Interplay between $H \to b\bar{s}$ and $b \to s\gamma$ in the MSSM with NMFV

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based on collaboration with
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1. Introduction
2. Non Minimal Flavour mixing in the MSSM
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1. Introduction

Motivations

- Indirect SUSY searches: Complementary to direct searches

  Look for effects of particles beyond the SM by studying their radiative effects

- FCNC processes are ideal to look for indirect SUSY signals: extremely suppressed in the SM

- MSSM Flavour changing Higgs decay branching ratios are some orders of magnitude larger than the corresponding SM rates

$$BR(H_{SM} \to b\bar{s} + s\bar{b}) \approx 4 \times 10^{-8} \qquad BR(H \to b\bar{s} + s\bar{b}) \approx 10^{-3}$$

  S. Bejar, F. Dilme, J. Guasch, J. Sola, hep-ph/0402188

  A. M. Curiel, M. J. Herrero, W. Hollik, F. Merz, S. Peñaranda, hep-ph/0312135

  A. M. Curiel, M. J. Herrero, D. Temes, hep-ph/0302107

- Compatibility with $b \to s\gamma$ data could restrict the size of these decays

Our intention is to provide a phenomenological analysis of the general constraints on flavour changing neutral Higgs decays

$$H \longrightarrow bs \equiv b\bar{s} + s\bar{b}$$

coming from bounds, imposed by $b \rightarrow s\gamma$, on the flavour mixing parameters in the MSSM squarks mass matrices

2. Non Minimal Flavour Violation (NMFV) in the MSSM

$\rightarrow$ Mixing of scalar quark families (beyond CKM)

- mixing between the 3^{rd} and 2^{nd} generation squarks can be numerically significant due to the third-generation Yukawa couplings involved
- experimentally only partially restricted (stringest constraints are given by $BR(b \rightarrow s\gamma)$):

$$|Re(\delta^d_{LL})_{23}| < \mathcal{O}(1)\,, \;\; |Re(\delta^d_{LR})_{23}| < 1.5 \times 10^{-2} \;\text{ for }\; M_{\tilde{q}} = M_{\tilde{g}} = 500 \text{ GeV}$$

- strong experimental bounds involving the 1^{st} generation, coming from data on K^0–$\bar{K}^0$ and D^0–$\bar{D}^0$ mixing

F. Gabbiani et al, hep-ph/9604387; M. Misiak et al, hep-ph/9703442...

For the general case of mixing between the third and second generation of squarks ($\tilde{t}/\tilde{c}$ and $\tilde{b}/\tilde{s}$ sectors)

E.g. Mixing of stop/scharm

$$(\tilde{t}_L, \tilde{t}_R, \tilde{c}_L, \tilde{c}_R) \begin{pmatrix} \widetilde{T} & 0 \\ 0 & \widetilde{C} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \\ \tilde{c}_L \\ \tilde{c}_R \end{pmatrix} \quad \Rightarrow \quad (\tilde{t}_L, \tilde{t}_R, \tilde{c}_L, \tilde{c}_R) \begin{pmatrix} \widetilde{T} & \neq 0 \\ \neq 0 & \widetilde{C} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \\ \tilde{c}_L \\ \tilde{c}_R \end{pmatrix}$$

add NMFV

Squark Generation Mixing via Soft Breaking

Parametrization of non-diagonal squark mass matrices

$$M^2_{\tilde{u}} = \left(\begin{array}{ccc|ccc} M^2_{\tilde{L}_u} & 0 & 0 & m_u X_u & 0 & 0 \\ 0 & M^2_{\tilde{L}_c} & \Delta^{\tilde{u}}_{LL} & 0 & m_c X_c & \Delta^{\tilde{u}}_{LR} \\ 0 & \Delta^{\tilde{u}}_{LL} & M^2_{\tilde{L}_t} & 0 & \Delta^{\tilde{u}}_{RL} & m_t X_t \\ \hline m_u X_u & 0 & 0 & M^2_{\tilde{R}_u} & 0 & 0 \\ 0 & m_c X_c & \Delta^{\tilde{u}}_{RL} & 0 & M^2_{\tilde{R}_c} & \Delta^{\tilde{u}}_{RR} \\ 0 & \Delta^{\tilde{u}}_{LR} & m_t X_t & 0 & \Delta^{\tilde{u}}_{RR} & M^2_{\tilde{R}_t} \end{array}\right)$$

$$\begin{aligned} M^2_{\tilde{L}_q} &= M^2_{\tilde{Q}_q} + m_q^2 + \cos 2\beta \, M_Z^2 (T_3^q - Q_q s_W^2) \\ M^2_{\tilde{R}_q} &= M^2_{\tilde{U}_q} + m_q^2 + \cos 2\beta \, M_Z^2 Q_q s_W^2 \\ X_q &= A_q - \mu (\tan\beta)^{-2T_3^q} \quad (q = u, t, c) \end{aligned}$$

$$\Delta^{\tilde{u}}_{LL} \equiv \lambda^{\tilde{u}}_{LL} M_{\tilde{L}_c} M_{\tilde{L}_t} \quad , \quad \Delta^{\tilde{u}}_{LR} \equiv \lambda^{\tilde{u}}_{LR} M_{\tilde{L}_c} M_{\tilde{R}_t}$$

$$\Delta^{\tilde{u}}_{RR} \equiv \lambda^{\tilde{u}}_{RR} M_{\tilde{R}_c} M_{\tilde{R}_t} \quad , \quad \Delta^{\tilde{u}}_{RL} \equiv \lambda^{\tilde{u}}_{RL} M_{\tilde{R}_c} M_{\tilde{L}_t} \quad (\lambda^{\tilde{u}}_{ab} \equiv (\delta_{ab})_{23})$$

Similarly for the down sector ($u \leftrightarrow d \,, t \leftrightarrow b \,, c \leftrightarrow s$), with $M_{\tilde{Q}_u} = M_{\tilde{Q}_d} \,, M_{\tilde{Q}_c} = M_{\tilde{Q}_s} \,, M_{\tilde{Q}_t} = M_{\tilde{Q}_b}$

Mass eigenstates :

