Large tanβ effects in flavour physics

Gino Isidori

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

FlaviAnet

- Introduction: the SUSY flavour problem & the MFV hypothesis
- MFV at large tanβ: general considerations
- Large tanβ effects in B (and K) physics
- Lepton Flavour violation and LF non-universality at large tanβ
- Conclusions

The SUSY flavour problem & the MFV hypothesis

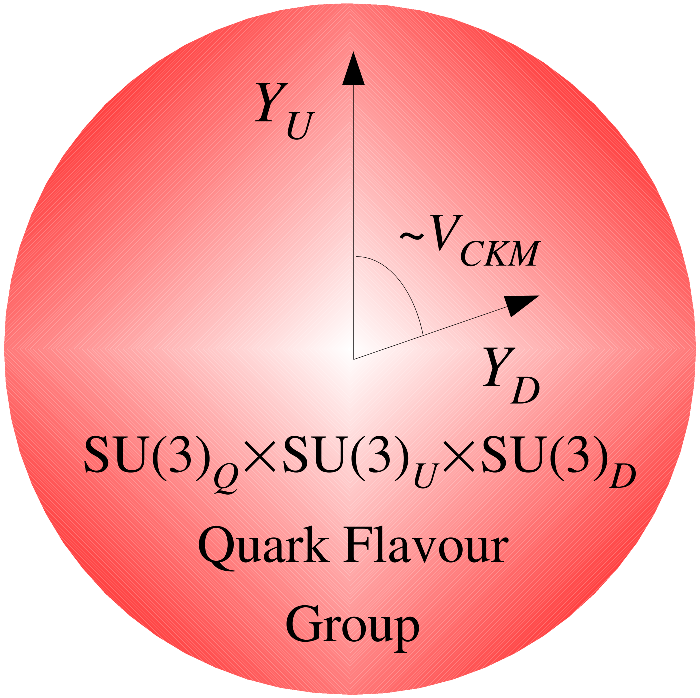
The flavour structure of the SM is quite constrained:

- a large global symmetry in the gauge sector
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
- broken only by the Yukawa couplings
  $Y_D \sim \bar{3}_Q \times 3_D \quad Y_U \sim \bar{3}_Q \times 3_U \quad (Y_E \sim \bar{3}_L \times 3_E)$

↓

This specific symmetry + symmetry-breaking pattern is responsible for the suppression of FCNCs, the suppression of CPV, etc...

The ugly (but highly successful...) part of the SM



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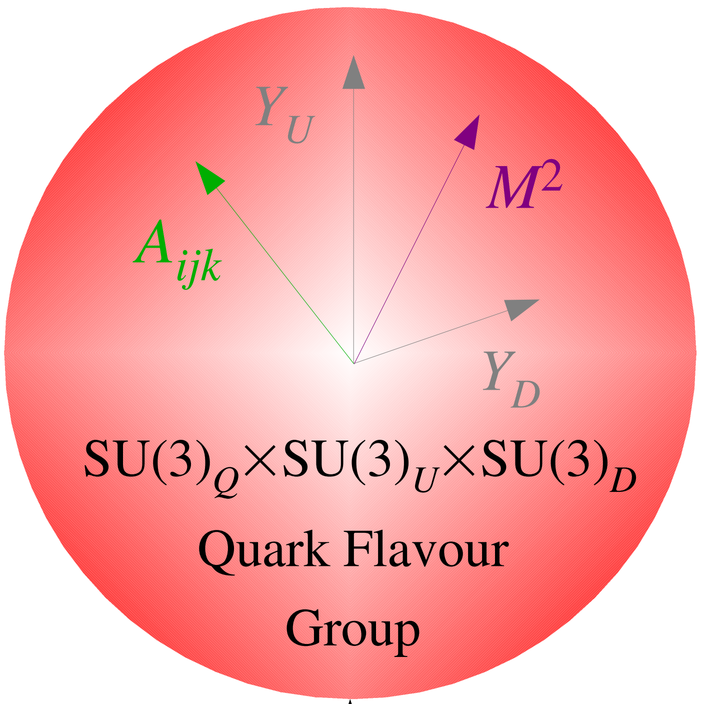


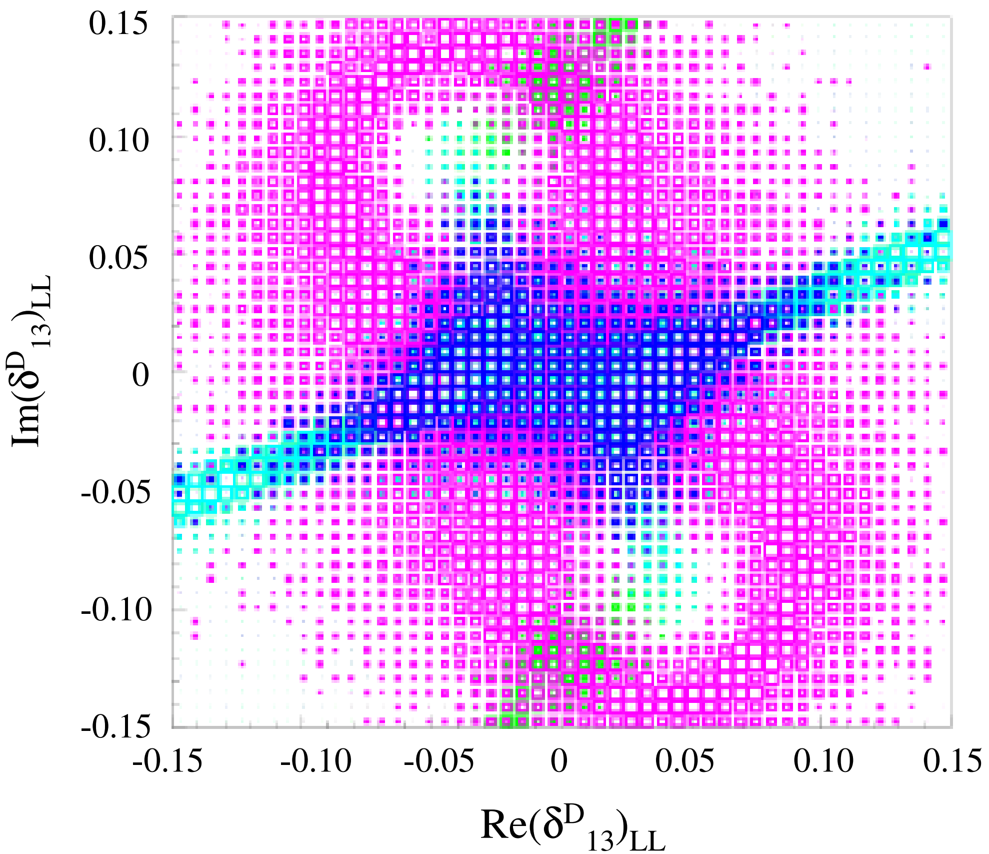
In principle, the soft breaking terms of the MSSM allow a much reacher symmetry-breaking structure:

$$\mathscr{L}_{soft} \subset (M^2)_{ij}\, \phi_i\, \phi_j + A_{ijk}\, \phi_i \phi_i \phi_k$$

New flavour-breaking terms not necessarily related to the Yukawa couplings

In practice, the absence of deviations form the SM in rare processes implies *severe constraints* on flavour-symmetry breaking terms beyond the SM Yukawas (at last in the quark sector...)

