DCPT/02/128
KA-TP–22–2002
MPI-PhT/2002-74

IPPP/02/64
LMU 16/02
LC-TH-2002-016
hep-ph/0212037

# The Higgs Boson Masses of the Complex MSSM: A Complete One-Loop Calculation*

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**Abstract**

In the Minimal Supersymmetric Standard Model with complex parameters (cMSSM) we perform a complete one-loop calculation for the Higgs boson masses (including the momentum dependence) and the mixing angles. These corrections are obtained in the Feynman-diagrammatic approach using the on-shell renormalization scheme. The impact of the newly evaluated corrections is analyzed numerically. The full one-loop result, supplemented by the leading two-loop contributions taken over from the real MSSM are implemented into the public Fortran code *FeynHiggs*2.0.

*Talk given by S. Heinemeyer at SUSY02, June 2002, DESY, Germany

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# 1 Introduction

The search for the lightest Higgs boson is a crucial test of Supersymmetry (SUSY) which can be performed with the present and the next generation of accelerators. The prediction of a relatively light Higgs boson is common to all supersymmetric models whose couplings remain in the perturbative regime up to a very high energy scale [1]. A precise prediction for the mass of the lightest Higgs boson and its couplings to other particles in terms of the relevant SUSY parameters is necessary in order to determine the discovery and exclusion potential of LEP2 and the upgraded Tevatron, and for physics at the LHC and future linear colliders, where eventually a high-precision measurement of the properties of the Higgs boson might be possible [2].

The case of the Higgs sector in the $\mathcal{CP}$-conserving MSSM (rMSSM) has been tackled up to the two-loop level by different methods such as the Effective Potential (EP) method [3–6], the renormalization group (RG) improved one-loop EP approach [7] and the Feynman-diagrammatic (FD) method using the on-shell renormalization scheme [8,9]. This method has provided the only complete calculation at the one-loop level including momentum dependence [10] and furthermore the dominant logarithmic and non-logarithmic corrections at the two-loop level [9, 11]. The application of different methods lead to thorough comparisons between the different approaches.

In the case of the MSSM with complex parameters (cMSSM) the higher order corrections have been performed, after the first more general investigations [12], in the EP approach and in the RG improved one-loop EP method [13–17]. In the context of the FD approach, so far an exploratory study, including a calculation of the leading terms has been performed [18]. A full one-loop calculation, including momentum dependence, as well as an evaluation of the leading two-loop corrections have been missing so far.

This paper provides the next step into this direction: We present the full one-loop calculation for the Higgs boson masses and mixing angles in the cMSSM. Concerning the Higgs boson masses, the full momentum dependence has been taken into account. In this paper we present briefly the calculation and discuss the effects on the Higgs boson masses that originate from the new terms that extend the available calculations obtained using the EP and RG approach. More details about the evaluation as well as a more detailed numerical analysis can be found in Refs. [19, 20]. All results are incorporated into a public Fortran code, *FeynHiggs*2.0.

The rest of the paper is organized as follows. In Section 2 we review the Higgs sector and the scalar quark sector of the cMSSM, providing the relations of physical and unphysical parameters, the masses and the mixing angles. Section 3 contains the numerical analysis. We conclude with Section 4.

# 2 Calculational framework

## 2.1 The tree-level structure of the cMSSM Higgs sector

The cMSSM Higgs potential reads [21]:

$$V = m_1^2 \mathcal{H}_1 \bar{\mathcal{H}}_1 + m_2^2 \mathcal{H}_2 \bar{\mathcal{H}}_2 - (m_{12}^2 \epsilon_{ab} \mathcal{H}_1^a \mathcal{H}_2^b + \text{h.c.})$$

$$+\frac{g'^2+g^2}{8}\,(\mathcal{H}_1\bar{\mathcal{H}}_1-\mathcal{H}_2\bar{\mathcal{H}}_2)^2+\frac{g^2}{2}\,|\mathcal{H}_1\bar{\mathcal{H}}_2|^2, \tag{1}$$