In order to diagonalize the two 6×6 squark mass matrices, two 6×6 rotation matrices, $R_{\tilde{u}}$ and $R_{\tilde{d}}$, are needed,

$$\tilde{u}_\alpha = R_{\tilde{u}}^{\alpha,j} \begin{pmatrix} u_L \\ c_L \\ t_L \\ u_R \\ c_R \\ t_R \end{pmatrix}_j , \qquad \tilde{d}_\alpha = R_{\tilde{d}}^{\alpha,j} \begin{pmatrix} d_L \\ s_L \\ b_L \\ d_R \\ s_R \\ b_R \end{pmatrix}_j$$

$$R_{\tilde{q}}\, M_{\tilde{q}}^2\, R_{\tilde{q}}^\dagger = diag(1 \ldots 6) \qquad q = (u, d)$$

Flavour mixing through the flavour non-diagonal entries in the squark-mass matrices

$\longrightarrow$ generate large splittings between the squark-mass eigenvalues

$\Rightarrow$ Implemented in FeynArts, FormCalc (www.feynarts.de)

3. Flavour changing neutral Higgs decays: $H \to b\bar{s} + s\bar{b}$

- We focus in the particular decay $H \to bs$ $\quad (H \equiv h^0, H^0, A^0)$

  $\longrightarrow$ Similar dependence on MSSM parameters; as in flavour preserving decays.

  Six parameters: $m_{A^0}, \tan\beta, \mu, M_0, M_2, A$

  $\longrightarrow$ No renormalization needed

  $\longrightarrow$ Flavour parameters δ's enter in rotation matrices and physical squark masses

- We include the SM, $\tilde{q}$, $\tilde{g}$, $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$, $H^{\pm}$, contributions and their interference effects

  $\longrightarrow$ Full diagrammatic approach used (valid for all $\tan\beta$ values)

  $\longrightarrow$ Do not rely on the mass-insertion approximation

- We switched on :

  - only one of the off-diagonal elements of the squark-mass matrix
  - simultaneously several of these elements (several flavour violating parameters)

- We derive predictions for $H \to bs$ compatible with $b \to s\gamma$ constraints

Previous results ($H \to b\bar{s} + s\bar{b}$)

1. SUSY-QCD contributions (squark-gluino loops)

   $\longrightarrow$ Mixing only between the left-handed components of $\tilde{t}, \tilde{c}$ and $\tilde{b}, \tilde{s}$

   $\longrightarrow$ Switching on one specific off-diagonal element only: $(\delta_{LL})_{23}$

   - Large Higgs decay rates:
     $BR(H \to bs) < 0.2\,, BR(h^0 \to bs) < 0.01$ for $(\delta_{LL})_{23} < 0.6$
     A. M. Curiel, M. J. Herrero, D. Temes, hep-ph/0302107

   - $BR(b \to s\gamma)$ restricts the allowed values of Higgs decays rates:
     $BR(H \to bs) \sim 10^{-4} - 10^{-3} \quad (H \equiv h^0, H)$
     S. Bejar, F. Dilme, J. Guasch, J. Sola, hep-ph/0402188

2. SUSY-EW contributions (squark-chargino/neutralino loops)

   - $BR(H \to bs) \sim 10^{-3}\,, BR(h^0 \to bs) \sim 10^{-5}$

     - Subdominant with respect to the SUSY-QCD contributions

     - They contribute with opposite sign and induce significant interference that reduces the SUSY-QCD contributions

     A. M. Curiel, M. J. Herrero, W. Hollik, F. Merz, S. Peñaranda, hep-ph/0312135

Previous results ($b \to s\gamma$)

1. Experimental value: $BR(B \to X_s\gamma) = (3.34 \pm 0.38) \times 10^{-4}$

   M.Nakao, hep-ex/0312397 ;

   BABAR Collaboration, hep-ex/0207074 ; CLEO Collaboration, hep-ex/0108032

2. Bounds on the parameters in the squark mass matrices within the MSSM

   - Bound on the single off-diagonal element for the down sector, $(\delta^{\tilde{d}}_{LR})_{23}$, by using the mass insertion approximation and neglecting any kind of interference effects: $(\delta^{\tilde{d}}_{LR})_{23} \sim 10^{-2}$

     F. Gabbiani, E. Gabrielli, A. Masiero, L. Silvestrini, hep-ph/9604387 ; etc...

   - Interplay between the various sources of flavour violation and the interference effects of the SM and the various MSSM sectors explored

     \- Mass-eigenstate formalism used (valid when the intergenerational mixing elements are not small)

     \- Two combinations of elements of the soft parts of the down squark mass matrices considered

     Interference effects weaken the bounds: $(\delta^{\tilde{d}}_{LR})_{23} \sim 10^{-1}$

     T. Besmer, C. Greub, T. Hurth, hep-ph/0105292

RESULTS FOR $H \to bs$ AND $b \to s\gamma$

- Parameter scenario:

$$\mu = -700\,\text{GeV}\,,\ M_0 = 800\,\text{GeV}\,,\ A = 500\,\text{GeV}\,,$$
$$m_A = 400\,\text{GeV}\,,\ M_2 = 300\,\text{GeV}\,,\ \tan\beta = 35$$

- GUT relations assumed

- The same flavour mixing parameter in the up and down sectors is assumed: $(\delta^{\tilde{u}}_{ab})_{23} = (\delta^{\tilde{d}}_{ab})_{23}$

  A large difference between δ^t_{LL} and δ^b_{LL} is not allowed: LL blocks of the up- and down-squark mass matrices are not independent because of the $SU(2)$ gauge invariance.

