Flavor Violating Higgs Decays in Supersymmetric Models

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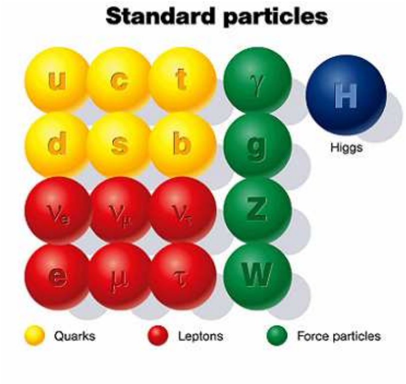
Overview

- Introduction to MSSM.
- Motivation to study Quark flavor violating Higgs decay $h \to b\bar{s} + \bar{b}s$.
- How to introduce flavor mixing in MSSM.
- Low energy constraints from Electroweak precision observables (EWPO) and B-Physics Observables (BPO).
- Quark flavor violating Higgs decay $h \to b\bar{s} + \bar{b}s$ will be studied in
  1. Model independent (MI) way.
  2. Minimal flavor violating CMSSM.

Standard Model

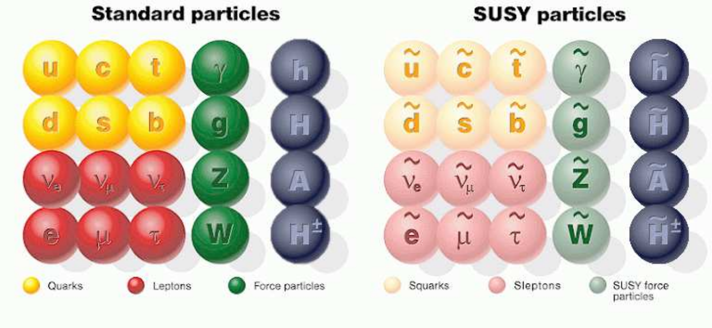


Successfully tested experimentally with high precision but

- No explanation for neutrino masses and mixing.
- No Dark Matter (DM) candidate.
- Higgs mass hierarchy problem.
- No gauge coupling unification.

We need to go beyond Standard Model.

Supersymmetry



- Theoretically most studied extension but no direct experimental evidence. We can study indirect effects of SUSY and most of these effects involve flavor observables.

Flavor Changing Neutral Current processes

In SM

- FCNC's are absent at tree level.
- Can only occur at one-loop level.
- CKM matrix is the only source for FCNC's.
- Highly suppressed due to GIM cancellation.

In SUSY

- Quark-squark misallignment is another source.
- Can dominate SM contribution by several orders of magnitude.
- Experimental deviation from SM could be a hint of SUSY.

QFV Higgs decay $h \to b\bar{s} + \bar{b}s$

- In SM $\mathrm{BR}(h \to b\bar{s} + \bar{b}s)$ can be atmost $\mathcal{O}(10^{-7})$.
- In MSSM SUSY-QCD loops can enhance the BR by several orders of magnitude.
- We (re-)calculate full one-loop contributions from SUSY-QCD and SUSY-EW loops.
- We take into account LL,LR,RL, RR mixing (prior to this only LL, RR mixing was analyzed). For our calculation, we define

$$\mathrm{BR}(h \to b\bar{s} + \bar{b}s) = \frac{\Gamma(h \to b\bar{s} + \bar{b}s)}{\Gamma_{h,\mathrm{tot}}^{\mathrm{MSSM}}} \tag{1}$$

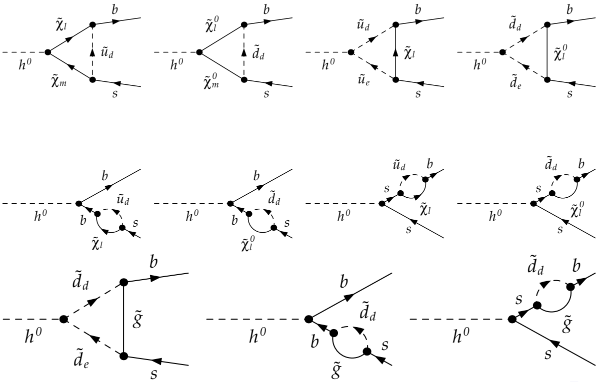
where $\Gamma_{h,\mathrm{tot}}^{\mathrm{MSSM}}$ is the total decay width of the light Higgs boson h of the MSSM, as evaluated with FeynHiggs.

