Higgs boson decay to charm pair at full one-loop level in the MSSM with flavour violation

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- Squark generation mixing in the MSSM
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- The decays of h^0 are usually assumed to be quark-flavour conserving (QFC)
- Generation mixing in the MSSM squark sector may influence the decay widths of h^0 at 1 loop level
- One can observe then quark flavour violating (QFV) h^0 decays with sizeable rates

Squark generation mixing in the MSSM

- In our study we assume non-minimal flavour violation (NMFV): new sources of QFV appear (not connected to the CKM matrix) that are free parameters in the theory
- The FV terms are contained in the mass matrices of the squarks at the electroweak scale

$$\mathcal{M}^2_{\tilde{q}} = \begin{pmatrix} \mathcal{M}^2_{\tilde{q}\,LL} & (\mathcal{M}^2_{\tilde{q}\,RL})^\dagger \\ \mathcal{M}^2_{\tilde{q}\,RL} & \mathcal{M}^2_{\tilde{q}\,RR} \end{pmatrix}, \; q = u, d.$$

- The 3×3 soft-breaking matrices can introduce flavour-violating (off-diagonal) terms, e.g. in the up-squark sector

$$\begin{aligned}
(\mathcal{M}^2_{\tilde{u}\,LL})_{\alpha\beta} &= M^2_{Q_u\alpha\beta} + \left[\left(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W\right)\cos 2\beta \; m_Z^2 + m^2_{u_\alpha}\right]\delta_{\alpha\beta} \\
(\mathcal{M}^2_{\tilde{u}\,RR})_{\alpha\beta} &= M^2_{U\alpha\beta} + \left[\left(\tfrac{2}{3}\sin^2\theta_W\right)\cos 2\beta \; m_Z^2 + m^2_{u_\alpha}\right]\delta_{\alpha\beta} \\
(\mathcal{M}^2_{\tilde{u}\,RL})_{\alpha\beta} &= (v_2/\sqrt{2})\; T_{U\beta\alpha} - m_{U_\alpha}\mu^* \cot\beta \; \delta_{\alpha\beta}
\end{aligned}$$

- After diagonalization with the rotation matrix $U^{\tilde{u}}_{6\times 6}$, the mass eigenstates are obtained $\tilde{u}_i = U^{\tilde{u}}_{i\alpha}\tilde{u}_{0\alpha}$, where $U^{\tilde{u}}\mathcal{M}^2_{\tilde{u}}U^{\tilde{u}\dagger} = \mathrm{diag}(m^2_{\tilde{u}_1}, \ldots, m^2_{\tilde{u}_6})$, $m_{\tilde{u}_i} < m_{\tilde{u}_j}$ for $i < j$, and $\tilde{u}_0 = (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)$.

Squark generation mixing in the MSSM

- In order to estimate the amount of QFV dimensionless parameters are introduced. In the up-type squark sector ($\alpha, \beta = u, c, t,\ \alpha \neq \beta$)

$$
\begin{aligned}
\delta^{LL}_{\alpha\beta} &\equiv M^2_{Q\alpha\beta}/\sqrt{M^2_{Q\alpha\alpha}M^2_{Q\beta\beta}}\ {}^{1} \\
\delta^{uRR}_{\alpha\beta} &\equiv M^2_{U\alpha\beta}/\sqrt{M^2_{U\alpha\alpha}M^2_{U\beta\beta}} \\
\delta^{uRL}_{\alpha\beta} &\equiv (v_2/\sqrt{2})T_{U_{\beta\alpha}}/\sqrt{M^2_{U\alpha\alpha}M^2_{Q\beta\beta}}
\end{aligned}
$$

- Analogously in the down-type squark sector ($\alpha, \beta = d, s, b,\ \alpha \neq \beta$)

$$
\begin{aligned}
\delta^{dRR}_{\alpha\beta} &\equiv M^2_{D\alpha\beta}/\sqrt{M^2_{D\alpha\alpha}M^2_{D\beta\beta}} \\
\delta^{dRL}_{\alpha\beta} &\equiv (v_2/\sqrt{2})T_{D_{\beta\alpha}}/\sqrt{M^2_{D\alpha\alpha}M^2_{Q\beta\beta}}
\end{aligned}
$$