  M. Misiak, S. Pokorski and J. Rosiek,hep-ph/9703442.

- Higgs-bosons masses and total decay widths computed with FeynHiggs

  S. Heinemeyer, W. Hollik, G. Weiglein, hep-ph/9812320, http://www.feynhiggs.de

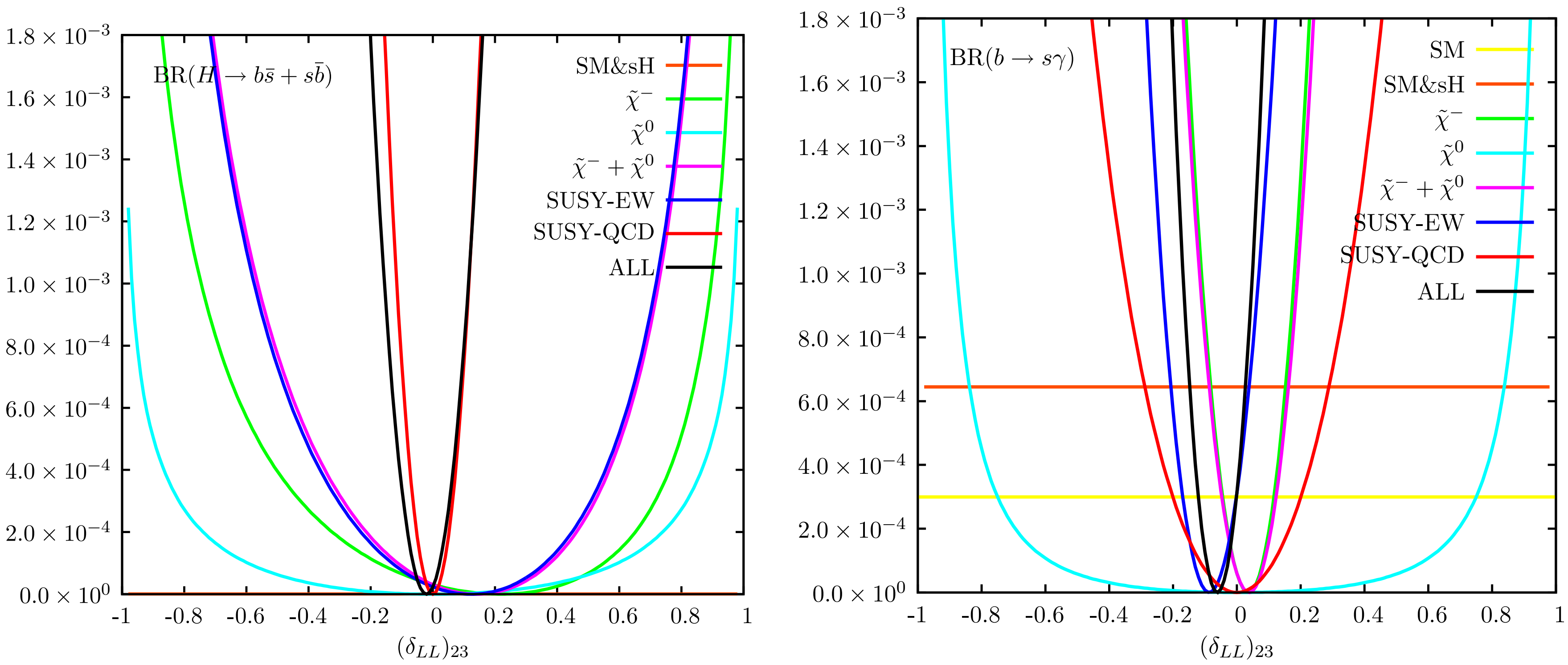
- Results obtained with FeynArts and FormCalc : Feynman rules of MSSM vertices with FC effects are implemented in FeynArts , extending the previous model file

  By T. Hahn and J.I. Illana, http://www.feynarts.de

  T. Hahn, C. Schappacher, Comput. Phys. Commun. **143** (2002) 54, hep-ph/0105349; and ref. therein.

Switching on one specific off-diagonal element only $(\delta_{LL})_{23}$

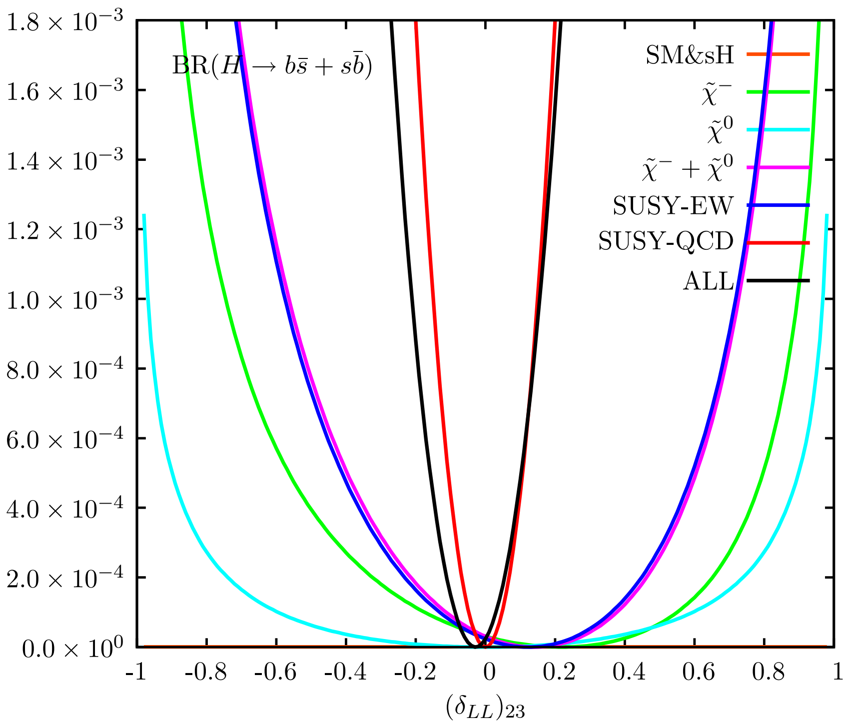
$BR(H \to b\bar{s} + s\bar{b})$ $BR(b \to s\gamma)$

