Minimal Flavour Violation: an effective field theory approach

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Outline

- Minimal Flavour Violation (MFV) in various extensions of the Standard Model
- Goal of our approach
- MFV, effective theory with one Higgs: phenomenology
- MFV, effective theory with two Higgses: Peccei-Quinn symmetry breaking and phenomenology
- Conclusions

From the work of G. D. G.F. Giudice, G. Isidori, A. Strumia, hep-ph/0207036

Technicolour

- In Technicolour in addition to SM fields we have a SU(2)$_W$ doublet of quarks, T, coupled to SU(N$_T$)$_W$ gauge group

$$\langle T\bar{T}\rangle \Rightarrow \begin{cases} SU(2)_W \otimes U(1) \text{ breaking} \\ m_q, m_l \sim \dfrac{2g_E^2\langle T\bar{T}\rangle}{M_{ETC}^2} \end{cases}$$

- Mixing T$\leftrightarrow$Q $\Rightarrow$ Large FCNC $M_{ETC} > 1.6 \times 10^4 \mathrm{GeV}$

- Chivukula and Georgi 86 SM fields: 3 families of Q(quark left-doublet) U(right-singlet u-quark) D(right-singlet d-quark) L(lepton left-doublet) E (lepton right-singlet) have a global symmetry G$_F$ $= U(3)^5$ broken only by spurion fields: the Yukawas, Y$_{U,D,E}$

$\Downarrow$

$\boxed{\text{Underlying preonic dynamics preserving } G_F}$

$\downarrow$

$\boxed{\text{SM gauge group}, \langle T\bar{T}\rangle, G_F, Y_{u,d,l}}$

- ΔS=2 preserve GIM mechanism and thus $M_{ETC} \sim$ 5 TeV :

$$\frac{1}{M_{ETC}^2}(\bar{Q}\gamma^\mu Y_U Y_U^\dagger Q)^2 \sim \frac{V_{td}^* V_{ts}\dfrac{m_t^2}{v^2}}{M_{ETC}^2}(\bar{s}\gamma^\mu d)^2$$

Supersymmetric Flavour Problem

- An analogous problem exists in Supersymmetry: 3 families of (Q,U,D,L,E) with superpartners.
- Supersymmetry must be broken

$$-\mathcal{L}_{soft} = m_Q^2 \tilde{Q}^\dagger \tilde{Q} + m_L^2 \tilde{L}^\dagger \tilde{L} + a_u \bar{\tilde{U}} \tilde{Q} H_u + \ldots$$

- $m_Q^2, m_L^2, a_u, \ldots$ are matrices in flavour space and thus they carry additional (to $Y_{u,d,l}$) non-trivial flavour structures

$$\Downarrow$$

$$\text{Large FCNC: } \mathcal{H}_{\Delta S=2} \sim \frac{(\bar{s}d)^2}{m_{\tilde{Q}}^2}$$

$$\Downarrow$$

$$m_{\tilde{Q}} > 100\mathrm{TeV}$$

- Gauge mediation

  Problem ameliorated by assuming a hierararchy among the scale of supersymmetry breaking (Λ_S) and the scale of where flavor structures are generated (Λ_F):

  $\Lambda_F > \Lambda_S \Rightarrow m_Q^2, m_L^2, a_u, \ldots$ know only the structures $Y_{u,d,l}$

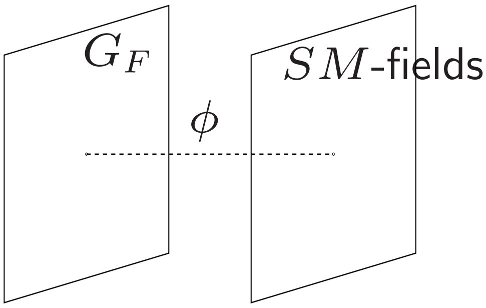
and thus $m_{\tilde{Q}} > 5\mathrm{TeV}$ (Dine,Nelson, Shirman; Giudice, Rattazzi)

Large Extra dimension Flavour Problem

- Large extra dimensions also address the issue of fermion mass generation Arkani-Hamed et al., Dine et al.