[1] $\delta^{uLL}_{\alpha\beta} \equiv \delta^{dLL}_{\alpha\beta} \equiv \delta^{LL}_{\alpha\beta}$

Constraints on the MSSM parameters

- Theoretical constraints from vacuum stability on T_U and T_D matrices
- Strong constraints on mixing involving the first generation squarks from precision measurements of K and B meson decays
- $\Rightarrow$ only mixing between 2$^{\text{nd}}$ and 3$^{\text{rd}}$ generation squarks is considered. Appreciable mixing is still possible despite the B physics constraints
- SUSY mass limits and Higgs mass limits from direct collider searches
- Electroweak precision and low-energy measurements (95%CL)

$$\mathrm{B}(b \to s\gamma) = (3.4 \pm 0.61) \times 10^{-4}$$
$$\Delta M_{B_s} = (17.77 \pm 3.3)\ \mathrm{ps}^{-1}$$
$$\Delta\rho\ (\mathrm{SUSY}) < 0.0012$$
$$\mathrm{B}(b \to s\ \mu^+\mu^-) = (1.60 \pm 0.91) \times 10^{-6}$$
$$\mathrm{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 1.43) \times 10^{-9}$$

$h^0 \to c\bar{c}$ @ full one-loop level

- We study the decay of the lightest neutral Higgs boson, $h^0 \to c\bar{c}$, at full one-loop level in the MSSM with non-minimal flavour violation
- The partial decay width, including one-loop contributions can be written as

$$\Gamma(h^0 \to c\bar{c}) = \Gamma^{\text{tree}}(h^0 \to c\bar{c}) + \Delta\Gamma^{\text{1loop}}(h^0 \to c\bar{c})\,,$$

where the tree-level decay width is

$$\Gamma^{\text{tree}}(h^0 \to c\bar{c}) = \frac{\mathrm{N_C}}{8\pi} m_{h^0} (s_1^c)^2 \left(1 - \frac{4m_c^2}{m_{h^0}^2}\right)^{3/2}, \quad \text{with } \mathrm{N_C} = 3\,,$$

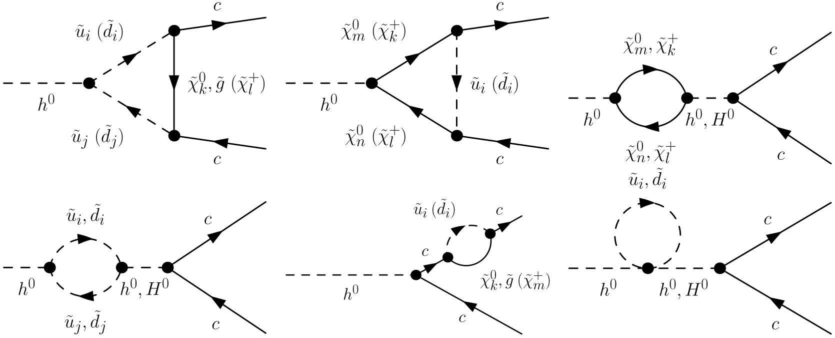
and the tree-level coupling s_1^c reads

$$s_1^c = -g \frac{m_c}{2m_W} \frac{\cos\alpha}{\sin\beta} = -\frac{h_c}{\sqrt{2}} \cos\alpha\,.$$

Here α is the mixing angle of h^0 and H^0.

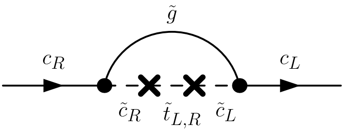
$h^0 \to c\bar{c}$ @ full one-loop level
Contributions

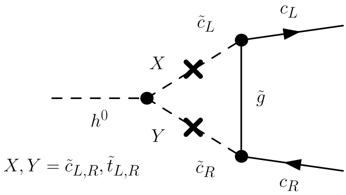
- All 1-loop contributions to $\Delta\Gamma^{1\text{loop}}(h^0 \to c\bar{c})$ include: SM contributions, Higgs contributions, SUSY contributions
- The flavour mixing is induced by 1-loop diagrams with squarks