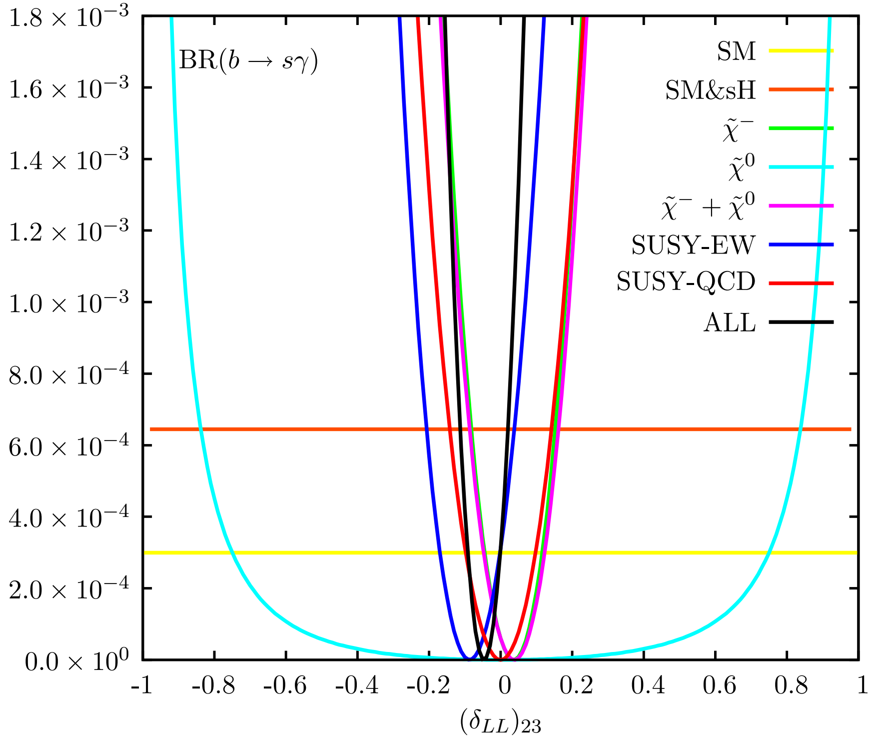


- For $BR(H \to b\bar{s} + s\bar{b})$, the SUSY-QCD contributions are the dominant ones. SUSY-EW contribution is subdominant, but interferes
- For $BR(b \to s\gamma)$, SUSY-QCD contribution is subdominant with respect to SUSY-EW (depending of the parameters set and the assumption of GUT relations: $M_2 = 300\, GeV \Rightarrow M_{\tilde{g}} = 1\, TeV$ and then, gluinos decouple and the gluino contribution decreases fast with $M_{\tilde{g}}$, getting smaller gluino versus chargino contributions)

⟶ Remove the $[M_2 - M_{\tilde{g}}]$ relation $\leftrightarrow$ $M_{\tilde{g}}$ is an input parameter

⟶ $M_{\tilde{g}} = 300\,GeV$





$\Rightarrow$

- The choice of the MSSM inputs parameters play an important role on the analysis
- Interference effects of the various MSSM sectors must be carefully considered

4. Compatibility $H \to bs \iff b \to s\gamma$

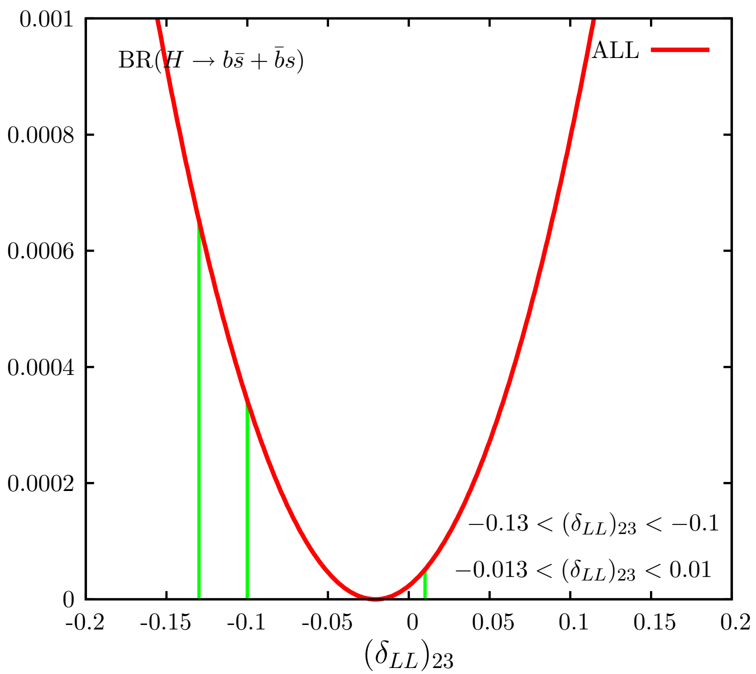
$\longrightarrow$ Include all SM + new-physics contributions

$\longrightarrow$ Switching on one specific off-diagonal element only at a time ($(\delta_{LL})_{23}$)

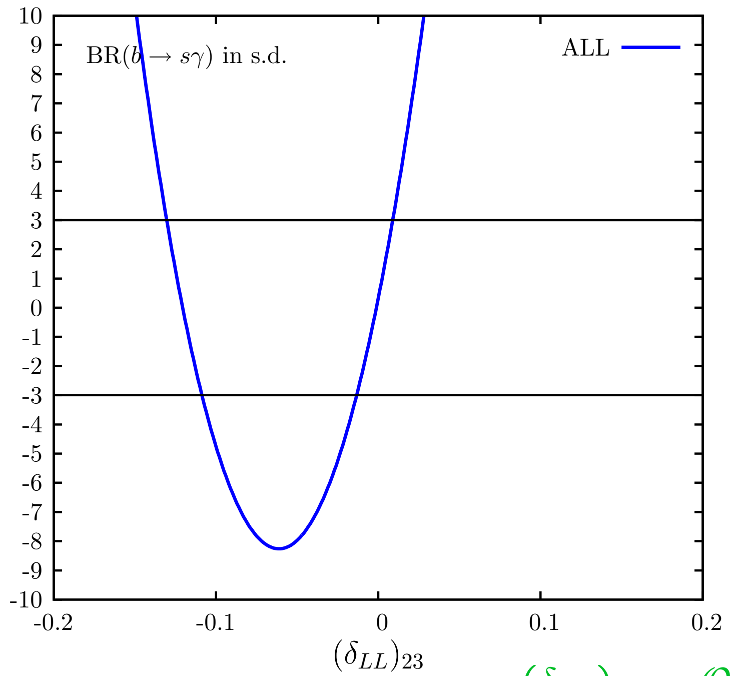
$\longrightarrow$ The horizontal lines in $BR(b \to s\gamma)$ denote the experimental value with a 3σ error.

$\longrightarrow$ Vertical green bands on $BR(H \to bs)$ represents the allowed values for the specific off-diagonal element

