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Higher-order corrections to decays and masses of charged Higgs bosons

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For the calculation of the partial decay widths of a charged Higgs boson, the value of the pole mass of the charged Higgs boson is needed as an input value. Depending on the specific model as well as on the applied renormalization scheme, radiative corrections have to be taken into account for a precise prediction of the mass value of the charged Higgs boson. These aspects and the status of predictions of the two-body partial decay widths of the charged Higgs boson will be discussed.

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1. Introduction

The discovery of a Higgs boson during Run I at the LHC [1, 2] is a milestone in particle physics. This discovered particle conforms so far with the Higgs boson of the Standard Model, however, many extensions of the Standard Model addressing different shortcomings of the Standard Model predict several Higgs bosons where the discovered one would be one of several. The discovery of a charged Higgs boson would be a clear sign of an extended Higgs sector and, hence, physics beyond the Standard Model. The search for such a charged Higgs boson is ongoing, see e.g. [3, 4].

For the interpretation of the experimental data, not only experimental knowledge is needed but also input from the theory side in form of predictions of cross sections and partial decay widths. Accurate predictions have to take into account quantum corrections of higher orders, and consistent input is needed. If the production cross section and the partial decay width are calculated separately and are only combined via a narrow width approximation to obtain a prediction of the complete process, the charged Higgs boson appears as an external particle. In this case in particular, on-shell properties of the charged Higgs boson have to be ensured. The procedure of how to obtain the corresponding pole mass depends on the definition of the parameter for the mass of the charged Higgs boson. The definition is fixed via a renormalization condition. Most commonly used are two kinds of renormalization conditions, on-shell conditions where parameters referring to masses of particles are identified with the corresponding pole masses and conditions where parameters are defined as running parameters. The first type is useful if, for example, on-shell properties of particles are needed; the second one is well-suited, for instance, if the model is considered at different, largely separated scales.

The first part of these proceedings focuses on higher-order corrections to the mass of the charged Higgs boson while in the second part higher-order corrections to the partial decay widths of the charged Higgs boson decaying into two particles are discussed within different models.

2. Higher-order corrections to the mass of the charged Higgs boson

The simplest extension of the Standard Model that gives rise to a charged Higgs boson is the Two-Higgs-Doublet Model (2HDM). Assuming CP conservation, the form of the general Higgs potential of the 2HDM, V_{2HDM}, reduces to

$$\begin{aligned} V_{\text{2HDM}} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\varepsilon^{ij} \Phi_1^i \Phi_2^j + \text{h.c.}) \\ & + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ & + \lambda_4 \left(\varepsilon^{ij} \Phi_1^i \Phi_2^j\right) \left(\varepsilon^{kl} (\Phi_1^\dagger)^k (\Phi_2^\dagger)^l\right) + \lambda_5 \left[\left(\varepsilon^{ij} \Phi_1^i \Phi_2^j\right)^2 + \left(\varepsilon^{ij} (\Phi_1^\dagger)^i (\Phi_2^\dagger)^j\right)^2\right] \\ & + \left\{\left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right] \varepsilon^{ij} \Phi_1^i \Phi_2^j + \text{h.c.}\right\} \end{aligned} \tag{2.1}$$

with seven real quartic coupling parameters λ_i, $i = 1, \ldots, 7$, and 3 mass parameters m_{11}^2, m_{22}^2, m_{12}^2 [5, 6, 7], and $\varepsilon^{12} = 1$. The two Higgs doublets with hypercharge[1] $Y = -1$ and $Y = 1$ are denoted

[1]The choice of two Higgs doublets with opposite hypercharge was made for an easy comparison with the MSSM. The following discussion for the 2HDM does not depend on the hypercharge of the Higgs doublets.

by Φ_1 and Φ_2 and can be expanded about their vacuum expectation values (vev) v_1 and v_2

$$\Phi_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - \mathrm{i}\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + \mathrm{i}\chi_2) \end{pmatrix} \tag{2.2}$$

where ϕ_i, χ_i and $\phi_i^\pm$, $i = 1,2$, denote the neutral and charged component fields, respectively. The λ_6 and λ_7 terms in the potential in Eq. (2.1) can be eliminated if the discrete symmetry $\Phi_1 \to -\Phi_1$ is imposed; allowing for terms of 2 dimensions that violate this symmetry softly m_{12}^2 may still have non-zero values [5, 7].