E.g.: Constraints on $(\delta^D{}_{13})_{LL}$ from B_d-meson mixing [L. Silvestrini @ CKM 2006]



$$(\delta^D{}_{13})_{LL} = \frac{(M^D{}_{13})^2{}_{LL}}{\langle M^D{}_{11}\rangle \langle M^D{}_{33}\rangle}$$

Δm_B only
sin 2β only
sin 2β and cos 2β
All constraints

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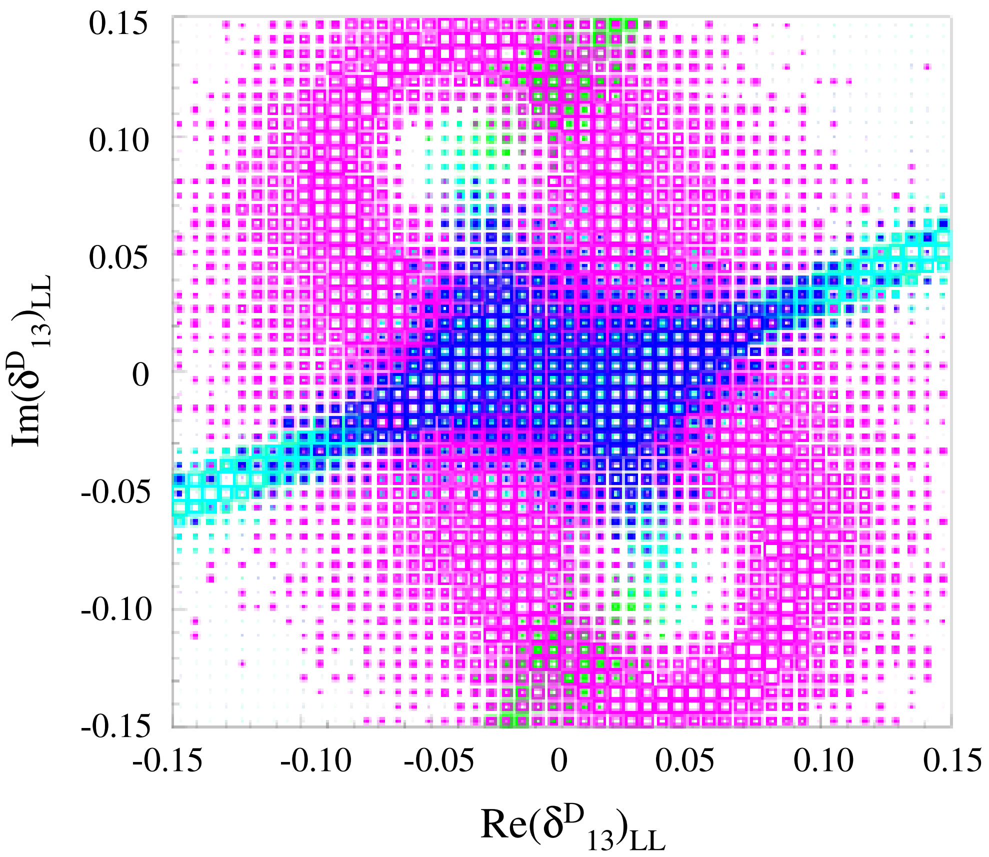

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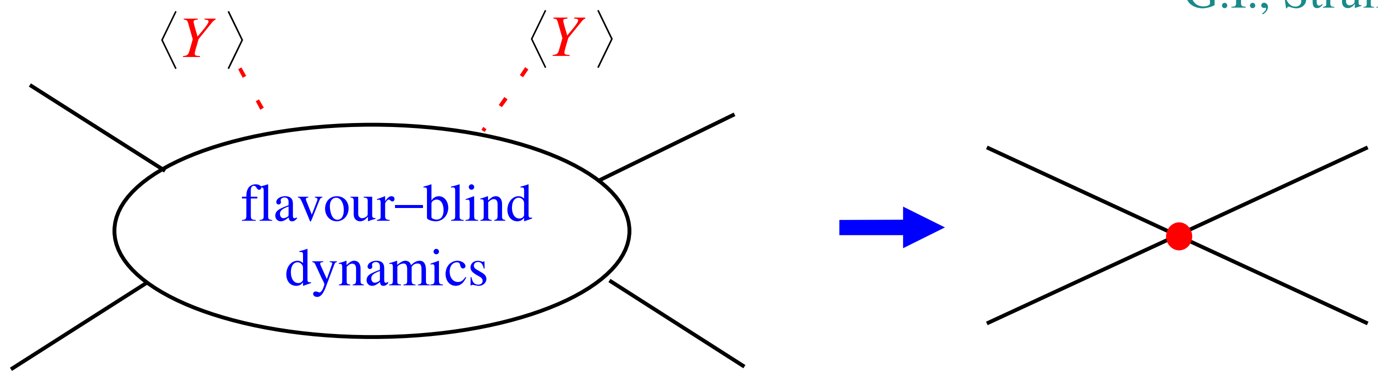
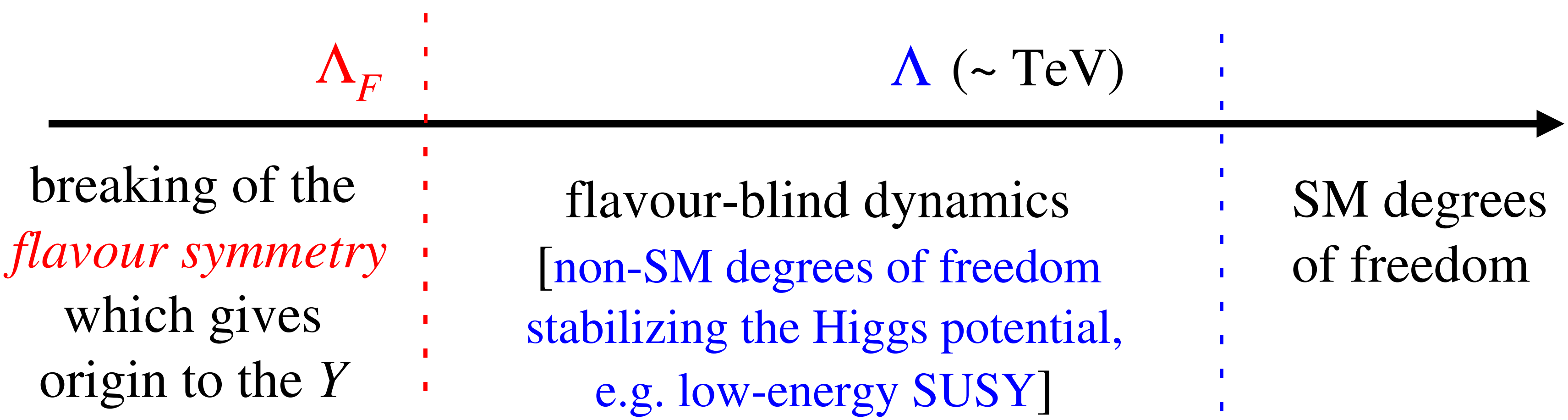
Similar (even more stringent) bounds are obtained also on many other δ's – taking into account ε_K, Δm_K, $K \to \pi\nu\nu$, $B \to X\gamma$, $B \to X l^+ l^-$, $B \to \mu\mu$, Δm_{Bs},...

The most pessimistic (but also most natural) way out to this problem is the so-called Minimal Flavour Violation [MFV] hypothesis: *the Yukawa couplings are the only irreducible sources of flavour symmetry breaking*

General principle (symmetry + symmetry-breaking structure) which can be formulated for any (TeV-scale) SM extension:

D'Ambrosio,Giudice, G.I., Strumia '02





Within the MSSM, the MFV hypothesis implies a strong restriction on the favour-structure of the soft breaking terms:

E.g.: $M_Q^2\, \tilde{Q}_L^+ \tilde{Q}_L \longrightarrow M_Q^2 \propto \Sigma\, a_n (Y_U Y_U^+)^n \sim a_0 I + a_1 Y_U Y_U^+$

- More general than universality [$M_Q^2 \propto I$]
- RGE invariant structure [with the a_n linked together by RGE]
- Perfectly compatible with persent data without fine-tuning on the a_n

$(\delta^D_{ij})_{LL} \propto y_t^2 (V_{CKM})_{3i}^* (V_{CKM})_{3j}$

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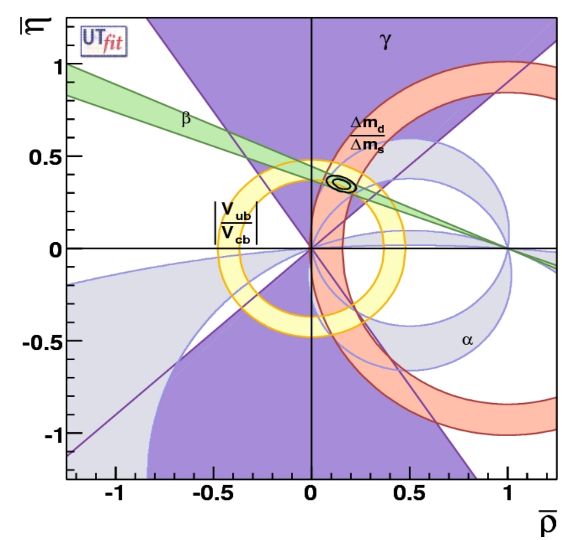
⇒ Same CKM factors as in SM:
only the flavour–independent magnitude
of FCNC amplitudes can be modified
[$A(b\to s\gamma) \propto V_{tb}V_{ts}$, $\Delta M_{Bd} \propto (V_{tb}V_{td})^2$,...]