QFV Higgs decay $h \to b\bar{s} + \bar{b}s$

Major SUSY contributions to this process come from

1. Diagrams with squarks and gluinos in loop (SUSY-QCD).
2. Diagrams with squarks and neutralino-chargino in loop (SUSY-EW).

1. Feynman diagrams (shown below) are generated and further evaluated using FeynArts/FormCalc setup.



Sfermion mixing

- Left-Right mixing

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} cos\theta_t & -sin\theta_t \\ sin\theta_t & cos\theta_t \end{pmatrix} . \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} , \tag{2}$$

- Flavor mixing

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix} = R^{\tilde{u}} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} \tag{3}$$

$R^{\tilde{u}}$ is 6×6 rotation matrix.

- Sfermion with different flavor can mix among each other

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix} = R^{\tilde{u}} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} , \quad \begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix} = R^{\tilde{d}} \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix} \tag{4}$$

$R^{\tilde{u}}$ and $R^{\tilde{d}}$ being the 6×6 rotation matrices.

$$\mathrm{diag}\{m^2_{\tilde{u}_1}, m^2_{\tilde{u}_2}, m^2_{\tilde{u}_3}, m^2_{\tilde{u}_4}, m^2_{\tilde{u}_5}, m^2_{\tilde{u}_6}\} = R^{\tilde{u}} \, \mathcal{M}^2_{\tilde{u}} \, R^{\tilde{u}\dagger} \tag{5}$$

$$\mathrm{diag}\{m^2_{\tilde{d}_1}, m^2_{\tilde{d}_2}, m^2_{\tilde{d}_3}, m^2_{\tilde{d}_4}, m^2_{\tilde{d}_5}, m^2_{\tilde{d}_6}\} = R^{\tilde{d}} \, \mathcal{M}^2_{\tilde{d}} \, R^{\tilde{d}\dagger} \tag{6}$$

Squark Mass Matrices

- 6×6 non-diagonal mass matrix for squarks.

$$\mathcal{M}^2_{\tilde{F}} = \begin{pmatrix} M^2_{\tilde{F}\,LL} & M^2_{\tilde{F}\,LR} \\ M^{2\,\dagger}_{\tilde{F}\,LR} & M^2_{\tilde{F}\,RR} \end{pmatrix} \tag{7}$$

where $F = U, D$ and $\mathcal{M}^2_{\tilde{U}}$, $\mathcal{M}^2_{\tilde{D}}$ are mass matrices for up-type squarks and down-type squarks respectively.

- Off-diagonal entries are parametrized in terms of dimensionless parameters δ^{FAB}_{ij}.

$$M^2_{\tilde{U}\,LL} = \begin{pmatrix} m^2_{\tilde{U}_1} & \delta^{QLL}_{12} m_{\tilde{U}_1} m_{\tilde{U}_2} & \delta^{QLL}_{13} m_{\tilde{U}_1} m_{\tilde{U}_3} \\ \delta^{QLL}_{21} m_{\tilde{U}_2} m_{\tilde{U}_1} & m^2_{\tilde{U}_2} & \delta^{QLL}_{23} m_{\tilde{U}_2} m_{\tilde{U}_3} \\ \delta^{QLL}_{31} m_{\tilde{U}_3} m_{\tilde{U}_1} & \delta^{QLL}_{32} m_{\tilde{U}_3} m_{\tilde{U}_2} & m^2_{\tilde{U}_3} \end{pmatrix} \tag{8}$$

- In total, there are 21 flavor violating δ^{FAB}_{ij} in squarks sector.
- δ^{FAB}_{ij}s induced by the RGE running (CMSSM) or put in by hand (model independent analysis) .

Low Energy Constraints

Electroweak ρ parameter

- ρ parameter is a measure of relative strength of neutral and charged-current interactions at zero momentum transfer. In SM at tree level

$$\rho = \frac{M_W^2}{Cos^2\theta_W M_Z^2} = 1 \tag{9}$$

- Higher order corrections modify this relation to

$$\rho = \frac{1}{1 - \Delta\rho} \tag{10}$$

- Here $\Delta\rho$ parametrizes the leading universal corrections to EWPO induced by the mass splitting between the fields in an isospin doublet

$$\Delta\rho = \frac{\Sigma_{ZZ}(0)}{M_Z} - \frac{\Sigma_{WW}(0)}{M_W} \tag{11}$$

Here $\Sigma_{ZZ}(0)$ and $\Sigma_{WW}(0)$ are unrenormalized Z and W boson self-energies (Transverse parts only).