- Severe FCNC unless MFV is imposed

- SM-fields live on one brane while flavour breaking is comunicated by a messanger-field ϕ. However since flavour is broken only trough $Y_{U,D,E}$, (G_F is preserved) is possible to solve FCNC-problems (Rattazzi, Zaffaroni)



Motivation of a systematic study of Minimal Flavour violation (MFV)

- To write a theory of flavours (valid also beyond the SM), which is potentially consistent with Higgs stabilized $100\mathrm{TeV} \rightarrow 5\mathrm{TeV}$

- We want to know, which scales are we probing in CKM-fit or rare decays in a theory where the Flavor problem has been "solved".

- This should motivate which physics we should look

- We can study also in a systematic and general way, from an effective field theory point of view, the MFV model with two Higgs doublets

- This will allow to uncover new phenomenology (two-loop $\tan\beta$-enhanced) for $B \rightarrow X_s\gamma$, ΔM_B and $B \rightarrow \ell^+\ell^-$

Description of the MFV effective theory

We write an effective theory for the 3 families of Q, U, D, L, E_R which has the global symmetry broken by the Yukawas Y_{U,D,E_R}

$$G_F \equiv$$

$$\mathrm{SU}(3)^3_q \otimes \mathrm{SU}(3)^2_\ell \otimes \overbrace{\mathrm{U}(1)_B \otimes \mathrm{U}(1)_L \otimes \mathrm{U}(1)_Y}^{\text{preserved by}\mathrm{Y_{U,D,E}}} \underbrace{\otimes \mathrm{U}(1)_{\mathrm{PQ}} \otimes \mathrm{U}(1)_{E_R}}_{\text{broken by}Y_{U,D,E}}$$

- We will see that the $\mathrm{U}(1)_{\mathrm{PQ}}-$ breaking will be relevant for the two Higgs model

Giving the transformation properties of the spurions

$$Y_U \sim (3, \bar{3}, 1)_{\mathrm{SU}(3)^3_q}\ , \quad Y_D \sim (3, 1, \bar{3})_{\mathrm{SU}(3)^3_q}\ , \quad Y_E \sim (3, \bar{3})_{\mathrm{SU}(3)^2_\ell}$$

we have the dim-4 lagrangian

$$\mathcal{L} = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + \bar{L}_L Y_E E_R H \ + \ \mathrm{h.c.}$$

We can choose the fields Q_L, U, D so that

$$Y_D = \lambda_d\ , \qquad Y_U = V^\dagger \lambda_u\ ,$$

All the non-trivial structure to the dim-6 lagrangian is generated by

$$(\lambda_{\mathrm{FC}})_{ij} = \begin{cases} \left(Y_U Y_U^\dagger\right)_{ij} \approx \lambda_t^2 V_{3i}^* V_{3j} & i \neq j\ , \\ 0 & i = j \end{cases}$$

and it is dominated by the top contribution

MFV: $\Delta F = 2$

- There are two basic blocks to build the dim-6 lagrangian

$\bar{Q}_L \lambda_{\rm FC} Q_L$ and $\bar{D}_R \lambda_d \lambda_{\rm FC} Q_L$

- In fact there is only one operator affecting $B - \bar{B}$ and $K - \bar{K}$ mixing