⇒ very *efficient* suppression of NP effects in flavour physics, especially in the standard CKM fits...



Minimal Flavour Violation at large tanβ*: general considerations*

...however, with two Higgs doublets and a large ratio of vevs, interesting effects in rare decays can occur also under the pessimistic MFV hypothesis

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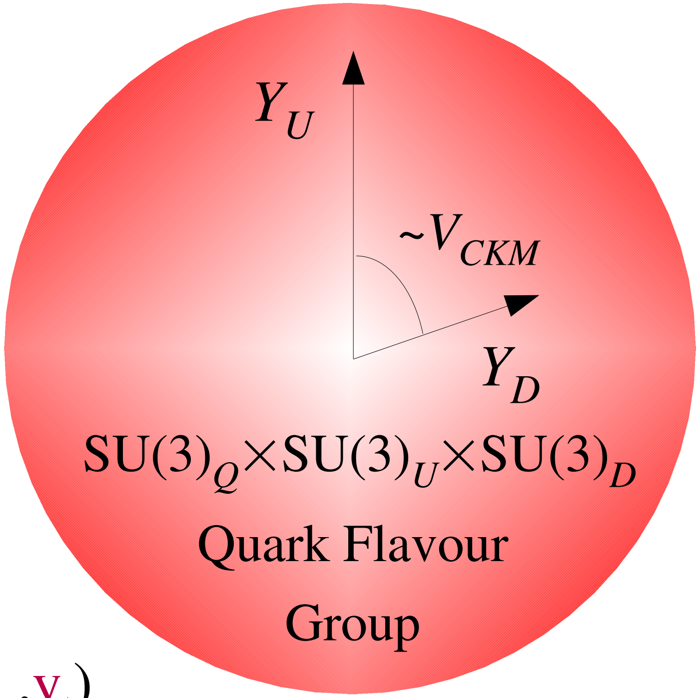
$$\mathscr{L}_{\text{q-Yukawa}} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + \text{h.c.}$$



Y_D & Y_U are still the only irreducible breaking sources of $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

→ negligible non-standard effects in the standard CKM fits

$$Y_D = \text{diag}(y_d, y_s, y_b) \qquad Y_U = (V_{ckm})^+ \times \text{diag}(y_u, y_c, y_t)$$

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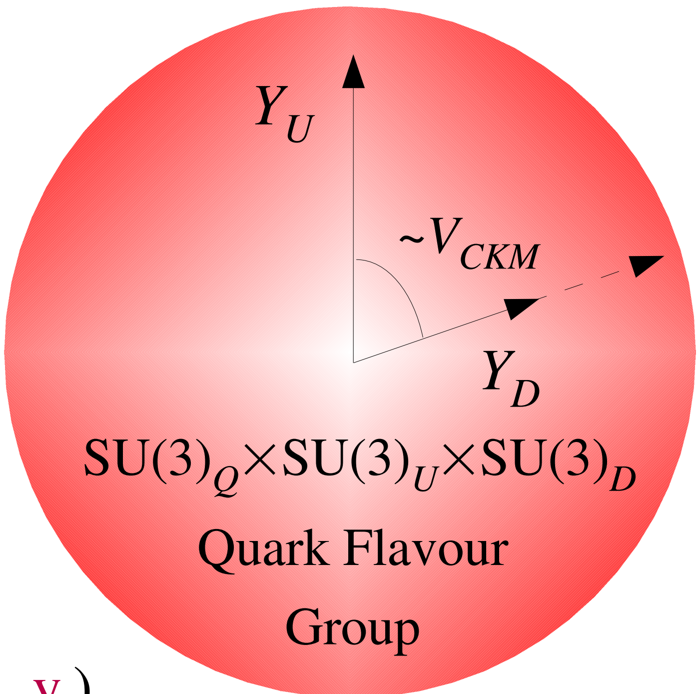

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However, we are free to change their overall normalization

$$y_u = m_u / \langle H_U \rangle \qquad y_d = m_d / \langle H_D \rangle = \tan\beta \, m_d / \langle H_U \rangle$$

→ sizable phenomenological consequences in helicity-supressed processes if $\tan\beta \gg 1$

Motivations

Large tanβ values are motivated by interesting theoretical considerations:

- tanβ ~ 40–50 allows the unification of top & bottom Yukawa couplings [⇒ SO(10) GUTs]

  wide literature

- tanβ ≫1 is a natural prediction of the Minimal Gauge-Mediated SUSY-breaking scenario [$\langle H_D \rangle = 0$ at the tree level], which also provide a natural dynamical motivation for MFV

  Dine, Nir, Shirman '96
  Rattazzi, Sarid '97

  Hisano, Shimizu '07

It's not a scenario ad hoc for flavour physics !

Motivations

Large tanβ values are motivated by interesting theoretical considerations

+

Intriguing phenomenological observations:

- Natural explanation of the ~ 3σ discrepancy in the anomalous magnetic moment of the muon:

$$\Delta a_\mu^{exp} = a_\mu^{exp} - a_\mu^{SM} = (29 \pm 9)10^{-10} \qquad (\sim 2 \times a_\mu^{ew\text{-}SM})$$ Hertzog et al. '07

$$\Delta a_\mu^{SUSY} \sim \tan\beta \times (m_W/M_{SUSY})^2 \times (a_\mu^{ew\text{-}SM}) \times \mathrm{sgn}(\mu)$$

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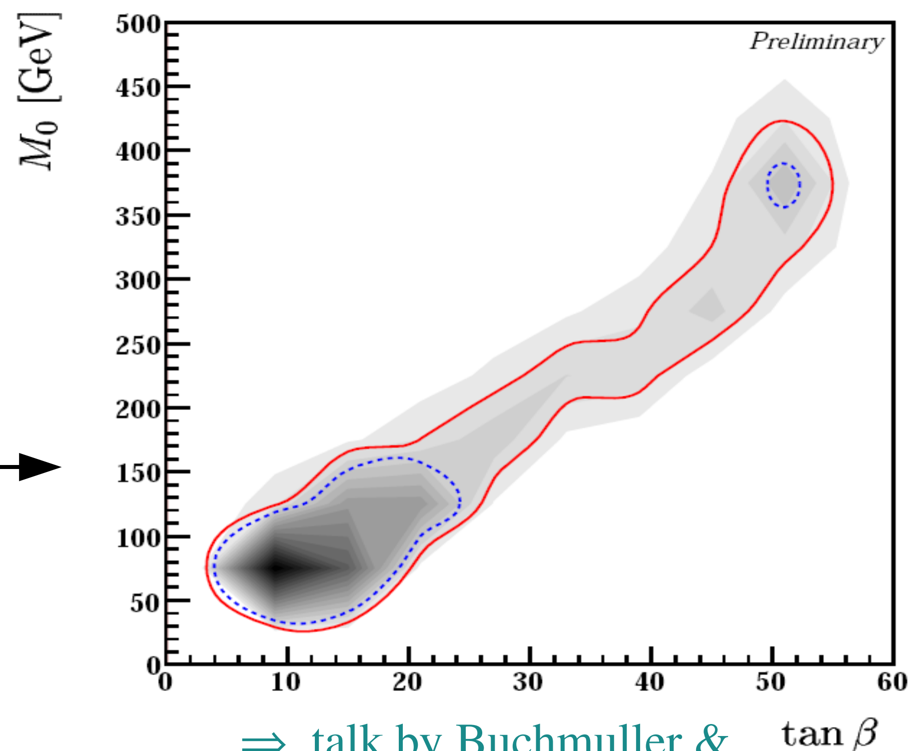
Intriguing phenomenological observations:

- Natural explanation of the ~ 3σ discrepancy in the anomalous magnetic moment of the muon

- Good consistency with e.w. & dark-matter constraints even in constrained scenarios

  - CMSSM [Buchmuller *et al.* '07] →

  - NUHM: large tanβ allowed even with (relatively) light M_H [Ellis, Heinemeyer, Olive, Weiglein '07]



⇒ talk by Buchmuller & Ronga in the Collider session

MSSM vs. Two-Higgs doublet models

Warning: the *effective* Yukawa interaction of the MSSM can be very different with respect to the non-superymmetric Two-Higgs Doublet Model of type-II, even in the limit of light Higgses & heavy squarks

$$\mathscr{L}_{\rm tree} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U$$

invariant under $U(1)_{PQ}$ ...

