Impact of quark flavor violation on the decay $h^0(125\text{GeV}) \rightarrow \bar{c}c$ in the MSSM

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We compute the decay width of $h^0 \rightarrow \bar{c}c$ in the MSSM with quark flavor violation (QFV) at full one-loop level in the DR renormalization scheme. We study the effects of $\tilde{c} - \tilde{t}$ mixing, taking into account the constraints on QFV from the B meson data. We find that the full one-loop corrected decay width $\Gamma(h^0 \rightarrow \bar{c}c)$ is very sensitive to the MSSM QFV parameters. In a scenario with large $\tilde{c}_{L,R} - \tilde{t}_{L,R}$ mixing, $\Gamma(h^0 \rightarrow \bar{c}c)$ can differ up to $\sim \pm 35\%$ from its SM value. After estimating the uncertainties of the width, we conclude that an observation of these QFV SUSY effects is possible at a future $e^+e^-$ collider such as ILC.

I. INTRODUCTION

It is the most important issue in the present particle physics world to determine if the SM (Standard Model)-like Higgs boson discovered at the LHC (Large Hadron Collider) in 2012 [1, 2] is the SM Higgs boson or a Higgs boson of New Physics. In this article based on our paper [3], we study the possibility that it is the lightest Higgs boson $h^0$ of the Minimal Supersymmetric Standard Model (MSSM), by focusing on the width of the decay $h^0 \rightarrow \bar{c}c$. We compute the decay width at full one-loop level in the DR renormalization scheme in the MSSM with nonminimal Quark Flavor Violation (QFV).

II. DEFINITION OF THE QFV PARAMETERS

In the super-CKM basis of $\tilde{q}_\gamma = (\tilde{q}_{1L}, \tilde{q}_{2L}, \tilde{q}_{3L}, \tilde{q}_{1R}, \tilde{q}_{2R}, \tilde{q}_{3R})$, $\gamma = 1, \ldots, 6$, with $(q_1, q_2, q_3) = (u, c, t)$, $(d, s, b)$, one can write the squark mass matrices in their most general $3 \times 3$-block form

$$M^2_\tilde{q} = \begin{pmatrix} M^2_{\tilde{q},LL} & M^2_{\tilde{q},LR} \\ M^2_{\tilde{q},RL} & M^2_{\tilde{q},RR} \end{pmatrix},$$

with $\tilde{q} = \tilde{u}, \tilde{d}$. The left-left and right-right blocks in eq. (1) are given by

$$M^2_{\tilde{q},LL} = V_{CKM}M^2_QV_{CKM}^\dagger + D_{\tilde{q},LL}1 + \hat{m}^2_u,$$
$$M^2_{\tilde{q},RR} = M^2_U + D_{\tilde{q},RR}1 + \hat{m}^2_d,$$
$$M^2_{\tilde{d},LL} = M^2_Q + D_{\tilde{d},LL}1 + \hat{m}^2_d,$$
$$M^2_{\tilde{d},RR} = M^2_D + D_{\tilde{d},RR}1 + \hat{m}^2_d,$$

where $M_{Q,U,D}$ are the hermitian soft SUSY-breaking mass matrices of the squarks and $\hat{m}_{u,d}$ are the diagonal mass matrices of the up-type and down-type quarks. $D_{\tilde{q},LL}$ and $D_{\tilde{d},RR}$ are the D terms. Due to the $SU(2)_L$ symmetry the left-left blocks of the up-type and down-type squarks in eq. (2) are related by the CKM matrix $V_{CKM}$. The left-right and right-left blocks of eq. (1) are given by

$$M^2_{\tilde{q},RL} = M^2_{\tilde{q},LR} = \frac{v_T}{\sqrt{2}}(T_U - \mu^*\hat{m}_u \cot \beta),$$
$$M^2_{\tilde{d},RL} = M^2_{\tilde{d},LR} = \frac{v_T}{\sqrt{2}}(T_D - \mu^*\hat{m}_d \tan \beta),$$

