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

FeynArts/FormCalc updated

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based on collaboration with
T. Hahn, *W. Hollik* and *J.I. Illana*

1. Introduction
   - Non Minimal Flavour mixing in the MSSM
2. FeynArts and FormCalc updated
3. Compatibility $H \to b\bar{s} \Longleftrightarrow b \to s\gamma$
4. Conclusions

1. Introduction

- Motivation: 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

- To provide a phenomenological analysis of the general constraints on FC neutral Higgs decays $H \to bs \equiv b\bar{s} + s\bar{b}$ coming from bounds, imposed by $b \to s\gamma$ and $b \to sl^+l^-$, on the flavour mixing parameters in the MSSM squarks mass matrices

- FeynArts and FormCalc updated with the NMFV MSSM

Non Minimal Flavour Violation (NMFV) in the MSSM

→ Mixing of scalar quark families (beyond CKM)

Parametrization of non-diagonal squark mass matrices

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

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

$$\Delta^{\tilde{u}}_{LL} \equiv (\delta^{\tilde{u}}_{LL})_{23}\, M_{\tilde{L}_c} M_{\tilde{L}_t} \quad , \quad \Delta^{\tilde{u}}_{LR} \equiv (\delta^{\tilde{u}}_{LR})_{23}\, M_{\tilde{L}_c} M_{\tilde{R}_t}$$

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

Similarly for the down sector ($u \leftrightarrow d\,, t \leftrightarrow b\,, c \leftrightarrow s$), and for all three generations

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,

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

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

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

2. FeynArts and FormCalc updated

FeynArts http://www.feynarts.de

FormCalc http://www.feynarts.de/formcalc

- The programs can be used for one-loop calculations and they work together smoothly

Diagram generation	• Create the topologies • Insert fields • Apply the Feynman rules • Paint the diagrams	FeynArts
↓		
Algebraic simplification	• Contract indices • Calculate traces • Reduce tensor integrals • Introduce abbreviations	FormCalc
↓		
Numerical evaluation	• Convert **Mathematica** output to **Fortran code** • Supply a driver program	FormCalc
	• Implementation of the integrals	LoopTools

- Automatic Installation with `FeynInstall`

NMFV MSSM in FeynArts

T. Hahn, W. Hollik, J.I. Illana, S. Peñaranda, hep-ph/0512315.

- New Feynman rules for the NMFV MSSM included.
  - The new model file FVMSSM.mod generalizes the squark couplings in MSSM.mod to the NMFV case
  - Technically: it reads in MSSM.mod and applies algebraic substitutions to yield the new couplings
  - The list of couplings can also be found in FVMSSM.ps , located in the Models subdirectory of FeynArts .
  - FVMSSM.mod contains the following new quantities:

UASf[s_1,s_2,t]	the squark mixing matrix $R_{u,d}$ $(s_1, s_2 = 1 \ldots 6,\ t = 3(u), 4(d))$
MASf[s,t]	the squark masses $(s = 1 \ldots 6,\ t = 3(u), 4(d))$.

NMFV MSSM in FormCalc

T. Hahn, W. Hollik, J.I. Illana, S. Peñaranda, hep-ph/0512315.

- Model Initialization in FormCalc .
  - Initialization routines for the squark masses and mixings (MASf and UASf), i.e. the 6×6 diagonalization of the mass matrix
  - It must be enabled by defining a preprocessor flag in run.F :

    ```
    #define FLAVOUR_VIOLATION
    ```

  - The NMFV parameters δ are represented by the deltaSf matrix:

    double complex deltaSf(s_1,s_2,t) the matrix $(\delta_t)_{s_1 s_2}$ $(s_1, s_2 = 1 \ldots 6,\ t = 3(u), 4(d))$

  - The trilinear couplings A acquire non-zero off-diagonal entries in the presence of NMFV through the relations

$$m_{q,i}(A_q)_{ij} = (M_q^2)_{i,j+3} \quad , \quad q = u, d\,,\ i, j = 1 \ldots 3\,.$$

    These off-diagonal trilinear couplings appear in the Higgs–squark–squark couplings.

Summary

- Including NMFV effects requires only three minor changes compared to calculations with the MFV MSSM :
  - choosing FVMSSM.mod instead of MSSM.mod ,
  - setting the `FLAVOUR_VIOLATION` preprocessor flag in run.F ,
  - providing values for the deltaSf matrix.