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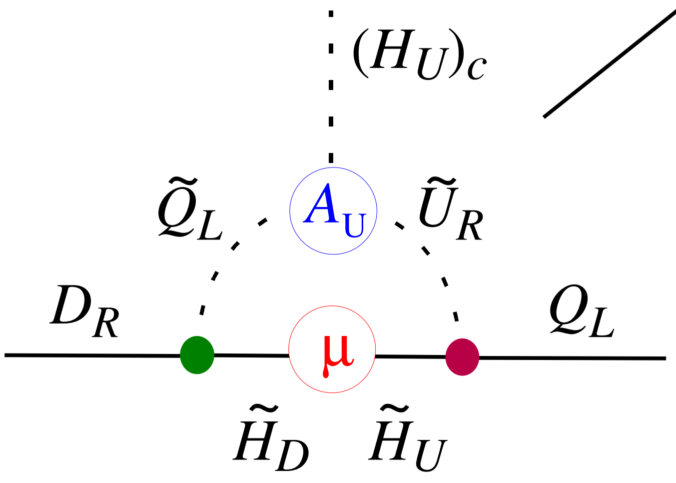
$$\mathscr{L}_{\rm eff} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + \epsilon_1 \bar{Q}_L Y_U Y_U^+ Y_D D_R (H_U)_c + \ldots$$

...possible large $U(1)_{PQ}$ breaking induced by the μ term



Even if $\epsilon_i \sim (16\pi^2)^{-1}$ these (*non-holomorphic*) terms are a potential large destabilization of the tree-level Yukawa strucutre:

- $\epsilon_i \times \tan\beta \sim 1$
- dim-4 ops. ⇒ non-decoupling effects

Hall, Rattazzi, Sarid, '94

Blazek, Raby, Pokorski, '95

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⇒ non-decoupling effects, inlcude Higgs-mediated FCNC's

A complete re-diagonalization of all the effective dim-four Yukawa terms is necessary in order to re-sum the large $\epsilon_i \times \tan\beta$ terms beyond ordinary perturbation theory [correct identification of the ground state]

Babu & Kolda '00; G.I. & Retico '02; Dedes & Pilaftsis '03,...

No further large quantum corrections if

- $\tilde{M}_Q \gg M_A \gg m_W$
- tanβ defined as $\langle H_U \rangle / \langle H_D \rangle$

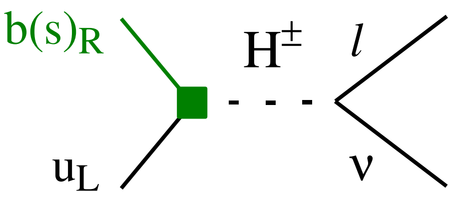
Alternative hierarchies and/or different tanβ definitions can be more problematic

Freitar, Gasser, Haisch, '07

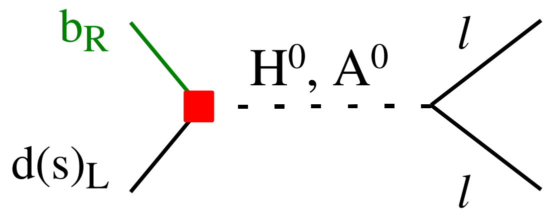
⇒ talk by S.Trine in the Flavour Session

*Large tan*β *effects in B (and K) decays*

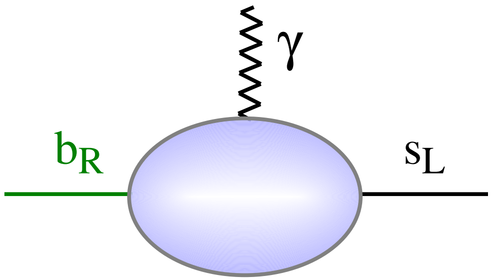
Three most interesting sets of observables:



$P^{\pm} \to l^{\pm}\nu$



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



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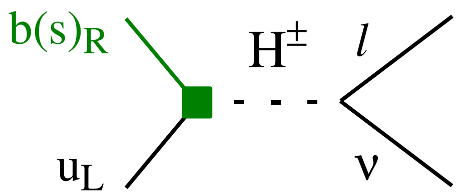

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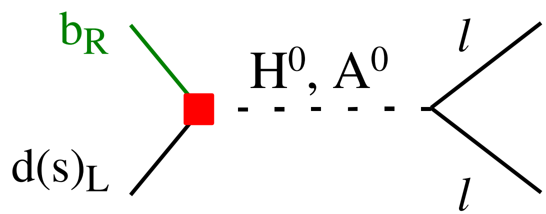

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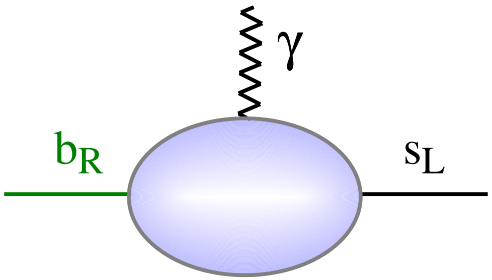


$B \to X_s \gamma$

Simplest M_H & tanβ dependence [mild dependence on other parameters]

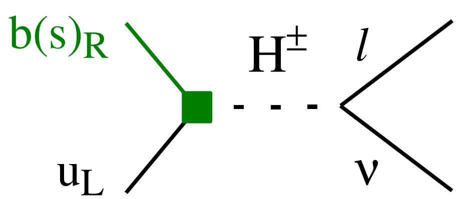
$$BR = BR_{SM} \times \left(1 - \frac{m_P^2 \tan\beta^2}{M_H^2 (1 + \epsilon_0 \tan\beta)} \right)^2$$

- $O(100\%)$–$O(10\%)$ in $B^{\pm} \to l^{\pm}\nu$
  [most likely $BR_{SUSY} < BR_{SM}$]
- $O(1\%)$–$O(0.1\%)$ in $K^{\pm} \to l^{\pm}\nu$
  [necessarily $BR_{SUSY} < BR_{SM}$]

G. Hou, '93; Ackeroid, Recksiegel, '03

G.I. Paradisi '06

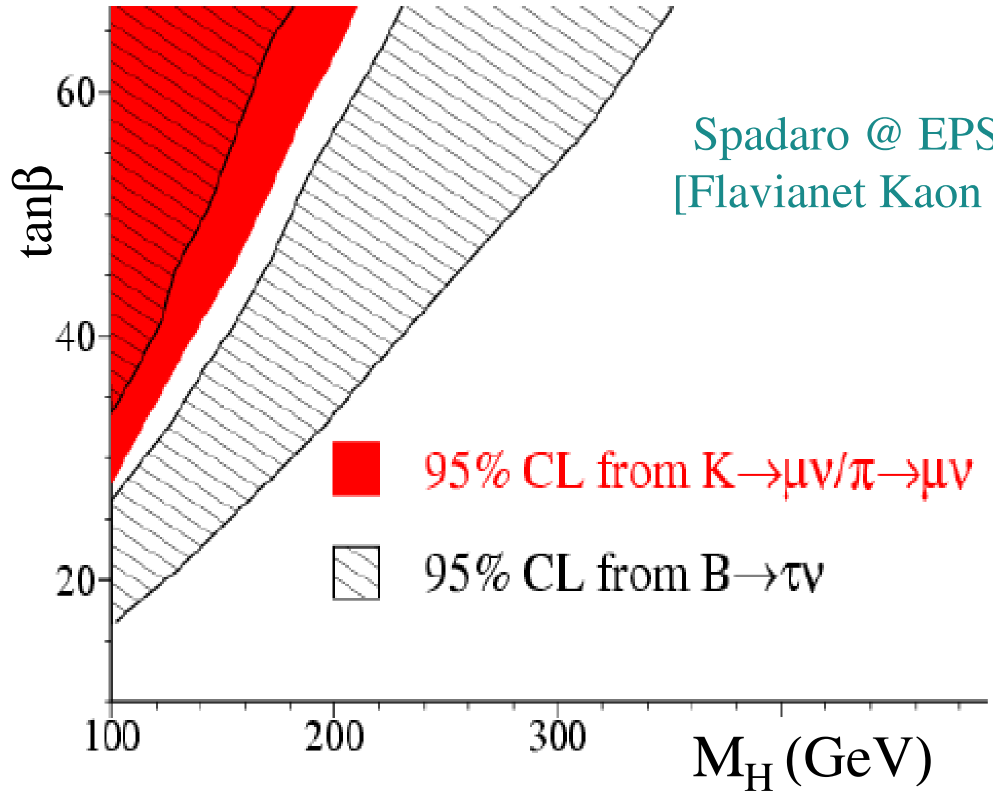
Large tanβ effects in B (and K) decays



$P^{\pm} \to l^{\pm}\nu$

$B(B \to \tau\nu) = (1.43 \pm 0.43)\times 10^{-4}$

$[B_{SM} \approx 1.2\times 10^{-4}]$ [Babar+Belle '07]



