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Renormalization of the Complex MSSM in FeynArts/FormCalc

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Abstract

The consistent renormalization of all relevant sectors of the MSSM with complex parameters (cMSSM) and the inclusion in the `FeynArts/FormCalc` package has recently been completed and is reviewed here. A comparison of renormalization schemes in the electroweakino sector, and an automated setup to implement the optimal scheme is also discussed. We show some example calculations applying this framework. These include the partial decay widths of electroweak supersymmetric particles.

Keywords: Beyond Standard Model, Supersymmetry, Renormalization

1. Introduction

Two of the main motivations for the experiments at the Large Hadron Collider (LHC) are the quest to understand the origin of the mechanism of electroweak symmetry breaking (EWSB) and the search for physics beyond the Standard Model (SM). The discovery by ATLAS and CMS [1, 2] of a new scalar with a mass of around 125 GeV opens a new era in particle physics. While the properties of the new scalar are in agreement of those of the SM Higgs boson, the present experimental uncertainties still leave space for deviations from the theoretical predictions of the SM. A precise determination of the new scalar sector, in particular of possible deviations from the SM, is one of the main tasks in the near future.

The extent to which the LHC results can discriminate between a SM Higgs boson and possible alternatives depends both on the experimental precision and on the nature of the mechanism of EWSB realized in nature. One of the best motivated candidates for an extension of the SM is Supersymmetry (SUSY) which solves some of the most severe problems of the SM. In particular, the Minimal Supersymmetric Standard Model (MSSM) [3, 4, 5], with minimal particle content, has been widely studied. The MSSM predicts a Higgs boson with a mass which, at tree level, must be lighter than the Z-boson mass. However, loop corrections are known to give large numerical effects, shifting the upper bound on this Higgs boson to around 135 GeV at the two-loop level [6]. Since the Higgs mass is strongly dependent on the MSSM parameters, which enter at loop-level, radiative corrections must be well under control in order to confront the theoretical predictions with the experimental results of the measurements of a scalar with a mass $m_h = 125.09 \pm 0.24$ [7]. The current theoretical uncertainty in the MSSM, of 3 GeV [6], is an order of magnitude larger than the experimental one, highlighting the need to further improve the theoretical calculations.

Since physics beyond the SM may soon be discovered at the LHC, precise theoretical calculations of all the new measurable observables need to be available. In the MSSM these calculations include a large set of

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masses, cross sections, branching ratios, and angular distributions. The precision will need to be significantly improved to match the more precise measurements at a linear collider (LC) [8].

Loop calculations in the SM with Feynman-diagrammatic methods can lead to a large number of Feynman diagrams. This situation worsens in models such as the MSSM where the number of fields and parameters is larger than in the SM, requiring the automation of the calculations with powerful software packages. This automation needs to be performed in a reasonably general way, allowing for a general choice of parameters. In particular, in the MSSM there are several parameters which can be complex, introducing new sources of CP-violation in the system.

Here we review the renormalization of the cMSSM, i.e. the MSSM with complex parameters, and the corresponding implementation in a model file [9] into the `FeynArts` [10, 11, 12, 13]/`FormCalc` [14] framework. This framework allows for a consistent automated calculation of arbitrary processes at the one-loop level involving external supersymmetric particles. As an example, we discuss in more detail the on-shell renormalization of the electroweak (EW) sector of the cMSSM, addressing the different possibilities to choose the renormalization conditions depending on the chosen parameters. Finally we discuss the application of the new `FeynArts` model file to the evaluation of partial decay widths of the EW SUSY particles [15].

2. Renormalization of the cMSSM

Computing radiative corrections in the cMSSM is much more involved than in the SM for a number of reasons. Supersymmetry imposes relations among parameters which are crucial e.g. for the cancellation of divergences and hence must be preserved by the renormalization scheme. On the technical level, the usual dimensional regularization procedure breaks SUSY, though this can be fixed (at least at one-loop level) by applying dimensional reduction [16]. Then there are more mass scales than free parameters so one needs to choose between the several possible choices of the renormalization conditions, see Sec. 3.

The biggest issue is that several supersymmetric sectors enter at the same time, however. While some calculations in the past have been done restricting oneself to only one sector, as e.g. the self-annihilation of the lightest supersymmetric particle (LSP) or some one-loop partial decay widths, most processes involve different sectors. A relevant example is the evaluation of branching ratios of supersymmetric particles at the one-loop level. In order to obtain a consistent calculation of the total decay width one needs to evaluate all possible decay channels of the corresponding supersymmetric particle. Another example is the calculation of observables at the two-loop level, which requires the sub-loop renormalization of the one-loop diagrams. Consequently, the full renormalization at the one-loop level is necessary in order to evaluate observables, such as the Higgs mass, at the two-loop level.