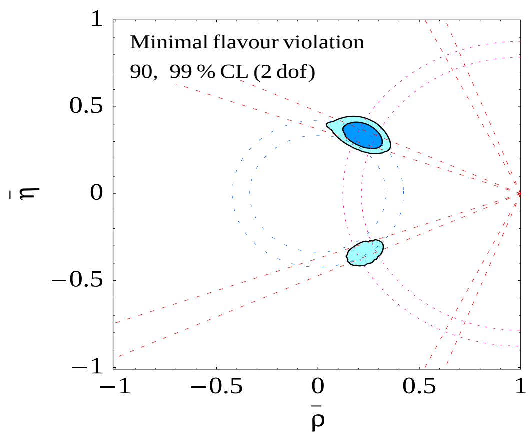
$$\frac{(V_{3i}^* V_{3j})^2}{\Lambda^2} a_0 \mathcal{O}_0$$

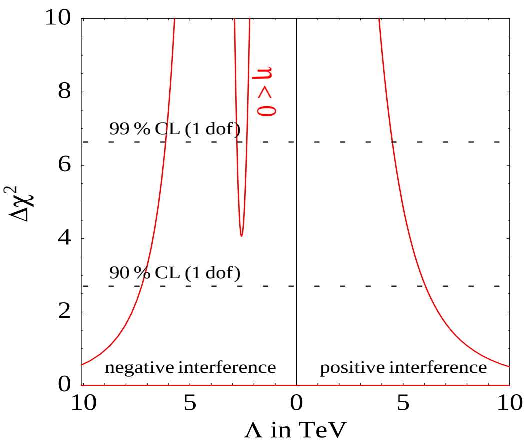
$$\mathcal{O}_0 = \frac{1}{2} \left(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L \right)^2$$

- Implyng a strong constrain on the coefficient of $\mathcal{O}_0$ when compared the SM

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = \frac{G_F^2 M_W^2}{8\pi^2} (V_{3i}^* V_{3j})^2 C_0 \left[\bar{d}_i \gamma_\mu (1-\gamma_5) d_j \right]^2 ,$$

- We fix $a_0 = 1$ and determine the limit on Λ^2





- MFV could flip the sign of $\Delta F = 2$ transitions, but low quality fit
Buras et al, Ligeti et al, G.D., Giudice, Isidori, Strumia

$\Delta F = 1$ gauge fields

- The operators contributing are

$$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\mathrm{FC}} \sigma_{\mu\nu} T^a Q_L \right) G^a_{\mu\nu}$$
$$\mathcal{O}_{G2} = \left(\bar{Q}_L \lambda_{\mathrm{FC}} \gamma_\mu T^a Q_L \right) D_\mu G^a_{\mu\nu}$$

- From comparing the experimental data

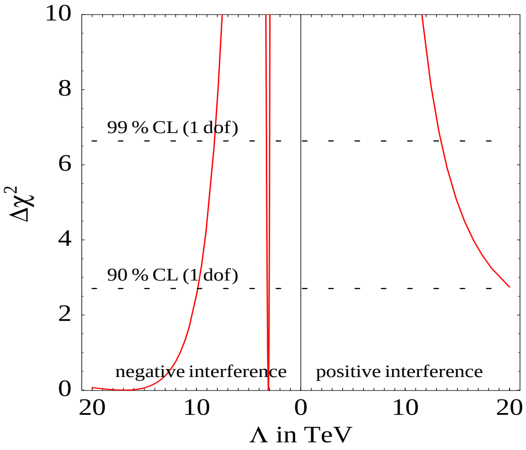
$$\mathcal{B}(B \to X_s \gamma) = (3.23 \pm 0.42) \times 10^{-4}$$