where $m_1^2, m_2^2, m_{12}^2$ are soft SUSY-breaking terms ($m_{12}^2$ can be complex), $g, g'$ are the $SU(2)$ and $U(1)$ gauge couplings, and $\epsilon_{12}=-1$. The doublet fields $\mathcal{H}_1$ and $\mathcal{H}_2$ are decomposed in the following way:

$$\begin{aligned}
\mathcal{H}_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1^0 + i\chi_1^0)/\sqrt{2} \\ \phi_1^- \end{pmatrix}, \\
\mathcal{H}_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = e^{i\xi}\begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + i\chi_2^0)/\sqrt{2} \end{pmatrix}.
\end{aligned} \tag{2}$$

$\xi$ is a phase between the two Higgs doublets. In the Higgs potential it appears only in the combination $\xi' = \xi + \arg(m_{12}^2)$. From the unphysical parameters in Eq. (1) the transition to the physical parameters (including the tadpoles) is performed by the substitution (see Refs. [19, 20] for details):

$$v_1,\ v_2,\ g_1,\ g_2,\ m_1^2,\ m_2^2,\ |m_{12}^2|,\ \xi' \ \to\ e,\ s_W,\ M_Z,\ \tan\beta,\ M_{H^\pm}^2,\ T_h,\ T_H,\ T_A\ . \tag{3}$$

$e$ is the electric charge, $s_W^2 = 1 - c_W^2$ with $c_W \equiv M_W/M_Z$, where $M_W$ and $M_Z$ are the masses of the $W$ and the $Z$ boson, respectively. Furthermore, $\tan\beta$ is the ratio of the two vacuum expectation values, $\tan\beta = v_2/v_1$ ($s_\beta \equiv \sin\beta\,, c_\beta \equiv \cos\beta$ ), $M_{H^\pm}$ is the mass of the charged Higgs boson, and $T_x, x = h, H, A$ denote the tadpoles of the fields $h$, $H$ and $A$, see below.

At the tree-level, the tadpoles have to be zero. In the case of $T_A$ this can only be fulfilled if $\xi' = 0$. Thus $\mathcal{CP}$-violation is absent at the tree-level. The bilinear part of the Higgs potential has to be diagonalized to obtain the mass eigenstates. In the $\mathcal{CP}$-even sector this is done with the help of the angle $\alpha$, and results in the two neutral $\mathcal{CP}$-even Higgs bosons $h$ and $H$. In the $\mathcal{CP}$-odd sector the diagonalization can be performed with the angle $\beta$, leading to the $\mathcal{CP}$-odd $A$ boson and the neutral Goldstone boson $G$. The charged Higgs sector is also diagonalized with the angle $\beta$, resulting in the charged Higgs bosons $H^\pm$ and the Goldstone bosons $G^\pm$. One arrives at the following masses at tree-level:

$$\begin{aligned}
H &: \ m_H^2 = \frac{1}{2}\left[\bar{M}_{H^\pm}^2 + M_Z^2 + \sqrt{(\bar{M}_{H^\pm}^2 + M_Z^2)^2 - 4M_Z^2\bar{M}_{H^\pm}^2 c_{2\beta}^2}\ \right] \\
h &: \ m_h^2 = \frac{1}{2}\left[\bar{M}_{H^\pm}^2 + M_Z^2 - \sqrt{(\bar{M}_{H^\pm}^2 + M_Z^2)^2 - 4M_Z^2\bar{M}_{H^\pm}^2 c_{2\beta}^2}\ \right] \\
A &: \ m_A^2 = M_{H^\pm}^2 - M_W^2 \quad (\equiv \bar{M}_{H^\pm}^2) \\
G &: \ m_G^2 = M_Z^2 \\
H^\pm &: \ M_{H^\pm}^2 \\
G^\pm &: \ m_{G^\pm}^2 = M_W^2
\end{aligned} \tag{4}$$

$M_{H^\pm}$ and $\tan\beta$ are chosen as input parameters. The entries for the Goldstone bosons $G$ and $G^\pm$ are to be understood in the Feynman gauge. Since there is no $\mathcal{CP}$-violation in the cMSSM Higgs sector at tree-level, there is no mixing between $h$ and $H$ and the fields $A$ and $G$.