Most published calculations in the MSSM which need to go beyond tree-level choose a renormalization prescription that is tailored to one specific calculation, and in some cases to one specific part of the (c)MSSM parameter space. However, since the specific values of the SUSY parameters realized in nature are unknown, scans over vast regions of the cMSSM parameter space are necessary. Furthermore, as mentioned before, some observables, e.g. branching ratios, require several processes to be evaluated simultaneously. Both requirements make a *complete renormalization of the cMSSM* that is *valid over large parts of the parameter space* necessary to perform fully automated calculations in the cMSSM. The full one-loop renormalization of all physical sectors of the cMSSM has recently been completed [15, 17, 18, 19, 20, 21, 22, 23] and included as a model file `MSSMCT.mod` [9] in the `FeynArts` package. The renormalization includes the scalar fermion sector, the chargino/neutralino sector, and the Higgs sector, which have been extensively tested in the above mentioned references. These evaluations are complete at the one-loop level, including hard and soft QED and QCD radiation.

The renormalization procedure, fixed by the choice of renormalization conditions, has been developed with the requirement that the one-loop corrections stay "small" over most of the parameter range. This requirement cannot be fulfilled over the whole parameter space with a single choice of renormalization conditions due to the non-trivial relation between input parameters in the (c)MSSM. The solution involves choosing a different set of renormalization schemes (RS) for each region in parameter space. The issue will be discussed in more detail in Sec. 3 for the chargino/neutralino sector.

Details on the full renormalization of the cMSSM can be found in [15, 17, 18, 19, 20, 21, 22, 23]. The renormalization of the chargino/neutralino sector will be discussed in more detail in Sec. 3, where we address problems arising in on-shell renormalization schemes related to the choice of renormalization conditions.

3. The chargino/neutralino sector: RS choice

The chargino/neutralino sector contains two soft SUSY-breaking gaugino mass parameters M_1 and M_2 corresponding to the bino and the wino fields, respectively, as well as the Higgs superfield mixing parameter μ, which, in general, can be complex. Since not all the possible phases of the cMSSM Lagrangian are physical, it is possible (without loss of generality) to choose some parameters real. This applies in particular to one out of the three parameters M_1, M_2, and M_3, the gluino mass parameter. While usually M_2 is chosen real, we do not make such an assumption for the analytical derivation of the renormalization constants. Further details on the chargino/neutralino sector can be found in, e.g., Ref. [15].

The multiplicative renormalization procedure leads to the following replacements of the model parameters and the chargino and neutralino fields, $\tilde{\chi}_i^-$ and $\tilde{\chi}_k^0$, respectively,

$$M_1 \to M_1 + \delta M_1, \tag{1}$$

$$M_2 \to M_2 + \delta M_2, \tag{2}$$

$$\mu \to \mu + \delta\mu, \tag{3}$$

$$\omega_{L(R)}\tilde{\chi}_i^- \to \left[\mathbb{1} + \frac{1}{2}\delta\mathbf{Z}_{\tilde{\chi}^-}^{L(R)}\right]_{ij} \omega_{L(R)}\tilde{\chi}_j^- \,, \tag{4}$$

$$\omega_{L(R)}\tilde{\chi}_k^0 \to \left[\mathbb{1} + \frac{1}{2}\delta\mathbf{Z}_{\tilde{\chi}^0}^{(*)}\right]_{kl} \omega_{L(R)}\tilde{\chi}_l^0 \,, \tag{5}$$

where $\omega_{L(R)}$ denotes the left handed (right handed) projector on the fermion fields, $i, j = 1, 2$, and $k, l = 1, 2, 3, 4$. We do not renormalize the chargino/neutralino diagonalization matrices, which defines the renormalized mass matrix and their counter terms.

Instead of choosing the three parameters M_1, M_2, μ to be independent, we impose on-shell conditions on three out of the six chargino/neutralino masses. The default choice, denoted CCN[1], is to choose the two chargino masses and the smallest neutralino mass on-shell. This ensures that the tree-level and the one-loop chargino masses are equal, avoiding IR divergences in processes with external charginos. These divergences arise in the case that the tree-level and the one-loop chargino masses differ by a finite mass shift due to a renormalization condition different from the on-shell one; the cancellation between the IR divergences from one-loop processes with an internal photon and the corresponding (tree-level) soft-photon-radiation ones is then destroyed.

