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The $h(125)$ decays to $c\bar{c}$, $b\bar{b}$, $b\bar{s}$, $\gamma\gamma$ and gg in the light of the MSSM with quark flavor violation

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We study the Higgs boson decays $h^0 \to c\bar{c}, b\bar{b}, b\bar{s}, \gamma\gamma, gg$ in the Minimal Supersymmetric Standard Model (MSSM) with general quark flavor violation (QFV), identifying the h^0 as the Higgs boson with a mass of 125 GeV. We compute the widths of the h^0 decays to $c\bar{c}, b\bar{b}, b\bar{s}(s\bar{b})$ at full one-loop level. For the h^0 decays to photon photon and gluon gluon we compute the widths at NLO QCD level. We perform a systematic MSSM parameter scan 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 and electroweak precision data, as well as recent limits on Supersymmetric (SUSY) particle masses and the 125 GeV Higgs boson data from LHC experiments. From the parameter scan, we find that the deviations of these MSSM widths from the Standard Model (SM) values can be quite sizable. All of these large deviations in the h^0 decays are due to large scharm-stop mixing, large scharm/stop involved trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, large sstrange-sbottom mixing, and large sstrange/sbottom involved trilinear couplings $T_{D23}, T_{D32}, T_{D33}$. International Linear Collider (ILC) can observe such large deviations from the SM at high signal significance. In case the deviation pattern shown here is really observed at ILC, then it would strongly suggest the discovery of QFV SUSY (the MSSM with 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 significant (substantial) new findings.

2. Key parameters of the MSSM

Key parameters in this study are the 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 we perform a MSSM-parameter scan 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 recent limits on SUSY particle 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].

4. Parameter scan for $h^0(125) \to c\bar{c}, b\bar{b}, b\bar{s}$

We perform the MSSM parameter scan for the decay widths $\Gamma(h^0 \to c\bar{c})$, $\Gamma(h^0 \to b\bar{b})$ and $\Gamma(h^0 \to b\bar{s})$ computed at full 1-loop level in the MSSM with QFV respecting all the relevant constraints mentioned above. Concerning squark generation mixings, we only consider the mixing between the second and third generation of squarks. We generate the input parameter points by using random numbers in the ranges shown in Table 1, where some parameters are fixed as given in the last box. All input parameters are $\overline{\text{DR}}$ parameters defined at scale Q = 1 TeV, except m_A(pole) which is the pole mass of the CP odd Higgs boson A^0. The parameters that are not shown explicitly are taken to be zero. 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 all scatter plots in this article.

Table 1: Scanned ranges and fixed values of the MSSM parameters (in units of GeV or GeV^2, except for $\tan\beta$). The parameters that are not shown explicitly are taken to be zero. $M_{1,2,3}$ are the U(1), SU(2), SU(3) gaugino mass parameters, respectively.

$\tan\beta$	M_1	M_2	M_3	μ	$m_A(pole)$
$10 \div 80$	$100 \div 2500$	$100 \div 2500$	$2500 \div 5000$	$100 \div 2500$	$1350 \div 6000$

M^2_{Q22}	M^2_{Q33}	$\lvert M^2_{Q23}\rvert$	M^2_{U22}	M^2_{U33}	$\lvert M^2_{U23}\rvert$
$2500^2 \div 4000^2$	$2500^2 \div 4000^2$	$< 1000^2$	$1000^2 \div 4000^2$	$600^2 \div 3000^2$	$< 2000^2$

M^2_{D22}	M^2_{D33}	$\lvert M^2_{D23}\rvert$	$\lvert T_{U23}\rvert$	$\lvert T_{U32}\rvert$	$\lvert T_{U33}\rvert$
$2500^2 \div 4000^2$	$1000^2 \div 3000^2$	$< 2000^2$	< 4000	< 4000	< 5000

$\lvert T_{D23}\rvert$	$\lvert T_{D32}\rvert$	$\lvert T_{D33}\rvert$	$\lvert T_{E33}\rvert$
< 3000	< 3000	< 4000	< 500

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

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 $\Gamma(h^0 \to b\bar{s})$ at full 1-loop level in the $\overline{DR}$ renormalization scheme in the MSSM with QFV [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 the widths of these decays. This is mainly due to the following reasons: The lighter up-type squarks $\tilde{u}_{1,2,3}$ are strong $\tilde{c}_{L,R}$ - $\tilde{t}_{L,R}$ mixtures for large M^2_{Q23}, M^2_{U23}, $T_{U23,32,33}$. The lighter down-type squarks $\tilde{d}_{1,2,3}$ are strong $\tilde{s}_{L,R}$ - $\tilde{b}_{L,R}$ mixtures for large M^2_{Q23}, M^2_{D23}, $T_{D23,32,33}$. Here note that $|T_{U23,32,33}|$, the sizes of which are controlled by Y_t due to the vacuum stability conditions, can be large because of large Y_t. Similarly $|T_{D23,32,33}|$, the sizes of which are controlled by Y_b due to the vacuum stability conditions, can be large thanks to large Y_b for large $\tan\beta$ [4]. In the following we assume these setups.

