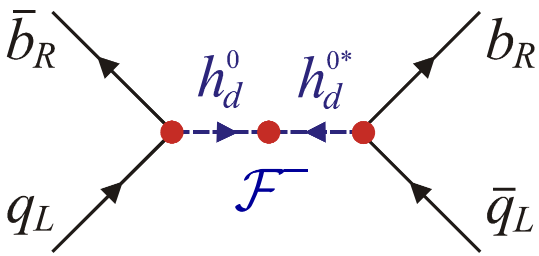


Note: many refs!

[Haber,Hempfling '93][Carena,Espinosa,Quirós,Wagner '95][Beneke,Ruiz-Femenia,Spinrath '08]…

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

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.

Typical size of the new effect

$$X=\frac{(\varepsilon_Y 16\pi^2)^2}{(1+\tilde{\varepsilon}_3\tan\beta)^2(1+\varepsilon_0\tan\beta)^2}\frac{m_t^4}{M_W^2 M_A^2}\left[\frac{\tan\beta}{50}\right]^4$$

$$\begin{cases} |V_{ts}|=0.041;\ F_{B_s}=0.24\,GeV \\ |V_{td}|=0.0086;\ F_{B_d}=0.20\,GeV \end{cases}$$

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

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

Can be complex! ☺

Typical size of the new effect

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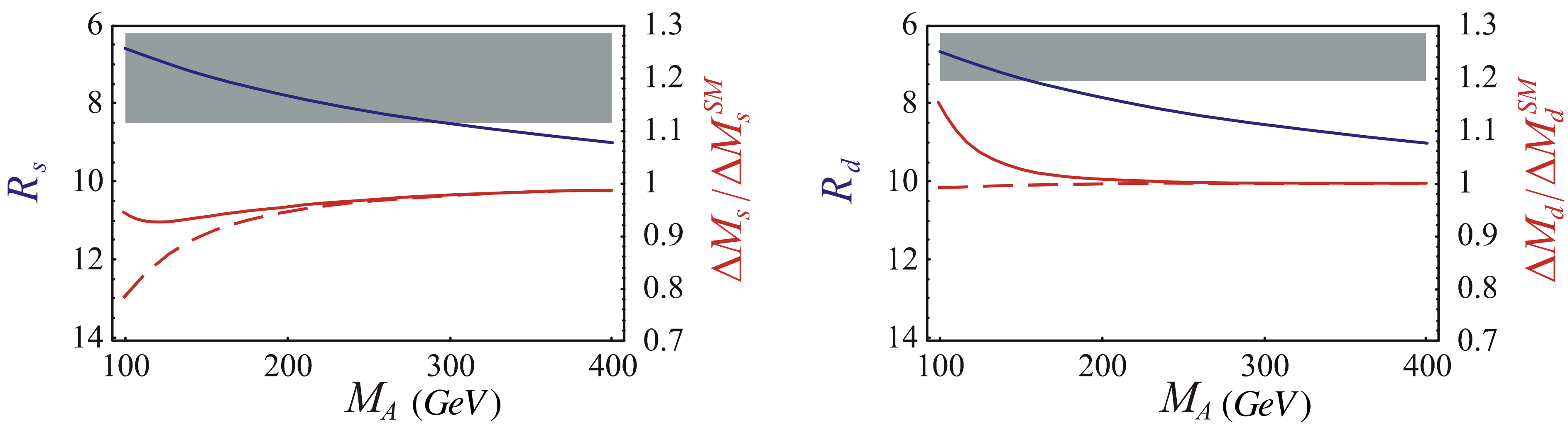
However, typically: $M_{\tilde{q}} = \mu = a_{t,b} \Rightarrow \sim \frac{(y_t^4 + y_b^4)}{2} \frac{M_W^2}{M_A^2}$

New effect only 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 '00]
[Chankowski,Sławianowska '01]
[Bobeth et al. '01] [Huang et al. '01]
[Buras et al. '02][Isidori,Retico '01]
...



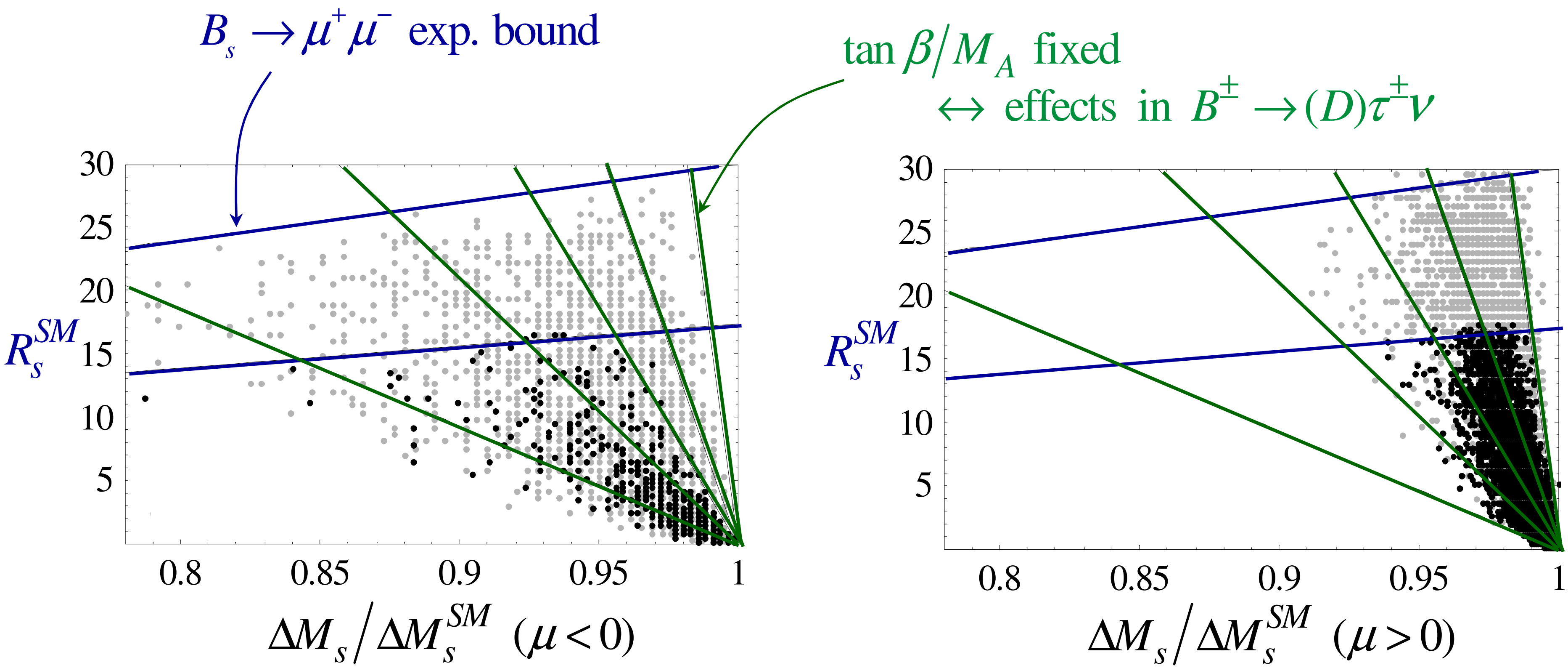
Plain: $\Delta M_q = \Delta M_q^{SM+LR+RR}$