The on-shell conditions in the CCN[1] scheme fix the on-shell renormalized self-energies $\hat{\Sigma}$ of the charginos and the lightest neutralino

$$\left(\left[\widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{\chi}^-}(p)\right]_{ii}\tilde{\chi}_i^-(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_i^\pm}} = 0 \quad (i = 1, 2)\,, \tag{6}$$

$$\left(\left[\widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{\chi}^0}(p)\right]_{11}\tilde{\chi}_1^0(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_1^0}} = 0\,, \tag{7}$$

where $\widetilde{\mathrm{Re}}$ denotes the real part with respect to the loop integrals, but allowing for complex couplings. This way we are not including the absorptive contributions in the renormalization conditions. It should be noted that, at the one-loop level, absorptive contributions are always finite and do not need to be renormalized. As said above, these conditions are equivalent to setting the renormalized chargino and lightest neutralino masses to their tree-level values. For the remaining three renormalized neutralino masses, however, we distinguish between the tree-level mass $m_{\tilde{\chi}_k^0}$ and the on-shell mass

$$\hat{m}_{\tilde{\chi}_k^0} = m_{\tilde{\chi}_k^0} + \Delta m_{\tilde{\chi}_k^0}, \tag{8}$$

where the finite mass shift is given as a function of the vector and scalar components of the renormalized self-energies,

$$\Delta m_{\tilde{\chi}_i^0} = -\,\mathrm{Re}\left\{\widetilde{\mathrm{Re}}\left[m_{\tilde{\chi}_i^0}\hat{\Sigma}^L_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^{SL}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0})\right]\right\}\,. \tag{9}$$

These mass shifts are of one-loop order and are therefore expected to be small, i.e. of the order of a few GeV, whenever the radiative corrections show a good convergence.

For the further determination of the field renormalization constants one needs to impose the relations

$$\lim_{p^2\to m^2_{\tilde{\chi}_i}}\left(\frac{(\not{p} + m_{\tilde{\chi}_i})\left[\widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{\chi}_i}(p)\right]_{ii}}{p^2 - m^2_{\tilde{\chi}_i}}\tilde{\chi}_i(p)\right) = 0 \qquad , \tag{10}$$

where $\tilde{\chi}_i$ represents both the charginos and the neutralinos, with i running over $1, 2$ and $1, 2, 3, 4$, respectively.

Eqs. (6), (7) and (10) allow to obtain the counterterms δM_1, δM_2 and $\delta\mu$. Explicit expressions can be found in Ref. [15]. Both δM_2 and $\delta\mu$ show a singularity as $|M_2| = |\mu|$. Therefore, for $|M_2| \approx |\mu|$ the counterterms are large, leading to a bad convergence of the one-loop corrections. This will be reflected in large one-loop corrections to all observables with some dependence on the gaugino and higgsino parameters.

The solution involves finding a better combination of the on-shell conditions. It was shown in Refs. [24, 25] that for numerically stable results, one bino-, wino-, higgsino-like particle should be chosen on-shell. In [25] it is argued that the more effective way of achieving this is choosing one higgsino-like neutralino and one

wino-like chargino, in addition to the most bino-like neutralino. The advantage of choosing the higgsino-like neutralino is that, for real parameters, one of the higgsino-like neutralinos will have the opposite CP quantum number than the wino-like neutralino, leading to a small mixing between the two states, even in the region where the wino and higgsino parameters are approximately equal. However, for processes involving external charginos it is convenient to be able to choose their masses as input parameters, as argued before.

In [25] the ideal RS has been obtained comparing the mass shifts in the masses of the neutralinos for special parameter choices. If we want to scan an extensive region of parameter space, however, we will encounter numerical instabilities in the one-loop calculations. Therefore we need to be able to switch between different RS as we change our input parameters. In addition, if we intend to automate the calculations, we need to define conditions which let our code decide how to obtain the ideal RS.