δM_W and $\delta Sin^2\theta_{eff}$

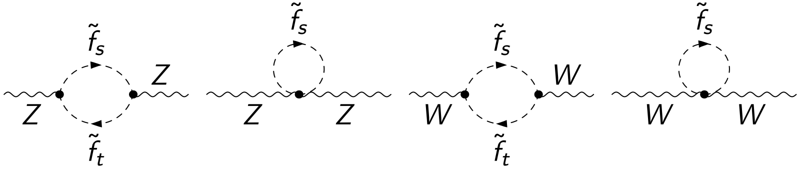
- $\Delta\rho$ enters in δM_W and $\delta Sin^2\theta_{eff}$ through the equation

$$\delta M_W = \frac{M_W}{2}\frac{Cos^2\theta_W}{Cos^2\theta_W - Sin^2\theta_W}\Delta\rho \tag{12}$$

$$\delta Sin^2\theta_{eff} = -\frac{Cos^2\theta_W Sin^2\theta_W}{Cos^2\theta_W - Sin^2\theta_W}\Delta\rho \tag{13}$$

$$\tag{14}$$

Generic Feynman diagrams for the W or Z boson self-energies.



Electroweak Precision Observables

Mass of the W-boson M_W is very precisely measured.

- $M_W^{exp,current} = 80.385 \pm 0.015\, GeV$
- $\delta M_W^{\text{exp,future}} \sim 4\ \mathrm{MeV}$ (at ILC).
- $\delta M_W^{\text{MSSM}} \sim (5 - 10)\ \mathrm{MeV}$ (depending on SUSY mass scale).

Similarly effective leptonic weak mixing angle $Sin^2\theta_{eff}$ is very precisely measured.

- $Sin^2\theta_{eff}^{exp,current} = 0.23146$
- $\delta Sin^2\theta_{eff}^{exp,current} = 15 \times 10^{-5}$
- $\delta Sin^2\theta_{eff}^{\text{exp,future}} \sim 1.3 \times 10^{-5}$ (at GigaZ option of the ILC)

We use Feynhiggs for the evaluation of EWPO.

BPO

1. For $\mathrm{BR}(B \to X_s\gamma)$, loop contributions to the Wilson coefficients come from
   1. Loops with Higgs bosons.
   2. Loops with charginos.
   3. Loops with gluinos.
2. For $\mathrm{BR}(B_s \to \mu^+\mu^-)$, loop contributions to the Wilson coefficients come from
   1. Box diagrams.
   2. Z-penguin diagrams and
   3. Neutral Higgs boson ϕ-penguin diagrams.
3. For ΔM_{B_s}, loop contributions to the Wilson coefficients come from
   1. Box diagrams.
   2. Z-penguin diagrams.
   3. double Higgs-penguin diagrams

BPO

Observable	Experimental Value	SM Prediction
$\mathrm{BR}(B \to X_s\gamma)$	$3.43 \pm 0.22 \times 10^{-4}$	$3.15 \pm 0.23 \times 10^{-4}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$(3.0)^{+1.0}_{-0.9} \times 10^{-9}$	$3.23 \pm 0.27 \times 10^{-9}$
ΔM_{B_s}	$116.4 \pm 0.5 \times 10^{-10}$	$(117.1)^{+17.2}_{-16.4} \times 10^{-10}$

Table: Experimental status of BPO with their SM prediction. ΔM_{B_s} given in MeV. The most up to date value of $\mathrm{BR}(B_s \to \mu^+\mu^-) = 2.9 \pm 0.7 \times 10^{-9}$ would have had a minor impact on our analysis.

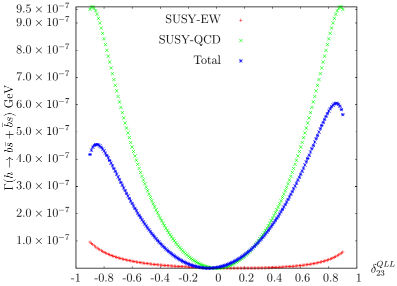
- We used B-physics subroutine from the SuFla code (added in a private version of FeynHiggs).