- Input: Process definition.
  Output: Fortran code to compute e.g. cross-sections, decay rates, etc...

- It can easily be linked with the new version of the SUSY Les Houches Accord 2 (SLHALib2) to obtain its data from the SLHA records.

  See hep-ph/0605049 (by T. Hahn).

3. Compatibility $H \to b\bar{s} \iff b \to s\gamma$

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

- We focus in the particular decay $H \to bs$ $(H \equiv H^0, A^0)$
  - $\longrightarrow$ 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
  - $\longrightarrow$ Include all SM + new-physics contributions
  - $\longrightarrow$ 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-physics experimental data ($B \to X_s\gamma$ and $B \to X_s l^+ l^-$ constraints)

$\mathcal{B}(B \to X_s \gamma)$

- We consider the expression for the branching ratio $\mathcal{B}(B \to X_s \gamma)$ to NLO

  A. L. Kagan, M. Neubert, hep-ph/9803368; hep-ph/9805303.

  In the MSSM with NMFV , the relevant operators of the effective Hamiltonian are:

$$
\begin{aligned}
O_2 &= \bar{s}_L \gamma_\mu c_L \gamma^\mu b_L \,, \\
O_7 &= \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R \,, \qquad & \tilde{O}_7 &= \frac{e}{16\pi^2} m_b \bar{s}_R \sigma_{\mu\nu} F^{\mu\nu} b_L \,, \\
O_8 &= \frac{g_s}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} G_a^{\mu\nu} t_a b_R \,, \qquad & \tilde{O}_8 &= \frac{g_s}{16\pi^2} m_b \bar{s}_R \sigma_{\mu\nu} G_a^{\mu\nu} t_a b_L \,.
\end{aligned}
$$

$\longrightarrow$ Wilson coefficients $C_{2,7,8}$ and $\tilde{C}_{7,8}$ calculated to one loop.
$\longrightarrow$ The tilded operators do not contribute in the SM or in the MSSM with MFV, in the limit of massless strange quark.

- The data from $B \to X_s \mu^+ \mu^-$ require that the sign of the coefficient $C_7(m_b)$ is the same as in the SM.

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

- Parameter scenario:

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

- GUT relations assumed

  $M_3 = \alpha_s/\alpha\, s_W^2\, M_2$ and $M_1 = 5/3\, s_W^2/c_W^2\, M_2$

- 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

  http://www.feynhiggs.de

NMFV MSSM in FeynHiggs

By S. Heinemeyer, T.Hahn

- The one-loop corrections to Higgs masses and mixing angles are now evaluated with the full 6×6 NMFV contributions (including off-diagonal mass terms and A terms).
- The CKM matrix corrections are included.
- The corresponding information can be passed with the new version of the SUSY Les Houches Accord 2 (SLHALib2)

  See hep-ph/0605049 (by T. Hahn).
- The $\mathcal{B}(B \to X_s\gamma)$ is evaluated, including NMFV effects

  See hep-ph/0512315 for details.
- As additional constraints, M_W and $\sin^2\theta_{eff}$, are evaluated, including NMFV effects (full SM + $\Delta\rho$ SUSY corrections).
- Everything is available at www.feynhiggs.de .

Numerical results: One flavour-mixing parameter

⟶ Switching on one specific off-diagonal element only at a time.