After electroweak symmetry breaking, five physical Higgs bosons are obtained, two CP-even, one CP-odd and two charged Higgs bosons. One combination of the two vev, $\sqrt{v_1^2 + v_2^2}$, is determined in such a way that it can reproduce the value of the vev of the Standard Model. The other combination, $\tan\beta = v_2/v_1$, is kept as free parameter. The parameters m_{11}^2 and m_{22}^2 can then be fixed via the minimum condition for the potential. After applying these conditions, we are left with 6 parameters, m_{12}^2 and λ_1 to λ_5 and four masses, three for the neutral and one for the charged Higgs bosons. That means there are enough parameters to define all Higgs masses independently (and to keep two further parameters as independent). Hence, renormalization conditions for all the masses can be chosen to ensure that the parameters referring to the masses of the particles, such as $M_{H^\pm}$ for the mass of the charged Higgs boson, are directly related to the pole masses, and no higher-order corrections have to be calculated to obtain the correct pole mass. However, four of the parameters m_{12}^2 and λ_1 to λ_5 are then given as a combination of the independent parameters, and the relations between these parameters are modified by quantum corrections.

The minimal supersymmetric extension of the Standard Model (MSSM) requires a second Higgs doublet for the generation of up- and down-type fermion masses and to keep the theory anomaly free. The underlying supersymmetric structure gives rise to specific expressions of the quartic couplings in the Higgs potential, V_{MSSM},

$$\begin{aligned} V_{\mathrm{MSSM}} = {} & (m_1^2 + |\mu|^2)\Phi_1^\dagger\Phi_1 + (m_2^2 + |\mu|^2)\Phi_2^\dagger\Phi_2 - m_{12}^2(\varepsilon^{ij}\Phi_1^i\Phi_2^j + \mathrm{h.c.}) \\ & + \frac{g^2+g'^2}{8}(\Phi_1^\dagger\Phi_1)^2 + \frac{g^2+g'^2}{8}(\Phi_2^\dagger\Phi_2)^2 + \frac{g^2-g'^2}{4}(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ & - \frac{g^2}{2}\left(\varepsilon^{ij}\Phi_1^i\Phi_2^j\right)\left(\varepsilon^{kl}(\Phi_1^\dagger)^k(\Phi_2^\dagger)^l\right), \end{aligned} \tag{2.3}$$

depending on the $U(1)$ and the $SU(2)$ gauge boson couplings g' and g. The soft supersymmetry-breaking mass parameters m_1^2 and m_2^2 appear in the combination with the μ parameter. Analogous to m_{11}^2 and m_{22}^2 of the 2HDM, these combinations $m_i^2 + \mu^2$ can be fixed via the minimum conditions. The gauge couplings are usually determined within the gauge sector so the remaining free parameters are m_{12}^2 and $\tan\beta$. Thus, there are fewer parameters than masses to determine, and it is impossible to define all masses independently. Since $\tan\beta$ is usually kept as a free parameter, only one Higgs-boson mass can be defined independently.

In the CP-conserving MSSM, often the mass of the CP-odd Higgs boson M_A is chosen as input parameter. In this case, the mass of the charged Higgs boson, $M_{H^\pm}$, (as well as all the other Higgs masses) is a dependent parameter and can be calculated. The tree-level relation,