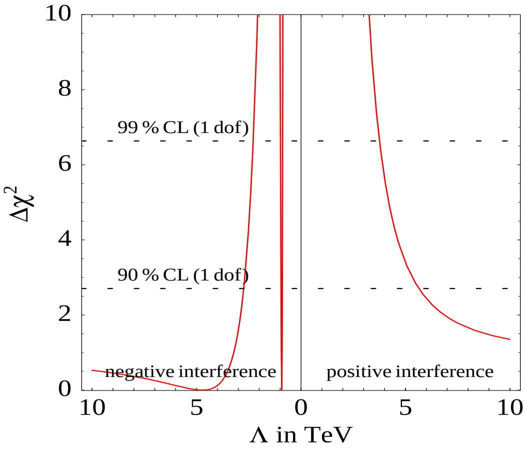
- to SM expectation Gambino Misiak

$$\mathcal{B}(B \to X_s \gamma)_{\mathrm{SM}} = (3.73 \pm 0.30) \times 10^{-4}$$

- we can get a strong a bound on the deviations from SM, $\delta C_{7\gamma,8G}$

$$\frac{\mathcal{B}(B \to X_s \gamma)}{\mathcal{B}(B \to X_s \gamma)_{\mathrm{SM}}} = 1 - 2.4 \delta C_{7\gamma} - 0.7 \delta C_{8G}$$





Rare FCNC decays into a lepton pair

- The SM Wilson coefficients $C_{\nu\bar{\nu}}$, C_{9V} and C_{10A} receive MFV contributions from

$$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)\,(\bar{L}_L \gamma_\mu L_L) \qquad \mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)\,(\bar{L}_L \gamma_\mu \tau^a L_L)$$
$$\mathcal{O}_{\ell 3} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)\,(\bar{E}_R \gamma_\mu E_R)$$

- MFV contributions to C_{9V} and C_{10A} limited by measurements $K_L \to \ell^+\ell^-$ and $\mathcal{B}(B \to K\ell^+\ell^-)$
- Actually already non-trivial MFV tests $B \leftrightarrow K$ physics
- $C_{\nu\bar{\nu}}$ limited by the measurements $K^+ \to \pi^+\nu\bar{\nu}$
- $\Rightarrow$ Limits on the MFV-scale for different operators

MFV dim-6 operator	main observables	Λ [TeV] $-$	$+$
$\mathcal{O}_0$	$\epsilon_K, \quad \Delta m_{B_d}$	6.4	5.0
$\mathcal{O}_{F1}$	$B \to X_s\gamma$	8.3	13.4
$\mathcal{O}_{G1}$	$B \to X_s\gamma$	2.3	3.8
$\mathcal{O}_{\ell 1}$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7
$\mathcal{O}_{\ell 2}$	$B \to (X)\ell\bar{\ell}, K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0
$\mathcal{O}_{H1}$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6
$\mathcal{O}_{q5}$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1	

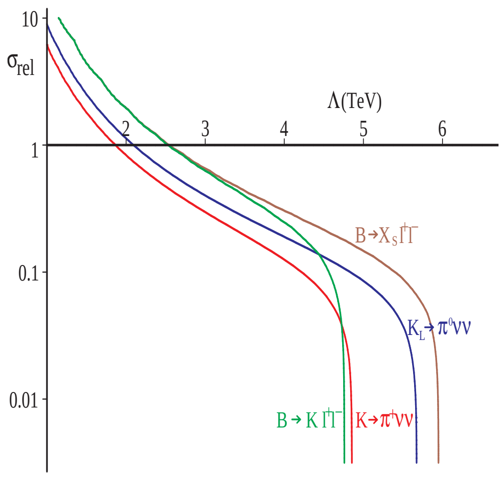
Bounds on MFV operators

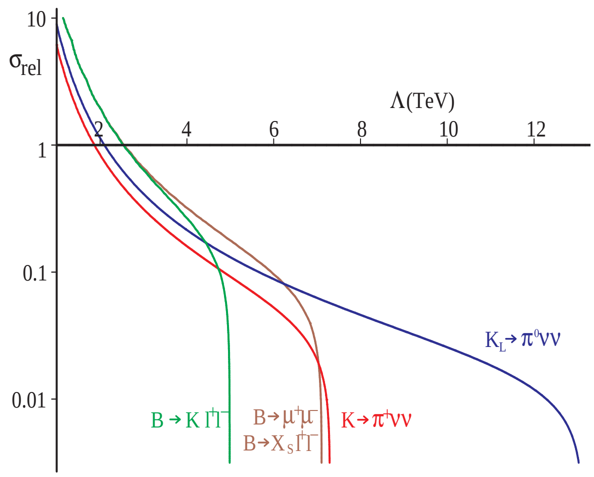
- $\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$
- $\mathcal{O}_{q5}$ 4-quark operator