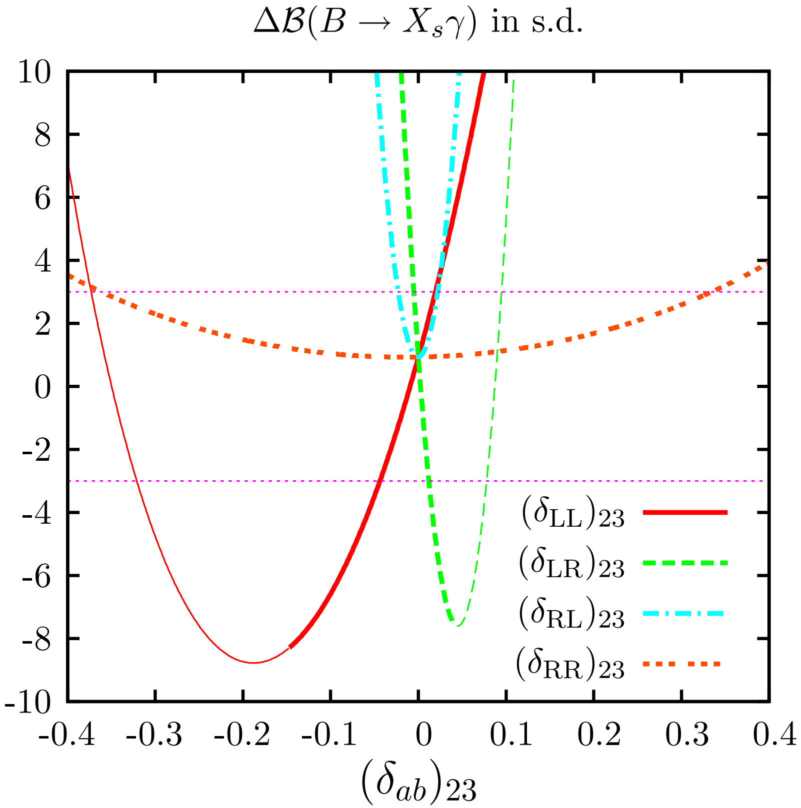
⟶ The horizontal lines in $BR(b \to s\gamma)$ denote the experimental value with a 3σ error.

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

M.Nakao, hep-ex/0312397; BABAR Col., hep-ex/0207074; CLEO Col., hep-ex/0108032

⟶ The thinner lines for $(\delta_{LL})_{23}$ and $(\delta_{LR})_{23}$ correspond to regions disfavoured by $B \to X_s\mu^+\mu^-$.

$$\frac{\Delta\mathcal{B}(B\to X_s\gamma)}{1 s.d.} = \frac{\mathcal{B}(B\to X_s\gamma) - \mathcal{B}(B\to X_s\gamma)_{\rm exp}}{\Delta\mathcal{B}_{\rm exp}}.$$



- the flavour-off-diagonal elements are independently constrained to be at most

$$\delta_{ab} \sim 10^{-3}\text{–}10^{-1}$$

- As expected, the bounds on $\delta_{\rm LR}$ are the strongest,

$$\delta_{\rm LR} \sim 10^{-3}\text{–}10^{-2}$$

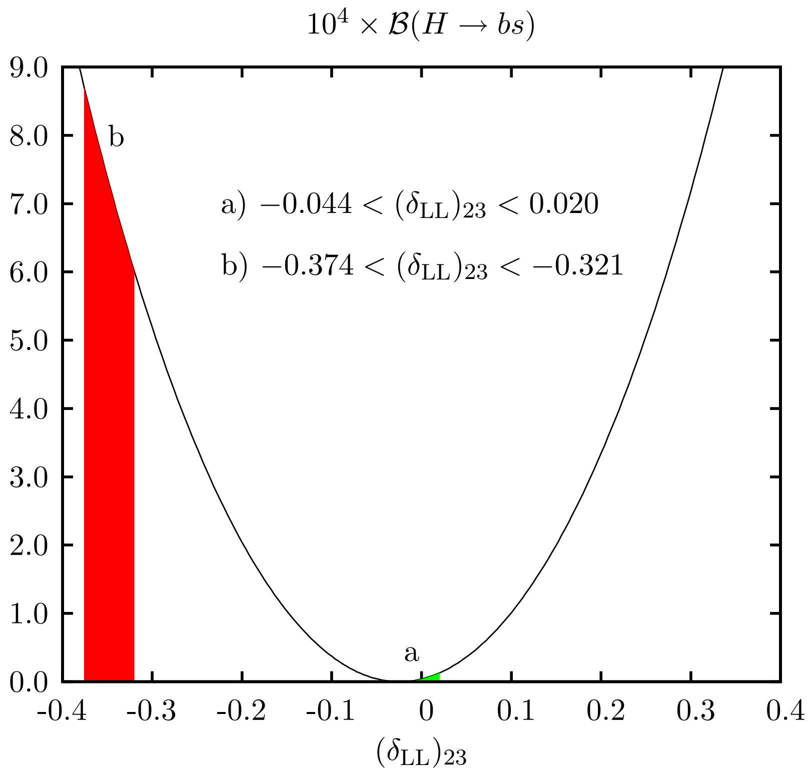
F. Borzumati *et al.*, hep-ph/9911245; T. Besmer *et al.*, hep-ph/0105292; hep-ph/0111389; F. Gabbiani *et al.*, hep-ph/9604387; M. Misiak *et al.*, hep-ph/9703442...