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

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

$\tan\beta = 40$; $M_{\tilde{q}} = M_2 = 1 TeV$
$a_{t,b} = 2 TeV$; $\mu = M_{\tilde{g}} = 1.5 TeV$
$M_1 = 0.5 TeV$

Scan of parameter space



$R_s^{SM} \equiv \mathcal{B}(B_s \to \mu^+\mu^-) / \mathcal{B}(B_s \to \mu^+\mu^-)^{SM}$

Grey points: $\mathcal{B}(B_s \to \mu^+\mu^-) < 10^{-7}$

Black points: $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-8}$

$\tan\beta \in [10, 60]$

$M_A \in [120, 600]\, GeV$

$M_{SUSY} \in [600, 1800]\, GeV$

Conclusion (scenario 1)

MSSM with large tanβ

$\Rightarrow$ Higgs-mediated FCNC

Systematic investigation of all Higgs-mediated contributions to $\Delta M_{s,d}$

- No new large effects are found
- In principle: corrections to Higgs masses/mixings relevant for small M_A
- Essentially excluded by the experimental upper bound on $\mathcal{B}(B_s \to \mu^+\mu^-)$

Meson-antimeson mixing phenomenology:

- Correlation to $B_s \to \mu^+\mu^-$ remains essentially intact
- ΔM_s: Max decrease of ~20% (~ 7%) for $\mu < 0$ ($\mu > 0$) if $M_A < 600 GeV$
- No possibility to account for sizeable CPV phases in the $B_{s,d}$ systems

IV. Imprints of large θ_ν on (s)quark mixings in GUTs

Specific scenario : SUSY SO(10) model proposed by
Chang, Masiero, Murayama (CMM)

Many related works: [Moroi '00][Baek et al. '00][Hisano,Shimizu '03][Harnik et al. '02] [Ciuchini et al. '03][Jäger,Nierste '03][Cheung et al. '07][Girrbach et al. '11]…

Main idea

① RGE

$$\mu \lesssim O(M_{Pl}) \qquad \left(\mathbf{M}^2_{\tilde{d}}\right)^{\mathrm{IB}}_{\mathrm{RR}} = m_0^2\ \mathbf{1}$$

IB = Interaction Basis

$$\mu = O(M_Z) \qquad \left(\mathbf{M}^2_{\tilde{d}}\right)^{\mathrm{IB}}_{\mathrm{RR}} \simeq m^2_{\tilde{d}}\, diag\left(1,1,1-\Delta_{\tilde{d}}\right)$$

② GUT matching condition:
(SU(5) threshold)

$$\mathbf{Y}_d = \mathbf{Y}_e^T$$

$$diag\left(m_d, m_s, m_b\right) = diag\left(m_e, m_\mu, m_\tau\right)$$

$$\mathbf{V}^*_{e_R} = \mathbf{V}_{d_L} = \mathbf{V}^\dagger_{CKM}\ \mathbf{V}_{u_L}$$

$$\mathbf{V}^*_{d_R} = \mathbf{V}_{e_L} = \mathbf{V}_{PMNS}\ \mathbf{V}_{\nu_L}$$

⇨ In the sCKM basis (i.e., diagonalizing d-quark mass terms):

$$\left(\mathbf{M}^2_{\tilde{d}}\right)^{\mathrm{sCKM}}_{\mathrm{RR}} \simeq m^2_{\tilde{d}}\ \mathbf{V}^*_{PMNS}\, diag\left(1,1,1-\Delta_{\tilde{d}}\right) \mathbf{V}^T_{PMNS}$$

Explicitly: imprints of θ_{atm} on $b \to s$ transitions

Tribimaximal ν mixing:

$$\mathbf{V}_{PMNS} = \frac{1}{\sqrt{6}} P_L \begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & \sqrt{3} \\ 1 & -\sqrt{2} & \sqrt{3} \end{pmatrix} P_R$$

$$P_L = e^{i\, diag(0, \alpha_1 - \alpha_2, \alpha_1 - \alpha_3)}$$

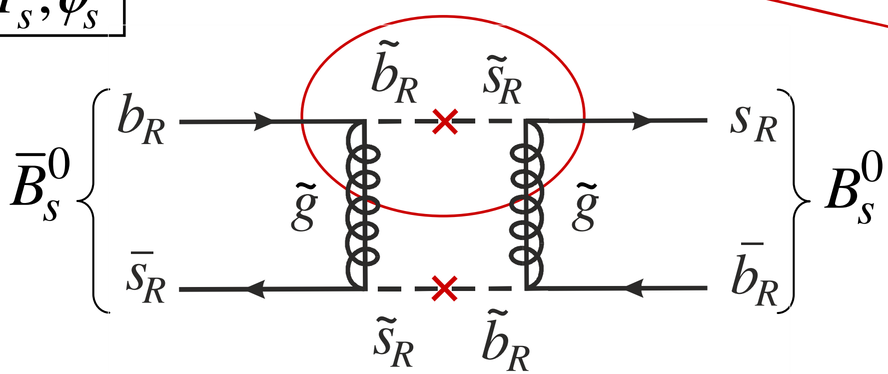
$$P_R = e^{-i\, diag(\alpha_1, \alpha_4, \alpha_5)}$$

(In the lepton sector: absorbed in field redef.)