$BR(H \to b\bar{s} + s\bar{b})$



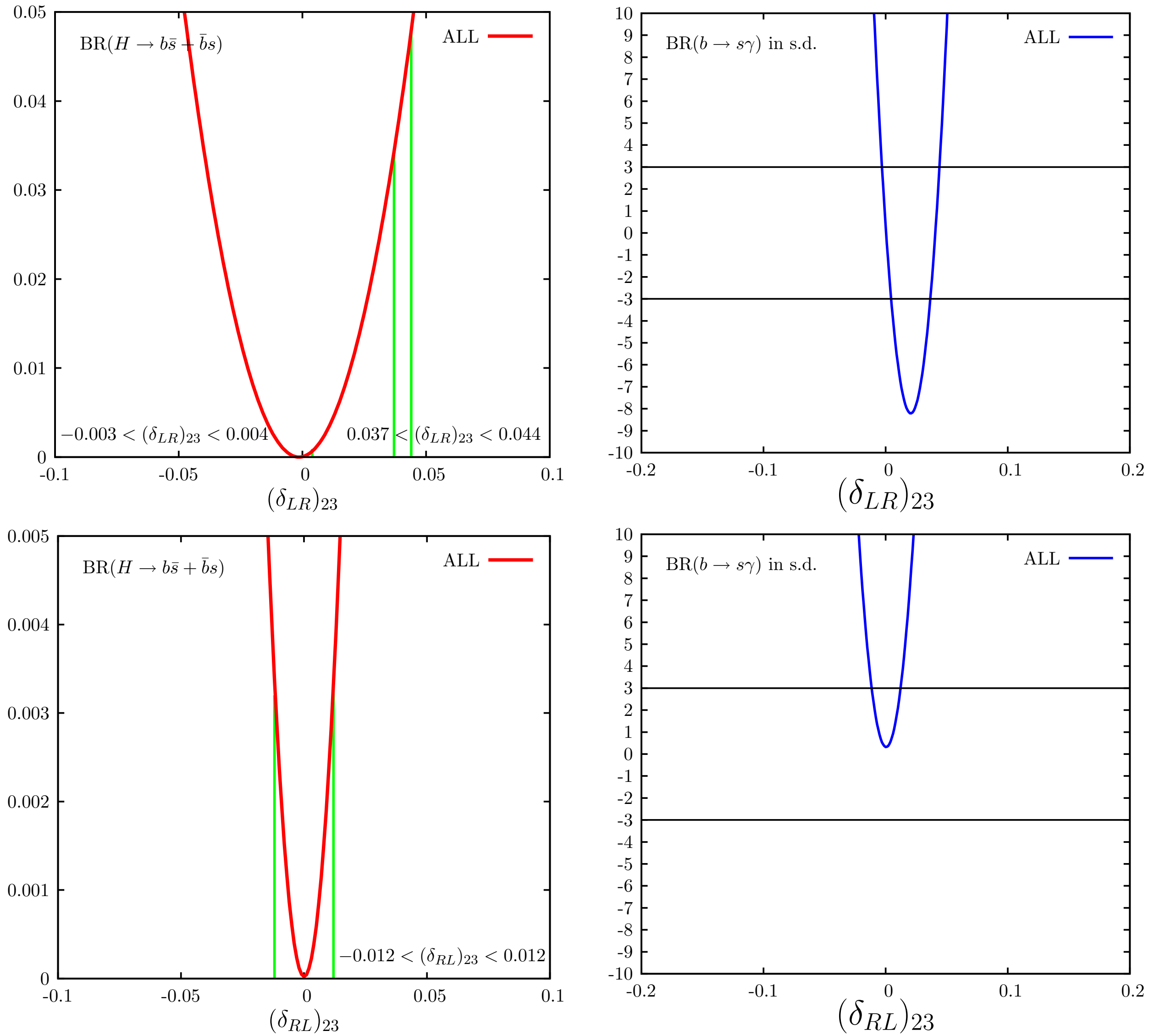
$BR(b \to s\gamma)$ in s.d.



$(\delta_{LL})_{23} \sim \mathcal{O}(10^{-2} - 10^{-1})$

$\Rightarrow$ The maximum value of $BR(H \to bs)$ that is allowed by the experimental data is $BR(H \to bs)_{\text{max}} \sim 10^{-4}$

$\longrightarrow$ Switching on only one specific off-diagonal element ($(\delta_{LR})_{23}$, $(\delta_{RL})_{23}$)

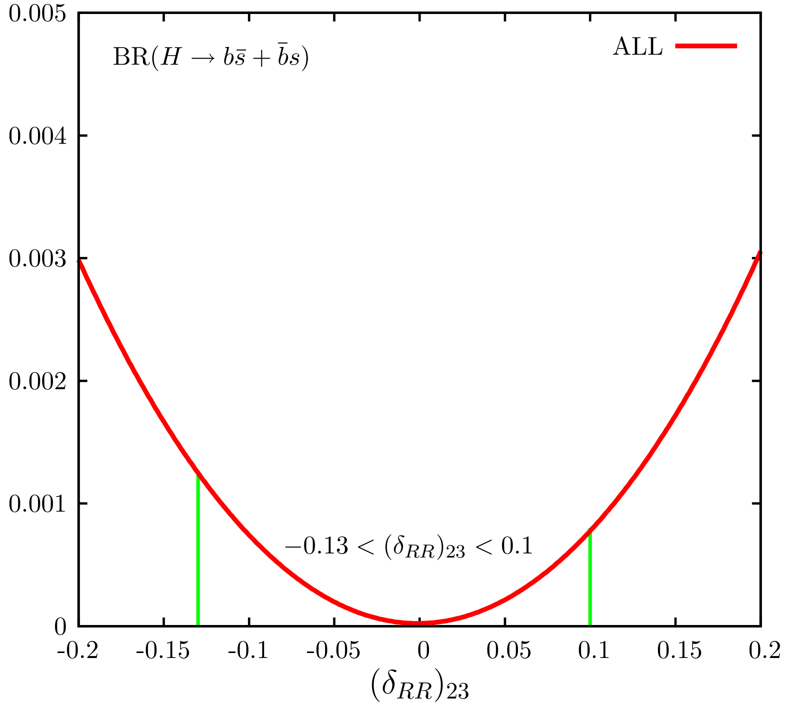


$(\delta_{LR})_{23} \sim \mathcal{O}(10^{-3} - 10^{-2})$, $(\delta_{RL})_{23} \sim \mathcal{O}(10^{-2})$