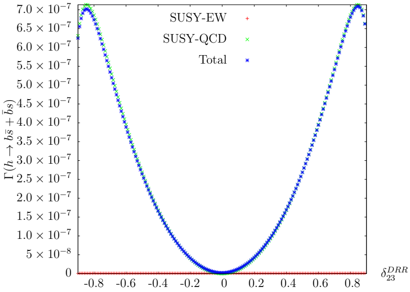
Model independent analysis.

$\Gamma(h \to b\bar{s} + \bar{b}s)$

For input parameters

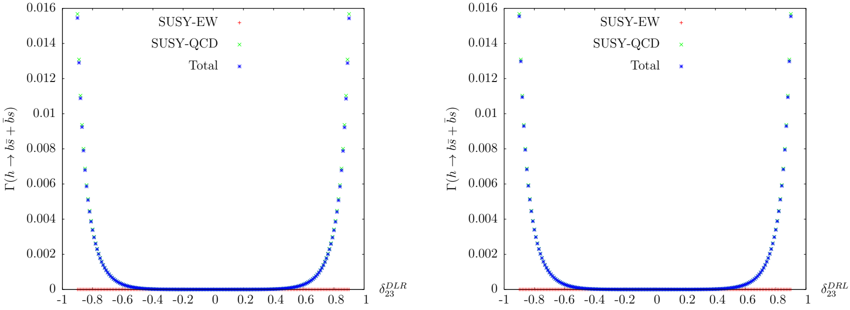
$$\mu = 800 \text{ GeV}, \ m_{susy} = 800 \text{ GeV}, \ A_f = 500 \text{ GeV}, \\ M_A = 400 \text{ GeV}, \ M_2 = 300 \text{ GeV}, \ tan\beta = 35\,, \quad (15)$$





- $\Gamma(h \to b\bar{s} + \bar{b}s)$ as a function of δ_{23}^{QLL} and δ_{23}^{DRR} (Known results).

$\Gamma(h \to b\bar{s} + \bar{b}s)$



- $\Gamma(h \to b\bar{s} + \bar{b}s)$ as a function of δ_{23}^{DLR} and δ_{23}^{DRL} (new results).

Input parameters

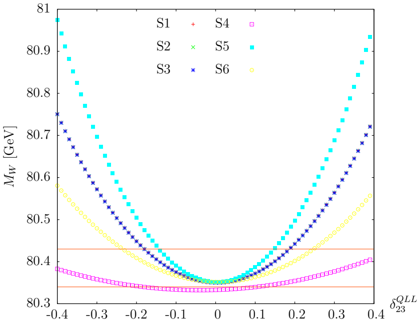
	S1	S2	S3	S4	S5	S6
$m_{\tilde{L}_{1,2}}$	500	750	1000	800	500	1500
$m_{\tilde{L}_3}$	500	750	1000	500	500	1500
M_2	500	500	500	500	750	300
A_τ	500	750	1000	500	0	1500
μ	400	400	400	400	800	300
$tan\beta$	20	30	50	40	10	40
M_A	500	1000	1000	1000	1000	1500
$m_{\tilde{Q}_{1,2}}$	2000	2000	2000	2000	2500	1500
$m_{\tilde{Q}_3}$	2000	2000	2000	500	2500	1500
$A_{t,b}$	2300	2300	2300	1000	2500	1500

Table: Selected points in MSSM parameter space. All Masses and trilinear couplings are in GeV. We have used GUT relation. Trilinear couplings not mentioned in the table are zero.

Constraints on squark mixing δ_{ij}^{FAB}s

- No assumption is made on the origin of the flavor mixing.
- Sfermion mixing (δ_{ij}^{FAB}) is introduced by hand.
- The constraints for the case of one $\delta_{ij}^{FAB} \neq 0$ from BPO were calculated in Arxive:1405.6960.
- We extended their analysis to EWPO.

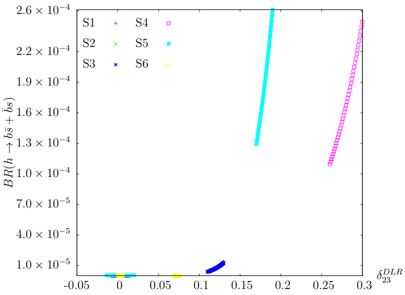
M_W with squark mixing



- M_W as a function of δ_{23}^{QLL} for the MSSM points defined in Table 2.
- The area between the orange lines shows the allowed values of M_W with 3σ uncertainty.