## 2.2 The fermion and gaugino sectors of the cMSSM

Possibly $\mathcal{CP}$-violating parameters occur in all other SUSY sectors of the cMSSM. Most important for Higgs boson phenomenology is the scalar quark sector. The mass matrix of two squarks of the same flavor, $\tilde{q}_L$ and $\tilde{q}_R$, is given by

$$M_{\tilde{q}} = \begin{pmatrix} M_L^2 + m_q^2 & m_q X_q^* \\ m_q X_q & M_R^2 + m_q^2 \end{pmatrix} \tag{5}$$

with

$$\begin{aligned} M_L^2 &= M_{\tilde{Q}}^2 + M_Z^2 \cos 2\beta \, (I_3^q - Q_q s_W^2) \\ M_R^2 &= M_{\tilde{Q}'}^2 + M_Z^2 \cos 2\beta \, Q_q s_W^2 \\ X_q &= A_q - \mu^* \{\cot\beta \, , \tan\beta\}, \end{aligned} \tag{6}$$

where $\{\cot\beta \, , \tan\beta\}$ applies for $\{\mathrm{up, down}\}$-type squarks, respectively. $A_q$ and $\mu$ can be complex. In an isodoublet the $SU(2)$ symmetry enforces that $M_{\tilde{Q}}$ has to be chosen equal for both squark types. The $M_{\tilde{Q}'}$ on the other hand can be chosen independently for every squark type. In the scalar quark sector of the cMSSM $N_q + 1$ phases are present, one for each $A_q$ and one for $\mu$. The squark mass eigenstates are obtained by diagonalizing the mass matrix and are given by

$$m_{\tilde{q}_{1,2}}^2 = m_q^2 + \frac{1}{2}\left[M_L^2 + M_R^2 \mp \sqrt{(M_L^2 - M_R^2)^2 + 4 m_q^2 |X_q|^2}\,\right]. \tag{7}$$

The masses are independent of the phase of $X_q$. However, the phase of $A_q$ affects the mass eigenvalues since it changes the absolute value of $X_q$.

The other possibly complex parameters are $M_1$ and $M_2$, which are the soft SUSY-breaking parameters in the gaugino sector, and $m_{\tilde{g}}$, the gluino mass. These parameters are less important for the Higgs sector phenomenology; $m_{\tilde{g}}$ enters the predictions only at the two-loop level.

## 2.3 The neutral Higgs boson sector at the one-loop level

The inverse neutral Higgs boson propagator matrix in the cMSSM at the one-loop level is given by

$$(\Delta_{\rm Higgs})^{-1} = -i \begin{pmatrix} q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) & \hat{\Sigma}_{hH}(q^2) & \hat{\Sigma}_{hA}(q^2) \\ \hat{\Sigma}_{Hh}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{HA}(q^2) \\ \hat{\Sigma}_{Ah}(q^2) & \hat{\Sigma}_{AH}(q^2) & q^2 - m_A^2 + \hat{\Sigma}_{AA}(q^2) \end{pmatrix}. \tag{8}$$

$\hat{\Sigma}$ denotes the renormalized Higgs boson self-energies (at the one-loop level). $\mathcal{CP}$-violation occurs, i.e. mixing between the $\mathcal{CP}$-even Higgs bosons $h$, $H$, and the $\mathcal{CP}$-odd Higgs boson $A$ occurs if the self-energies $\hat{\Sigma}_{AH} = \hat{\Sigma}_{HA}$ and/or $\hat{\Sigma}_{Ah} = \hat{\Sigma}_{hA}$ are non-zero. This can happen if the complex parameters in the cMSSM possess an imaginary part. Also the pure $\mathcal{CP}$-even self-energies, $\hat{\Sigma}_{hh}$, $\hat{\Sigma}_{HH}$ and $\hat{\Sigma}_{hH}$, and the pure $\mathcal{CP}$-odd self-energy, $\hat{\Sigma}_{AA}$, are numerically affected if some cMSSM parameters are complex. Details about the calculation of the renormalized Higgs boson self-energies and the on-shell renormalization procedure can be found in Refs. [18–20].