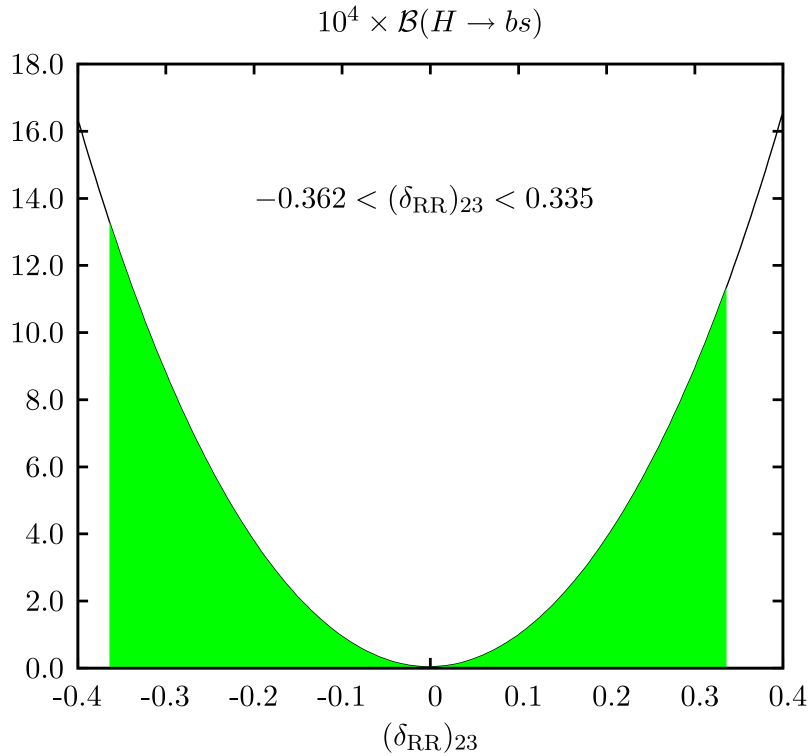
- The data from $B \to X_s\mu^+\mu^-$ further constrain the parameters $\delta_{\rm LL}$ and $\delta_{\rm LR}$, the others remaining untouched

Results for $\mathcal{B}(H^0 \to bs)$ as a function of δ_{ab} (I)

$\longrightarrow$ The allowed intervals of δ_{ab} determined from $b \to s\gamma$ are indicated by coloured areas.

$\longrightarrow$ The red areas are disfavoured by $B \to X_s\mu^+\mu^-$.