→ Large $\left(\delta_{23}^d\right)_{RR}$ are produced:

$$\left(\mathbf{M}_{\tilde{d}}^2\right)_{\mathrm{RR}}^{\mathrm{sCKM}} \simeq m_{\tilde{d}}^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 - \frac{1}{2}\Delta_{\tilde{d}} & -\frac{1}{2}\Delta_{\tilde{d}}\, e^{-i\phi_{B_s}} \\ 0 & -\frac{1}{2}\Delta_{\tilde{d}}\, e^{i\phi_{B_s}} & 1 - \frac{1}{2}\Delta_{\tilde{d}} \end{pmatrix}$$

$\boxed{\Delta M_s, \phi_s}$



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$$\mathbf{V}^*_{d_R} = \mathbf{V}_{e_L} = \mathbf{V}_{PMNS}\, \mathbf{V}_{\nu_L}$$

$\boxed{m_{d/s} = m_{e/\mu} \text{ must be corrected}}$ $\Rightarrow$ $\boxed{\text{effects also in } s \to d \text{ and } b \to d}$

New contributions to ϕ_d?

[S.T., Westhoff, Wiesenfeldt '09]

Corrections to Yukawa unification

Introduce effective Yukawa interactions at the GUT scale

In SU(5), matter fields in $\overline{5}^I, 10^J$, Higgs fields in 24_H, $5_H (\ni H_u)$, $\overline{5}_H (\ni H_d)$:

$$(\mathcal{L}_Y^{e,d})^{5\mathrm{d}} = \left(10^{Iab}\mathbf{Y}^{IJ}_{\sigma_1}\,\overline{5}^J_a\right)\frac{24^c_{Hb}}{M_{Pl}}\overline{5}_{Hc} + \left(10^{Iab}\mathbf{Y}^{IJ}_{\sigma_2}\,\overline{5}^J_c\right)\frac{24^c_{Hb}}{M_{Pl}}\overline{5}_{Ha}$$

$$\langle 24_H \rangle = \sigma\ diag(2,2,2,-3,-3)$$

$$u^c_R \oplus \begin{pmatrix} u_L \\ d_L \end{pmatrix} \oplus e^c_R \qquad\qquad d^c_R \oplus \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

[Ellis,Gaillard '79]

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$$\langle 24_H \rangle = \sigma\ diag(2,2,2,-3,-3)$$

Corrected GUT matching condition:

$$\mathbf{Y}_d = \mathbf{Y}_e^T + 5\frac{\sigma}{M_{Pl}}\mathbf{Y}_{\sigma_2}$$

$$diag(m_d, m_s, m_b) = diag(m_e, m_\mu, m_\tau) + \frac{\sigma}{M_{Pl}} diag(\delta_{m_d}, \delta_{m_s}, \delta_{m_b})$$

$$\mathbf{V}_{e_R}^* = \delta\mathbf{V}_{e_R}\mathbf{V}_{d_L} = \delta\mathbf{V}_{e_R}\mathbf{V}_{CKM}^\dagger\mathbf{V}_{u_L}$$

$$\mathbf{V}_{d_R}^* = \delta\mathbf{V}_{d_R}\mathbf{V}_{e_L} = \delta\mathbf{V}_{d_R}\mathbf{V}_{PMNS}\,\mathbf{V}_{\nu_L}$$

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(similarly for $\delta\mathbf{V}_{e_R}$)

$$\delta\mathbf{V}_{d_R} = \begin{pmatrix} c_\theta e^{i\phi_1} & -s_\theta e^{i\phi_1 - i\phi_2 + i\phi_3} & 0 \\ s_\theta e^{i\phi_2} & c_\theta e^{i\phi_3} & 0 \\ 0 & 0 & e^{i\phi_4} \end{pmatrix}$$

CMM model: SUSY-conserving sector

SUSY SO(10) GUT, matter fields in spinor representation 16^I

$$\text{SSB}: \quad \text{SO}(10) \xrightarrow{16_H,\overline{16}_H,45_H} \text{SU}(5) \xrightarrow{45_H} \text{SU}(3)_C\times\text{SU}(2)_L\times\text{U}(1)_Y \xrightarrow{10_H,10'_H} \text{SU}(3)_C\times\text{U}(1)_Q$$

$$W_Y = \underbrace{\left(16^I\,\mathbf{Y}_1^{IJ}\,16^J\right)10_H + \left(16^I\,\mathbf{Y}_N^{IJ}\,16^J\right)\frac{\overline{16}_H\overline{16}_H}{M_{Pl}}}_{u^I \text{ and } \nu^I \text{ masses}} + \underbrace{\left(16^I\,\mathbf{Y}_2^{IJ}\,16^J\right)\frac{45_H}{M_{Pl}}10'_H}_{d^I \text{ and } e^I \text{ masses}}$$

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Corrections to Yukawa unification via SU(5)-breaking vev of 45_H :

$$\mathbf{Y}_d = \mathbf{Y}_e^T + 5\frac{\sigma}{M_{10}}\mathbf{Y}_\sigma$$

CMM model: SUSY-conserving sector

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Hyp: $\mathbf{Y}_1$ and $\mathbf{Y}_N$ can be diagonalized simultaneously. In that basis:

$$\mathbf{V}^*_{e_R} = \delta\mathbf{V}_{e_R} \mathbf{V}^\dagger_{CKM}, \quad \mathbf{V}^*_{d_R} = \delta\mathbf{V}_{d_R} \mathbf{V}_{PMNS}$$

↑

Visible effect of $\theta \neq 0$?

