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# Imprint of quark flavor violating SUSY in h(125) decays at future lepton colliders

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We study the CP-even neutral Higgs boson decays $h \to c\bar{c}, b\bar{b}, b\bar{s}, \gamma\gamma, gg$ in the Minimal Supersymmetric Standard Model (MSSM) with general quark flavor violation (QFV), identifying the h as the Higgs boson with a mass of 125 GeV. We compute the widths of the h decays to $c\bar{c}, b\bar{b}, b\bar{s}(s\bar{b})$ at full one-loop level. For the loop-induced h decays to photon photon and gluon gluon we compute the widths at NLO QCD level. *For the first time*, we perform a systematic MSSM parameter scan including Supersymmetric (SUSY) QFV parameters respecting all the relevant constraints, i.e. theoretical constraints from vacuum stability conditions and experimental constraints, such as those from K- and B-meson data, electroweak precision data, and the 125 GeV Higgs boson data from recent LHC experiments, as well as the limits on SUSY particle masses from the LHC experiment. We also take into account the expected SUSY particle mass limits from the future HL-LHC experiment in our analysis. *In strong contrast to* the usual studies in the MSSM with quark flavor conservation, we find that the deviations of these MSSM decay widths from the Standard Model (SM) values can be quite sizable and that there are significant correlations among these deviations. All of these sizable deviations in the h decays are due to (i) large scharm-stop mixing and large scharm/stop involved trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, (ii) large sstrange-sbottom mixing and large sstrange/sbottom involved trilinear couplings $T_{D23}, T_{D32}, T_{D33}$ and (iii) large bottom Yukawa coupling $Y_b$ for large $\tan\beta$ and large top Yukawa coupling $Y_t$. Future lepton colliders such as ILC, CLIC, CEPC, FCC-ee and MuC can observe such sizable deviations from the SM at high signal significance *even after* the failure of SUSY particle discovery at the HL-LHC. In case the deviation pattern shown here is really observed at the lepton colliders, then it would strongly suggest the discovery of QFV SUSY (the MSSM with general QFV).

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## 1. Introduction

What is the SM-like Higgs boson discovered at LHC? It can be the SM Higgs boson. It can be a Higgs boson of New Physics. This is one of the most important issues in the present particle physics field. Here we study a possibility that it is the lightest Higgs boson $h^0$ of the Minimal Supersymmetric Standard Model (MSSM), focusing on the decays $h^0(125) \to c\bar{c}, b\bar{b}, b\bar{s}, \gamma\gamma, gg$. This work is based on the update of our previous papers [1–3] and contains substantial new findings.

## 2. Key parameters of the MSSM

Key parameters in this study are Supersymmetric (SUSY) quark flavor violating (QFV) parameters $M^2_{Q_u 23} (\simeq M^2_{Q23})$, $M^2_{U23}$, $T_{U23}$, $T_{U32}$, $M^2_{Q23}$, $M^2_{D23}$, $T_{D23}$ and $T_{D32}$ which describe the $\tilde{c}_L - \tilde{t}_L$, $\tilde{c}_R - \tilde{t}_R$, $\tilde{c}_R - \tilde{t}_L$, $\tilde{c}_L - \tilde{t}_R$, $\tilde{s}_L - \tilde{b}_L$, $\tilde{s}_R - \tilde{b}_R$, $\tilde{s}_R - \tilde{b}_L$, and $\tilde{s}_L - \tilde{b}_R$ mixing, respectively. The quark flavor conserving (QFC) parameters $T_{U33}$ and $T_{D33}$ which induce the $\tilde{t}_L - \tilde{t}_R$ and $\tilde{b}_L - \tilde{b}_R$ mixing, respectively, also play an important role in this study. All the parameters in this study are assumed to be real, except the CKM matrix. We also assume that R-parity is conserved and that the lightest neutralino $\tilde{\chi}^0_1$ is the lightest SUSY particle (LSP).