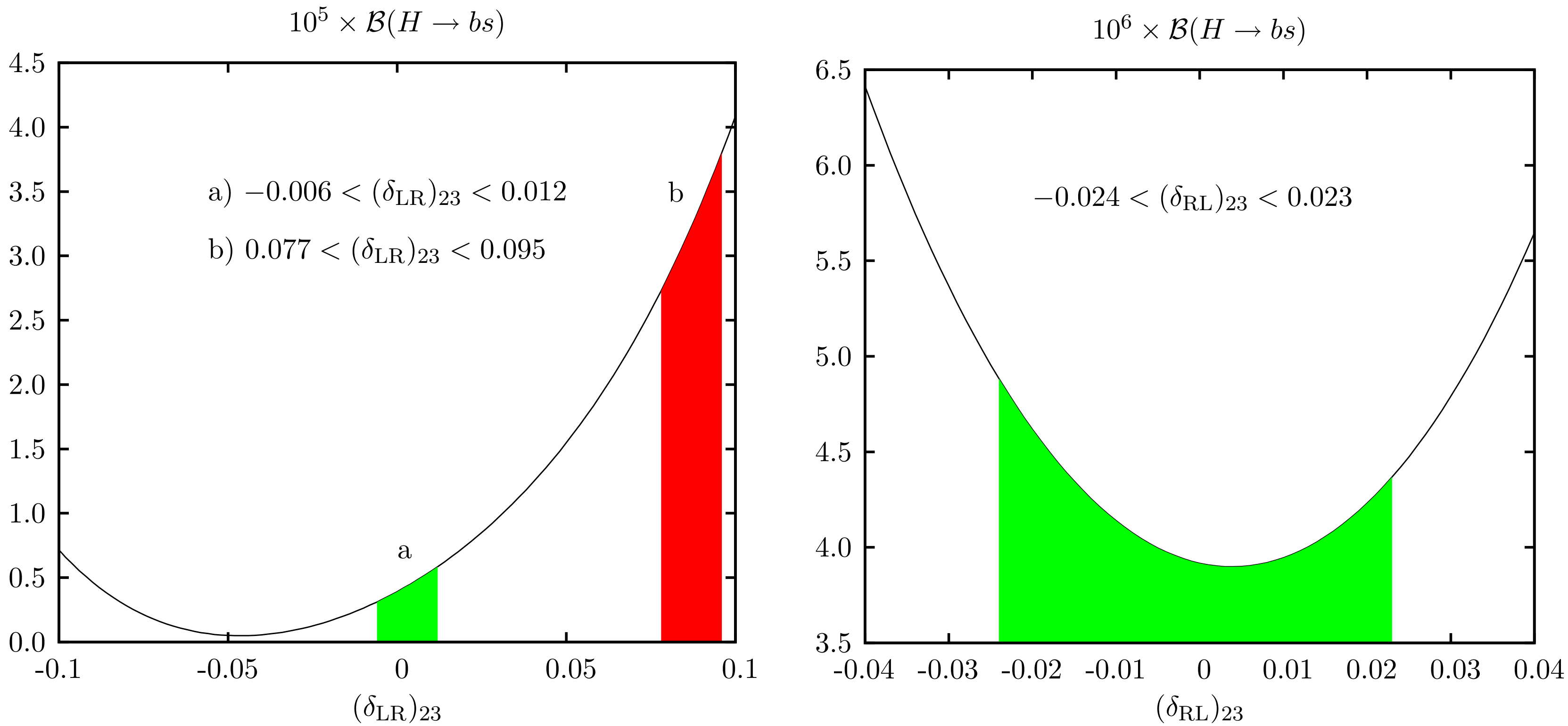




- The largest allowed value of $\mathcal{B}(H^0 \to bs)$, of $\mathcal{O}(10^{-3})$ or $\mathcal{O}(10^{-5})$, is induced by $\delta_{\rm RR}$ or $\delta_{\rm LL}$, respectively.

  These are the flavour-changing parameters least stringently constrained by the $b \to s\gamma$ data.

Results for $\mathcal{B}(H^0 \to bs)$ as a function of δ_{ab} (II)



- $\mathcal{B}(H^0 \to bs)$ can reach $\mathcal{O}(10^{-6})$ if induced by $\delta_{\rm LR}$ or by $\delta_{\rm RL}$, the most stringently constrained flavour-changing parameter.

- Because of the restrictions imposed by $b \to s\gamma$, $\mathcal{B}(H^0 \to bs)$ depends very little on $\delta_{\rm LR}$ and $\delta_{\rm RL}$.