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$$\mathbf{Y}_d = \mathbf{Y}_e^T + 5\frac{\sigma}{M_{10}} \mathbf{Y}_\sigma$$

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RGE

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In the sCKM basis (i.e., diagonalizing d-quark mass terms):

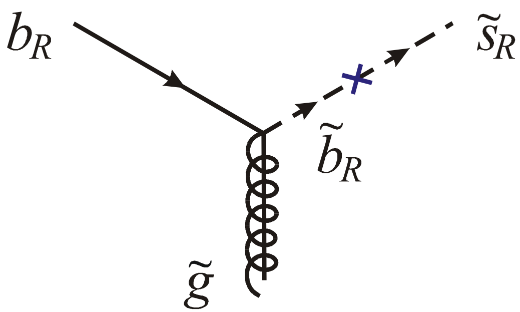
$$\left(\mathbf{M}^2_{\tilde{d}}\right)^{\mathrm{sCKM}}_{\mathrm{RR}} \simeq m^2_{\tilde{d}} \left(\boldsymbol{\delta}\mathbf{V}_{d_R}\mathbf{V}_{PMNS}\right)^* diag\left(1,1,1-\Delta_{\tilde{d}}\right)\left(\boldsymbol{\delta}\mathbf{V}_{d_R}\mathbf{V}_{PMNS}\right)^T$$

$$\overset{\mathrm{TB}}{\simeq} m^2_{\tilde{d}} \begin{pmatrix} 1-\frac{1}{2}\Delta_{\tilde{d}}(\sin\theta)^2 & \frac{1}{4}\Delta_{\tilde{d}}\sin(2\theta)\ e^{-i\phi_K} & \frac{1}{2}\Delta_{\tilde{d}}\sin\theta\ e^{-i\phi_B} \\ \frac{1}{4}\Delta_{\tilde{d}}\sin(2\theta)\ e^{i\phi_K} & 1-\frac{1}{2}\Delta_{\tilde{d}}(\cos\theta)^2 & -\frac{1}{2}\Delta_{\tilde{d}}\cos\theta\ e^{-i\phi_{B_s}} \\ \frac{1}{2}\Delta_{\tilde{d}}\sin\theta\ e^{i\phi_B} & -\frac{1}{2}\Delta_{\tilde{d}}\cos\theta\ e^{i\phi_{B_s}} & 1-\frac{1}{2}\Delta_{\tilde{d}} \end{pmatrix}$$

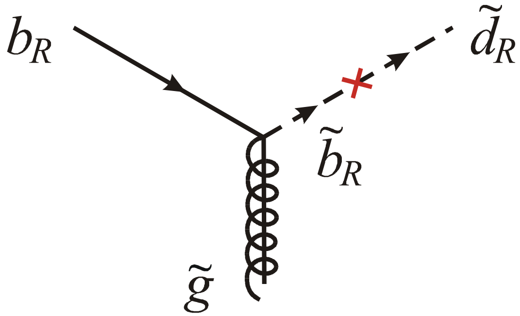
Rem: $\phi_B = \phi_{B_s} + \phi_K$

$b \to s,\ b \to d,\ s \to d$ flavour transitions

Main effect from quark-squark-gluino vertices:

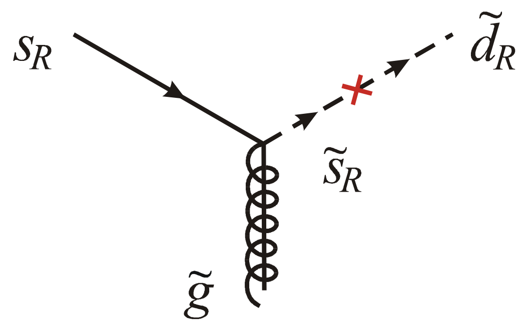


$$\propto -\tfrac{1}{2}\Delta_{\tilde{d}} \cos\theta \, e^{-i\phi_{B_s}}$$



$$\propto \tfrac{1}{2}\Delta_{\tilde{d}} \sin\theta \, e^{-i\phi_{B}}$$

new

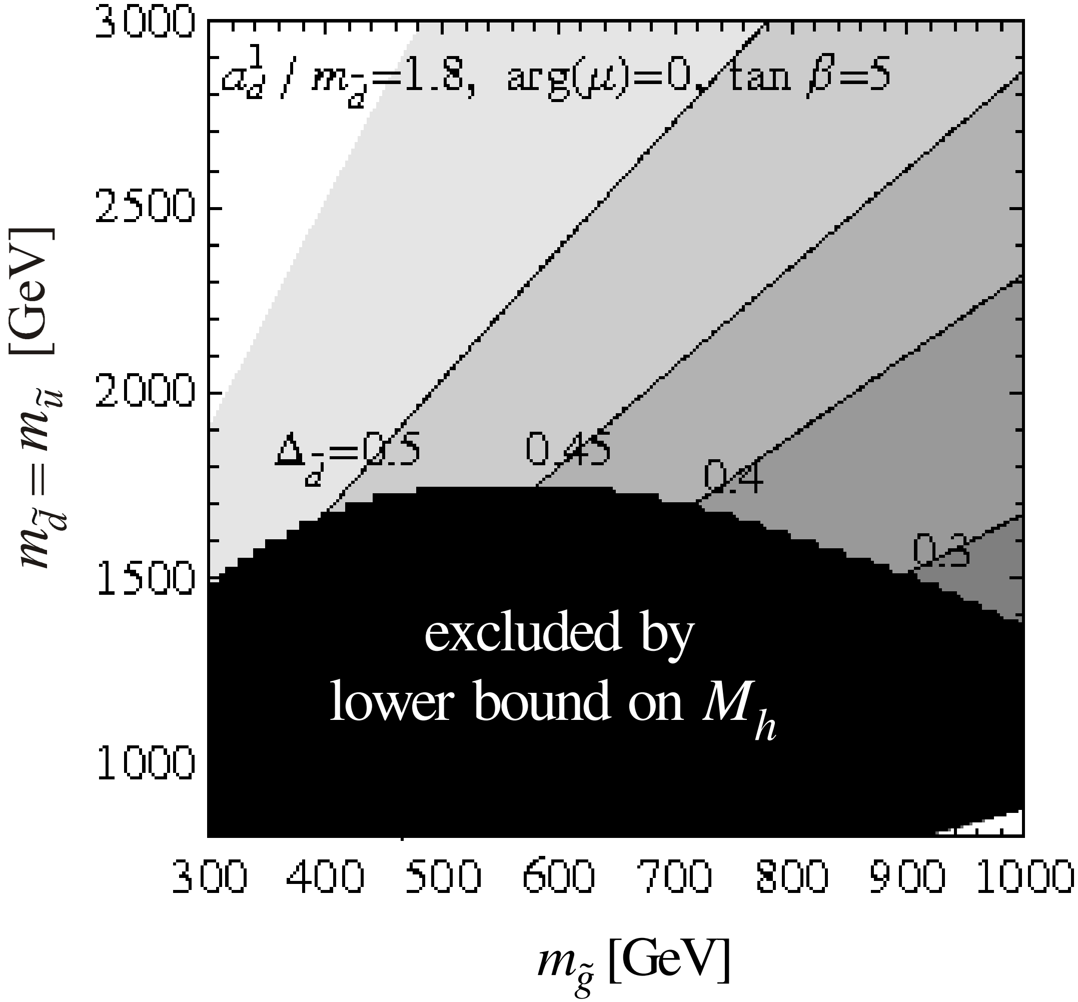


$$\propto \tfrac{1}{4}\Delta_{\tilde{d}} \sin(2\theta) \, e^{-i\phi_{K}}$$

Rem: no MIA

Typical $\Delta_{\tilde{d}}$ values

6 SUSY inputs at the weak scale: $m_{\tilde{g}}, m_{\tilde{d}}, m_{\tilde{u}}, a_d^1 \equiv \mathbf{A}_d^{11} / \mathbf{Y}_d^{11}, \arg(\mu), \tan\beta$



RGE to $\mu \lesssim O(M_{Pl})$ and back to impose GUT relations and universality of SB terms

[Girrbach, Jäger, Knopf, Martens, Nierste, Scherrer, Wiesenfeldt '11]

Look at flavour-diagonal and $b \to s \,/\, \tau \to \mu$ constraints:

M_h !!!

$b \to s\gamma,\ \tau \to \mu\gamma,$

ΔM_{B_s} (specify ϕ_{B_s}), ...

$B_s - \bar{B}_s$ mixing phase

Phase measured in $B_s \to J/\psi\phi$ time-dependent angular distribution:

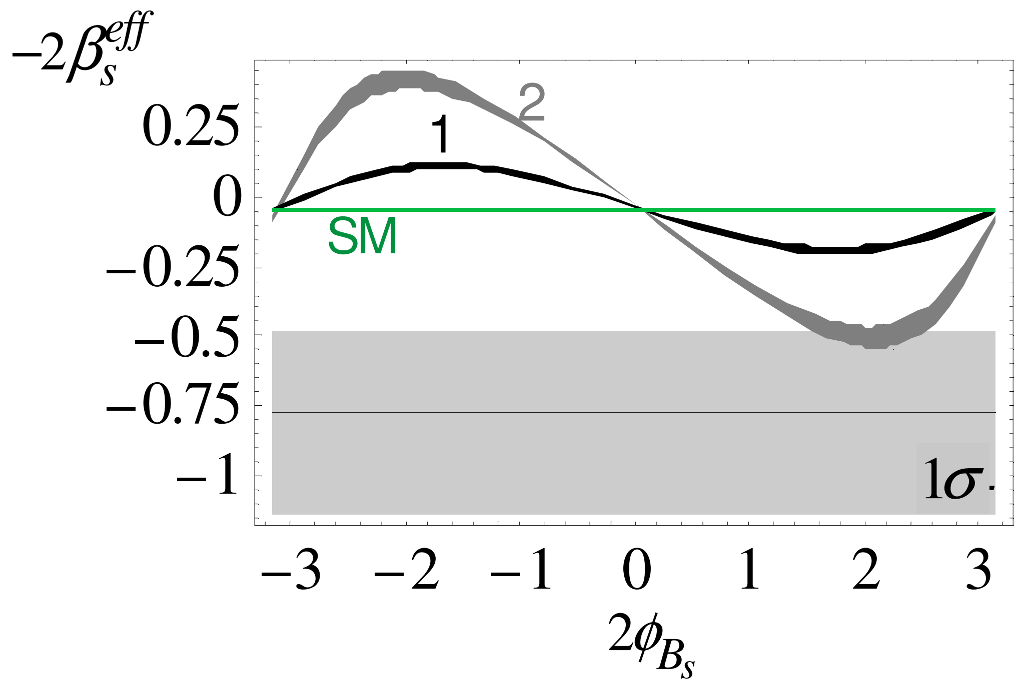
CDF+D0 $\quad -2\beta_s^{\rm eff} = \left(-0.83^{+0.30}_{-0.36}\right) \cup \left(-2.31^{+0.36}_{-0.30}\right)$ *[HFAG '10]*

SM $\quad -2\beta_s^{SM} \simeq -0.04$ $\quad \rightarrow 2.3\sigma$ discrepancy

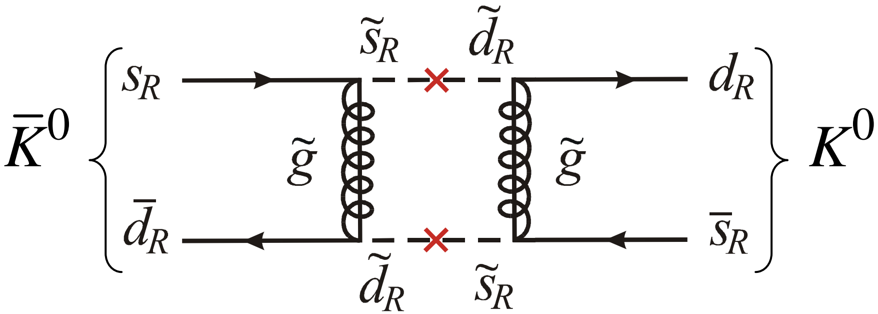
CMM contributions are able to reduce this discrepancy down to 1σ

example 1	example 2
$m_{\tilde{g}} = 700\,{\rm GeV}$	$m_{\tilde{g}} = 400\,{\rm GeV}$
$m_{\tilde{d}}^2 / m_{\tilde{g}}^2 = 8$	$m_{\tilde{d}}^2 / m_{\tilde{g}}^2 = 25$
$\Delta_{\tilde{d}} = 0.44$	$\Delta_{\tilde{d}} = 0.52$