The poles of the Higgs boson propagator matrix are the squares of the pole masses of the three neutral Higgs bosons including higher-order corrections. The masses are denotes by $m_{h_1}$, $m_{h_2}$, $m_{h_3}$ with $m_{h_1} \leq m_{h_2} \leq m_{h_3}$.

Besides the Higgs boson masses, also the effects of the higher-order corrected self-energies on the Higgs boson couplings to SM gauge bosons and fermions can be evaluated. In the limit of $q^2 = 0$, i.e. $\hat{\Sigma}(q^2) \to \hat{\Sigma}(0)$, the transition from the tree-level states $h, H, A$ to the mass eigenstates at higher orders, $h_1, h_2, h_3$ can be described with the rotation matrix $U$,

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} u_{11} & u_{12} & u_{13} \\ u_{21} & u_{22} & u_{23} \\ u_{31} & u_{32} & u_{33} \end{pmatrix} \begin{pmatrix} h \\ H \\ A \end{pmatrix} \equiv U \begin{pmatrix} h \\ H \\ A \end{pmatrix} . \tag{9}$$

$U$ includes the dominant corrections (coming from Higgs boson propagators) into the effective couplings [22]. The explicit formulas are given in Refs. [16, 18].

The Higgs boson self-energies have been evaluated by taking into account all sectors of the cMSSM, including possibly complex parameters and the full momentum dependence. The evaluation has been done with the help of the programs *FeynArts* [23] (using the MSSM model file [24]) and *FormCalc* [25]. The results, supplemented by the leading two-loop contributions taken over from the rMSSM [4, 8, 9], have been transformed into the Fortran code *FeynHiggs*2.0 [26]. The code evaluates the Higgs boson masses, the mixing matrix and the corresponding corrections to the couplings of the Higgs bosons to SM gauge bosons and fermions. *FeynHiggs*2.0 is available at `www.feynhiggs.de` .

# 3 Numerical examples and discussion

In this section numerical examples are presented and discussed. They are meant to illustrate on the one hand the possible effects of complex phases in the MSSM and on the other hand the effects of the newly evaluated terms. For a more detailed phenomenological analysis constraints on $\mathcal{CP}$-violating parameters from experimental bounds, e.g. on electric dipole moments (EDMs), have to be taken into account [27]. However, in our analysis below we only take non-zero phases for $A_t = A_b$ and $M_2$, which are not severely restricted from EDM bounds.

The numerical analysis given below has been performed in the "CPX" scenario [28], where the parameters are fixed to

$$\begin{aligned} &M_{\rm SUSY} = 500 \text{ GeV}, \ |A_t| = |A_b| = 1000 \text{ GeV}, \ \mu = 2000 \text{ GeV}, \ M_2 = 500 \text{ GeV}, \\ &M_{H^\pm} = 150 \text{ GeV}, \ \tan\beta = 5 \ , \end{aligned} \tag{10}$$

if not indicated differently. The phases are always defined explicitly. However, our analysis is confined to $\phi_\mu = 0$, since this is the most restricted phase, see e.g. Ref. [29] and references therein. The CPX scenario has been defined in order to maximize the effects of complex phases. It should be kept in mind that while the relatively high value of $|\mu|$ is not realized in minimal models like mSUGRA, mGMSB or mAMSB, it can lead to large effects especially in the $b/\tilde{b}$ sector.

In our numerical analysis we concentrate on the Higgs boson masses derived from the one-loop corrections only. This is sufficient to show the effects of the newly evaluated corrections. A more detailed numerical analysis, including also the effects on the rotation matrix and correspondingly to the Higgs boson couplings to SM gauge bosons and fermions can be found in Refs. [19, 20].