## 3. Constraints on the MSSM

In our study, *for the first time*, we perform a systematic MSSM-parameter scan including SUSY QFV parameters respecting all the relevant constraints, i.e. the theoretical constraints from vacuum stability conditions and the experimental constraints, such as those from $K$- and $B$-meson data and electroweak precision data, as well as the limits on SUSY particle (sparticle) masses and the $H^0$ mass and coupling data from LHC experiments. Here $H^0$ is the discovered SM-like Higgs boson which we identify as the lightest $CP$ even neutral Higgs boson $h^0$ in the MSSM. The details of these constraints are summarized in Ref. [4] [1].

## 4. Parameter scan

We compute the decay widths $\Gamma(h^0 \to c\bar{c})$, $\Gamma(h^0 \to b\bar{b})$ and $\Gamma(h^0 \to b\bar{s}/\bar{b}s)$ at full 1-loop level and the loop-induced decay widths $\Gamma(h^0 \to \gamma\gamma)$ and $\Gamma(h^0 \to gg)$ at NLO QCD level in the MSSM with QFV [1–3]. We perform the MSSM parameter scan for these decay widths respecting all the relevant constraints mentioned above. We generate the input parameter points by using random numbers in the ranges shown in Table 1 of Ref. [4]. All input parameters are $\overline{\rm DR}$ parameters defined at scale Q = 1 TeV, except $m_A$(pole) which is the pole mass of the $CP$ odd Higgs boson $A^0$. We don't assume a GUT relation for the gaugino masses $M_1$, $M_2$, $M_3$.

From 377180 input points generated in the scan, 3208 points survived all the constraints. We show these survival points in the scatter plot in this article.

[1]The recent W boson mass ($m_W$) data from CDF II [5] is quite inconsistent with the other experimental data. This issue of the $m_W$ anomaly is not yet settled. Hence, we do not take into account this $m_W$ constraint on the MSSM parameters in our analysis.

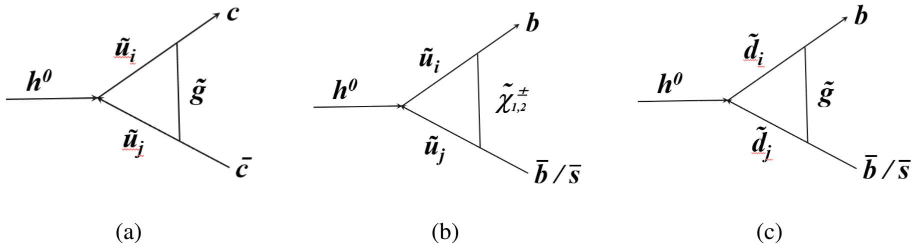


**Figure 1:** (a) The $\tilde{u}_i$-$\tilde{g}$ loop corrections to $\Gamma(h^0 \to c\bar{c})$, (b) the $\tilde{u}_i$-$\tilde{\chi}^\pm_{1,2}$ loop and (c) the $\tilde{d}_i$-$\tilde{g}$ loop corrections to $\Gamma(h^0 \to b\ \bar{b}/\bar{s})$.

## 5. $h^0(125) \to c\bar{c}, b\bar{b}, b\bar{s}$ in the MSSM

We compute the decay widths $\Gamma(h^0 \to c\bar{c})$, $\Gamma(h^0 \to b\bar{b})$ and $\Gamma(h^0 \to b\bar{s}/\bar{b}s)$ at full 1-loop level in the $\overline{DR}$ renormalization scheme in the MSSM with QFV using Fortran codes developed by us [1, 2]. We find that large squark trilinear couplings $T_{U23,32,33}$, $T_{D23,32,33}$, large $M^2_{Q23}$, $M^2_{U23}$, $M^2_{D23}$, large bottom Yukawa coupling $Y_b$ for large $\tan\beta$, and large top Yukawa coupling $Y_t$ can lead to large MSSM 1-loop corrections to these widths, resulting in large deviation of these MSSM widths from their SM values.