We have computed the counterterms in all RS in the chargino/neutralino system in which one or two neutralino masses are on-shell. We denote with CCN[i] scenarios where both chargino masses and the i-th neutralino mass are on-shell. Choosing the ideal CCN[i] is trivial, since we only need to decide which neutralino has the largest bino component. For one chargino and two neutralino masses on-shell we define the CNN[i, j, k] scenarios, where the indices i, j, k refer to the chargino and neutralino indices, respectively. In order to illustrate the abovementioned problems with the convergence of the radiative corrections we show in Fig. 1 the partial decay widths of the heaviest chargino to the lightest neutralino and a W gauge boson, evaluated at tree-level and full one-loop level in three different schemes, CCN[1] (solid black, dash-double-dotted orange), CNN[2, 1, 3] (dashed black, solid red) and CNN[2, 1, 2] (dotted purple, dash-dotted blue). The input superymmetric parameters are chosen so that μ = 405 GeV, $\tan\beta = 10$, and M_1 is related to M_2 by the GUT relation, which leads to $M_1 \approx M_2/2$. We observe, as expected, a singularity for $M_2 = \mu$ in the one-loop corrections for the CCN[1] scheme. We have not computed the decay for a small region around $M_2 = \mu$. We also do not show the tree result for those parameters, even though they are perfectly well defined. The same singularity appears for the CNN[2, 1, 2] scheme. This is to be expected, due to the strong dependence between the chargino and the neutralino sectors: for a scenario with positive parameters and $M_1 < M_2, \mu$, as in this case, both the second lightest neutralino and the lightest chargino, as well as the heaviest chargino and

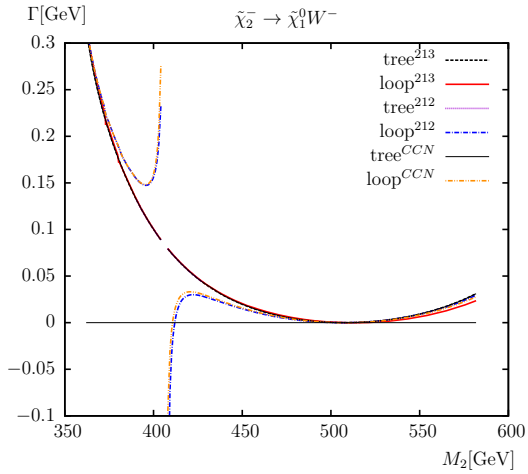

Figure 1: Comparison of renormalization scheme choices for the partial decay widths of $\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-$, for the parameters given in Sec. 3. Here "tree" and "loop" denote, respectively, the tree-level and one-loop calculation, the superscripts 213 and 212 refer to the CNN scenario. The input parameters are given in the text.

neutralino, have a very similar dependence on the input parameters. On the other hand, the CNN[2, 1, 3] is perfectly convergent, which leads to small radiative corrections for $M_2 \approx \mu$. However, for $M_2 \gg \mu$ the corrections in the CNN[2, 1, 3] scheme are larger than in the CNN[2, 1, 2], leading to larger values for δM_2. A scan in M_2 would therefore need to switch between the CNN[2, 1, 3] and CNN[2, 1, 2] schemes, or equivalently between CNN[2, 1, 3] and CCN[1], for $M_2 \approx |\mu| \pm 50$ GeV. This change of RS will result in a change of the one-loop results within the theory uncertainty. Therefore, in addition to finding the ideal scheme one should also find regions where more than one scheme can be applied so that their differences is of higher order, allowing the switching between them.

4. The MSSMCT model file

The model file is the source of all physics information in `FeynArts` [10, 11, 12, 13]. It declares the properties of the fields, their propagators, and their couplings. In the model file the generic parameters of the Lagrangian are used, not a restricted set of input parameters.

There are two versions of the renormalized MSSM model file in `FeynArts`, both of which follow the conventions (for the MSSM at tree-level) of Refs. [4, 26] and are based on the existing MSSM model file included in `FeynArts` [10, 11, 12, 13]. The file `MSSMCT.mod` defines the complete (electroweak and strong) cMSSM

including all counterterms. `SQCDCT.mod` contains only the SQCD part, i.e. the $\alpha_{\rm em} = 0$ limit, which is extracted from `MSSMCT.mod` at load time. Technical details about the model file `MSSMCT.mod` can be found in [9] (see also [27]), where tables describing the names of the fields and their masses with index notation, symbols used for the MSSM parameters, as well as the pre-defined filters are given.

The counterterms have been derived via multiplicative renormalization applied to all two-, three- and four-point interactions in the Lagrangian. Special care has been taken to include counterterms that appear due to particle mixing for vertices that are zero at the tree level, such as the $HZ\gamma$-vertex (which obtains a counterterm contribution from the non-vanishing tree-level HZZ-vertex and one-loop Z–γ mixing). Feynman gauge is used throughout the model file.

Absorptive contributions arise from the product of imaginary parts of complex couplings in a diagram and imaginary parts of the loop functions in wave-function corrections (self-energy insertions on external legs), i.e. in processes with unstable external particles. These corrections are taken into account via wave-function correction factors, denoted $\delta\check{Z}$ (not to be confused with the field renormalization constants δZ introduced by the multiplicative renormalization procedure). The corrections from the absorptive parts can be sizable [15, 19, 20, 28].