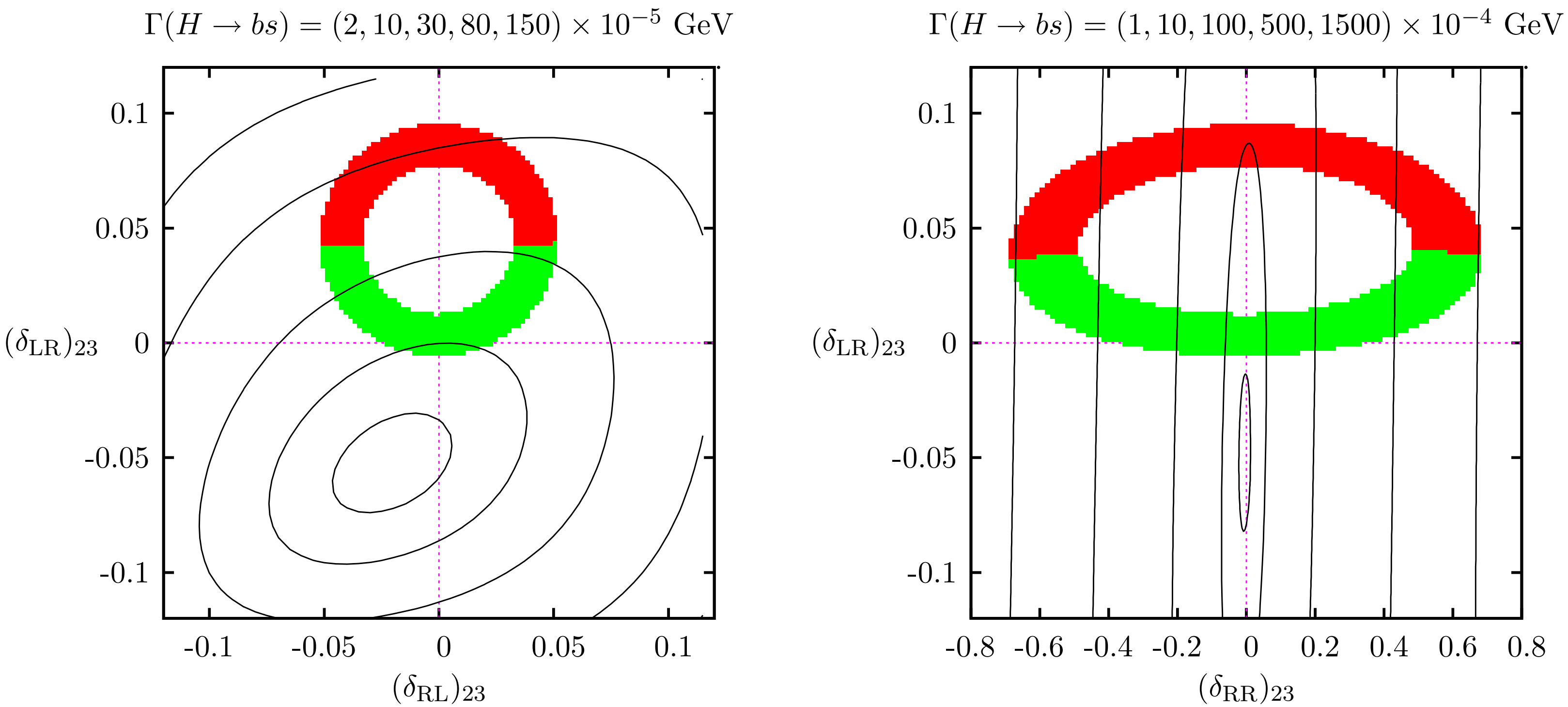
Numerical results: Two flavour-mixing parameter

We investigate whether the previous bounds obtained remain stable

$\longrightarrow$ Contours of constant $\Gamma(H^0 \to bs)$ in various planes of δ_{ab} .

$\longrightarrow$ The coloured bands indicate regions experimentally allowed by $B \to X_s\gamma$.

$\longrightarrow$ The red bands show regions disfavoured by $B \to X_s\mu^+\mu^-$.