In Fig. 1 we show the two lighter masses, $m_{h_1}$ and $m_{h_2}$, for the parameters in Eq. (10) as a function of $\phi_{A_t}$. The dotted line shows the result for the (s)fermion sector[1] in the $q^2 = 0$ approximation, the dashed line shows the full cMSSM with $q^2 = 0$, and the full line also includes the momentum contributions. The effect of the subleading one-loop contributions, i.e. the ones beyond the (s)fermion sector, can give rise to changes in $m_{h_1}$ and $m_{h_2}$ of $\mathcal{O}(4$ GeV$)$. The further inclusion of the momentum dependence can result in a shift of $m_{h_1}$ of $\mathcal{O}(2$ GeV$)$ for large values of $\phi_{A_t}$.

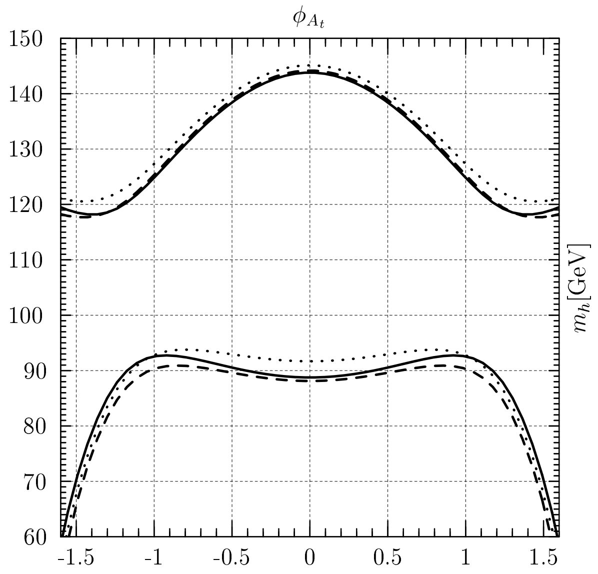


Figure 1: $m_{h_1}$ and $m_{h_2}$ are shown as a function of $\phi_{A_t}$ for the parameters of Eq. (10). The dotted line shows the result for the (s)fermion sector in the $q^2 = 0$ approximation, the dashed line shows the full cMSSM with $q^2 = 0$, and the full line also includes the effects of the non-vanishing momentum.

All neutral Higgs boson masses, $m_{h_1}$, $m_{h_2}$, $m_{h_3}$, are shown as a function of $M_{H^\pm}$ in Fig. 2 for the parameters of Eq. (10). It becomes apparent that especially when two mass eigenvalues are close to each other, the newly evaluated terms and the momentum dependent contribution can change the results by several GeV. Especially the inclusion

[1]With the (s)fermion sector we denote here the $t/\tilde{t}/b/\tilde{b}$ sector. The effects of the other fermions and sfermions are numerically small and stay below 1 GeV [19, 20].

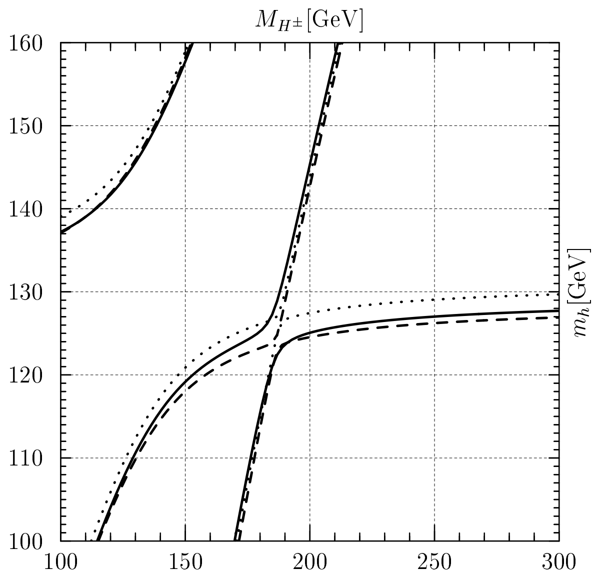


Figure 2: $m_{h_1}$, $m_{h_2}$ and $m_{h_3}$ are shown as a function of $M_{H^\pm}$ for the parameters of Eq. (10) and $\phi_{A_t} = \pi/2$. The line styles are as in Fig. 1.