$h^0 \to c\bar{c}$ @ full one-loop level
Flavour violation

- Flavour violation enters through mixing of the squarks, example: schematically in the up-type squarks -gluino contribution ($\tilde{u}_{1,2} = \tilde{c}_{R,L} - \tilde{t}_{R,L}$ mixture)





- In the super-CKM basis, the Lagrangian including the coupling of up-type squarks to h^0 contains the trilinear couplings $(T_U)_{ij}$ which are explicitly flavour-breaking terms that couple "left-handed" to "right-handed" squarks

$$\mathcal{L} \ni -\frac{g_2}{2m_W} h^0 \Big[\tilde{u}^*_{iR}\tilde{u}_{jL} \Big(\mu^* \frac{\sin\alpha}{\sin\beta} m_{u,i}\delta_{ij} + \frac{\cos\alpha}{\sin\beta}\frac{v_2}{\sqrt{2}}(T_U)_{ji} \Big) + \text{h.c.} \Big]$$

- Calculating higher order corrections requires renormalisation due to UV and IR divergences
- For the UV divergences we adopt the $\overline{\mathrm{DR}}$ renormalisation scheme at one-loop level: all tree-level input parameters (masses, fields and parameters in the couplings) of the Lagrangian are UV finite (everywhere $\Delta = 0$) and defined at a fixed scale $Q = m_{h^0} = 125.5$ GeV
- The renormalised finite one-loop amplitude is given by

$$\mathcal{M}^{1loop} = \mathcal{M}^{vertex} + \mathcal{M}^{WFR} \left(+\mathcal{M}^{CT}\right)$$

- In order to get rid of the IR divergences one must include the contribution of the real soft/hard gluon and photon radiation from the final charm quarks
- The convergent decay width $\Gamma^{corr}(h^0 \to c\bar{c})$ in the limit of vanishing gluon/photon mass, $\lambda = 0$, is given by

$$\Gamma^{\rm corr}(h^0 \to c\bar{c}) = \Gamma^{\rm tree+virtual}(h^0 \to c\bar{c}) + \Gamma^{\rm hard}(h^0 \to c\bar{c}g/\gamma)$$

where e.g. the hard gluon radiation width is given by

$$\Gamma^{hard}(h^0 \to c\bar{c}g) = \frac{2\alpha_s |s_1^c|^2}{\pi^2 m_{h^0}} \left[J_1 - (m_{h^0}^2 - 4m_c^2)(J_2 - (m_{h^0}^2 - 2m_c^2)J_3)\right]$$

with $J_1, J_2, J_3, = J_1, J_2, J_3(m_c, m_{h^0}, \lambda)$ [Denner '93]

$h^0 \to c\bar{c}$ @ full one-loop level
Gluon improvement

- The corrected width with gluon can be written in the compact form

$$\Gamma^{\text{corr}} = \Gamma^{\text{tree}}(m_c) \left(1 + \frac{4}{3} \frac{\alpha_s}{\pi} \Delta^H \right)$$

Here m_c denotes the on-shell charm mass, Δ^H see e.g. [J. Braaten & J.P. Leveille, '80, M. Drees & K.-I. Hikasa '89, A. Dabelstein 95]. We can neglect m_c, $m_c \ll m_{h^0}$ or $1 - \beta \sim 3 \times 10^{-4}$. With $\Delta^H = -3 \log \frac{m_{h^0}}{m_c} + \frac{9}{4}$ and $\frac{\delta m_c^g}{m_c} = \frac{\alpha_s}{3\pi} \left(-6 \log \frac{m_{h^0}}{m_c} + r - 5 \right)$ we get [2]

$$\Gamma^{\text{corr}} = \Gamma^{\text{tree}}(m_c|_{\text{SM}}) \left(1 + \frac{19 - 2r}{3} \frac{\alpha_s}{\pi} \right) .$$

where $\log \frac{m_{h^0}}{m_c}$ is absorbed into $m_c|_{\text{SM}} = m_c + \delta m_c^g$, see e.g. [H. E. et al. '99].

- Numerically we also included higher order α_s contributions, see e.g. [M. Spira '97].