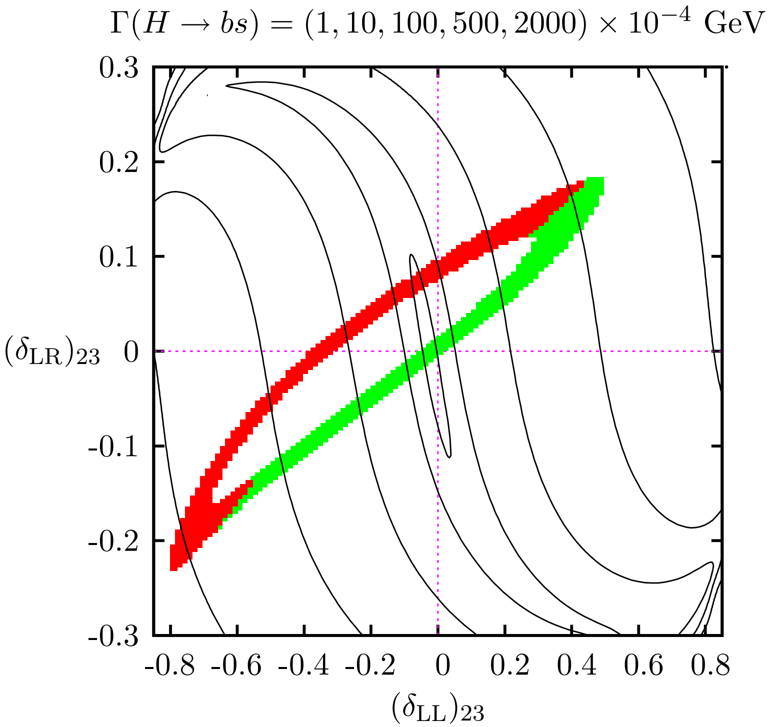


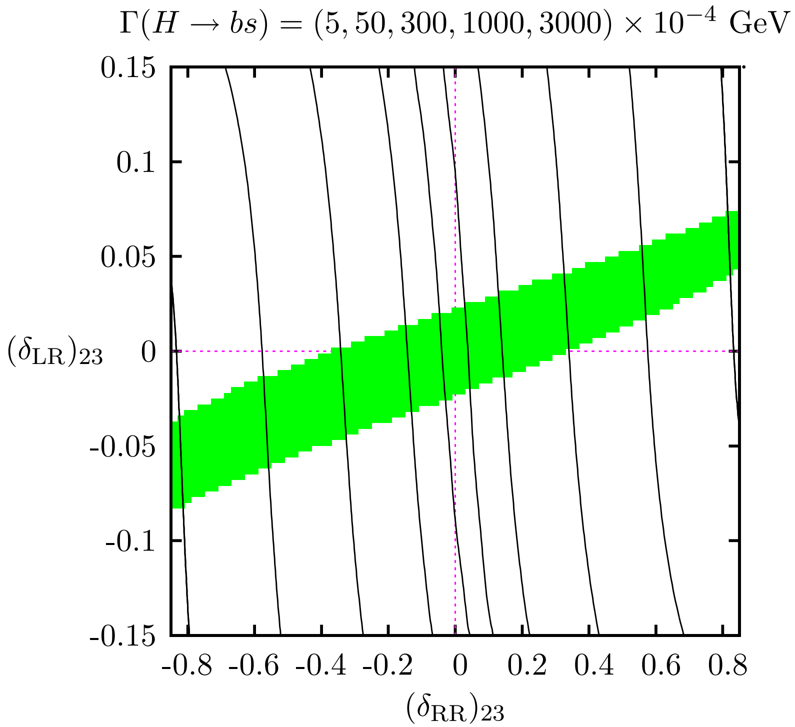
$\Gamma(H^0 \to bs)_{\text{max}} = 3 \times 10^{-4}\, GeV$ for $\delta_{\text{LR}} = 0.04$, $\delta_{\text{RL}} = 0.04$

$\Rightarrow \mathcal{B}(H^0 \to bs)_{\text{max}} \sim 10^{-5}$

$\Gamma(H^0 \to bs)_{\text{max}} = 0.15\, GeV$ for $\delta_{\text{LR}} = 0.035$, $\delta_{\text{RR}} = \pm 0.7$

$\Rightarrow \mathcal{B}(H^0 \to bs)_{\text{max}} \sim 10^{-3}$





$\Gamma(H^0 \to bs)_{\mathrm{max}} = 0.25\, GeV$
for $\delta_{LR} = -0.22\,,\ \delta_{LL} = -0.8$

$\Gamma(H^0 \to bs)_{\mathrm{max}} = 0.35\, GeV$
for $\delta_{RL} = \pm 0.04\,,\ \delta_{RR} = -0.15$

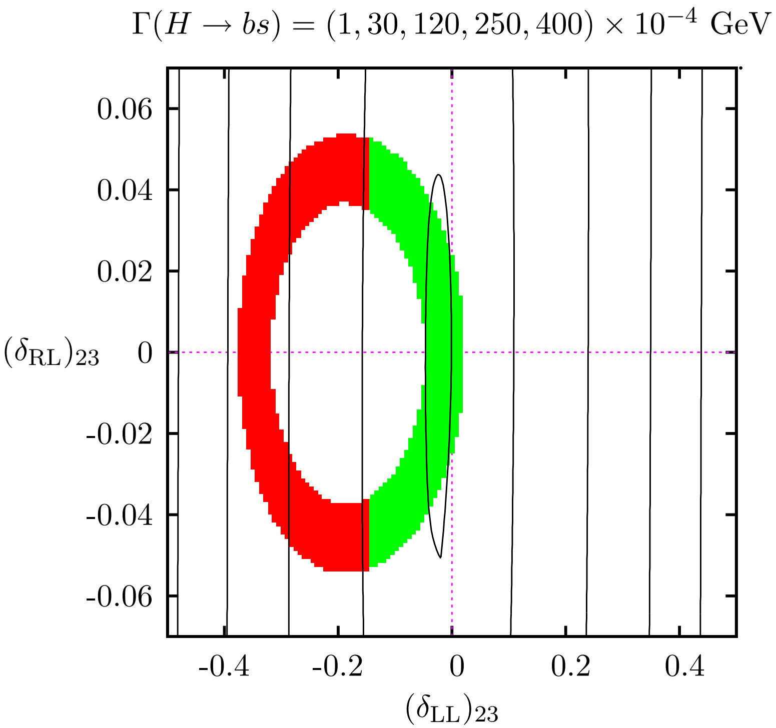
$\Rightarrow\ \mathcal{B}(H^0 \to bs)_{\mathrm{max}} \sim 10^{-2}$