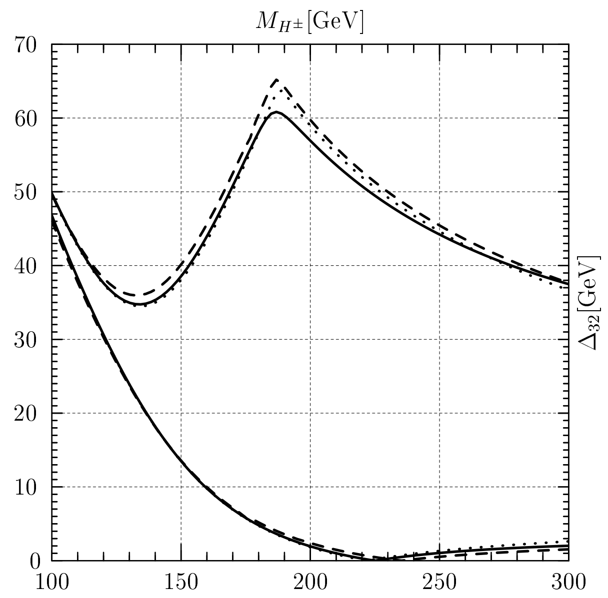


Figure 3: $\Delta_{32} = m_{h_3} - m_{h_2}$ is shown as a function of $M_{H^\pm}$ for the parameters of Eq. (10). The line styles are as in Fig. 1. The upper and lower curves correspond to $\phi_{A_t} = \pi/2$ and $\phi_{A_t} = 0$.

of the momentum dependence results here in a larger mass gap of the two lightest masses compared to the result where the momentum dependence has been neglected.

Of particular interest is the mass gap between the two heavier neutral Higgs boson masses. For values of $M_{H^\pm} \gtrsim 200$ GeV, $m_{h_2}$ and $m_{h_3}$ can be very close to each other, which makes their experimental resolution at a collider experiment difficult. In Fig. 3 we show $\Delta_{32} = m_{h_3} - m_{h_2}$ as a function of $M_{H^\pm}$ in the rMSSM, i.e. for $\phi_{A_t} = 0$ (lower set of curves) and for $\phi_{A_t} = \pi/2$ (upper set). The different line styles are as in Fig. 1. In the chosen scenario $\Delta_{32}$ is always larger in the case of $\phi_{A_t} = \pi/2$ as compared to the case where $\phi_{A_t} = 0$. The induced difference in $\Delta_{32}$ can be larger than 50 GeV. The impact of the non-(s)fermionic terms can be of $\mathcal{O}(5$ GeV). It should be kept in mind that changing the phase of $A_t$ also effects the absolute value of $X_t$. In fact, in Refs. [19, 20] it is demonstrated that every mass gap that can appear in the cMSSM can (for another choice of parameters) also be accommodated in the rMSSM.

Finally, in Fig. 4 we show the effect of $\phi_{M_2}$ on the lightest Higgs boson mass in the scenario of Eq. (10). The dashed (full) line shows the difference of the full MSSM with $q^2 = 0$ ($\neq 0$) to the (s)fermion approximation with $q^2 = 0$. The effect of the non-

