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$h^0(125GeV) \to c\bar{c}$ as a test case for quark flavor violation in the MSSM

Keisho Hidaka*
Department of Physics, Tokyo Gakugei University, Tokyo 184-8501, Japan
E-mail: hidaka@u-gakugei.ac.jp

A. Bartl
Universität Wien, Fakultät für Physik, A-1090 Vienna, Austria
E-mail: Alfred.bartl@univie.ac.at

H. Eberl, E. Ginina and W. Majerotto
Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, A-1050 Vienna, Austria
E-mail: helmut.eberl@oeaw.ac.at, elena.ginina@oeaw.ac.at, and Walter.Majerotto@oeaw.ac.at

We calculate the decay width of $h^0(125GeV) \to c\bar{c}$ in the Minimal Supersymmetric Standard Model (MSSM) with *non-minimal* quark flavor violation (QFV) at full one-loop level. We adopt the $\overline{\rm DR}$ renormalization scheme. We study the effects of the mixing of the second and third squark generations (i.e. scharm-stop mixing) on the decay width, respecting the experimental constraints from B-meson data, the Higgs mass measurement and supersymmetric (SUSY) particle searches. We show that the decay width $\Gamma(h^0 \to c\bar{c})$ at the full one-loop level is very sensitive to the SUSY QFV parameters. In a scenario with large scharm-stop mixing, the decay width can differ up to $\sim \pm 35\%$ from its SM prediction. After taking into account the experimental and theoretical uncertainties of the decay width, we conclude that these QFV SUSY effects can be observed at a future e^+e^- collider such as ILC (International Linear Collider).

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*Speaker.

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1. Introduction

The properties of the Higgs boson with a mass of 125 GeV, discovered by ATLAS [1] and CMS [2] at the LHC (Large Hadron Collider), are consistent with the predictions of the Standard Model (SM). It is the most important issue in the present particle physics world to determine if it 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 decay $h^0 \to c\bar{c}$, where c is a charm quark. We calculate the decay width $\Gamma(h^0 \to c\bar{c})$ at full one-loop level in the $\overline{\rm DR}$ renormalization scheme in the MSSM with *non-minimal* quark flavor violation (QFV).

2. Definition of the QFV parameters

In the super-CKM basis of $\tilde{q}_{0\gamma} = (\tilde{q}_{1\rm L}, \tilde{q}_{2\rm L}, \tilde{q}_{3\rm L}, \tilde{q}_{1\rm R}, \tilde{q}_{2\rm R}, \tilde{q}_{3\rm R})$, $\gamma = 1,...6$, with $(q_1, q_2, q_3) = (u,c,t)$, (d,s,b), one can write the squark mass matrices in their most general 3×3-block form

$$\mathcal{M}^2_{\tilde{q}} = \begin{pmatrix} \mathcal{M}^2_{\tilde{q},LL} & \mathcal{M}^2_{\tilde{q},LR} \\ \mathcal{M}^2_{\tilde{q},RL} & \mathcal{M}^2_{\tilde{q},RR} \end{pmatrix}, \tag{2.1}$$

with $\tilde{q} = \tilde{u}, \tilde{d}$. The left-left and right-right blocks in eq. (2.1) are given by

$$\begin{aligned} \mathcal{M}^2_{\tilde{u},LL} &= V_{\rm CKM} M_Q^2 V_{\rm CKM}^\dagger + D_{\tilde{u},LL}\mathbf{1} + \hat{m}_u^2, \\ \mathcal{M}^2_{\tilde{u},RR} &= M_U^2 + D_{\tilde{u},RR}\mathbf{1} + \hat{m}_u^2, \\ \mathcal{M}^2_{\tilde{d},LL} &= M_Q^2 + D_{\tilde{d},LL}\mathbf{1} + \hat{m}_d^2, \\ \mathcal{M}^2_{\tilde{d},RR} &= M_D^2 + D_{\tilde{d},RR}\mathbf{1} + \hat{m}_d^2, \end{aligned} \tag{2.2}$$

where $M_{Q,U,D}$ are the hermitian soft supersymmetry (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 $D_{\tilde{q},RR}$ are the D terms. Due to the $SU(2)_{\rm L}$ symmetry the left-left blocks of the up-type and down-type squarks in eq. (2.2) are related by the CKM matrix $V_{\rm CKM}$. The left-right and right-left blocks of eq. (2.1) are given by