[2] r = 0 for $\overline{\text{DR}}$ and r = 1 for $\overline{\text{MS}}$ scheme

- The gluino 1-loop contribution, renormalised in the $\overline{\mathrm{DR}}$ scheme reads

$$\Gamma^{\tilde{g}} = \frac{\mathrm{N_C}}{4\pi} m_{h^0}\ s_1^c\ \mathrm{Re}(\Delta S_1^{c,\tilde{g}}) \left(1 - \frac{4m_c^2}{m_{h^0}^2}\right)^{3/2}$$

- $\Delta S_1^{c,\tilde{g}}$ acquires contributions from the vertex correction and the wave-function correction due to gluino interaction

$$\Delta S_1^{c,\tilde{g}} = \delta S_1^{c(\tilde{q},v)} + \delta S_1^{c(\tilde{q},\omega)} \left(+\delta S_1^{c(\tilde{q},0)}\right) .$$

Using $\alpha_{ij} = U_{i2}^{\tilde{u}*} U_{j2}^{\tilde{u}} + U_{i5}^{\tilde{u}*} U_{j5}^{\tilde{u}}$, $\beta_{ij} = U_{i2}^{\tilde{u}*} U_{j5}^{\tilde{u}} + U_{i5}^{\tilde{u}*} U_{j2}^{\tilde{u}}$ and $m_c \sim 0$ we can write

$$\Delta S_1^{c,\tilde{g}} = \frac{\alpha_s}{3\pi} \left\{ m_{\tilde{g}} \beta_{ij} \left(G_{ij1}^{\tilde{u}} C_0^{ij} + 4 s_1^c \delta_{ij} \dot{B}_0^i \right) + s_1^c \left(\alpha_{ii} B_1^i + \Delta \right) \right\}$$

$h^0 \longrightarrow c\bar{c}$ @ full one-loop level
Gluino decoupling limit

- In the limit $m_{\tilde{g}} \to \infty$ we get

$$\Delta S_1^{c,\tilde{g}} \sim \frac{2\alpha_s}{3\pi} s_1^c B_1^i \quad \text{with } B_1 \sim \ln \frac{m_{\tilde{g}}}{m_{h^0}}$$

- On the other side, we take $m_c(m_c)|_{\overline{\text{MS}}} = 1.27$ GeV as input. With [SPA project, EPJC 46 '06]

$$m_c \equiv m_c(m_{h^0})|_{\overline{\text{DR}}} = m_c(m_c)|_{\overline{\text{MS}}} + \delta m_c^{\tilde{g}} + \ldots$$

we see that the running $h^0 c\bar{c}$ tree-level coupling $\propto m_c$ has an intrinsic dependence on

$$\delta m_c^{\tilde{g}} = -\frac{\alpha_s}{3\pi}\left\{ m_c \alpha_{ii} B_1^i + m_{\tilde{g}} \beta_{ii} B_0^i \right\} \sim -\frac{2\alpha_s}{3\pi} m_c B_1^i + \ldots$$

Thus, the sum $\Gamma^{\text{tree}} + \Gamma^{\tilde{g}}$ is decoupling in this limit.

- The same arguments hold for the chargino and neutralino contributions.

- We can write the gluon improved result as

$$\Gamma^{\text{tree, impr}} + \Gamma^{\text{g, impr}}$$

with $\Gamma^{\text{tree, impr}} = \Gamma^{\text{tree}} \frac{m_c^2|_{\text{SM}}}{m_c^2}$.

- The one-loop result with gluino and EW contributions reads

$$\Gamma^{\text{tree}} + \Gamma^{\tilde{g}} + \Gamma^{EW}$$

- In order to combine both results we use $\Gamma^{\text{tree, impr}} = \Gamma^{\text{tree}} - \Gamma^{\text{tree}} \frac{\Delta}{m_c^2}$ with $\Delta = m_c^2 - m_c^2|_{\text{SM}}$. We get

$$\Gamma^{\text{1loop, impr}} = \Gamma^{\text{tree}} + \underbrace{\left(\Gamma^{\text{g, impr}} - \Gamma^{\text{tree}} \frac{\Delta}{m_c^2} \right)}_{\equiv \Gamma^{\text{g}}} + \Gamma^{\tilde{g}} + \Gamma^{EW}$$