$(\theta = 0)$

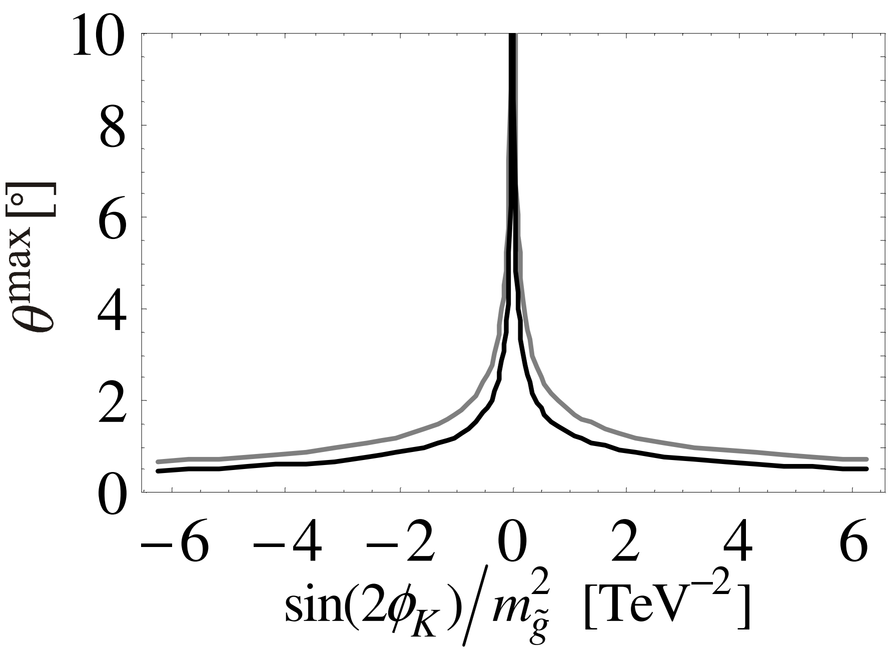


Constraints from $K-\bar{K}$ mixing



ε_K suppressed in the SM
$\Rightarrow$ CMM contribution comparatively large

$$|\varepsilon_K|^{\mathrm{CMM}} \simeq \frac{\mathrm{Im}\, M_{12}^K}{\sqrt{2}\,\Delta M_K} \propto \frac{M_K F_K^2 \hat{B}_K}{\Delta M_K}\, \alpha_s^2\, \frac{\sin(2\phi_K)}{m_{\tilde{g}}^2}\, L\left(m_{\tilde{d}}^2 / m_{\tilde{g}}^2, \Delta_{\tilde{d}}\right) \sin^2(2\theta)$$



$m_{\tilde{d}}^2 / m_{\tilde{g}}^2 = 8,\ \Delta_{\tilde{d}} = 0.44$

$m_{\tilde{d}}^2 / m_{\tilde{g}}^2 = 3,\ \Delta_{\tilde{d}} = 0.32$

$\theta^{\max} \lesssim 3^\circ$ for $m_{\tilde{g}} \sim 500\,\mathrm{GeV}$
as long as $|\phi_K| > 2^\circ$

Constraints from $B-\bar{B}$ mixing

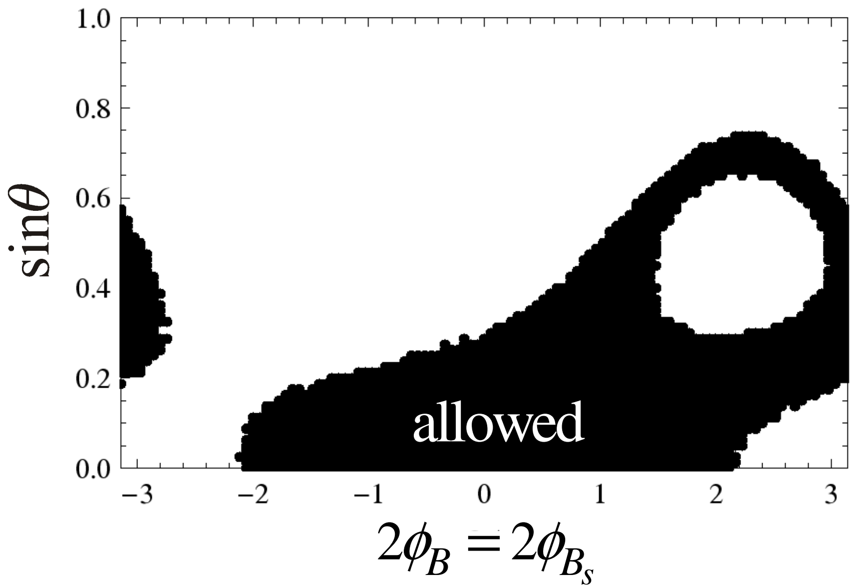
$\sin(2\phi_K)$ close to zero $\Rightarrow$ look at the B system. Typically: $\theta^{\max} = 10^\circ - 30^\circ$

example 1 $\quad m_{\tilde{g}} = 700\,\mathrm{GeV},\ \ m_{\tilde{d}}^2 / m_{\tilde{g}}^2 = 8,\ \Delta_{\tilde{d}} = 0.44$