Main MSSM 1-loop corrections to $\Gamma(h^0 \to c\bar{c})$ stem from the lighter up-type squarks ($\tilde{u}_{1,2,3}$) - gluino ($\tilde{g}$) loops at the decay vertex, where $\tilde{u}_{1,2,3}$ are strong $\tilde{c}_{L,R}$ - $\tilde{t}_{L,R}$ mixtures (see Fig. 1(a)). The large $T_{U23,32,33}$ can enhance the $h^0 - \tilde{u}_i - \tilde{u}_j$ couplings, resulting in enhancement of the $\tilde{u}_i$-$\tilde{g}$ loop corrections to $\Gamma(h^0 \to c\bar{c})$.

Main MSSM 1-loop corrections to $\Gamma(h^0 \to b\bar{b})$ and $\Gamma(h^0 \to b\bar{s}/\bar{b}s)$ stem from (i) $\tilde{u}_{1,2,3}$ - chargino ($\tilde{\chi}^\pm_{1,2}$) loops at the decay vertex which have $h^0 - \tilde{u}_i - \tilde{u}_j$ couplings to be enhanced by large $T_{U23,32,33}$ (see Fig. 1(b)) and (ii) $\tilde{d}_{1,2,3}$ - $\tilde{g}$ loops at the decay vertex, where $\tilde{d}_{1,2,3}$ are strong $\tilde{s}_{L,R}$ - $\tilde{b}_{L,R}$ mixtures (see Fig. 1(c)). The large $T_{U23,32,33}$ and $T_{D23,32,33}$ can enhance the $\tilde{u}_i$ - $\tilde{\chi}^\pm_{1,2}$ and $\tilde{d}_i$ - $\tilde{g}$ loop corrections to $\Gamma(h^0 \to b\bar{b})$, $\Gamma(h^0 \to b\bar{s}/\bar{b}s)$, respectively.

We define the deviation of the MSSM width from the SM width as $DEV(X) \equiv \Gamma(h^0 \to X\bar{X})_{MSSM}/\Gamma(h^0 \to X\bar{X})_{SM} - 1$, (X=c,b). DEV(X) is related with the coupling modifier $\kappa_X \equiv C(h^0 X\bar{X})_{MSSM}/C(h^0 X\bar{X})_{SM}$ as $DEV(X) = \kappa_X^2 - 1$.

In Fig. 2 we show the scatter plot in the DEV(c)-DEV(b) plane obtained from the MSSM parameter scan described above, respecting all the relevant constraints shown in Section 3. We see that DEV(c) and DEV(b) can be quite large simultaneously: DEV(c) can be as large as $\sim \pm 60\%$ and DEV(b) can be as large as $\sim \pm 20\%$. ILC together with HL-LHC can observe such large deviations from SM at high significance [6].

We have found that the deviation of the width ratio $\Gamma(h^0 \to b\bar{b})/\Gamma(h^0 \to c\bar{c})$ in the MSSM from the SM value can exceed +100%.

From our MSSM parameter scan we find that QFV decay branching ratio $B(h^0 \to bs) \equiv B(h^0 \to b\bar{s}) + B(h^0 \to \bar{b}s)$ can be as large as $\sim 0.2\%$ (see also [7]) while it is almost zero in the SM. The ILC250/500/1000 sensitivity to this branching ratio could be $\sim 0.1\%$ at $4\sigma$ signal significance [8]. Note that LHC and HL-LHC sensitivity should not be so good due to huge QCD background. From the scan we find that $B(h^0 \to bs)$ can be large for large $|T_{D23}|$ and $|T_{D32}|$ being

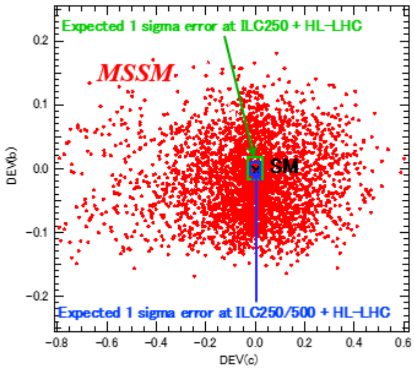


**Figure 2:** The scatter plot in the DEV(c)-DEV(b) plane obtained from the MSSM parameter scan described in Section 4. "X" marks the SM point. The green and blue box indicate the expected $1\sigma$ error at [ILC250 + HL-LHC] and [ILC250/500 + HL-LHC], respectively [6].

the size of the $\tilde{s}_R - \tilde{b}_L$ and $\tilde{s}_L - \tilde{b}_R$ mixing parameter, respectively.