Main MSSM 1-loop corrections to $\Gamma(h^0 \to c\bar{c})$ stem from the up-type squarks ($\tilde{u}_{1,2,3}$) - gluino ($\tilde{g}$) loops at the decay vertex which have $h^0 - \tilde{u}_i - \tilde{u}_j$ couplings containing $H^0_2 - \tilde{c}_R - \tilde{t}_L$, $H^0_2 - \tilde{c}_L - \tilde{t}_R$, $H^0_2 - \tilde{t}_L - \tilde{t}_R$ couplings, i.e., $T_{U23,32,33}$ (see Fig. 1(a)). Hence, large trilinear couplings $T_{U23,32,33}$ can enhance the $h^0 - \tilde{u}_i - \tilde{u}_j$ couplings, which results in enhancement of the MSSM 1-loop corrections to $\Gamma(h^0 \to c\bar{c})$ due to the $\tilde{u}_i$-$\tilde{g}$ loops, leading to large deviation of the MSSM width $\Gamma(h^0 \to c\bar{c})$ from its SM value. 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 which have $h^0 - \tilde{d}_i - \tilde{d}_j$ couplings containing $H^0_1 - \tilde{s}_R - \tilde{b}_L$, $H^0_1 - \tilde{s}_L - \tilde{b}_R$, $H^0_1 - \tilde{b}_L - \tilde{b}_R$ couplings, i.e.,

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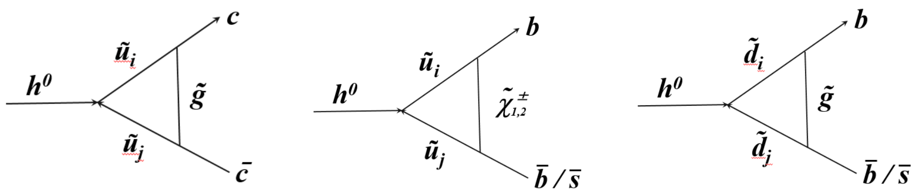

(a) (b) (c)

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 $\Gamma(h^0 \to b\ \bar{b}/\bar{s})$.

$T_{D23,32,33}$ (see Fig. 1(c)). Hence large trilinear couplings $T_{U23,32,33}$ and $T_{D23,32,33}$ can enhance the MSSM 1-loop corrections to $\Gamma(h^0 \to b\bar{b})$ and $\Gamma(h^0 \to b\bar{s}/\bar{b}s)$ due to the $\tilde{u}_i$ - $\tilde{\chi}^{\pm}_{1,2}$ and $\tilde{d}_i$ - $\tilde{g}$ loops, leading to large deviation of the MSSM widths $\Gamma(h^0 \to b\bar{b})$ and $\Gamma(h^0 \to b\bar{s}/\bar{b}s)$ from their SM values.

We define the deviation of the MSSM width from the SM width as:

$$DEV(X) \equiv \frac{\Gamma(h^0 \to X\bar{X})_{MSSM}}{\Gamma(h^0 \to X\bar{X})_{SM}} - 1 \ (X = c, b) \tag{1}$$

DEV(X) is related with the coupling modifier $\kappa_X \equiv C(h^0X\bar{X})_{MSSM}/C(h^0X\bar{X})_{SM}$ as $DEV(X) = \kappa_X^2 - 1$. We compute the decay widths $\Gamma(h^0 \to X\bar{X})$ (X=c,b) at full 1-loop level in the $\overline{DR}$ renormalization scheme in the MSSM with QFV using Fortran codes developed by us [1, 2].

In Fig. 2 we show the scatter plot in the DEV(c)-DEV(b) plane obtained from the MSSM parameter scan described above (see Table 1), respecting all the relevant constraints shown in Section 3. From Fig. 2 we see that DEV(c) and DEV(b) can be quite large simultaneously: DEV(c) can be as large as $\sim \pm 50\%$ 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 [5]: The expected 1σ error of DEV(c) is ΔDEV(c) =(3.60%, 2.40%, 1.58%) and that of DEV(b) is ΔDEV(b) =(1.98%, 1.16%, 0.94%) at (ILC250, ILC250/500, ILC250/500/1000) together with HL-LHC, respectively (see Fig. 2).

As for the explicitly QFV decay branching ratio $B(h^0 \to bs) \equiv B(h^0 \to b\bar{s}) + B(h^0 \to \bar{b}s)$, from our MSSM parameter scan we find that it can be as large as $\sim 0.17\%$ in the MSSM with QFV (see also [6]) while it is almost zero in the SM. On the other hand, the ILC250/500/1000 sensitivity to this branching ratio could be $\sim 0.1\%$ at 4σ signal significance [7]. Note that LHC and HL-LHC sensitivity should not be so good due to huge QCD background. In Fig. 3 we show the scatter plot in the T_{D23}-$B(h^0 \to bs)$ plane obtained from the MSSM parameter scan described above (see Table 1), respecting all the relevant constraints shown in Section 3. From Fig. 3 we see that there is a strong correlation between T_{D23} and $B(h^0 \to bs)$: $B(h^0 \to bs)$ can be large for large $|T_{D23}|$ being the size of the $\tilde{s}_R - \tilde{b}_L$ mixing parameter. We have obtained a similar result for the scatter plot in the T_{D32}-$B(h^0 \to bs)$ plane with T_{D32} being the $\tilde{s}_L - \tilde{b}_R$ mixing parameter.