- The numerical calculations are performed with our own developed code with the help of FeynArts and FormCalc. We also use SPheno v3.3.3 and SSP
- The corresponding theoretical and experimental constraints are taken into account
- Mixing between the second and the third generation up-type squarks ($\tilde{c} - \tilde{t}$ mixing) is considered
- M_3 is chosen so that the gluino is within the reach of the LHC
- The gaugino masses M_1, M_2 and M_3 are satisfying GUT relations $M_1 \approx 0.5\ M_2,\ M_3/M_2 = g_3^2/g_2^2 \approx 3$, where g_2 and g_3 are the SU(2) and SU(3) gauge coupling constants, respectively
- The lightest Higgs mass is within the range of the Higgs signal at the LHC, $h^0 \approx 126$ GeV [3]

[3] At our reference scenario

$h^0 \longrightarrow c\bar{c}$ @ full one-loop level
Reference scenario

- MSSM input parameters at $Q = m_{h^0} = 125.8$ GeV for our reference scenario. $T_{U\alpha\alpha} = T_{D\alpha\alpha} = 0$, except for $T_{U33} = -2050$ GeV ($\delta^{uRL}_{33} = -0.2$)

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	0.05	0.06

$h^0 \to c\bar{c}$ @ full one-loop level
Numerical results

- On-shell masses of the particles [GeV] in our reference scenario

$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_2^+}$
260	534	2019	2021	534	2021

m_{h^0}	m_{H^0}	m_{A^0}	m_{H^+}
125.77	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	773	956	1801	2298	2300	2332

- Flavour decomposition of $\tilde{u}_1$ and $\tilde{u}_2$ in our reference scenario (shown are the squared coefficients)

	$\tilde{u}_L$	$\tilde{c}_L$	$\tilde{t}_L$	$\tilde{u}_R$	$\tilde{c}_R$	$\tilde{t}_R$
$\tilde{u}_1$	0	0.0004	0.0148	0	0.507	0.477
$\tilde{u}_2$	0	0.0005	0.0067	0	0.492	0.5

$h^0 \longrightarrow c\bar{c}$ @ full one-loop level

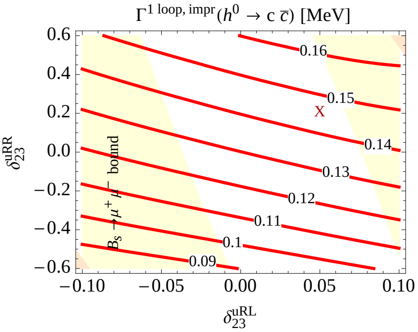
- We consider $\tilde{c} - \tilde{t}$ mixing $\Rightarrow$ the relevant QFV parameters are

$$\delta_{23}^{LL} (\approx M_{Q23}^2) \equiv \ \tilde{c}_L - \tilde{t}_L \text{ mixing parameter}$$
$$\delta_{23}^{uRR} (\approx M_{U23}^2) \equiv \ \tilde{c}_R - \tilde{t}_R \text{ mixing parameter}$$
$$\delta_{23}^{uLR} (\approx T_{U23}) \equiv \ \tilde{c}_L - \tilde{t}_R \text{ mixing parameter}$$
$$\delta_{23}^{uRL} (\approx T_{U32}) \equiv \ \tilde{c}_R - \tilde{t}_L \text{ mixing parameter}$$

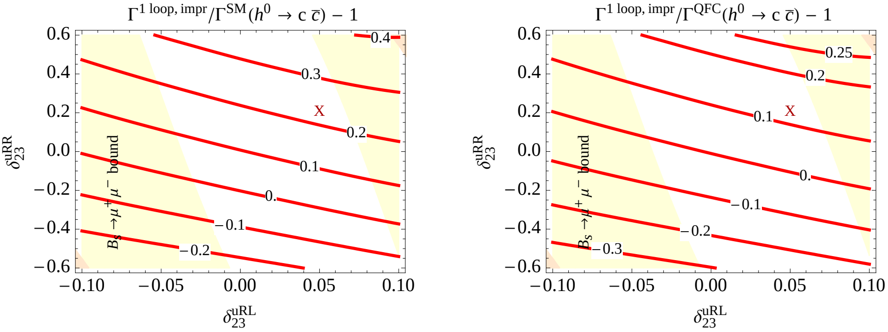
- Plus an important QFC parameter

$$\delta_{33}^{uRL} (\approx T_{U33}) \equiv \ \tilde{t}_L - \tilde{t}_R \text{ mixing parameter}$$