$$M_{H^\pm_{\mathrm{tree}}}^2 = M_A^2 + M_W^2 \tag{2.4}$$

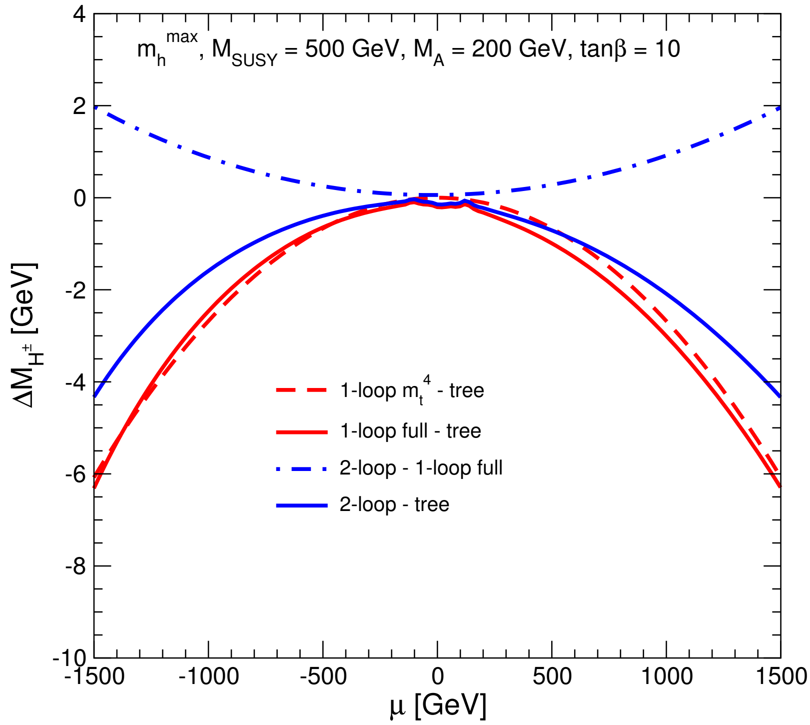

Figure 1: Higher-order contributions to the mass of the charged Higgs boson in dependence of μ. The corrections are shown as $\Delta M_{H^\pm} = M^2_{H^\pm_{\text{type}}} - M^2_{H^\pm_{\text{order}}}$ where, at one-loop level (red), the subscript "type" denotes the Higgs mass calculated in the m_t^4 approximation (dashed) and including the complete one-loop contributions (solid), respectively, while the subscript "order" refers to the tree-level mass value in both cases. At the two-loop level (blue), $M^2_{H^\pm_{\text{type}}}$ includes the full one-loop contributions plus the two-loop corrections up to the order of $\mathscr{O}(\alpha_t \alpha_s)$, however, the subscript "order" denotes the tree-level mass value (solid) and the mass value including one-loop corrections (dashed), respectively. The soft supersymmetry-breaking parameter is denoted by M_{SUSY}. This figure is taken from [8].

with M_W and $M_{H^\pm_{\text{tree}}}$ being the W boson mass and the mass of the charged Higgs boson at tree level, respectively, is changed by higher-order corrections resulting in

$$M^2_{H^\pm} = M^2_A + M^2_W - \hat{\Sigma}_{H^+H^-}\left(M^2_{H^\pm}\right) \tag{2.5}$$

where $\hat{\Sigma}_{H^+H^-}$ is the renormalized self energy of the charged Higgs boson.

In Fig. 1 taken from Ref. [8], the size of the quantum corrections to the pole mass of the charged Higgs boson are shown, $\Delta M_{H^\pm} = M^2_{H^\pm_{\text{type}}} - M^2_{H^\pm_{\text{order}}}$ where the subscripts "type" and "order" refer to the performed approximations. At one-loop level (red), the size of the complete one-loop contributions (solid) and the size of the corrections applying the m_t^4 approximation (dashed), i.e. including only terms proportional to m_t^4/M_W^2, can be compared—in both cases $M^2_{H^\pm_{\text{order}}} = M^2_{H^\pm_{\text{tree}}}$. The size of the one-loop contributions can be up to 6 GeV. For the shown parameter region, the m_t^4 approximation is a good approximation. This ensures that the m_t^4/M_W^2 contributions are the relevant part. At two-loop level at $\mathscr{O}(\alpha_t \alpha_s)$, only terms proportional to the strong coupling constant α_s and $\alpha_t = y_t^2/(4\pi)$, y_t being the top Yukawa coupling, and the top mass squared m_t^2 are included.

This approximation leads to a reliable result, since these $\mathcal{O}(\alpha_t\alpha_s)$ terms are the QCD corrections to the dominant m_t^4 one-loop terms. At the two-loop level (blue), the size of only the $\mathcal{O}(\alpha_t\alpha_s)$ corrections (dashed, $M_{H^\pm_{\text{order}}}$ is the Higgs mass including the complete one-loop contributions) and the size of the complete one-loop plus the two-loop $\mathcal{O}(\alpha_t\alpha_s)$ corrections (solid, $M^2_{H^\pm_{\text{order}}} = M^2_{H^\pm_{\text{tree}}}$) is depicted. The size of the two-loop corrections can be up to 2 GeV in this example.

Even if CP violation is taken into account in the MSSM, the Higgs sector of the MSSM remains CP conserved at tree level. However, higher-order corrections result in a mixture of CP-even and CP-odd Higgs states resulting in three neutral Higgs bosons with CP-even and CP-odd components. Since all the neutral Higgs boson fields have the same quantum numbers they can mix. In this case, it is advantageous to choose the mass of the charged Higgs boson as an input parameter and to calculate the three neutral Higgs-boson masses. Then, the mass of the charged Higgs boson can be fixed as pole mass and will not receive any higher-order corrections.