$\mathrm{BR}(h \to b\bar{s} + \bar{b}s)$ for one squark $\delta_{ij}^{FAB} \neq 0$

For realistic MSSM points defined in Table 2 with EWPO and BPO constraints.



- $\mathrm{BR}(h \to b\bar{s} + \bar{b}s)$ as a function of δ_{23}^{DLR}.
- $\mathrm{BR}(h \to b\bar{s} + \bar{b}s) \approx 2 \times 10^{-4}$ can be found, possibly in the reach of future e^+e^- colliders.

$\mathrm{BR}(h \to b\bar{s} + \bar{b}s)$ for two squark $\delta_{ij}^{FAB} \neq 0$

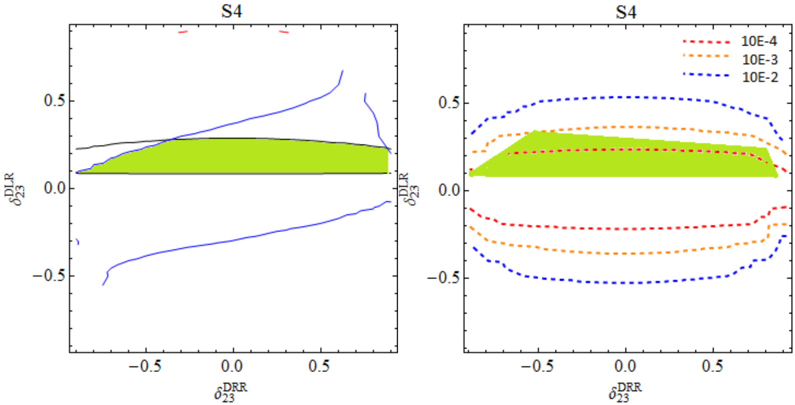


Figure: Left: Contours of $\mathrm{BR}(B \to X_s\gamma)$ (Black), $\mathrm{BR}(B_s \to \mu^+\mu^-)$ (Green), ΔM_{B_s}(Blue) and M_W (Red) in $(\delta_{23}^{QLL}, \delta_{23}^{DLR})$ plane for point S4. The shaded area shows the range of values allowed by all constraints. Right: corresponding contours for $\mathrm{BR}(h \to b\bar{s} + \bar{b}s)$.

$\mathrm{BR}(h \to b\bar{s} + \bar{b}s)$ for two squark $\delta_{ij}^{FAB} \neq 0$

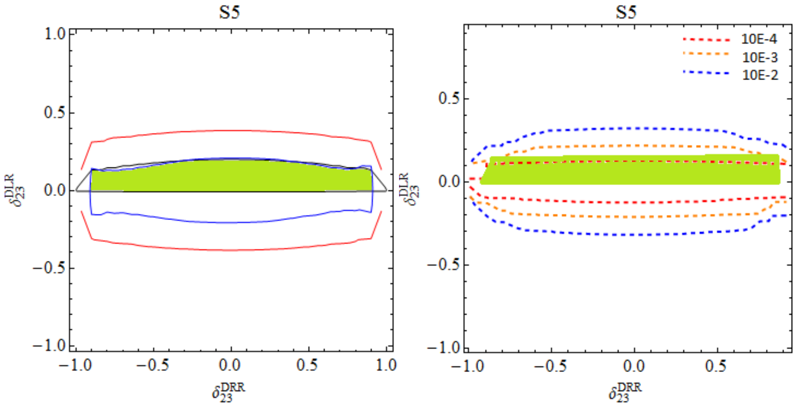


Figure: Left: Contours of $\mathrm{BR}(B \to X_s\gamma)$ (Black), $\mathrm{BR}(B_s \to \mu^+\mu^-)$ (Green), ΔM_{B_s}(Blue) and M_W (Red) in (δ_{23}^{QLL} , δ_{23}^{DLR}) plane for point S5. The shaded area shows the range of values allowed by all constraints. Right: corresponding contours for $\mathrm{BR}(h \to b\bar{s} + \bar{b}s)$.