## 6. $h^0(125) \to \gamma\gamma, gg$ in the MSSM

We compute the widths of the loop-induced $h^0$ decay to $\gamma\gamma$ and $gg$ at NLO QCD level [3]. From our MSSM parameter scan, we find (i) DEV($\gamma$) and DEV($g$) can be sizable simultaneously: DEV($\gamma$) and DEV($g$) can be as large as $\sim \pm 1\%$ and $\sim \pm 4\%$, respectively. (ii) There is a very strong correlation between DEV($\gamma$) and DEV($g$). (iii) The deviation of the width ratio $\Gamma(h^0 \to \gamma\gamma)/\Gamma(h^0 \to gg)$ in the MSSM from the SM value can be as large as $\sim \pm 5\%$. (iv) ILC250/500 together with HL-LHC can observe such large deviations from SM at fairly high significance [6], except DEV($\gamma$).

## 7. Benchmark scenario

In our analysis we also take into account the expected sparticle mass limits from the future HL-LHC experiment. From the allowed MSSM parameter points in the scan, we have selected a benchmark point P1 shown in Table 1 which satisfies also all the expected sparticle mass limits (including ($m_A/m_{H^+}$, $\tan\beta$) limits) from negative sparticle search in the HL-LHC experiment [9, 10]. The resulting physical masses of the particles are shown in Table 2. In Fig. 3 we show the contour plot of DEV(c) around P1 in the $T_{U32}$-$M^2_{U23}$ plane. We find that DEV(c) can be very large (about -30% to 10%) in the sizable region allowed by all the constraints including the expected sparticle mass limits from the future HL-LHC experiment. For DEV(b), DEV(g) and DEV($\gamma$) we have obtained similar results to those presented in Sections 5 and 6. We have also found that $B(h^0 \to bs)$ is sizable ($\sim 0.1\%$) in the allowed region of the $T_{U32}$-$M^2_{U23}$ plane.

## 8. Conclusion

We have studied the decays $h^0(125) \to c\bar{c}, b\bar{b}, b\bar{s}, \gamma\gamma, gg$ in the MSSM with general QFV. *For the first time*, we have performed the systematic MSSM parameter scan respecting all of the relevant

**Table 1:** The MSSM parameters for the reference point P1 (in units of GeV or GeV$^2$ except for $\tan\beta$). All parameters are defined at scale Q = 1 TeV, except $m_A(pole)$. The parameters that are not shown here are taken to be zero.

| $\tan\beta$ | $M_1$ | $M_2$ | $M_3$ | $\mu$ | $m_A(pole)$ |
|---|---|---|---|---|---|
| 33 | 1660 | 765 | 4615 | 870 | 5325 |

| $M^2_{Q22}$ | $M^2_{Q33}$ | $M^2_{Q23}$ | $M^2_{U22}$ | $M^2_{U33}$ | $M^2_{U23}$ |
|---|---|---|---|---|---|
| $3975^2$ | $3160^2$ | $920^2$ | $3465^2$ | $1300^2$ | $795^2$ |

| $M^2_{D22}$ | $M^2_{D33}$ | $M^2_{D23}$ | $T_{U23}$ | $T_{U32}$ | $T_{U33}$ |
|---|---|---|---|---|---|
| $2620^2$ | $2425^2$ | $-1625^2$ | -2040 | -1880 | -4945 |

| $T_{D23}$ | $T_{D32}$ | $T_{D33}$ | $T_{E33}$ |
|---|---|---|---|
| -2360 | 1670 | -2395 | -300 |

| $M^2_{Q11}$ | $M^2_{U11}$ | $M^2_{D11}$ | $M^2_{L11}$ | $M^2_{L22}$ | $M^2_{L33}$ | $M^2_{E11}$ | $M^2_{E22}$ | $M^2_{E33}$ |
|---|---|---|---|---|---|---|---|---|
| $4500^2$ | $4500^2$ | $4500^2$ | $1500^2$ | $1500^2$ | $1500^2$ | $1500^2$ | $1500^2$ | $1500^2$ |