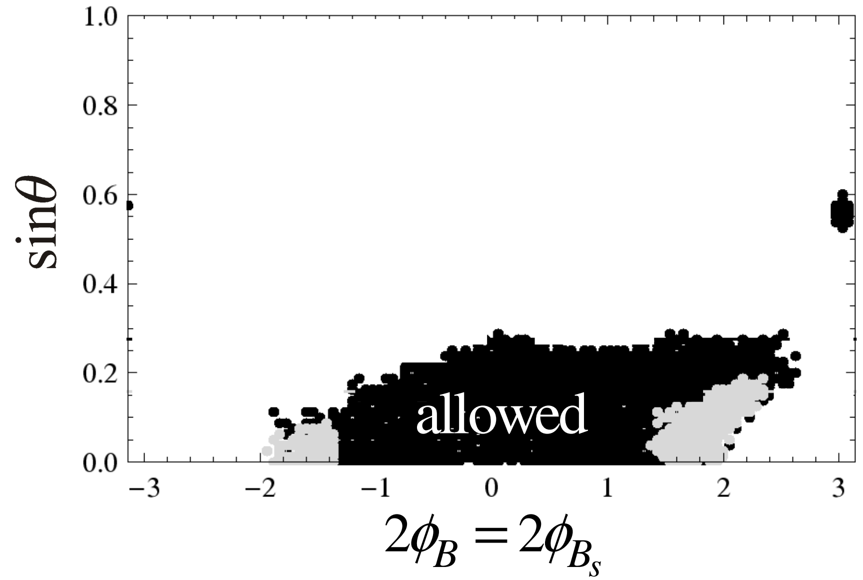
example 2 $\quad m_{\tilde{g}} = 400\,\mathrm{GeV},\ m_{\tilde{d}}^2 / m_{\tilde{g}}^2 = 25,\ \Delta_{\tilde{d}} = 0.52$

$(\phi_K = 0)$

constraint from $\Delta M_B / \Delta M_{B_s}$ alone



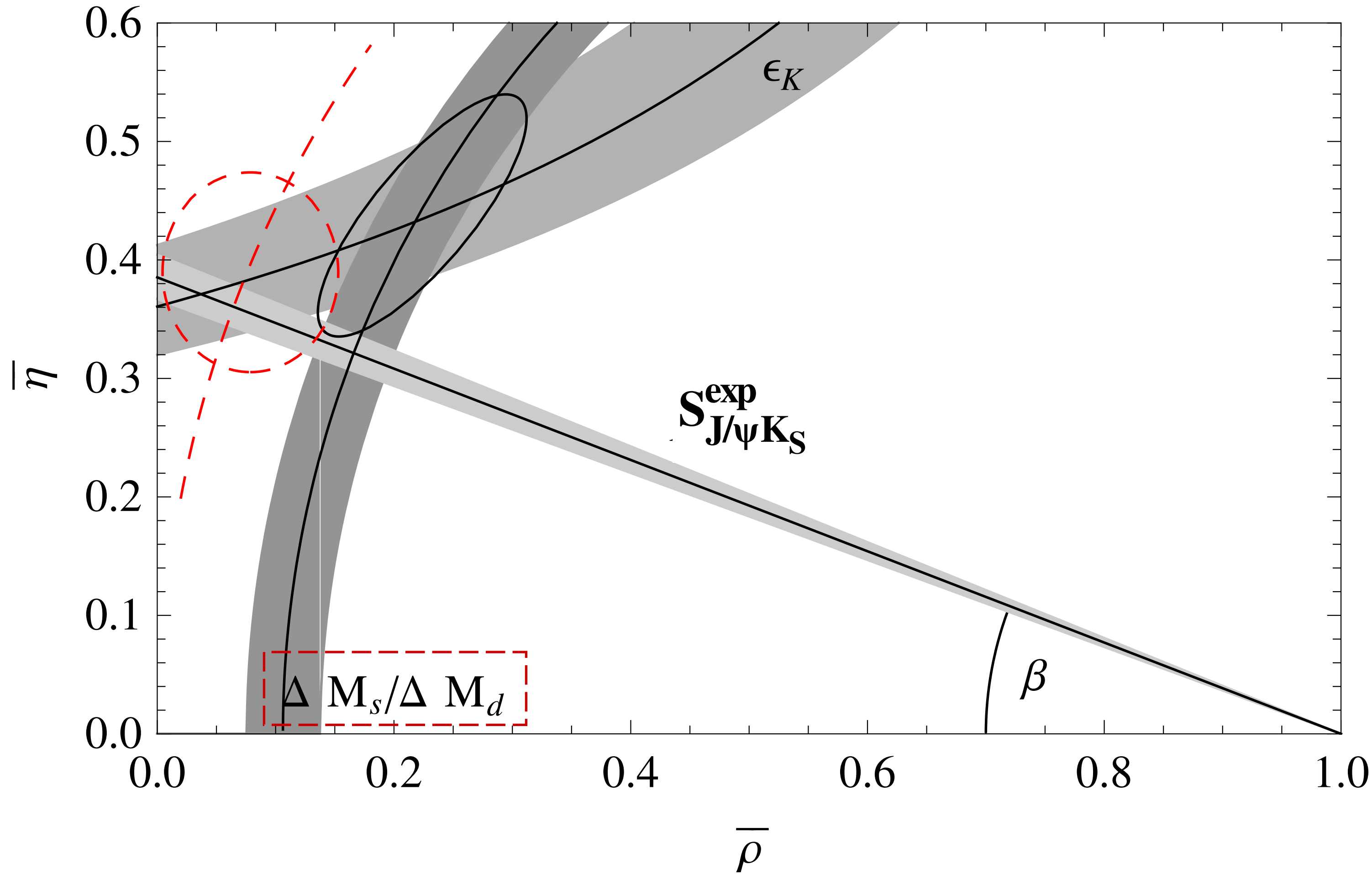
combined constraints: $\Delta M_B / \Delta M_{B_s},\ \Delta M_B,\ S_{J/\psi K_S},\ \Delta M_{B_s}$



Impact on unitarity triangle analysis

- Limit case 1: $\theta = 0$, $\phi_K \neq 0 \Rightarrow$ CMM effects in $B_s - \bar{B}_s$ mixing only