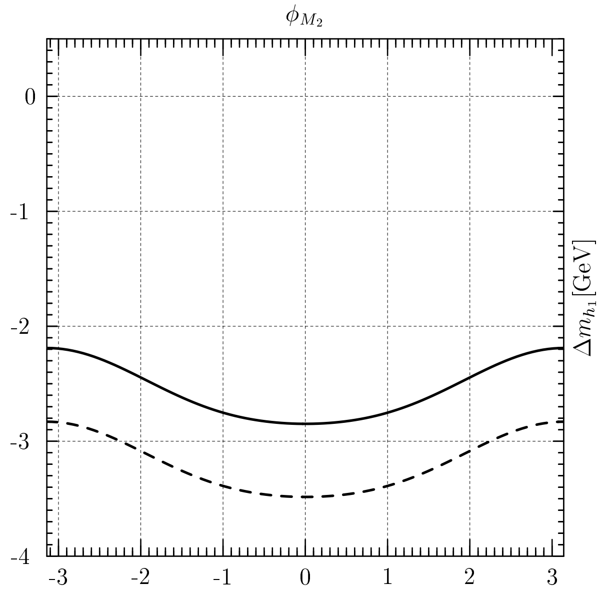


Figure 4: The effects on $m_{h_1}$ of the different sectors normalized to the (s)fermion sector evaluation only (i.e. the (s)fermion sector contribution subtracted) is shown as a function of $\phi_{M_2}$ for $\phi_\mu = \phi_{A_t} = 0$ and the other parameters as in Eq. (10). The dashed (full) line shows the result for the full cMSSM with $q^2 = 0$ ($\neq 0$).

(s)fermionic contribution are in this case of $\mathcal{O}(3$ GeV), and the momentum dependence induces a shift of $\mathcal{O}(1$ GeV). The effect of $\phi_{M_2}$ is $\lesssim 1$ GeV. Thus the phase of $M_2$ has a much smaller impact than the phases of the trilinear couplings. In a more detailed analysis of the cMSSM parameter space (see Refs. [19, 20]) it has been found that large effects of the phases of the gaugino mass parameters on $m_{h_1}, m_{h_2}, m_{h_3}$ or on the mixing of $\mathcal{CP}$-even and $\mathcal{CP}$-odd states can only occur if two mass eigenvalues are very close to each other. Thus, the effect observed in Ref. [15] that the mixing of the two heavier Higgs states depends strongly on the phase of $M_2$ or $M_1$ happens only in a very small part of the cMSSM parameter space.

# 4 Conclusions

We have presented a complete one-loop calculation of the Higgs boson masses in the MSSM with complex parameters. The calculation has been performed in the Feynman-diagrammatic approach, using the on-shell renormalization scheme. Besides the full spectrum of cMSSM particles also the momentum dependence has explicitly been included.

In the numerical analysis we have investigated the effects of the non-(s)fermionic sectors as well as the effects of the momentum dependence on the three neutral Higgs boson mass eigenvalues, $m_{h_1}$, $m_{h_2}$ and $m_{h_3}$. The analysis has been performed for a set of cMSSM parameters that maximizes the effects of the $\mathcal{CP}$-violating phases. In this case we find that the corrections of the non-(s)fermionic sector can be of $\mathcal{O}$(5 GeV), while the momentum dependence induces a shift of up to 2 GeV. These effects are more pronounced if two of the mass eigenvalues are close to each other. The observed effects on $m_{h_1}$, $m_{h_2}$ and $m_{h_3}$ of the newly included corrections are thus of the order of several GeV and have to be taken into account in phenomenological analyses of the cMSSM Higgs boson sector in view of the prospective experimental precision at the next generation of colliders. The phase of the gaugino mass parameters, $\phi_{M_2}$ and $\phi_{M_1}$, are found to have only a relatively small effect, except in a very small regions of the parameter space, where two of the mass eigenvalues are very close to each other.

The results of the full one-loop calculation, supplemented with the dominant and subdominant corrections taken over from the rMSSM, have been implemented into the Fortran program *FeynHiggs*2.0. The code can be obtained at `www.feynhiggs.de` .

## Acknowledgments

We thank C. Schappacher for helpful discussions. This work was partially supported by the European Community's Human Potential Programme under contract HPRN-CT-2000-00149 (Collider Physics).

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