Bounds on decay rates in MFV models

Observable	99(90) MFV limit	determined by	90% Exp. limit
$\mathcal{B}(B \to X_d \gamma)$	$2(2) \times 10^{-5}$	$\mathcal{B}(B \to X_s \gamma)$	—
$\mathcal{B}(B \to X_s \nu \bar{\nu})$	$8(6) \times 10^{-4}$		6.4×10^{-4}
$\mathcal{B}(B \to X_d \nu \bar{\nu})$	$3(2) \times 10^{-5}$	$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	—
$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$	$5(4) \times 10^{-10}$		5.9×10^{-7}
$\mathcal{B}(B_s \to \tau^+ \tau^-)$	$4(3) \times 10^{-6}$		—
$\mathcal{B}(B_d \to \tau^+ \tau^-)$	$1(1) \times 10^{-7}$	$\mathcal{B}(B \to X_s \bar{\ell} \ell)$	—
$\mathcal{B}(B_s \to \mu^+ \mu^-)$	$2(1) \times 10^{-8}$	$[\mathcal{B}(K_L \to \mu^+ \mu^-)]$	2.0×10^{-6}
$\mathcal{B}(B_d \to \mu^+ \mu^-)$	$6(5) \times 10^{-10}$		6.1×10^{-7}
$\mathcal{B}(K_L \to \pi^0 e^+ e^-)_{CP}$	$2(2) \times 10^{-11}$		5.6×10^{-10}

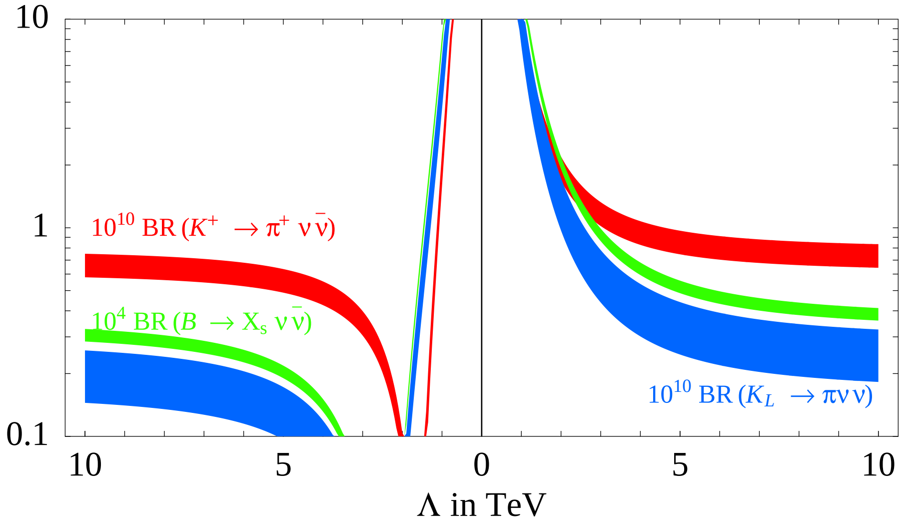
- Future experiments, in particular $K_L \to \pi^0 \nu \bar{\nu}$ will probe deeply MFV





- Left: 10% accuracy on the CKM , Right: 1%

MFV scale-sensitivity of different rare decays



- Branching ratios of various processes involving $d_i \longrightarrow d_j \nu \bar{\nu}$ transitions as functions of the scale of the effective operator $\mathcal{O}_{\ell 1}$. The bands represent 1σ uncertainties, taking into account the present determination of the CKM parameters