- Comparison of our gluon improved width with HDECAY:
  Our result: 0.112 MeV, HDECAY: 0.111 MeV
- Dependence of the decay width $\Gamma^{1\mathrm{loop,impr}}(h^0 \to c\bar{c})$ on the $\tilde{c}_R - \tilde{t}_L$ and the $\tilde{c}_R - \tilde{t}_R$ mixing parameters (δ_{23}^{uRL} and δ_{23}^{uRR})

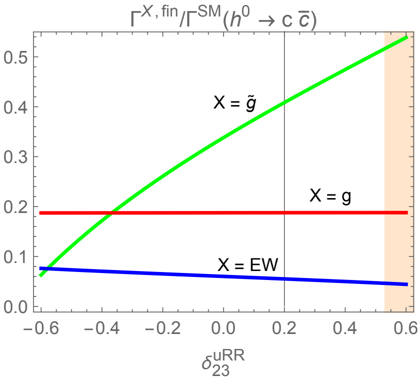


- Relative dependences of $\Gamma^{1\text{loop, impr}}(h^0 \longrightarrow c\bar{c})$ to $\Gamma^{\text{SM}} = 0.118$ MeV and $\Gamma^{\text{QFC}} = 0.129$ MeV as functions of the QFV parameters δ_{23}^{uRL} and δ_{23}^{uRR}



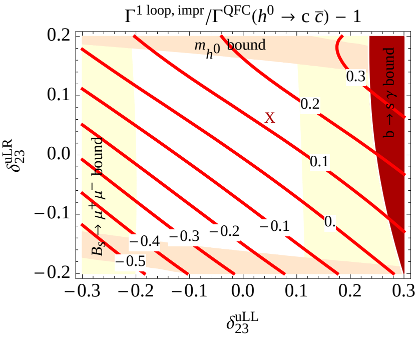
$h^0 \longrightarrow c\bar{c}$ @ full one-loop level
Numerical results

- Finite parts of gluino, electroweak and gluon contribution relative to $\Gamma^{\rm SM}$ as a function of the $\tilde{c}_R - \tilde{t}_R$ mixing parameter δ_{23}^{uRR}, finite means $\ln Q$ independent.



$h^0 \longrightarrow c\bar{c}$ @ full one-loop level
Numerical results

- Relative dependence of $\Gamma^{1\text{loop, impr}}(h^0 \longrightarrow c\bar{c})$ to $\Gamma^{\text{QFC}} = 0.129$ MeV as a function of the QFV parameters δ_{23}^{uLL} and δ_{23}^{uLR}



$h^0 \rightarrow c\bar{c}$ @ full one-loop level

Error estimation: theoretical errors

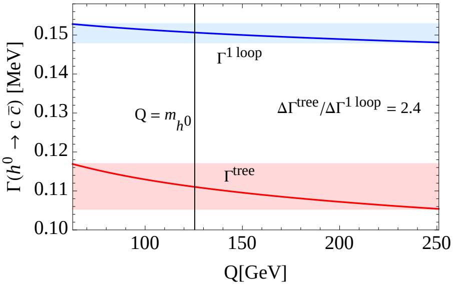
- $\Gamma^{SM}(h^0 \rightarrow c\bar{c}) = 0.118$ MeV (see PDG and [Higgs WG report 1310.8361]), SM prediction uncertainty $\Delta\Gamma^{SM}(h^0 \rightarrow c\bar{c}) \sim 11\%$, from which $\sim 7\%$ are due to the error of α_s
- $\Delta\Gamma^{MSSM}(h^0 \rightarrow c\bar{c}) \sim \sqrt{4^2 + 7?^2 + 2^2} \approx 8.3\%?$