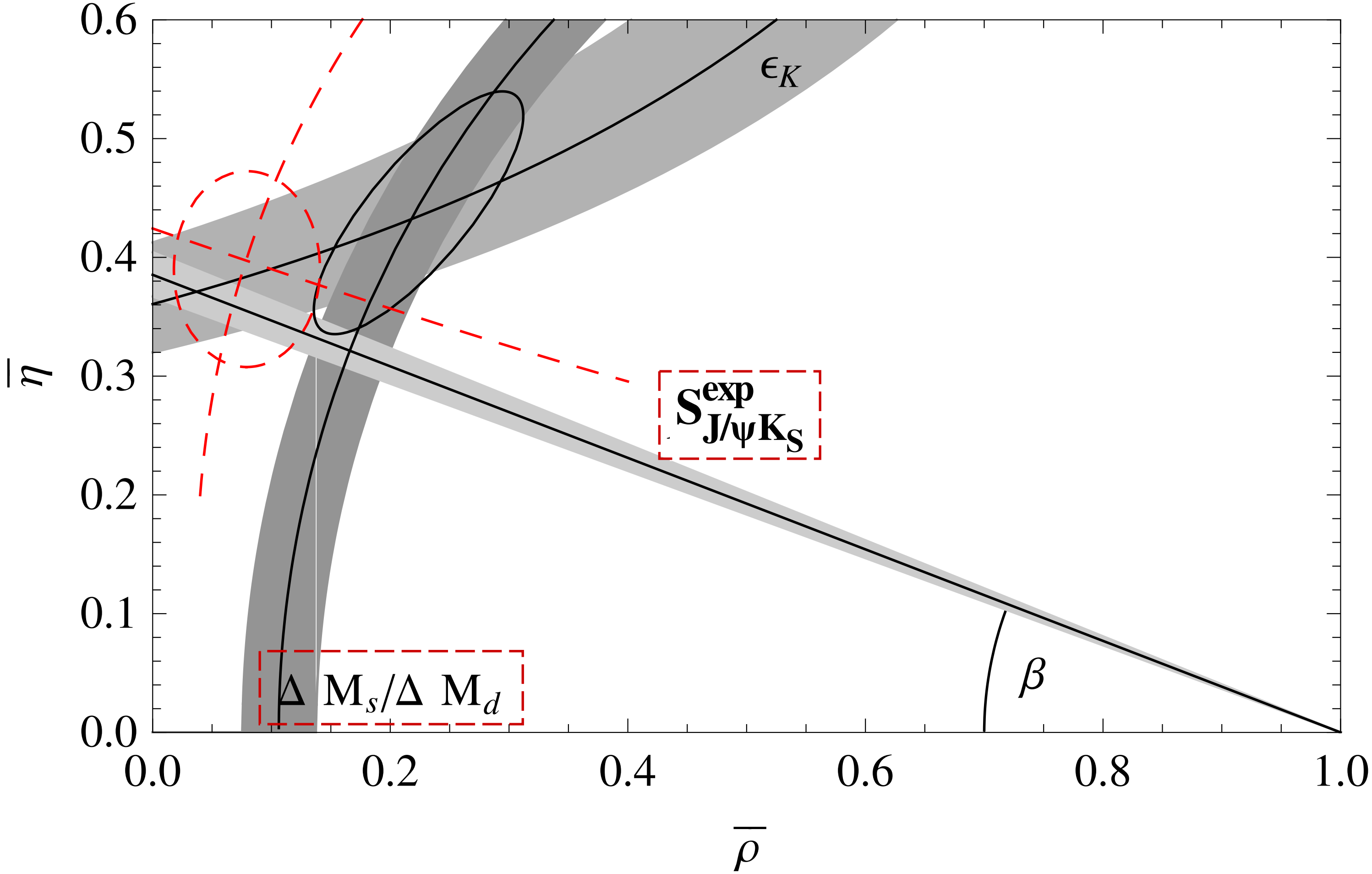
  example 2 $(m_{\tilde{g}} = 400\,\mathrm{GeV},\ m_{\tilde{d}}^2 / m_{\tilde{g}}^2 = 25,\ \Delta_{\tilde{d}} = 0.52)$ with $\phi_{B_s} = 0.7$



Impact on unitarity triangle analysis

- Limit case 2: $\theta \neq 0$, $\phi_K = 0 \Rightarrow$ CMM effects in $B_s - \bar{B}_s$ and $B - \bar{B}$ mixing

  example 2 $(m_{\tilde{g}} = 400\,\mathrm{GeV},\ m_{\tilde{d}}^2 / m_{\tilde{g}}^2 = 25,\ \Delta_{\tilde{d}} = 0.52)$ with $\phi_{B_s} = \phi_B = 0.7$, $\theta = 0.1$



Conclusion (scenario 2)

Yukawa unification $\mathbf{Y}_d = \mathbf{Y}_e^T$

$\Longrightarrow$ θ_{atm} can contaminate $\overset{(\sim)}{b}-\overset{(\sim)}{s}$ mixing

Corrections to Yukawa unification

$\Longrightarrow$ Impact of θ_{atm} on $\overset{(\sim)}{s}\rightarrow\overset{(\sim)}{d}$ and $\overset{(\sim)}{b}\rightarrow\overset{(\sim)}{d}$ transitions,
governed by a new parameter θ (+phases)

From K mixing (ε_K): either θ or ϕ_K must be unnaturally small

$\Longrightarrow$ Another aspect of the flavour problem in SUSY GUTs

Meson-antimeson mixing phenomenology:

- Possibility to account for a sizeable CPV phases in the $B_{s,d}$ systems
- Effects on UT analysis

Conclusion

Conclusion

Flavour-blind SUSY breaking does not (always) mean that flavour observables are automatically accounted for…

2 examples:

- MSSM with large tanβ
- MSSM in SO(10) context ($\neq$ mSUGRA!)

Flavour-blind: less parameters $\rightarrow$ better tested

In particular, if a large ϕ_s is confirmed, can it be accounted for?

- MSSM with large tanβ : NO
- MSSM in SO(10) context: YES

« SM flavour problem » (Yukawa structure) still to be addressed…