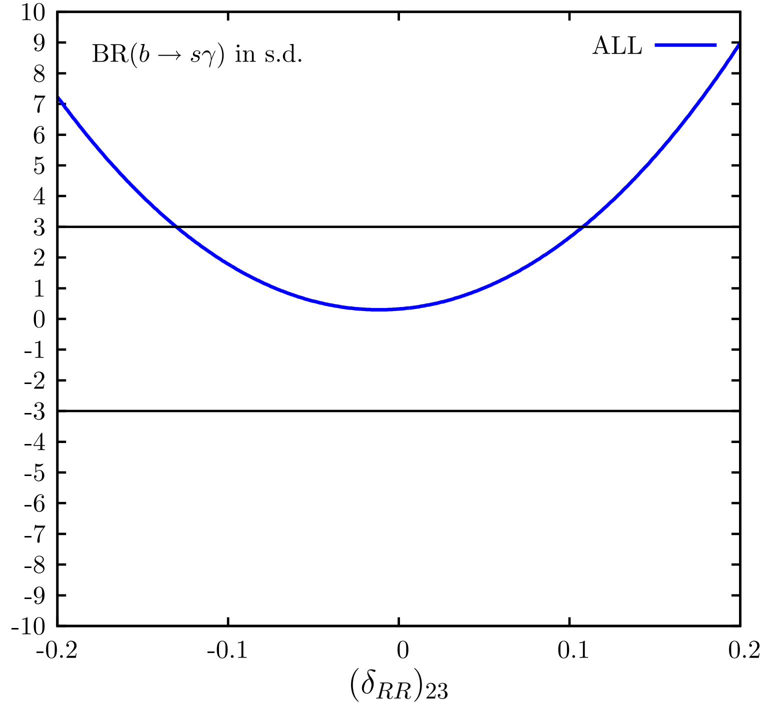
$\Rightarrow$ The maximum values allowed by the experimental data are $BR(H \to bs)_{\rm max} \sim 10^{-2}$ and $\sim 10^{-3}$ resp.

$\longrightarrow$ Switching on only one specific off-diagonal element ($(\delta_{RR})_{23}$)

$BR(H \to b\bar{s} + s\bar{b})$



$BR(b \to s\gamma)$ in s.d.



$(\delta_{RR})_{23} \sim \mathcal{O}(10^{-1})$

$\Rightarrow$ The maximum value allowed by the experimental data is :

$BR(H \to bs)_{\rm max} \sim 10^{-3}$

First analysis: Switching on only one specific off-diagonal element

- $(\delta_{ab})_{23}$, $ab \equiv LL, LR, RL, RR$ parameters are constrained not to be so large by $BR(b \to s\gamma)$: $(\delta_{ab})_{23} \sim 10^{-3} - 10^{-1}$

- Bounds on $(\delta_{LR})_{23}$ and $(\delta_{RL})_{23}$ flavour parameters are stronger, as expected

- The maximum value of $BR(H \to bs)$ that is allowed by the experimental data: $BR(H \to bs) \sim 10^{-2}$, is obtained by switching on only $(\delta_{LR})_{23}$

- $BR(H \to bs)$ is smaller if induced by $(\delta_{LL})_{23}$, but still sizeable

$$BR(H \to bs) \sim 10^{-4}$$

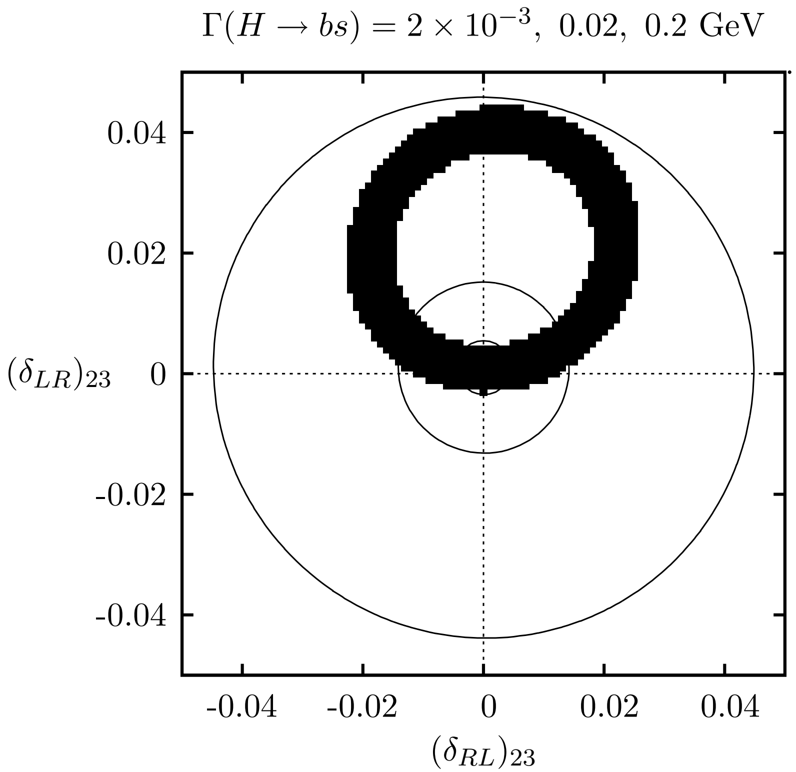
In agreement with hep-ph/0402188, hep-ph/0312135

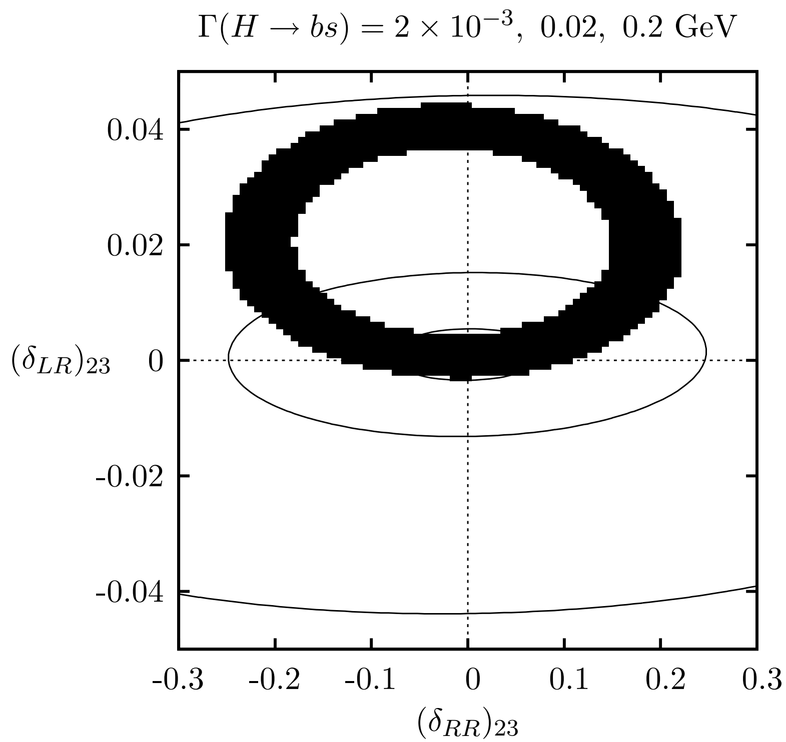
Switching on simultaneously several off-diagonal elements of the squark-mass matrix (several flavour mixing parameters)