Two-Higgs doublet MFV model

- The two-Higgs-doublet-model (2HD) is justified in several extensions of SM, including SUSY; we describe an effective theory with $m_H << \Lambda_F$

- to avoid disastrous tree level FCNC $\Rightarrow$ H_U and H_D, $\mathrm{U}(1)_{\mathrm{PQ}}$ Glashow-Weinberg

$$\mathcal{L}_{Y_0} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + \bar{L}_L Y_E E_R H_D$$

- $\mathrm{U}(1)_{\mathrm{PQ}}$ broken by terms in the potential (to have $m_a \neq 0$) i.e.

$$V(H) = \mu B H_U H_D$$

- New PQ-breaking (ϵ_{PQ}) operators to add $\mathcal{L}_{Y_0}$ are allowed,

$$\bar{Q}_L \left(\epsilon_1 Y_D Y_D^\dagger + \epsilon_2 Y_U Y_U^\dagger \right) Y_D D_R (H_U)^c$$

- New FCNC induced from the mismatch of the quark mass basis with these terms and the original $\mathcal{L}_{Y_0}$

- Large values of $\langle H_U \rangle / \langle H_D \rangle = \tan\beta$ may enhance this effect

Hall,Rattazzi,Sarid; Blazek al, Babu,Kolda;Isidori,Retico

- Typically ϵ loop-suppressed by $\sim 1/(4\pi)^2$ (Susy)

- Additional flavour violation source, compared to one Higgs:

$$Y_D Y_D^\dagger \approx \frac{2m_b^2 \tan^2\beta}{v^2}\Delta \ , \qquad \Delta = \mathrm{diag}(0,0,1) \ .$$

- The most general dim-4 $\mathcal{L}_{\epsilon Y_D}$:

$$\bar{Q}_L \left(\epsilon_0 + \epsilon_1 \Delta + \epsilon_2 \hat{\lambda}_{\rm FC} + \epsilon_3 \hat{\lambda}_{\rm FC} \Delta + \epsilon_4 \Delta \hat{\lambda}_{\rm FC}\right) \hat{\lambda}_d D_R (H_U)^c$$

- Strategy
  - Diagonalize the quark mass matrix from $\mathcal{L}_{Y_0} + \mathcal{L}_{\epsilon Y_D}$
  - shift the quark-fiels and V_{CKM}
  - and then determine the effective Higgs coupling (charged and neutral).