Spadaro @ EPS '07
[Flavianet Kaon WG]

$B(K \to \mu\nu(\gamma)) = (63.66 \pm 0.17)\%$ [KLOE]

+ f_K/f_π @ 0.7% [MILC/UKQCD '07]
+ V_{us} @ 0.5% [KLOE/NA48/KTeV + Theory]

Improving the measure of $B(B \to l\nu)$ provide very valuable infos on M_H & tanβ !

Large tanβ effects in B (and K) decays

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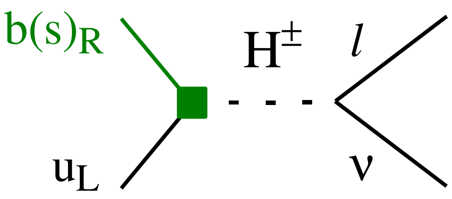

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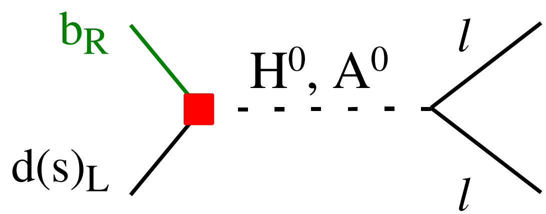

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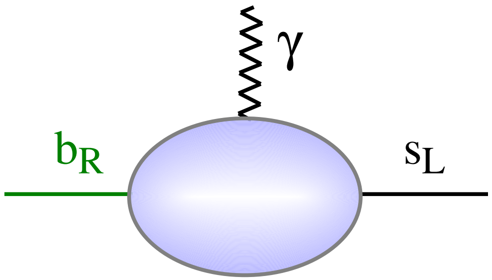
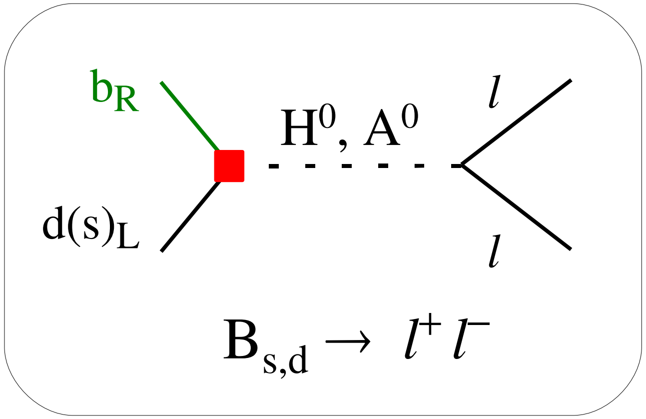


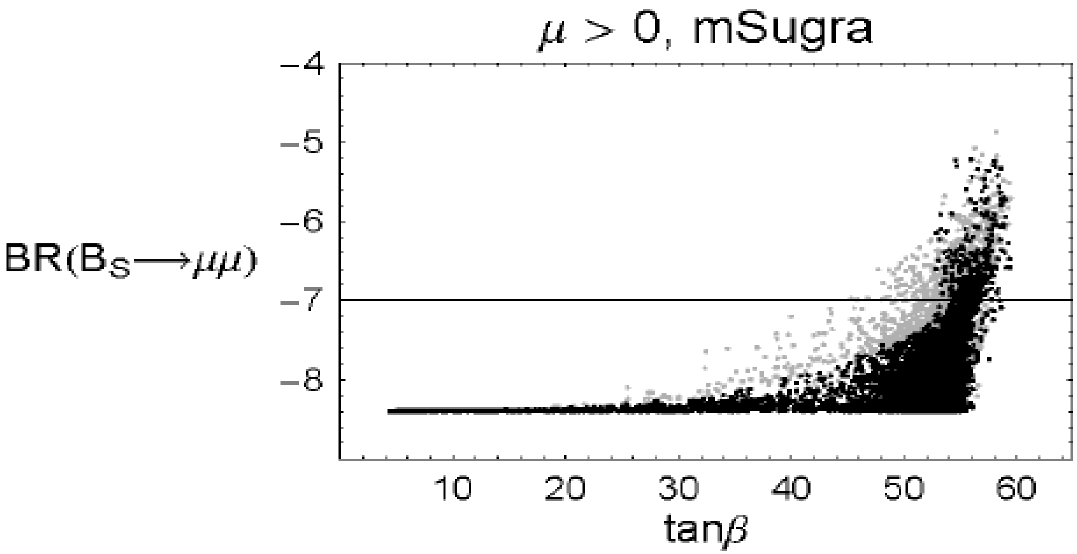
$B \to X_s\gamma$

Crucial dependence on μ and A_U [in addition to M_H & tanβ]

$$A(B\to ll)_H \sim \frac{m_b\, m_l}{M_A^2}\,\frac{\mu\, A_U}{\tilde{M}_q^2}\,\tan^3\beta$$

Possible large enhancement over the SM
but size (and magnitude) of the effect can change
substantially in different SUSY-breaking scenarios



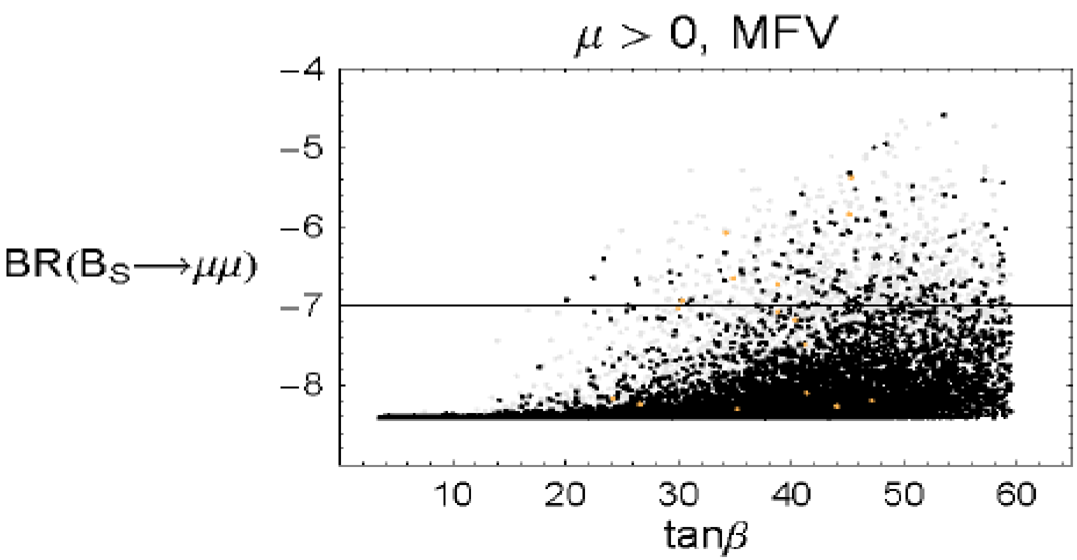


$B(B_s \to \mu\mu) < 5.8 \times 10^{-8}$ (95%CL)