where $v_T$ is the vacuum expectation value of the Higgs field in the MSSM.
where $T_{U,D}$ are the soft SUSY-breaking trilinear coupling matrices of the up-type and down-type squarks entering the Lagrangian $\mathcal{L}_{int} \supset -(T_{U,i0} \tilde{u}_R \tilde{u}_L \tilde{H}_2^0 + T_{D,i0} \tilde{d}_R \tilde{d}_L H_1^0)$, $\mu$ is the higgsino mass parameter, and $\tan \beta$ is the ratio of the vacuum expectation values of the neutral Higgs fields $v_2/v_1$, with $v_{1,2} = \sqrt{2} \langle H_{1,2}^0 \rangle$. The squark mass matrices are diagonalized by the $6 \times 6$ unitary matrices $\tilde{U}$, $\tilde{q} = \tilde{u}, \tilde{d}$, such that

$$U^\dagger M_{\tilde{q}}^2 (U^\dagger)^\dagger = \text{diag}(m_{\tilde{q}_1}^2, \ldots, m_{\tilde{q}_6}^2),$$

with $m_{\tilde{q}_1} < \cdots < m_{\tilde{q}_6}$. The physical mass eigenstates $\tilde{q}_i$, $i = 1, \ldots, 6$ are given by $\tilde{q}_i = U^\dagger \tilde{q}_{\alpha i}$.

We define the QFV parameters in the up-type squark sector $\delta_{\alpha\beta}^{LL}$, $\delta_{\alpha\beta}^{RR}$ and $\delta_{\alpha\beta}^{RL}$ ($\alpha \neq \beta$) as follows:

$$\delta_{\alpha\beta}^{LL} \equiv M_{Q\alpha\beta}^2 / \sqrt{M_{Q\alpha\alpha}^2 M_{Q\beta\beta}^2},$$

$$\delta_{\alpha\beta}^{RR} \equiv M_{U\alpha\beta}^2 / \sqrt{M_{U\alpha\alpha}^2 M_{U\beta\beta}^2},$$

$$\delta_{\alpha\beta}^{RL} \equiv (v_2 / \sqrt{2} T_{U,0\alpha}) / \sqrt{M_{U\alpha\alpha}^2 M_{Q\beta\beta}^2},$$

where $\alpha, \beta = 1, 2, 3$ ($\alpha \neq \beta$) denote the quark flavors $u, c, t$. In this study we consider $\tilde{c}_R - \tilde{t}_L$, $\tilde{c}_L - \tilde{t}_R$, $\tilde{c}_R - \tilde{t}_R$, $\tilde{c}_L - \tilde{t}_L$ mixing which is described by the QFV parameters $\delta_{23}^{RR}$, $\delta_{23}^{RL} \equiv (\delta_{23}^{RL})^*$, $\delta_{23}^{RR}$, and $\delta_{23}^{LL}$, respectively. We also consider $\tilde{t}_L - \tilde{t}_R$ mixing described by the QFC parameter $\delta_{33}^{RR}$ which is defined by eq. (7) with $\alpha = \beta = 3$. All QFV parameters and $\delta_{33}^{RL}$ are assumed to be real.

### III. Reference QFV Scenario

We take our reference QFV scenario as shown in Table I [3]. The resulting physical masses of the particles are shown in Table II. The flavor decomposition of the lightest up-type squarks $\tilde{u}_1$ and $\tilde{u}_2$ is shown in Table III. The main features of the scenario are: (i) it contains large $\tilde{t} - \tilde{t}$ (scharm-stop) mixings and large QFV trilinear couplings of squark-squark-Higgs, and (ii) it satisfies the strong constraints on QFV from the B meson data, such as BR($b \to s\gamma$), BR($B_s \to \mu^+\mu^-$) and $\Delta M_{B_s}$. And the constraints on the trilinear couplings from the vacuum stability conditions, where scharm [stop] is the supersymmetry (SUSY) partner of the charm [top] quark. In this scenario, the lightest up-type squarks $\tilde{u}_1$ and $\tilde{u}_2$ are strong mixtures of $\tilde{c}_{L/R} - \tilde{t}_{L/R}$, and the trilinear couplings ($\tilde{c}_L - \tilde{t}_R - h^0$, $\tilde{c}_R - \tilde{t}_L - h^0$, $\tilde{t}_L - \tilde{t}_R - h^0$ couplings) are large; therefore, $\tilde{u}_{1,2} - \tilde{u}_{1,2} - h^0$ couplings are large. This leads to an enhancement of the $\tilde{u}_{1,2} - \tilde{u}_{1,2} - \tilde{g}$ loop vertex correction to the decay amplitude of $h^0 \to c\bar{c}$ shown in Fig. 1, where $\tilde{g}$ is a gluino, which is the supersymmetric partner of the gluon. Thus, this results in a large deviation of the MSSM prediction for the decay width $\Gamma(h^0 \to c\bar{c})$ from the SM prediction.