MFV CMSSM analysis

Minimal flavor violating CMSSM

- Soft SUSY-breaking parameters are assumed to be universal at the Grand Unification scale $M_{\mathrm{GUT}} \sim 2 \times 10^{16}~\mathrm{GeV}$.

$$
\begin{aligned}
(m^2_Q)_{ij} = (m^2_U)_{ij} = (m^2_D)_{ij} = (m^2_L)_{ij} = (m^2_E)_{ij} = m^2_0~\delta_{ij}, \\
m^2_{H_1} = m^2_{H_2} = m^2_0, \\
m_{\tilde{g}} = m_{\tilde{W}} = m_{\tilde{B}} = m_{1/2}, \\
(A_U)_{ij} = A_0 (Y_U)_{ij}, \quad (A_D)_{ij} = A_0 (Y_D)_{ij}, \quad (A_E)_{ij} = A_0 (Y_E)_{ij}.
\end{aligned}
\tag{16}
$$

- Only four parameters $(m_0, m_{1/2}, A_0$ and $tan\beta)$.
- Flavor mixing in the quark sector is controlled by the CKM matrix.

Input parameters

- MSSM particle spectrum obtained by running RGEs using Spheno.
- Output from spheno in the form of SLHA handed over to Feynhiggs.
- We have scanned all combinations of

$$m_0 = 500 - 5000 \text{ GeV} , \tag{17}$$

$$m_{1/2} = 1000 - 3000 \text{ GeV} , \tag{18}$$

$$A_0 = -3000, -2000, -1000, 0 \quad \text{GeV} \tag{19}$$

$$tan\beta = 10, 20, 30, 45 \tag{20}$$

with $\mu > 0$.

- Here we show only representative results in the m_0–$m_{1/2}$ plane for different values of $tan\beta$ and A_0.

Squark δ_{ij}^{FAB}

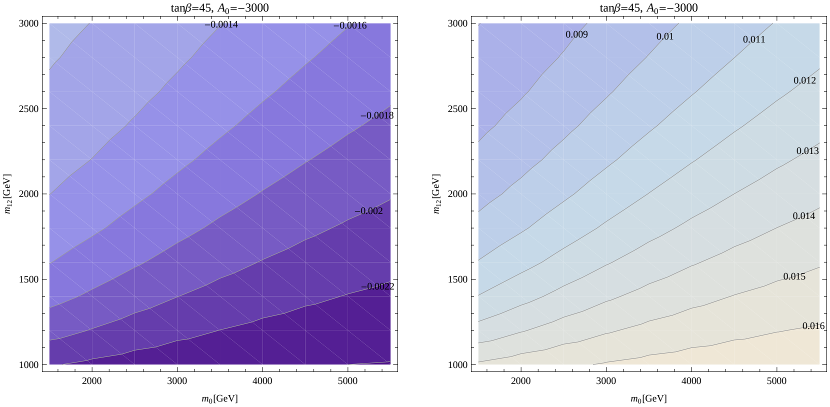
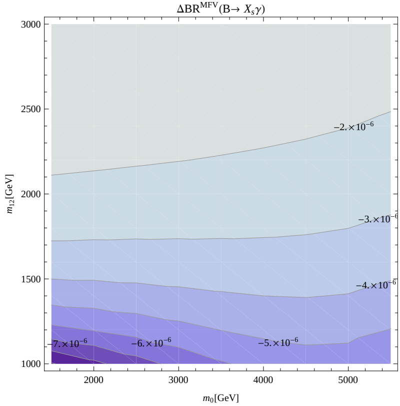
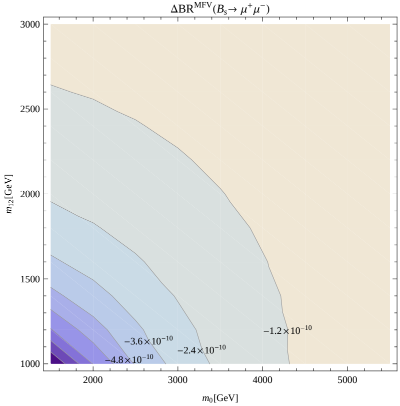


Figure: Contours of δ_{13}^{QLL}, δ_{23}^{QLL} in the m_0–$m_{1/2}$ plane.