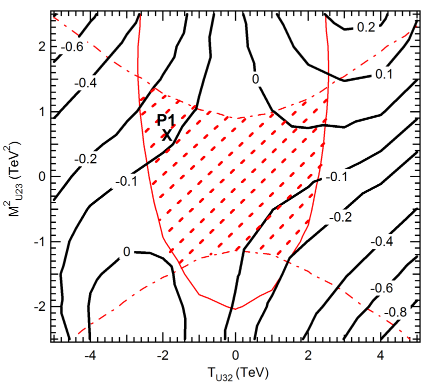


**Figure 3:** Contour plot of DEV(c) around P1 in the $T_{U32}$-$M^2_{U23}$ plane. "X" marks P1. The red hatched region is allowed by all the constraints including the expected sparticle mass limits from HL-LHC.

theoretical and experimental constraints. *In strong contrast to* the usual studies in the MSSM with quark flavor conservation, we have found that the deviations of these MSSM decay widths from the SM values can be quite sizable. Future lepton colliders such as ILC, CLIC, CEPC, FCC-ee and MuC can observe such sizable deviations from the SM at high signal significance *even after* the failure of SUSY particle discovery at the HL-LHC. In case the deviation pattern shown here is really observed at the lepton colliders, then it would strongly suggest the discovery of QFV SUSY (the MSSM with general QFV).

**Table 2:** Physical masses in GeV of the particles for the scenario of Table 1.

| $m_{\tilde{\chi}_1^0}$ | $m_{\tilde{\chi}_2^0}$ | $m_{\tilde{\chi}_3^0}$ | $m_{\tilde{\chi}_4^0}$ | $m_{\tilde{\chi}_1^+}$ | $m_{\tilde{\chi}_2^+}$ |
|---|---|---|---|---|---|
| 781 | 882 | 911 | 1669 | 782 | 914 |

| $m_{h^0}$ | $m_{H^0}$ | $m_{A^0}$ | $m_{H^+}$ |
|---|---|---|---|
| 124 | 5325 | 5325 | 5359 |

| $m_{\tilde{g}}$ | $m_{\tilde{u}_1}$ | $m_{\tilde{u}_2}$ | $m_{\tilde{u}_3}$ | $m_{\tilde{u}_4}$ | $m_{\tilde{u}_5}$ | $m_{\tilde{u}_6}$ |
|---|---|---|---|---|---|---|
| 4424 | 868 | 3011 | 3331 | 3877 | 4402 | 4402 |

| $m_{\tilde{d}_1}$ | $m_{\tilde{d}_2}$ | $m_{\tilde{d}_3}$ | $m_{\tilde{d}_4}$ | $m_{\tilde{d}_5}$ | $m_{\tilde{d}_6}$ |
|---|---|---|---|---|---|
| 1705 | 2833 | 3010 | 3877 | 4397 | 4403 |

| $m_{\tilde{\nu}_1}$ | $m_{\tilde{\nu}_2}$ | $m_{\tilde{\nu}_3}$ | $m_{\tilde{l}_1}$ | $m_{\tilde{l}_2}$ | $m_{\tilde{l}_3}$ | $m_{\tilde{l}_4}$ | $m_{\tilde{l}_5}$ | $m_{\tilde{l}_6}$ |
|---|---|---|---|---|---|---|---|---|
| 1509 | 1509 | 1528 | 1489 | 1489 | 1509 | 1512 | 1512 | 1545 |

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