### IV. $h^0 \to c\bar{c}$ at Full One-Loop Level with Flavor Violation

We compute the decay width $\Gamma(h^0 \to c\bar{c})$ at full one-loop level in the DR renormalization scheme taking the renormalization scale as $Q = 125.5$ GeV $\simeq m_{h^0}$ in the general MSSM with nonminimal QFV. In the general MSSM at one-loop level, in addition to the diagrams that contribute within the SM, $\Gamma(h^0 \to c\bar{c})$ also receives contributions from loop diagrams with additional Higgs bosons and supersymmetric particles. The flavor violation is induced by one-loop diagrams with squarks that have a mixed quark flavor nature. The one-loop contributions to $\Gamma(h^0 \to c\bar{c})$ contain three parts, QCD ($g$) corrections, SUSY-QCD ($\tilde{g}$) corrections and electroweak (EW) corrections including loops of neutralinos and charginos. In the latter we also include the Higgs contributions. Details of the computation of the decay width at a full one-loop level are described in Ref. [3].

### V. Numerical Results

In Fig. 2, we show the contour plot of the deviation of the MSSM prediction from the SM prediction $\Gamma_{\text{SM}}(h^0 \to c\bar{c}) = 0.118$ MeV [4] in the $\delta_{23}^{RR,RL}$ plane, where $\delta_{23}^{RR}$ and $\delta_{23}^{RL}$ are the $\tilde{c}_R - \tilde{t}_R$ and $\tilde{c}_L - \tilde{t}_L$ mixing parameters,
TABLE I: Reference QFV scenario: shown are the basic MSSM parameters at \( Q = 125.5 \) GeV \( \simeq m_{h^0} \), except for \( m_{A^0} \) which is the pole mass (i.e. the physical mass) of \( A^0 \), with \( T_{U33} = -2050 \) GeV (corresponding to \( \delta_{U33}^{uRL} = -0.2 \)). All other squark parameters not shown here are zero. \( M_{1,2,3} \) are the U(1), SU(2), SU(3) gaugino mass parameters.

| \( M_1 \) | \( M_2 \) | \( M_3 \) |
|---|---|---|
| 250 GeV | 500 GeV | 1500 GeV |

| \( \mu \) | \( \tan \beta \) | \( m_{A^0} \) |
|---|---|---|
| 2000 GeV | 20 | 1500 GeV |

| \( \alpha = 1 \) | \( \alpha = 2 \) | \( \alpha = 3 \) |
|---|---|---|
| \( M_{Q\alpha\alpha} \) | \( (2400)^2 \) GeV\(^2 \) | \( (2360)^2 \) GeV\(^2 \) | \( (1850)^2 \) GeV\(^2 \) |
| \( M_{U\alpha\alpha} \) | \( (2380)^2 \) GeV\(^2 \) | \( (1050)^2 \) GeV\(^2 \) | \( (950)^2 \) GeV\(^2 \) |
| \( M_{D\alpha\alpha} \) | \( (2380)^2 \) GeV\(^2 \) | \( (2340)^2 \) GeV\(^2 \) | \( (2300)^2 \) GeV\(^2 \) |

\[ \delta_{23}^{uRL} \delta_{23}^{uRR} \delta_{23}^{uLR} \delta_{23}^{uLL} \]

0.05 0.2 0.03 0.06

TABLE II: Physical masses in GeV of the particles for the scenario of Table I.