$$\begin{aligned} \mathcal{M}^2_{\tilde{u},RL} = \mathcal{M}^{2\dagger}_{\tilde{u},LR} &= \frac{v_2}{\sqrt{2}} T_U - \mu^* \hat{m}_u \cot\beta, \\ \mathcal{M}^2_{\tilde{d},RL} = \mathcal{M}^{2\dagger}_{\tilde{d},LR} &= \frac{v_1}{\sqrt{2}} T_D - \mu^* \hat{m}_d \tan\beta, \end{aligned} \tag{2.3}$$

where $T_{U,D}$ are the soft SUSY-breaking trilinear coupling matrices of the up-type and down-type squarks entering the Lagrangian $\mathcal{L}_{int} \supset -(T_{U\alpha\beta}\tilde{u}^\dagger_{R\alpha}\tilde{u}_{L\beta}H_2^0 + T_{D\alpha\beta}\tilde{d}^\dagger_{R\alpha}\tilde{d}_{L\beta}H_1^0)$, μ 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 $v_{1,2} = \sqrt{2}\left\langle H^0_{1,2}\right\rangle$. The squark mass matrices are diagonalized by the 6×6 unitary matrices $U^{\tilde{q}}$, $\tilde{q} = \tilde{u}, \tilde{d}$, such that

$$U^{\tilde{q}} \mathcal{M}^2_{\tilde{q}} (U^{\tilde{q}})^\dagger = {\rm diag}(m^2_{\tilde{q}_1}, \ldots, m^2_{\tilde{q}_6}), \tag{2.4}$$

with $m_{\tilde{q}_1} < \ldots < m_{\tilde{q}_6}$. The physical mass eigenstates $\tilde{q}_i, i = 1,...,6$ are given by $\tilde{q}_i = U^{\tilde{q}}_{i\alpha}\tilde{q}_{0\alpha}$.

PoS(EPS-HEP2015)131

We define the QFV parameters in the up-type squark sector $\delta^{LL}_{\alpha\beta}$, $\delta^{uRR}_{\alpha\beta}$ and $\delta^{uRL}_{\alpha\beta}$ $(\alpha \neq \beta)$ as follows:

$$\delta^{LL}_{\alpha\beta} \equiv M^2_{Q\alpha\beta}/\sqrt{M^2_{Q\alpha\alpha}M^2_{Q\beta\beta}}\,, \tag{2.5}$$

$$\delta^{uRR}_{\alpha\beta} \equiv M^2_{U\alpha\beta}/\sqrt{M^2_{U\alpha\alpha}M^2_{U\beta\beta}}\,, \tag{2.6}$$

$$\delta^{uRL}_{\alpha\beta} \equiv (v_2/\sqrt{2})T_{U\alpha\beta}/\sqrt{M^2_{U\alpha\alpha}M^2_{Q\beta\beta}}\,, \tag{2.7}$$

where $\alpha, \beta = 1,2,3$ $(\alpha \neq \beta)$ denote the quark flavors u, c, t. The relevant mixings in this study are $\tilde{c}_R - \tilde{t}_L$, $\tilde{c}_L - \tilde{t}_R$, $\tilde{c}_R - \tilde{t}_R$, and $\tilde{c}_L - \tilde{t}_L$ mixings which are described by the QFV parameters δ^{uRL}_{23}, $\delta^{uLR}_{23} \equiv (\delta^{uRL}_{32})^*$, δ^{uRR}_{23}, and δ^{LL}_{23}, respectively. We also consider $\tilde{t}_L - \tilde{t}_R$ mixing described by the quark flavor conserving (QFC) parameter δ^{uRL}_{33} which is defined by eq. (2.7) with $\alpha = \beta = 3$. All QFV parameters and δ^{uRL}_{33} are assumed to be real.

3. Reference QFV MSSM scenario

Our reference scenario of the MSSM with non-minimal QFV is shown in Table 1 [3]. Table 2 shows the resulting physical masses of the involved particles. Table 3 shows the flavor decomposition of the lightest up-type squarks $\tilde{u}_1$ and $\tilde{u}_2$. The reference scenario contains large $\tilde{c}_{L/R} - \tilde{t}_{L/R}$ mixings and large QFV trilinear couplings of $\tilde{c}_L - \tilde{t}_R - H^0_2$ and $\tilde{c}_R - \tilde{t}_L - H^0_2$, where $\tilde{c}_{L/R}$ and $\tilde{t}_{L/R}$ are the SUSY partners of the charm and top quark, respectively. It satisfies (i) the constraint from the observed Higgs boson mass at LHC, (ii) the recent LHC limits on the masses of squarks, gluino, charginos and neutralinos, (iii) the strong constraints on QFV from the B-meson experiments, such as BR($b \to s\gamma$), BR($B_s \to \mu^+\mu^-$) and ΔM_{B_s}, (iv) the constraints on the trilinear couplings from the vacuum stability conditions and (v) the experimental limit on SUSY contributions to the electroweak ρ parameter. In this decoupling Higgs scenario, $h^0 \simeq Re(H^0_2)$, 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 results in 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. Thus, this can lead to a large deviation of the MSSM prediction for the decay width $\Gamma(h^0 \to c\bar{c})$ from the SM prediction.