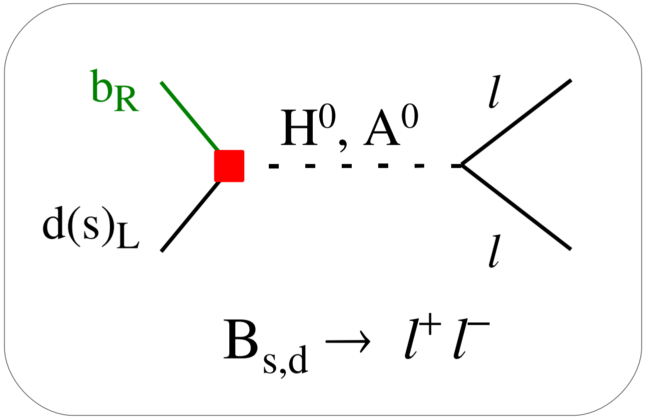
$[B_{SM} \sim 3\times10^{-9}]$

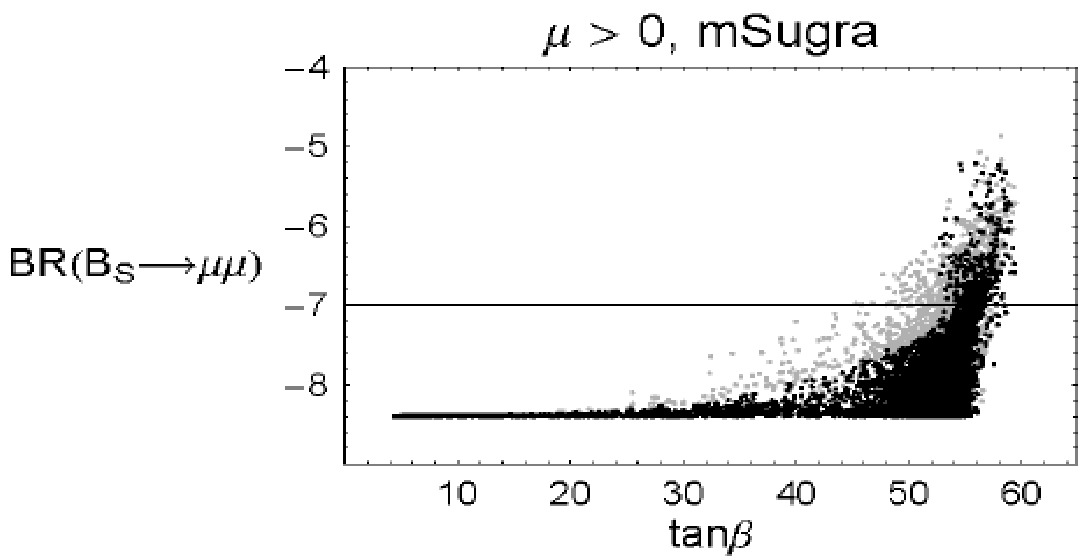
non-official CDF+D0 combined limit [EPS '07]

Significant constraint
but a good fraction of the
parameter sapce is still allowed



Lunghi, Porod, Vives '06





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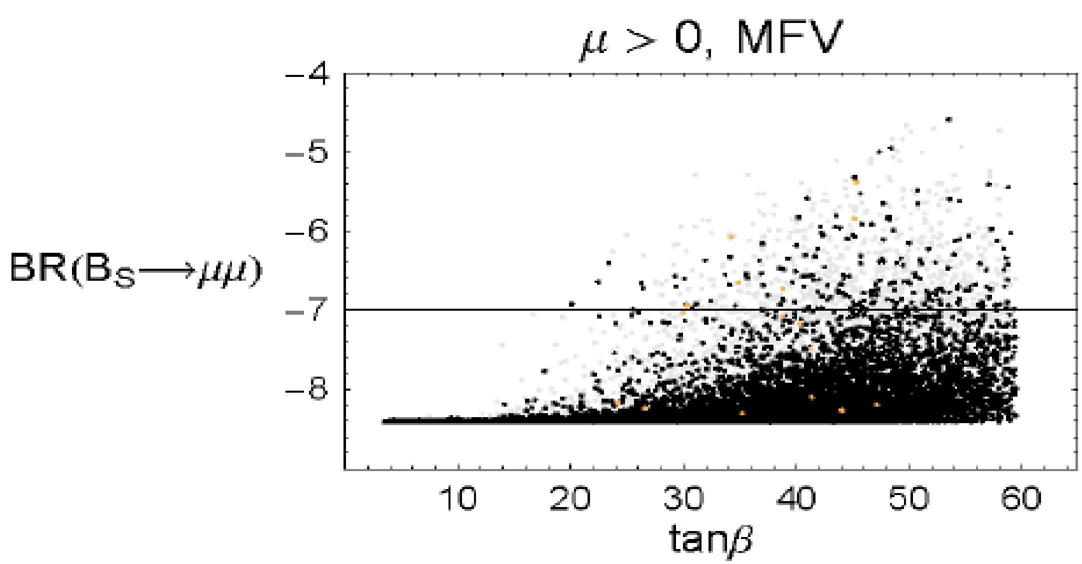

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importantant phenomenological implication:

negligible double-Higgs peunguin effect [Buras *et al.* '01] in ΔM_{B_s}

▶ *Large tanβ effects in B (and K) decays*

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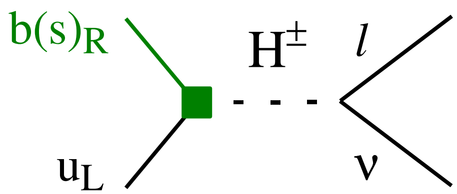
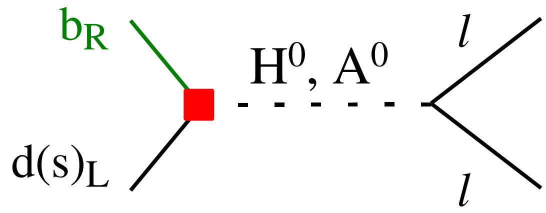


$P^{\pm} \to l^{\pm} \nu$



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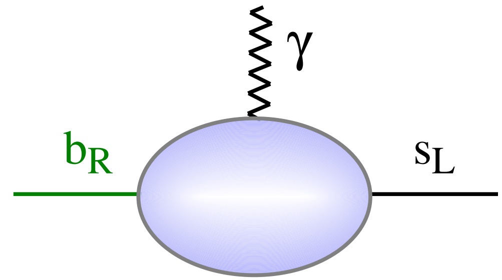

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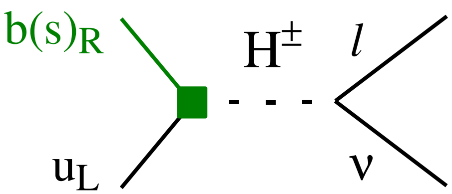

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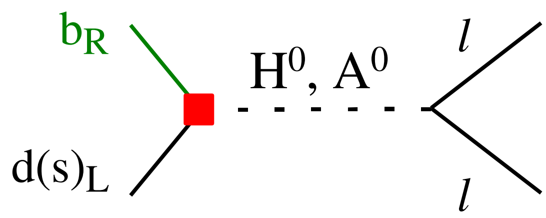

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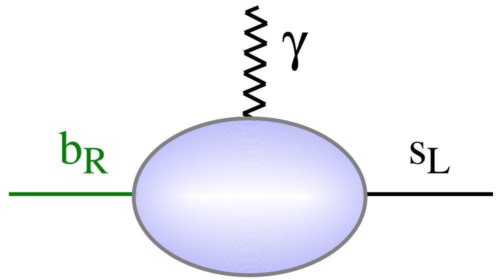
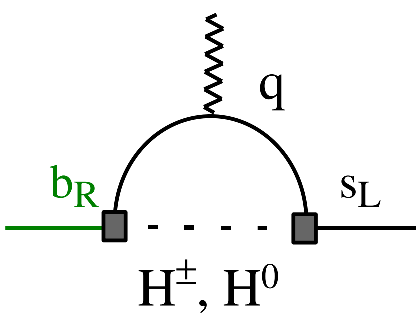
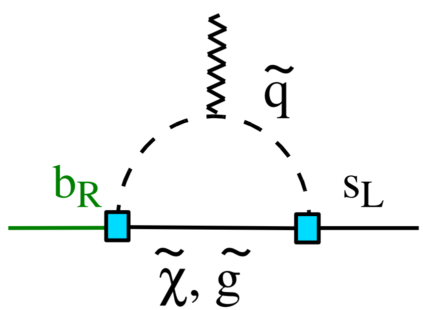