* error in the charm quark mass $m_c(m_c)$ ($\sim$ error in the charm Yukawa coupling $Y_c(m_c)$) $\sim 2\%$
* uncertainties due to the error in the strong coupling constant $\alpha_s(Q) \ \sim \ 7?\%$
  (Note: QCD/ SUSY QCD 1-loop corrections are proportional to $\alpha_s(Q)$!)
  (Note: The error in $\alpha_s(Q)$ induces additionally uncertainties in the scale evolution $m_c(m_c) \longrightarrow m_c(Q = m_{h^0})$!)
* uncertainties due to the renormalisation scale dependences of the width $\sim 2\%$

$h^0 \longrightarrow c\bar{c}$ @ full one-loop level

Error estimation: theoretical errors

- Dependence of $\Gamma(h^0 \rightarrow c\bar{c})$ on the renormalisation scale Q in the range $m_{h^0}/2 < Q < 2m_{h^0}$



- The renormalisation scale Q dependence of the MSSM width is rather small => it results in $\sim 2\%$ theoretical uncertainties

$h^0 \to c\bar{c}$ @ full one-loop level
Error estimation: experimental errors

- Measurement at the LHC: seems to be not possible
- However it is possible to be performed at the ILC
- Higgs coupling uncertainty in % from ILC at its various stages

[M.E. Peskin, 1312.4974]

	250	500	500up	1000	1000up
$c\bar{c}$	6.4	2.6	1.2	0.98	0.72

- $\Delta\Gamma^{\mathrm{DATA}}(h^0 \to c\bar{c}) \sim 1.2\%$ (at ILC(500 GeV and LumiUP))
- We find that the difference between MSSM and SM predictions for the width can be large compared to the expected experimental errors at the ILC, even if we take into account the theoretical uncertainties of the predictions

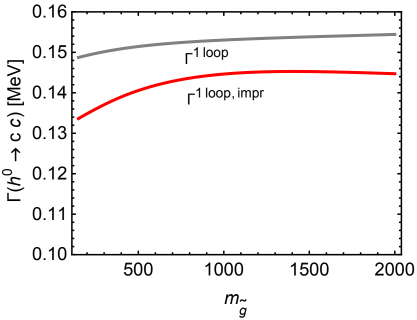
- We have studied the decay of the lightest neutral Higgs boson, $h^0 \to c\bar{c}$, at full one-loop level in the MSSM with non-minimal flavour violation
- We have renormalised the process in the $\overline{\mathrm{DR}}$ renormalisation scheme
- In the numerical analysis we consider mixing between the second and the third squark generations and the relevant constraints from B meson data are taken into account
- We have found that the full one-loop-corrected decay width $\Gamma(h^0 \to c\bar{c})$ can differ up to $\sim 35\%$ from its SM value, due to large $\tilde{c} - \tilde{t}$ mixing and large QFV/QFC trilinear couplings. The leading contributions are those with gluino
- After summarising the theoretical and experimental errors we conclude that an observation of these SUSY QFV effects is possible with a good chance at the ILC.

Thank you for your attention!

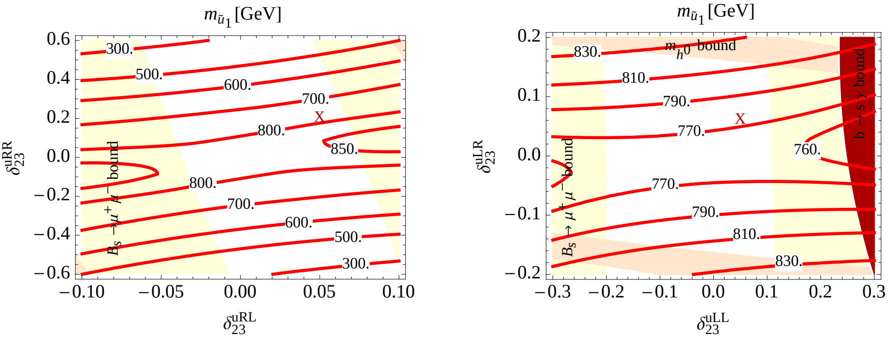
Some additional slides:

$h^0 \longrightarrow c\bar{c}$ @ full one-loop level
Numerical results

- $\Gamma^{1\,\mathrm{loop}}$ and $\Gamma^{1\,\mathrm{loop,\,impr}}$ at the reference point with $m_{\tilde{g}}$ varied in order to see the decoupling behavior.