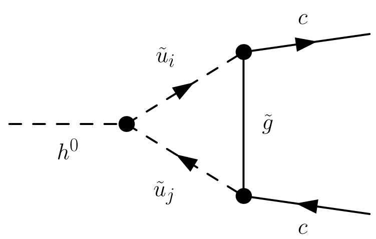

Figure 1: Gluino-loop vertex correction to $h^0 \to c\bar{c}$.

M_1	M_2	M_3
250 GeV	500 GeV	1500 GeV

μ	$\tan\beta$	m_{A^0}
2000 GeV	20	1500 GeV

	$\alpha = 1$	$\alpha = 2$	$\alpha = 3$
$M^2_{Q\alpha\alpha}$	$(2400)^2$ GeV^2	$(2360)^2$ GeV^2	$(1850)^2$ GeV^2
$M^2_{U\alpha\alpha}$	$(2380)^2$ GeV^2	$(1050)^2$ GeV^2	$(950)^2$ GeV^2
$M^2_{D\alpha\alpha}$	$(2380)^2$ GeV^2	$(2340)^2$ GeV^2	$(2300)^2$ GeV^2

δ^{LL}_{23}	δ^{uRR}_{23}	δ^{uRL}_{23}	δ^{uLR}_{23}
0.05	0.2	0.03	0.06

Table 1: 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 $\delta^{uRL}_{33} = -0.2$). All other squark parameters not shown here are zero. $M_{1,2,3}$ are the U(1), SU(2), SU(3) gaugino mass parameters.

$m_{\tilde\chi^0_1}$	$m_{\tilde\chi^0_2}$	$m_{\tilde\chi^0_3}$	$m_{\tilde\chi^0_4}$	$m_{\tilde\chi^+_1}$	$m_{\tilde\chi^+_2}$
260	534	2020	2021	534	2022

m_{h^0}	m_{H^0}	m_{A^0}	m_{H^+}
126.08	1498	1500	1501

$m_{\tilde g}$	$m_{\tilde u_1}$	$m_{\tilde u_2}$	$m_{\tilde u_3}$	$m_{\tilde u_4}$	$m_{\tilde u_5}$	$m_{\tilde u_6}$
1473	756	965	1800	2298	2301	2332

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

	$\tilde u_L$	$\tilde c_L$	$\tilde t_L$	$\tilde u_R$	$\tilde c_R$	$\tilde t_R$
$\tilde u_1$	0	0.0004	0.012	0	0.519	0.468
$\tilde u_2$	0	0.0004	0.009	0	0.480	0.509

Table 3: Flavor decomposition of $\tilde u_1$ and $\tilde u_2$ for the scenario of Table 1. Shown are the squared coefficients.

4. $\Gamma(h^0 \to c\bar{c})$ at full one-loop level in the MSSM with QFV

We calculate the decay width $\Gamma(h^0 \to c\bar{c})$ at full one-loop level in the general MSSM with non-minimal QFV. We adopt the $\overline{\mathrm{DR}}$ renormalization scheme taking the renormalization scale as $Q = 125.5$ GeV $\simeq m_{h^0}$. 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 corrections including loops with neutralinos, charginos and Higgs bosons. Details of the computation of the decay width at full one-loop level are described in Ref. [3].

5. Numerical results

Fig. 2 shows the contour plot of the deviation of the MSSM prediction from the SM prediction $\Gamma^{SM}(h^0 \to c\bar{c})$ = 0.118 MeV [4] in the δ^{uRR}_{23}-δ^{uLR}_{23} plane, where δ^{uRR}_{23} and δ^{uLR}_{23} are the $\tilde{c}_R - \tilde{t}_R$ and $\tilde{c}_L - \tilde{t}_R$ mixing parameters, respectively. As can be seen, the MSSM prediction is very sensitive to the QFV parameters δ^{uRR}_{23} and δ^{uLR}_{23}, and the deviation from the SM prediction can be very large (as large as $\sim \pm 35\%$). 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.