Also in extensions of the MSSM, the mass of the charged Higgs boson can be a good choice for an input parameter. For example, in the Next-to MSSM (NMSSM) which comprises an additional Higgs singlet superfield leading to one additional CP-even and CP-odd Higgs boson each, the CP-odd fields themselves are subject to mixing contributions since there are more than one physical CP-odd Higgs boson. Fixing the mass of the charged Higgs boson as pole mass, no quantum contributions have to be calculated to obtain the physical, i.e. the pole mass. Choosing a different renormalization condition, such as a running definition with a mass in the $\overline{\text{DR}}$ scheme where "DR" refers to the regularization scheme "dimensional reduction" [9, 10], higher-order corrections have to be taken into account when the pole mass of the charged Higgs boson is determined.

3. Higher-order corrections to the partial decay width of the charged Higgs boson

Since a long time, QCD corrections of next-to leading order are known for the hadronic two-body decay of a charged Higgs boson (including the decay into a top and bottom quark) within the 2HDM [11, 12, 13] and the MSSM [14, 15]. Dominant electroweak effects have also been discussed a long time ago within the MSSM [16]. In addition, resummation of large contributions have been performed in Ref. [17] for the MSSM.

Nowadays, the calculation of the complete electroweak corrections are performed for different partial two-body decay widths. In Ref. [18], the 2HDM is considered. The decay of a charged Higgs boson into a W boson and a light CP-even Higgs boson is calculated including the complete electroweak one-loop corrections. In particular for the electroweak corrections, a renormalization procedure has to be performed. Different choices of renormalization conditions are possible and the results are presented for different renormalization schemes. The electroweak corrections can be large up to several tens of percent but also strongly dependent on the chosen renormalization scheme[2].

In the MSSM, complete next-to leading order corrections have been calculated for different partial decay widths of the charged Higgs boson [20, 21]. The results of the different decay channels are implemented, for example, in the program `HFOLD` [21]. In the calculations for the predictions implemented in `HFOLD`, a $\overline{\text{DR}}$ renormalization scheme, i.e. the parameters are defined as

[2]A further renormalization scheme for the 2HDM has recently been proposed in Ref. [19]. Both, Ref. [18] and [19] focus on a gauge-independent renormalization prescription.

running parameters, is applied. In order to ensure on-shell properties of the external particles, the pole masses of the external particles have to be calculated from the running parameters. Using both, $\overline{\text{DR}}$ masses for internal and pole masses for external particles can lead to mixing of corrections of different higher orders and problems with the finiteness of the result can occur. Thus, special care has to be taken if this approach is chosen. In the MSSM with complex parameters, the complete one-loop corrections for the decay of the charged Higgs boson into a chargino and a neutralino have been calculated [22]. In this case, a mixed renormalization scheme with on-shell and $\overline{\text{DR}}$ conditions is applied [23, 24, 25, 26]; the mass of the charged Higgs boson is defined as pole mass so that no conversion involving radiative corrections is necessary to obtain the pole mass. The size of the one-loop corrections for the considered partial decay widths can be sizeable of the order of 10% [22].

For the NMSSM, predictions for the decay of the charged Higgs bosons are implemented in the programs `NMHDECAY` [27] and `NMSSMCALC` [28] where the latter program also allows for complex parameters. The predictions of the partial decay widths are based on the program `HDECAY` [29] in both programs and adapted to the NMSSM. A calculation of the complete one-loop corrections including electroweak contributions is still missing. However, definitions of a renormalization scheme [30, 31, 32, 33] which can be applied in the calculation of the partial decay widths of a charged Higgs boson already exist as do the tools for the calculation such as for example the programs `FeynArts` [34, 35] and `FormCalc` [36, 37]. Thus, the framework to perform these calculations is available.

4. Conclusion

In the first part of these proceedings, corrections to the mass of the charged Higgs boson have been discussed. Different models and renormalization schemes have been addressed. Defining the mass of the charged Higgs boson on-shell no radiative corrections have to be calculated since the pole mass is directly related to the tree-level mass of the charged Higgs boson. If other renormalization conditions are applied or the mass of the charged Higgs boson is not a free parameter, radiative corrections have to be taken into account in the calculation of the corresponding pole mass. In the shown MSSM example, the corresponding one-loop and two-loop $\mathcal{O}(\alpha_t \alpha_s)$ corrections amounted up to 4 GeV.

The second part discussed the status of the predictions of the partial decay widths of a charged Higgs boson for decays into two particles. Meanwhile, the complete electroweak one-loop corrections are available for partial decay widths in the 2HDM and the MSSM. The size of these corrections can be sizeable of the order of 10%. The framework is also there to perform the calculations in the NMSSM.

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