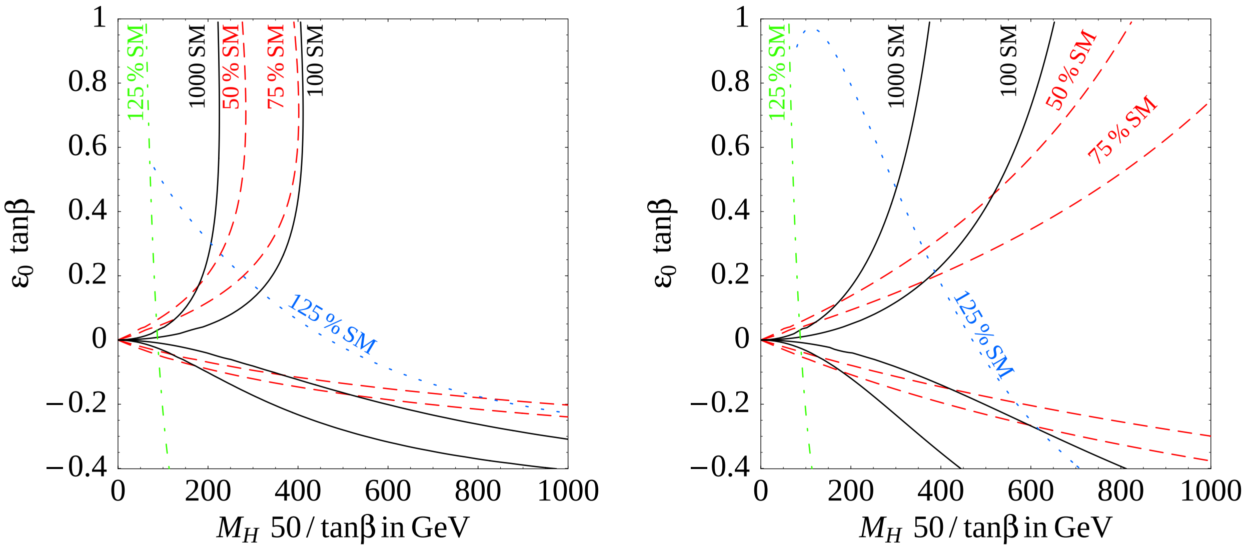
$$\Downarrow$$

- Interesting phenomenology for $B \to \ell^+ \bar{\ell}^-$, ΔM_{B_s} and $B \to X_s \gamma$, in particular for **Large** $\tan\beta$

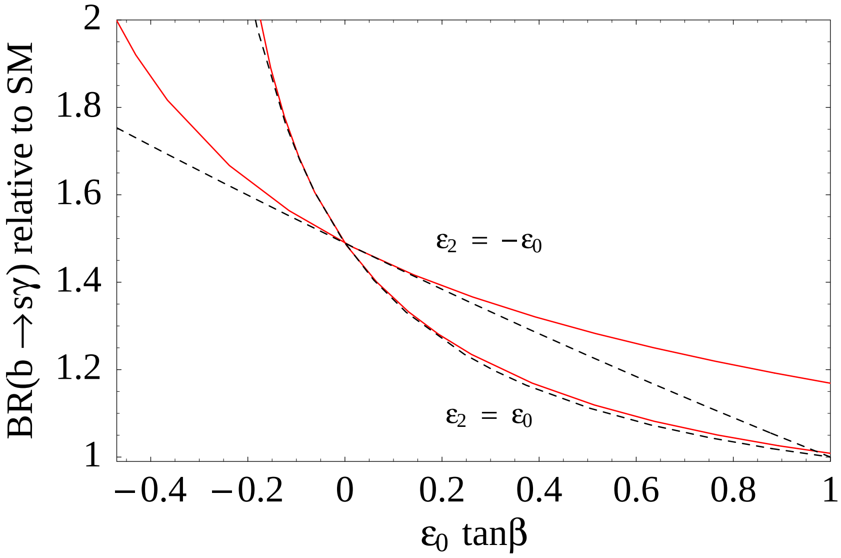
- In fact there are theoretical argument favouring $\epsilon \tan\beta \sim 1$ Hall *al*

- Our effective field theory approach, due to the complete resummation in $\epsilon \tan\beta$, has led us to uncover new FCNC contribution relevant in this limit

  Interesting phenomenology for $B \to \ell^+ \bar{\ell}^-$, ΔM_{B_s} and $B \to X_s \gamma$, in particular for **Large** $\tan\beta$



Large $\tan\beta$ **effects**: $B \to \ell^+\bar{\ell}^-$ *(continuous line)*, ΔM_{B_s} *(dashed red line)*, $B \to X_s\gamma$ *(dotted blue line)*, $B \to X\tau\bar{\nu}_\tau$ *(dot-dashed green line). Left and right panels correspond to* $\epsilon_2 = \epsilon_0$ *and* $\epsilon_2 = -\epsilon_0$*, respectively, in addition to the constraints*



Deviations of $\mathcal{B}(B \to X_s\gamma)$ with respect to the SM value due to (supersymmetric) heavy-Higgs exchanges. The two full (red) lines correspond to the full result, for $\epsilon_2 = \pm\epsilon_0$. The dashed lines do not contain the new (higher-order) contributions identified in this paper. All curves have been obtained for $M_H = 250$ GeV, $\tan\beta = 50$ and $\epsilon_0' = -\epsilon_0$.