| \( m_{\tilde{\chi}^0_1} \) | \( m_{\tilde{\chi}^0_2} \) | \( m_{\tilde{\chi}^0_3} \) | \( m_{\tilde{\chi}^0_4} \) | \( m_{\tilde{\chi}^-_1} \) | \( m_{\tilde{\chi}^-_2} \) |
|---|---|---|---|---|---|
| 260 GeV | 534 GeV | 2020 GeV | 2021 GeV | 534 GeV | 2022 GeV |

| \( m_{t^0} \) | \( m_{\tilde{t}^0} \) | \( m_{\tilde{t}^0} \) | \( m_{\tilde{t}^0} \) |
|---|---|---|---|
| 126.08 GeV | 1498 GeV | 1500 GeV | 1501 GeV |

| \( m_{\tilde{q}} \) | \( m_{\tilde{u}_1} \) | \( m_{\tilde{u}_2} \) | \( m_{\tilde{u}_3} \) | \( m_{\tilde{u}_4} \) | \( m_{\tilde{u}_5} \) |
|---|---|---|---|---|---|
| 1473 GeV | 756 GeV | 965 GeV | 1800 GeV | 2298 GeV | 2301 GeV |

TABLE III: Flavor decomposition of \( \tilde{u}_1 \) and \( \tilde{u}_2 \) for the scenario of Table I. Shown are the squared coefficients.

| \( \tilde{u}_1 \) | \( \tilde{c}_L \) | \( \tilde{t}_L \) | \( \tilde{u}_R \) | \( \tilde{c}_R \) | \( \tilde{t}_R \) |
|---|---|---|---|---|---|
| \( u_1 \) | 0.0004 | 0.012 | 0 | 0.519 | 0.468 |
| \( u_2 \) | 0.00004 | 0.009 | 0 | 0.480 | 0.509 |

respectively. We see that the MSSM prediction is very sensitive to the QFV parameters \( \delta_{23}^{uRR} \) and \( \delta_{23}^{uLR} \), and that the deviation of the MSSM prediction from the SM prediction can be very large (as large as \( \sim 35 \% \)). We have found that the MSSM prediction becomes nearly equal to the SM prediction if we switch off all the QFV parameters in our reference QFV scenario.

VI. OBSERVABILITY OF THE DEVIATION AT ILC

The observation of any significant deviation of the decay width from its SM prediction indicates new physics beyond the SM. It is important to estimate the theoretical and experimental uncertainties of the width reliably in order to confirm such a deviation. The relative error of the SM width is estimated to be \( \sim 6 \% \) [5]. The relative error of the MSSM width is also estimated to be \( \sim 6 \% \) [3]. As seen in Fig. 2, the deviation of the MSSM width from the SM width can be as large as \( \sim 35 \% \). Such a large deviation can be observed at a future e\(^+\)e\(^-\)
FIG. 1: Gluino-loop vertex correction to $h^0 \rightarrow c\bar{c}$.

FIG. 2: Contour plot of the deviation of the full one-loop level MSSM width $\Gamma(h^0 \rightarrow c\bar{c})$ from the SM width $\Gamma_{SM}(h^0 \rightarrow c\bar{c})$ for our reference QFV scenario of Table I. The shown range satisfies all the relevant experimental and theoretical constraints.

collider ILC (International Linear Collider) with a CM energy 500 GeV and an integrated luminosity of 1600 fb$^{-1}$, where the expected experimental error of the width is $\sim 3\%$ [6]. A measurement of the width at LHC is a hard task because of the difficulties in charm-tagging.

VII. CONCLUSION

In this article, we have shown that the full one-loop corrected decay width $\Gamma(h^0 \rightarrow c\bar{c})$ is very sensitive to the QFV parameters in the MSSM. In a scenario with large $\tilde{c} - \tilde{t}$ mixings, the width can differ up to $\sim 35\%$ from its SM value. After estimating the uncertainties of the width, we conclude that an observation of these MSSM QFV effects is possible at ILC. Therefore, we have a good opportunity to discover the QFV SUSY effect in this decay $h^0 \rightarrow c\bar{c}$ at ILC.

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