- Two contour plots of the mass of the lightest sup-quark



- The vacuum stability conditions lead to constraints on the trilinear coupling matrices

$$
\begin{aligned}
|T_{U\alpha\alpha}|^2 &< 3\, Y_{U\alpha}^2\, (M_{Q\alpha\alpha}^2 + M_{U\alpha\alpha}^2 + m_2^2)\ , \\
|T_{D\alpha\alpha}|^2 &< 3\, Y_{D\alpha}^2\, (M_{Q\alpha\alpha}^2 + M_{D\alpha\alpha}^2 + m_1^2)\ , \\
|T_{U\alpha\beta}|^2 &< Y_{U\gamma}^2\, (M_{Q\alpha\alpha}^2 + M_{U\beta\beta}^2 + m_2^2)\ , \\
|T_{D\alpha\beta}|^2 &< Y_{D\gamma}^2\, (M_{Q\alpha\alpha}^2 + M_{D\beta\beta}^2 + m_1^2)\ ,
\end{aligned}
$$

where $\alpha, \beta = 1, 2, 3,\ \alpha \neq \beta;\ \gamma = \mathrm{Max}(\alpha, \beta)$ and

$$
\begin{aligned}
m_1^2 &= (m_{H^+}^2 + m_Z^2 \sin^2\theta_W)\sin^2\beta - \frac{1}{2} m_Z^2, \\
m_2^2 &= (m_{H^+}^2 + m_Z^2 \sin^2\theta_W)\cos^2\beta - \frac{1}{2} m_Z^2.
\end{aligned}
$$

$Y_{U\alpha}$ and $Y_{D\alpha}$ are the Yukawa couplings of the up-type and down-type quarks.

- Calculating higher order corrections requires renormalisation due to UV and IR divergences
- For the UV divergences we employ the $\overline{\mathrm{DR}}$ renormalisation scheme at one-loop level: all tree-level input parameters (masses, fields and parameters in the couplings) of the Lagrangian are UV finite (everywhere $\Delta = 0$) and defined at a fixed scale $Q = m_{h^0} = 125.5$ GeV
- The renormalised finite one-loop amplitude is given by

$$\mathcal{M}^{1loop} = \mathcal{M}^{vertex} + \mathcal{M}^{WFR} \left(+\mathcal{M}^{CT}\right)$$

- The Higgs wave-function renormalisation constants read

$$\delta Z_{h^0 h^0} = -\mathrm{Re}\ \dot{\Pi}^H_{h^0 h^0}(m^2_{h^0})$$

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$$\delta Z_{h^0 H^0} = \frac{2}{m^2_{h^0} - m^2_{H^0}} \left(\mathrm{Re}\ \Pi^H_{h^0 H^0}(m^2_{h^0}) - \delta t_{h^0 H^0}\right)$$

where $\delta t_{h^0 H^0}$ are the tadpole contributions

$$\delta t_{h^0 H^0} = -\frac{1}{v}\left[\tau_{h^0}\left(\frac{s_\alpha^2 c_\alpha}{c_\beta} + \frac{c_\alpha^2 s_\alpha}{s_\beta}\right) + \tau_{H^0}\left(-\frac{c_\alpha^2 s_\alpha}{c_\beta} + \frac{s_\alpha^2 c_\alpha}{s_\beta}\right)\right]$$

with τ_{h^0} and τ_{H^0} are the loop corrections from the tadpole diagrams with h^0 and H^0 respectively

- The charm quark wave-function renormalisation constants are

$$\begin{aligned}
\delta Z_{cc}^{L/R} &= -\mathrm{Re}\ \Pi_{cc}^{L/R}(m_c) + \frac{1}{2m_c}\mathrm{Re}\left(\Pi_{cc}^{S,\ L/R}(m_c) - \Pi_{ii}^{S,\ R/L}(m_c)\right) \\
&\quad -m_c\mathrm{Re}\Big[m_c\left(\dot{\Pi}_{cc}^{L/R}(m_c) + \dot{\Pi}_{cc}^{R/L}(m_c)\right) \\
&\quad +\dot{\Pi}_{cc}^{S,\ L/R}(m_c) + \dot{\Pi}_{cc}^{S,\ R/L}(m_c)\Big]
\end{aligned}$$