$B \to X_s \gamma$

Most complicated observable with several, naturally competitive, contributions:



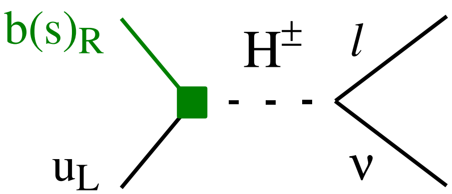
- positive
- decreasing with tanβ



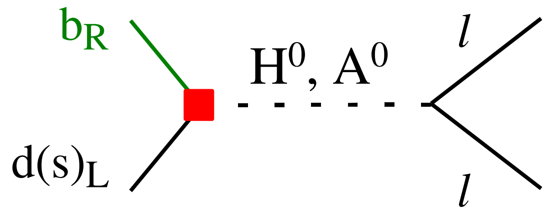
- sign ~ sgn(μ,A)
- increasing with tanβ

Large tanβ effects in B (and K) decays

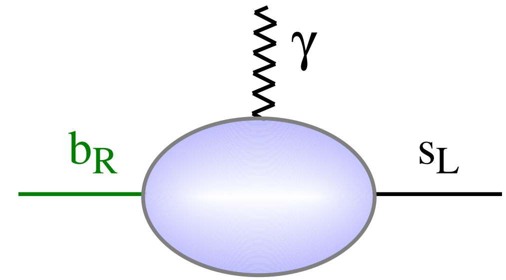
Three most interesting sets of observables:



$P^{\pm} \to l^{\pm}\nu$

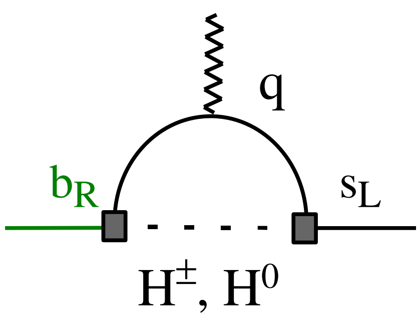


$B_{s,d} \to l^{+} l^{-}$

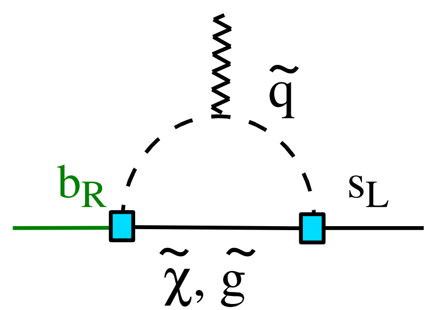


$B \to X_s \gamma$

Most complicated observable with several, naturally competitive, contributions:



- positive
- decreasing with tanβ



- sign ~ sgn(μ,A)
- increasing with tanβ

One of the most significant constraint of the MSSM:

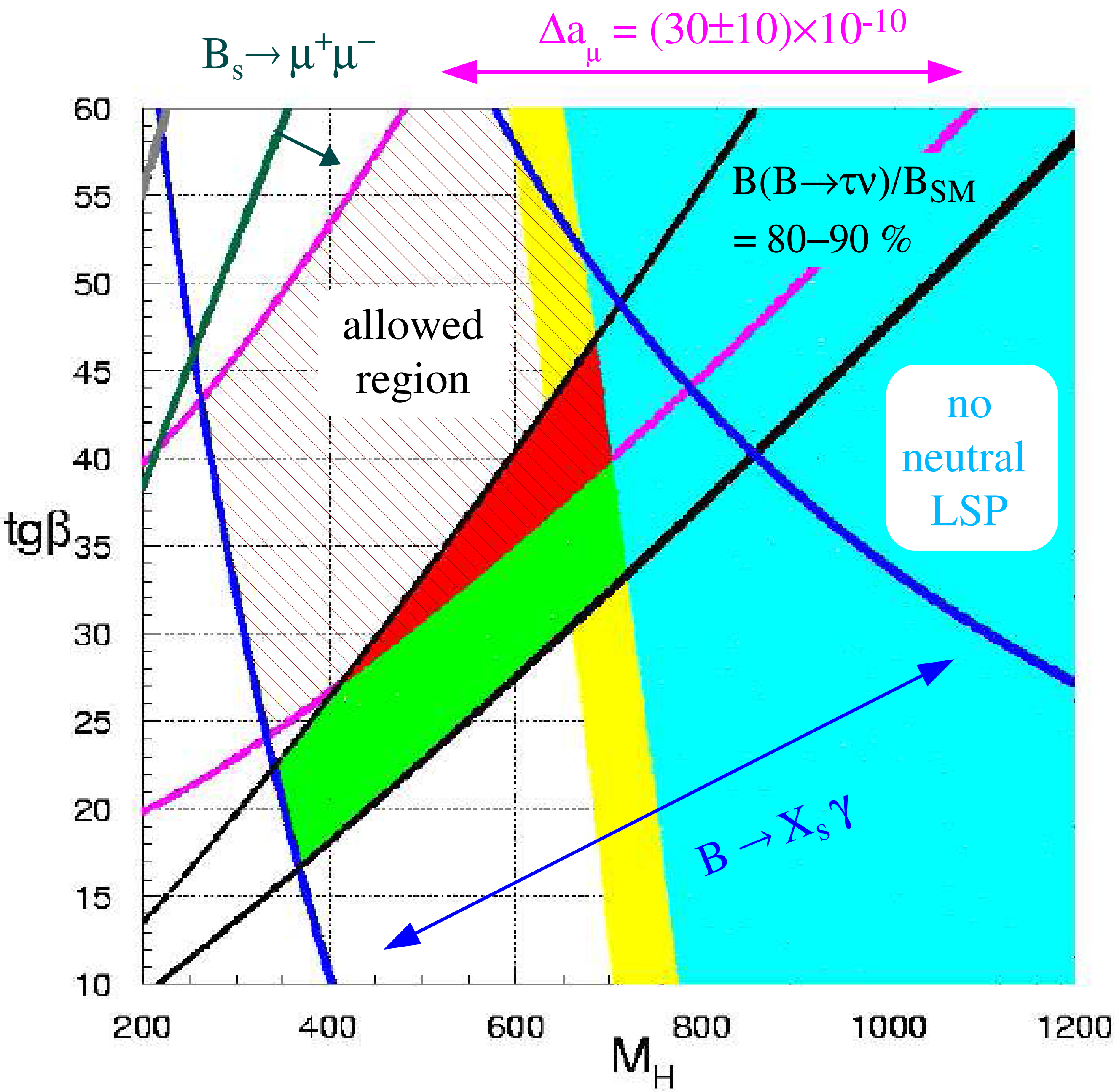
$$B(B \to X_s\gamma)^{exp} = (3.55 \pm 0.26)\times 10^{-4}$$

[HFAG '06]

$$B(B \to X_s\gamma)^{SM} = (3.15 \pm 0.23)\times 10^{-4}$$

[Misiak et al. '06]

E.g.: combined low-energy constraints
+ dark matter (A-funnel region)
+ heavy squarks



M_{sq} = 1.5 TeV M_{sl} = 0.5 TeV

A_u = -1.0 TeV μ = 0.5 TeV

G.I., Mescia, Paradisi, Temes, '07

Lepton Flavour violation and LF non-universality at large tanβ

Large tanβ values naturally enhance various LFV rates [e.g. $\Gamma(\mu \to e\gamma) \sim \tan\beta^2$,...], but interesting phenomena can show up also in the quark sector under specific circumstances:

If the model has sizable non-MFV sources of breaking in the lepton sector (non-minimal LFV) ⇒ possible visible violations of LF universality in $B(K) \to l\nu$

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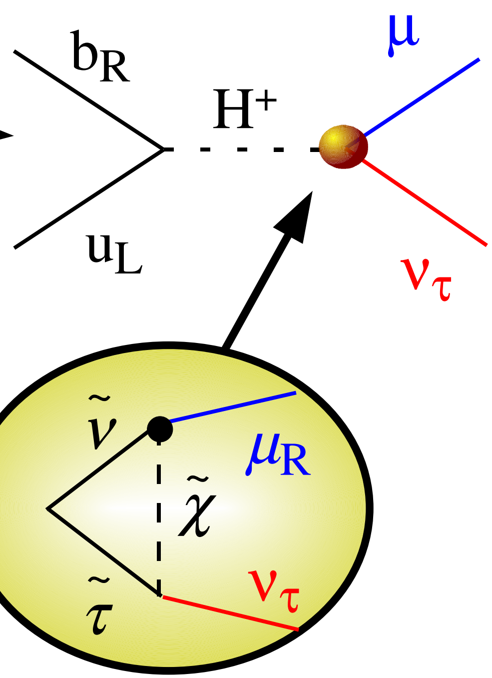
$$\Gamma(B \to \mu\nu)^{exp} = \Gamma(B \to \mu\nu_\mu) + \Gamma(B \to \mu\nu_e) + \Gamma(B \to \mu\nu_\tau)$$