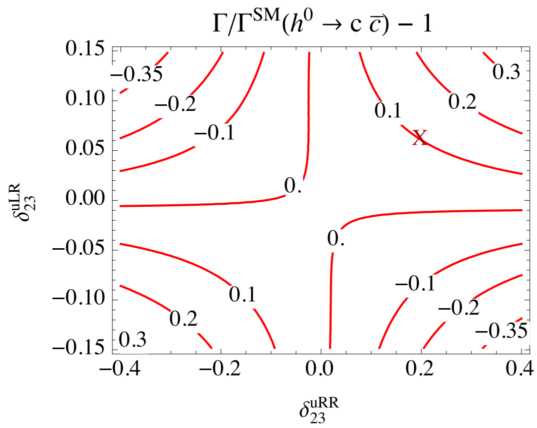

Figure 2: Contour plot of the deviation of the full one-loop level MSSM width $\Gamma(h^0 \to c\bar{c})$ from the SM width $\Gamma^{SM}(h^0 \to c\bar{c})$ for our reference QFV scenario of Table 1. The shown range satisfies all the relevant experimental and theoretical constraints described in Section 3.

6. Observability of the deviation at ILC

The observation of any significant deviation of the decay width $\Gamma(h^0 \to c\bar{c})$ from its SM prediction implies 'New Physics' beyond the SM. It is very important to estimate the theoretical and experimental uncertainties of the width reliably in order to confirm such a deviation. The relative theoretical error of the SM width is estimated to be $\sim 6\%$ [5]. The relative theoretical error of the MSSM width is also estimated to be $\sim 6\%$ [3]. The theoretical error stems from the parametric uncertainties (such as uncertainties of the charm quark mass m_c and the QCD coupling α_s) and the scale-dependence uncertainty. The latter uncertainty is estimated by varying the renormalization scale Q from Q/2 to 2Q. (Note that in our case $Q = m_{h^0}$.) The uncertainty due to the renormalization scale Q dependences of the MSSM width is small ($\simeq 0.5\%$) as can be seen in Fig.3. As shown

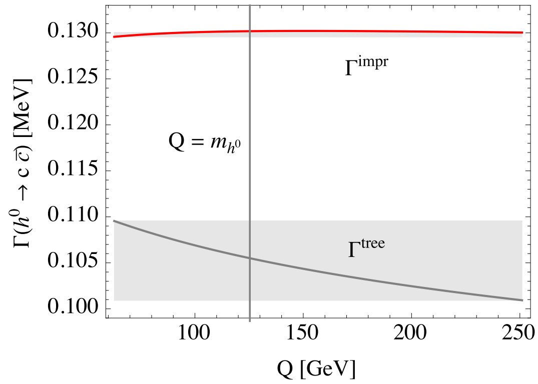

Figure 3: Renormalization-scale dependence of $\Gamma(h^0 \to c\bar{c})$ for the reference scenario of Table 1. $\Gamma^{\rm impr}(h^0 \to c\bar{c})$ is the improved one-loop corrected width. The vertical line shows $Q = m_{h^0}$.

in Fig.2, the deviation of the MSSM width from the SM width can be as large as $\sim \pm 35\%$. Such a large deviation can be observed at a future e^+e^- 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.

7. Conclusion

We have calculated the width $\Gamma(h^0 \to c\bar{c})$ at full one-loop level within the MSSM with non-minimal quark flavor violation. We have studied $\tilde{c}_{R,L} - \tilde{t}_{R,L}$ mixings, taking into account the experimental constraints from B-meson data, the Higgs mass measurement and SUSY particle searches. We have found the width $\Gamma(h^0 \to c\bar{c})$ is very sensitive to the QFV parameters, in particular to $\tilde{c}_{R,L} - \tilde{t}_{R,L}$ mixings. Whereas in the QFC MSSM case $\Gamma(h^0 \to c\bar{c})$ is only slightly different from its SM value, in the QFV case it can deviate from the SM value by up to $\sim \pm 35\%$. After taking into account the experimental and theoretical uncertainties of the decay width, we conclude that these QFV SUSY effects can be observed at ILC. Therefore, we have a good opportunity to discover the QFV SUSY effect in this decay $h^0 \to c\bar{c}$ at ILC.

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