We investigate whether the previous bounds obtained remain stable

$\longrightarrow$ Black region: represents the experimental allowed values for $BR(b \to s\gamma)$

$\longrightarrow$ Lines correspond to specific values of $\Gamma(H \to bs)$



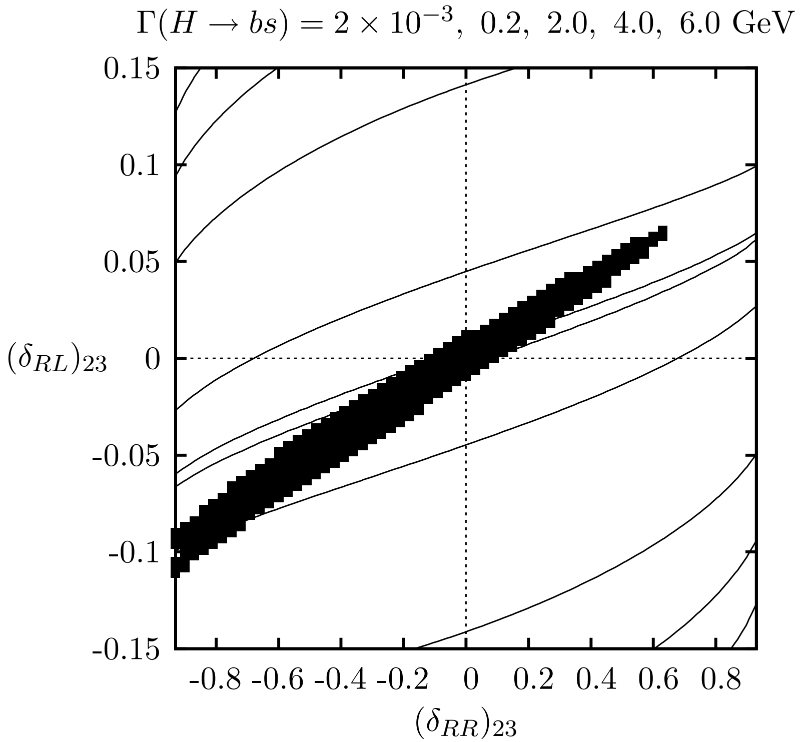


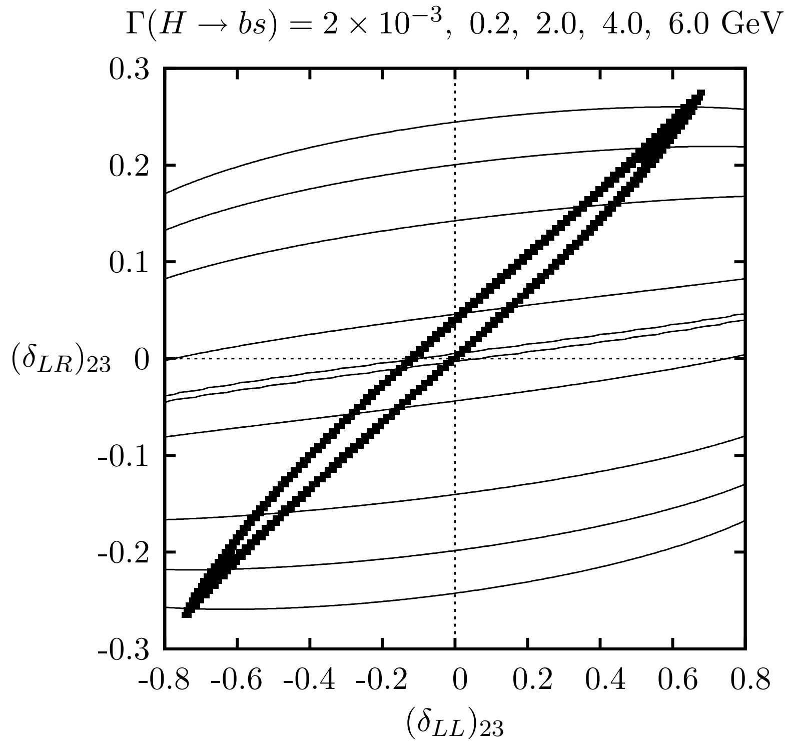
$\Gamma_{\text{max}} = 0.18\,GeV \Rightarrow BR(H \to bs)_{\text{max}} \sim 0.04$

for $(\delta_{LR})_{23} = 0.044$ & $(\delta_{RL})_{23} = 0.006$

$\Gamma_{\text{max}} = 0.18\,GeV \Rightarrow BR(H \to bs)_{\text{max}} \sim 0.04$

for $(\delta_{LR})_{23} = 0.044$ & $(\delta_{RR})_{23} = -0.045$





$\Gamma_{max} = 0.36\, GeV \Rightarrow BR(H \to bs)_{max} \sim 0.08$

for $(\delta_{RR})_{23} = -0.96$ & $(\delta_{RL})_{23} = -0.114$

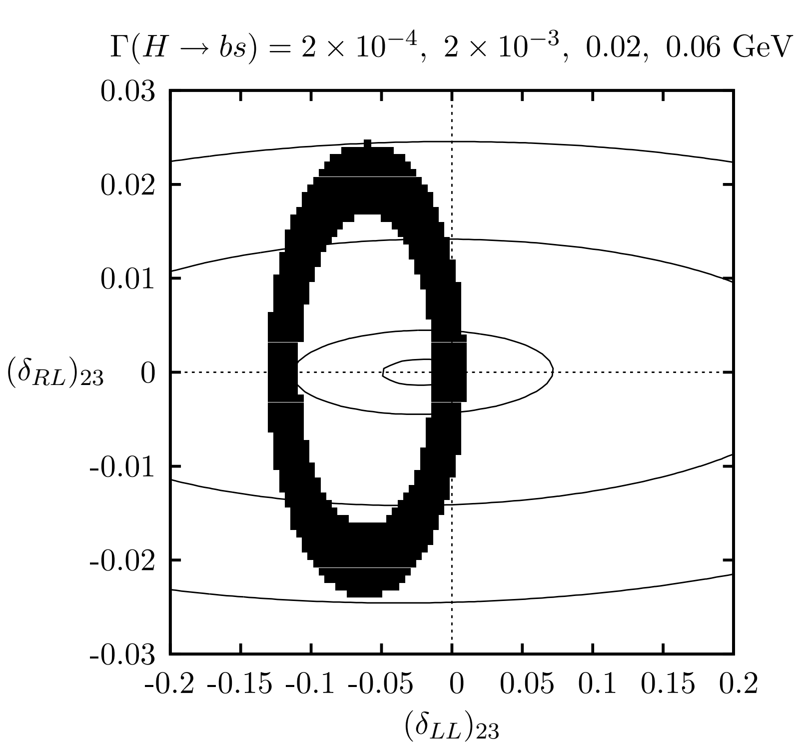
$\Gamma_{max} = 6.86\, GeV \Rightarrow BR(H \to bs)_{max} \sim 0.6$