SM 0 scalar LFV amplitude



sizable one-loop eff. coupl. because of 3rd generation & large mixing in the lepton sector

Masiero, Paradisi, Petronzio, '05

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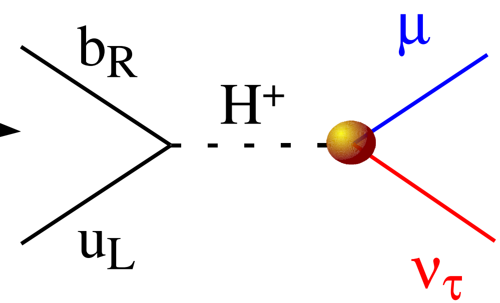


Possible probe of this effect in the ratios:

$$R^B_{\mu\tau} = \frac{\Gamma(B^+ \to \mu^+\nu)}{\Gamma(B^+ \to \tau^+\nu)} \qquad R^B_{e\tau} = \frac{\Gamma(B^+ \to e^+\nu)}{\Gamma(B^+ \to \tau^+\nu)}$$

up to +10% $(R^B_{\mu\tau})^{SM}$ up to $+10^3$ $(R^B_{e\tau})^{SM}$

deviations form the SM
$\sim (\tan\beta)^4 \times (\delta^{slept})_{23}$

Interesting correlation with the same phenomenon in the Kaon system, which so far set the best upper limit:

$$R^K_{\mu e} = \frac{\Gamma(K^+ \to \mu^+\nu)}{\Gamma(K^+ \to e^+\nu)} \rightarrow \text{up to 1\% diff. from SM}$$

2007 dedicated run by NA48 to reach 0.3% accuracy

Conclusions

The MSSM with MFV + large $\tan\beta$ is a quite interesting scenario:

- well motivated (not *ad hoc* for flavour physics)
- consistent with present data
  (no more fine-tuned than other MSSM scenarios)
- predictive, with enhanced correlations between low- and high-energy data which could possibly be falsified/verified in the (near ?) future

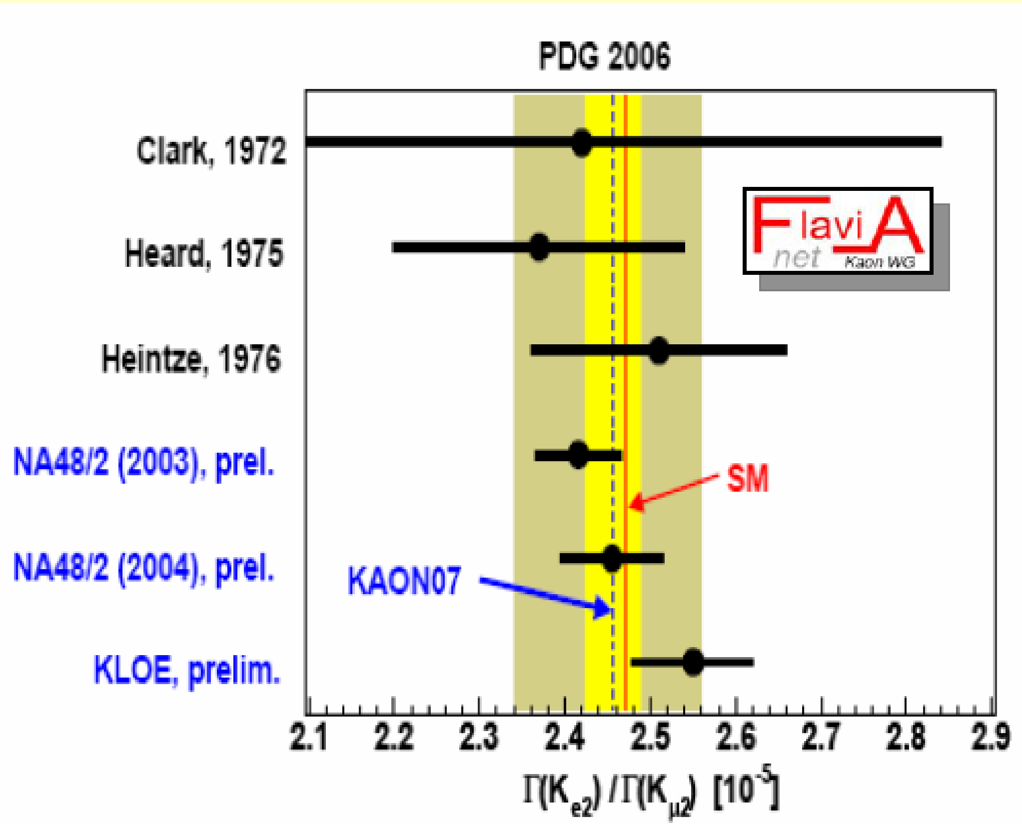
⬇

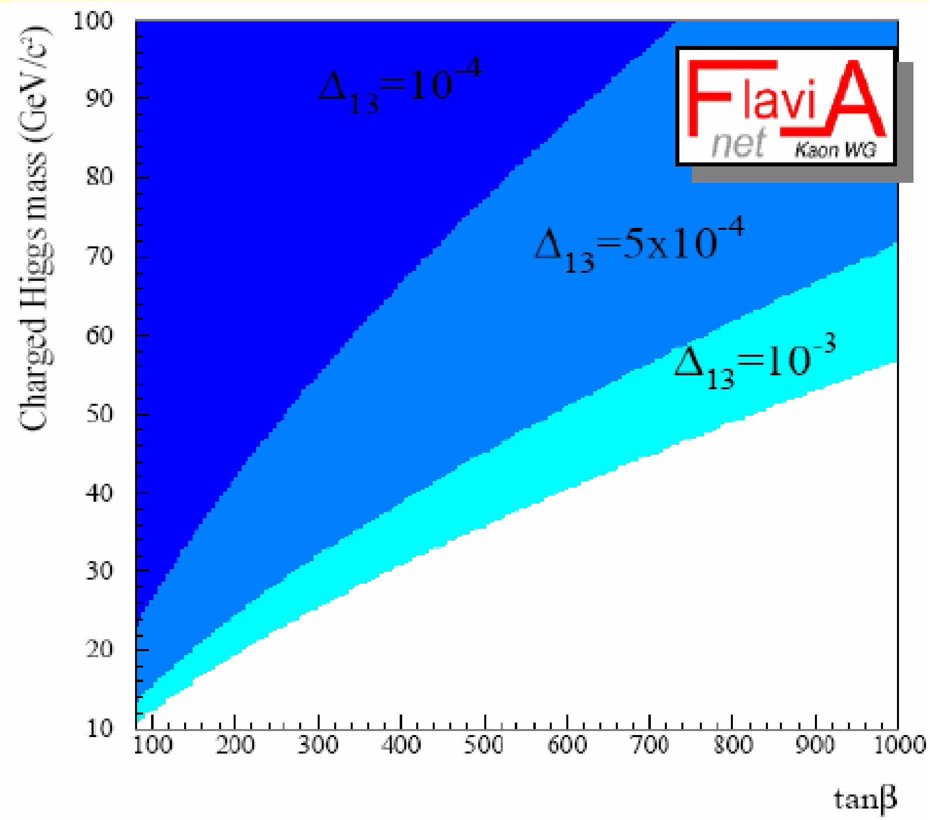
Key role played by future improvements on the helicity-suppressed modes $B(K) \to l\nu$, $B \to ll$, and $\mu \to e\gamma$

Backup

Backup

Limit on LFV in H^+ coupling $\Rightarrow$ $B(K \to e\nu) \,/\, B(K \to \mu\nu)$





$$\Delta_{13} \sim (\alpha/4\pi)\,(\delta_{RR})_{13}$$