BPO

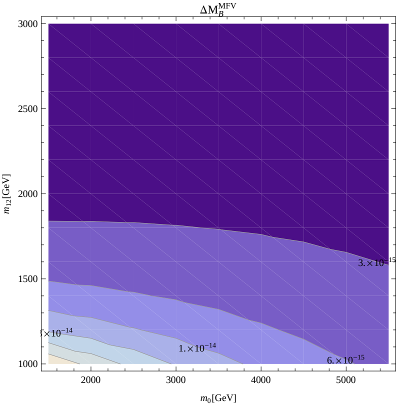
- $\Delta\mathrm{BR}^{\mathrm{MFV}}(B \to X_s\gamma) = \mathrm{BR}(B \to X_s\gamma) - \mathrm{BR}^{\mathrm{MSSM}}(B \to X_s\gamma)$
- $\Delta\mathrm{BR}^{\mathrm{MFV}}(B_s \to \mu^+\mu^-) = \mathrm{BR}(B_s \to \mu^+\mu^-) - \mathrm{BR}^{\mathrm{MSSM}}(B_s \to \mu^+\mu^-)$





BPO

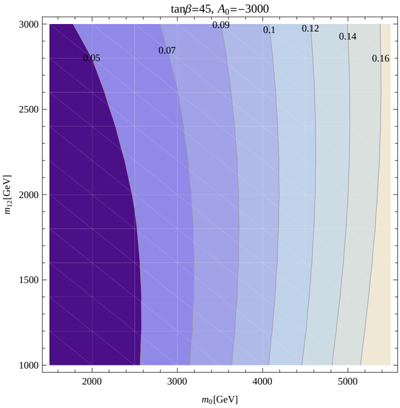
- $\Delta M_{B_s}^{\mathrm{MFV}} = \Delta M_{B_s} - \Delta M_{B_s}^{\mathrm{MSSM}}$

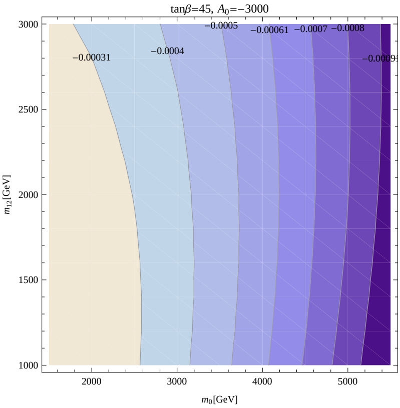


No constraints on the parameter space from BPO.

EWPO

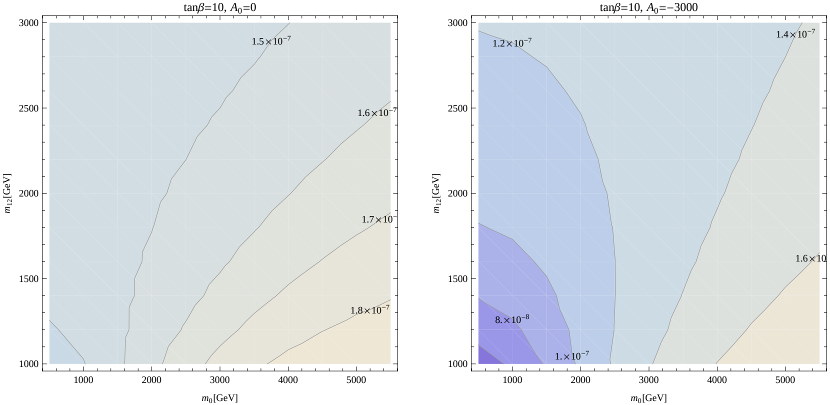
- $\delta M_W^{MFV} = M_W - M_W^{MSSM}, \quad \delta Sin^2\theta_{eff}^{MFV} = Sin^2\theta_{eff} - Sin^2\theta_{eff}^{MSSM}$





m_0 constrained from above.

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



No significant increase from SM pridictions.

Conclusion

1. Model independent analysis.
   - New constraints on squarks δ_{ij}^{FAB}s from EWPO.
   - $\mathrm{BR}(h \to b\bar{s} + \bar{b}s) \approx \mathrm{O}(10^{-3})$, possibly in the reach of future e^+e^- colliders.
2. CMSSM analysis.
   - δ_{ij}^{FAB}s $\approx \mathrm{O}(10^{-2})$ or less.
   - No constraints from BPO.
   - But m_0 can be constrained from above from EWPO.
   - $\mathrm{BR}(h \to b\bar{s} + \bar{b}s) \approx \mathrm{O}(10^{-7})$, No significant increase compared to SM contribution.

Thanks