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

For the h^0 decays to $\gamma\gamma$ and gg we compute the widths at NLO QCD level [3]. We perform the MSSM parameter scan respecting all the relevant theoretical and experimental constraints as

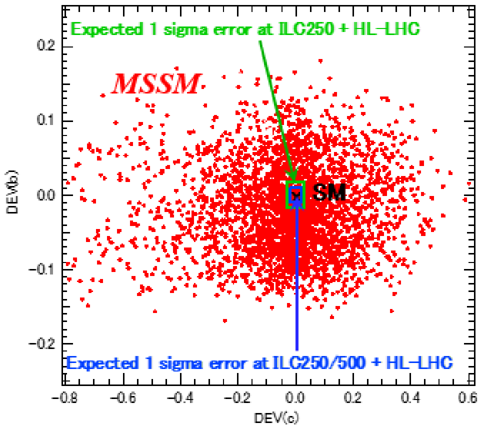

Figure 2: The scatter plot in the DEV(c)-DEV(b) plane obtained from the MSSM parameter scan described in Section 4. "X" marks the SM point. The green and blue box indicate the expected 1σ error at [ILC250 + HL-LHC] and [ILC250/500 + HL-LHC], respectively.

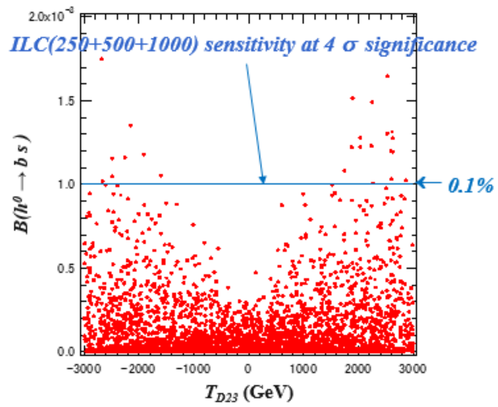

Figure 3: The scatter plot in the T_{D23}-$B(h^0 \to bs)$ plane obtained from the MSSM parameter scan described in Section 4. The blue horizontal line indicates the ILC(250+500+1000) sensitivity of ~0.1% at 4σ signal significance.

mentioned above. From the parameter scan, we find the followings [3]:
(i) DEV(γ) and DEV(g) can be sizable simultaneously: DEV(γ) and DEV(g) can be as large as $\sim +4\%$ and $\sim -15\%$, respectively.
(ii) There is a very strong correlation between DEV(γ) and DEV(g), which is due to the fact that the "stop"-loop (i.e. stop-scharm mixture loop) contributions dominate the two DEVs.
(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 $\sim +20\%$.
(iv) ILC250/500 together with HL-LHC can observe such large deviations from SM at high significance [5].
The scatter plots in the DEV(γ)-DEV(g) plane obtained from the MSSM parameter scan are shown in Ref. [3].

7. 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 QFV. Performing a systematic MSSM parameter scan respecting all of the relevant theoretical and experimental constraints, we have found the followings:
(A) DEV(c) and DEV(b) can be very large simultaneously: DEV(c) and DEV(b) can be as large as $\sim \pm 50\%$ and $\sim \pm 20\%$, respectively.
(B) 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%.
(C) $B(h^0 \to bs)$ can be as large as ~0.17% in the MSSM while ILC250/500/1000 sensitivity could be ~0.1% at 4σ signal significance.
(D) DEV(γ) and DEV(g) can be sizable simultaneously: DEV(γ) and DEV(g) can be as large as $\sim +4\%$ and $\sim -15\%$, respectively.
(E) 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 $\sim +20\%$.
(F) There is a very strong correlation between DEV(γ) and DEV(g).
(G) All of these large deviations in the $h^0(125)$ decays are due to (i) large $\tilde{c} - \tilde{t}$ mixing and large $\tilde{c}/\tilde{t}$ involved trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, (ii) large $\tilde{s} - \tilde{b}$ mixing and large $\tilde{s}/\tilde{b}$ involved trilinear couplings $T_{D23}, T_{D32}, T_{D33}$, (iii) large bottom Yukawa coupling Y_b for large $\tan\beta$, and large top Yukawa coupling Y_t.

ILC together with HL-LHC can observe such large deviations from SM at high significance. In case the deviation pattern shown here is really observed at ILC, then it would strongly suggest the discovery of QFV SUSY (the MSSM with QFV).

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