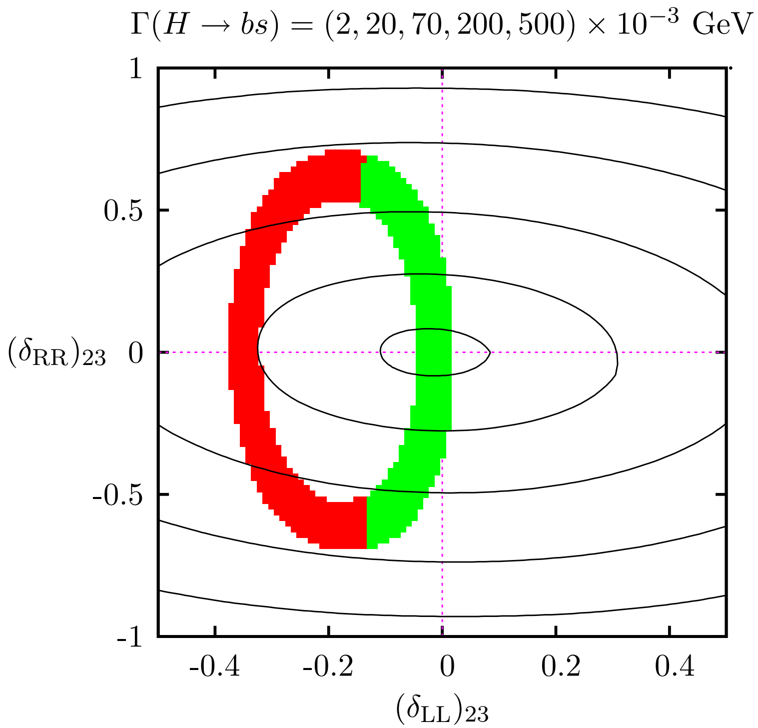
- The bounds on δ_{LR} , the best constrained for only one non-zero δ_{ab} , are dramatically relaxed when other flavour-changing parameters contribute simultaneously.

  $\Rightarrow$ Values of $\delta_{LR} \sim 10^{-1}$ are allowed.

  F. Borzumati *et al.*, hep-ph/9911245; T. Besmer *et al.*, hep-ph/0105292.

- In particular, large although fine-tuned values of δ_{LL} and δ_{LR} combined are not excluded by $b \to s\gamma$.





$\Gamma(H^0 \to bs)_{\rm max} = 2.5 \times 10^{-3}\, GeV$
for $\delta_{\rm RL} = 0.006\,,\ \delta_{\rm LL} = -0.128$

$\Rightarrow \mathcal{B}(H^0 \to bs)_{\rm max} \sim 10^{-4}$

$\Gamma(H^0 \to bs)_{\rm max} = 0.12\, GeV$
for $\delta_{\rm RR} = 0.65\,,\ \delta_{\rm LL} = \pm 0.14$

$\Rightarrow \mathcal{B}(H^0 \to bs)_{\rm max} \sim 10^{-2}$

Summary

- The predictions on $\mathcal{B}(H^0 \to bs)$ induced by $\delta_{\rm RR}$ or $\delta_{\rm LL}$ only, of $\mathcal{O}(10^{-3})$ or $\mathcal{O}(10^{-5})$, are greatly exceeded by the combinations of $\delta_{\rm LL}$-$\delta_{\rm LR}$ or $\delta_{\rm RR}$-$\delta_{\rm RL}$ or $\delta_{\rm LL}$-$\delta_{\rm RR}$, which are of $\mathcal{O}(10^{-2})$.
- Values of $\mathcal{B}(H^0 \to bs) \sim \mathcal{O}(10^{-3})$ emerge when considering LR–RR .

4. 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

- The interference effects of the combined set of flavour-mixing parameters leads to large allowed values for the $\mathcal{B}(H^0 \to bs)$, which in general can be one or two orders of magnitude larger than if induced by just one flavour-mixing parameter

- FeynArts, FormCalc and FeynHiggs now include NMFV MSSM