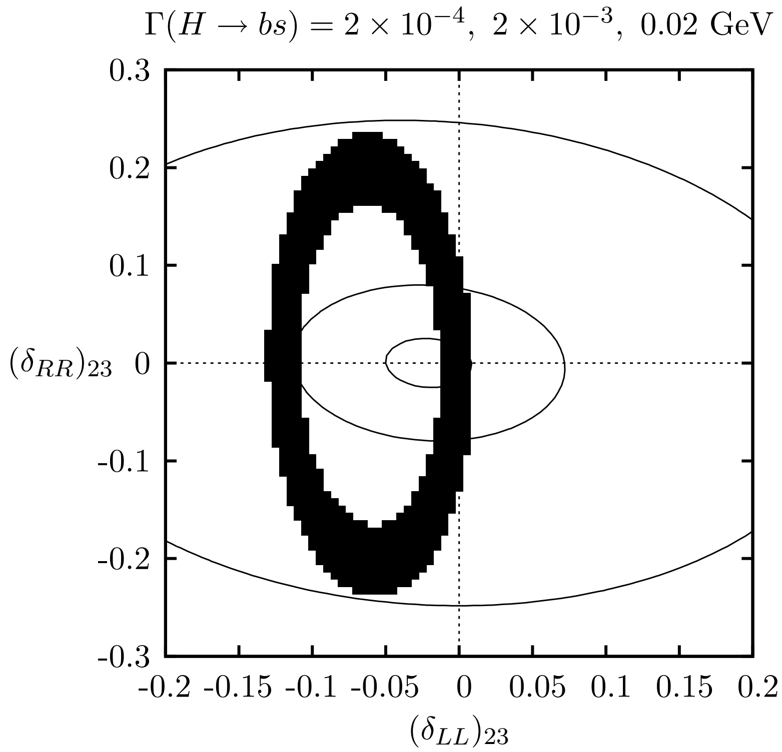
for $(\delta_{LL})_{23} = 0.68$ & $(\delta_{LR})_{23} = 0.275$

$\longrightarrow$ The combined effects of $[(\delta_{LR})_{23} \cdot (\delta_{RL})_{23}]$, $[(\delta_{LR})_{23} \cdot (\delta_{RR})_{23}]$ and $[(\delta_{RL})_{23} \cdot (\delta_{RR})_{23}]$ lead to $BR(H \to bs)_{max} \sim 10^{-2}$

$\longrightarrow$ The combined effects of $[(\delta_{LR})_{23} \cdot (\delta_{LL})_{23}]$ lead to $BR(H \to bs)_{max} \sim 10^{-1}$

$\Rightarrow$ The constraints from $b \to s\gamma$ are weaker





$\Gamma_{\rm max} = 0.06\, GeV \Rightarrow BR(H \to bs)_{\rm max} \sim 0.01$

$(\delta_{LL})_{23} = -0.06$ & $(\delta_{RL})_{23} = 0.0244$

$\Gamma_{\rm max} = 0.018\, GeV \Rightarrow BR(H \to bs)_{\rm max} \sim 0.004$

$(\delta_{LL})_{23} = -0.07$ & $(\delta_{LR})_{23} = -0.2325$

$\Rightarrow$ The bounds on $BR(H \to bs) \sim 10^{-4}$, obtained by switching on only $(\delta_{LL})_{23}$, get destroyed by the combined effects of $(\delta_{LL})_{23}$ with

$(\delta_{LR})_{23}$ ($\mathcal{O}(10^{-1})$) ; $(\delta_{RL})_{23}$ ($\mathcal{O}(10^{-2})$) ; $(\delta_{RR})_{23}$ ($\mathcal{O}(10^{-3})$)

Second analysis: Switching on several off-diagonal elements

- Interference effects weaken the bounds on $(\delta_{ab})_{23}$, $ab \equiv LL, LR, RL, RR$ flavour parameters imposed by $BR(b \to s\gamma)$
  In agreement with hep-ph/0105292

- Bounds on $BR(H \to bs)$:

Flavour parameter	$BR(H \to b\bar{s} + s\bar{b})_{\text{max}}$
$(\delta_{LR})_{23}$	10^{-2}
$(\delta_{RL})_{23}$	10^{-3}
$(\delta_{RR})_{23}$	10^{-3}
$(\delta_{LL})_{23}$	10^{-4}
$(\delta_{LL})_{23} \cdot (\delta_{RR})_{23}$	10^{-3}
$(\delta_{LL})_{23} \cdot (\delta_{RL})_{23}$	10^{-2}
$(\delta_{RR})_{23} \cdot (\delta_{LR})_{23}$	10^{-2}
$(\delta_{RL})_{23} \cdot (\delta_{LR})_{23}$	10^{-2}
$(\delta_{RR})_{23} \cdot (\delta_{RL})_{23}$	10^{-2}
$(\delta_{LL})_{23} \cdot (\delta_{LR})_{23}$	10^{-1}

- Our new predictions for $BR(H \to bs)$ are, in general, orders of magnitude larger than the ones for a single off-diagonal element.

5. Conclusions

- Constraints imposed by $b \to s\gamma$ on flavour changing neutral Higgs decays

$$H \to b\bar{s} + s\bar{b}$$

play an important role in the phenomenology of flavour processes

- Interference effects of SM and the various MSSM sectors must be carefully considered

- By switching on only one specific off-diagonal element ($(\delta_{LL})_{23}$) of the squark mass matrices, $BR(H \to b\bar{s} + s\bar{b})$ gets stringently constrained to $BR(H \to b\bar{s} + s\bar{b})_{\rm max} \sim 10^{-4}$

- Interference effects of switching on several off-diagonal elements raise the predictions for $BR(H \to b\bar{s} + s\bar{b})$ to $\mathcal{O}(10^{-3}) - \mathcal{O}(10^{-1})$

- Strategy: Perform the analysis for different choices of the MSSM parameters and for both h^0 and H^0/A^0

- FeynArts, FormCalc now include NMFV MSSM :
  6×6 generalized squark mixing matrices