Exhaustive checks of the model file have been performed in all sectors of the cMSSM. While the tree-level couplings, given by the original `MSSM.mod` model file [14], have already been extensively tested, the new parts, including counterterm vertices and renormalization constants, have been tested in two ways:

- Numerical and partial analytic checks of UV- and IR-finite parts for decays of neutralinos, charginos, stops, staus, gluinos and Higgs bosons [15, 18, 19, 20, 22, 21, 23]. In Ref. [15] we have compared all electroweak decays of the neutralinos, allowing for complex parameters, with results obtained in the scheme of Ref. [28]. We discuss this comparison in more detail in Sec. 5.

- Comparison of selected reactions in the literature, tuned to adjust the different renormalization prescriptions used. Most of these comparisons have been made in the MSSM with real parameters, given the lack of literature for the complex case. Specifically we have compared with other results in the literature the following processes: $\tilde{b}_{1,2} \to \tilde{t}_1 H^-$, $H \to hh$, $e^+e^- \to t\bar{t}$, $\tilde{\chi}_2^\pm \to \tilde{\chi}_1^0 W^\pm$, and stau decays.

5. Example applications

In Ref. [15] we have compared all electroweak decays of the heaviest neutralino, allowing for complex parameters, with results obtained in the scheme of Ref. [28], called here RSII. We have already introduced our RS in Sec. 3. This RS has been found to be equivalent to [28] for real parameters. In [28] the on-shell conditions are obtained replacing in Eqs. (6), (7) the $\widetilde{\mathrm{Re}}$ for a Re. This implies that, in RSII the phases of the chargino/neutralino fields, and consequently the phases of the parameter counterterms, are defined differently. Therefore, additional conditions are needed in order to ensure that the on-shell propagator has only a scalar and vector part. In RSII the phases of the input parameters are not renormalized. This implies that, here, only conditions for $\delta|M_1|$, $\delta|M_2|$ and $\delta|\mu|$ are obtained. This introduces differences between the two schemes once non-vanishing phases for the complex parameters are allowed. As we will illustrate below, however, these differences have been found to be of small and technically of higher order.

In order to test the one-loop renormalization of the cMSSM in the chargino/neutralino sector we have defined two benchmark scenarios for which most electroweak decays are open. This choice allows to evaluate all these processes simultaneously, a key issue in our project. Both scenarios have the same chargino masses, $m_{\tilde{\chi}_{1,2}^\pm}$, from which the gaugino and higgsino mass parameters, M_2 and μ, are obtained. The two possible solutions for real and positive parameters lead to one scenario in which $\tilde{\chi}_1^\pm$ is gaugino-like, denoted $\mathcal{S}_g$, and another scenario in which $\tilde{\chi}_1^\pm$ is higgsino-like, denoted $\mathcal{S}_h$, thus giving two representative benchmark scenarios of the chargino/neutralino sector. The parameters are

$$\begin{aligned} m_{\tilde{\chi}_1^\pm} &= 350\ \text{GeV}, & m_{\tilde{\chi}_2^\pm} &= 600\ \text{GeV}, \\ M_{H^\pm} &= 160\ \text{GeV}, & \tan\beta &= 20, \\ M_{\tilde{\ell}_L} &= 300\ \text{GeV}, & M_{\tilde{\ell}_R} &= 310\ \text{GeV}, \\ M_{\tilde{q}_L} &= 1100\ \text{GeV}, & M_{\tilde{q}_R} &= 1300\ \text{GeV}, \\ A_\ell &= 400\ \text{GeV}, & A_q &= 2000\ \text{GeV}, \end{aligned} \tag{11}$$

where $M_{H^\pm}$ is the charged Higgs-boson mass, $M_{\tilde{\ell}_L}, M_{\tilde{\ell}_R}$ are the diagonal entries in the slepton mass matrices (universal for the three generations), A_ℓ is the trilinear coupling of the leptonic sector, and $M_{\tilde{q}_L}, M_{\tilde{q}_R}, A_q$ are the corresponding squark parameters. For the bino parameter we chose for simplicity GUT relations, leading to $M_1 \approx M_2/2$.

For each possible two-body decay of the heaviest neutralino we have evaluated the partial decay width at tree-level "tree" and at the full one-loop level "full".

The full result includes the one-loop corrections and, when the final particles are electrically charged, the real (hard and soft) photon radiation. Each process has been evaluated in both renormalization schemes.

In Fig. 2 we show the results for the decay $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_1$ as a function of φ_{M_1}, the phase of M_1. In the upper panel we show the tree-level and full one-loop partial decay widths in scenarios $\mathcal{S}_g$ and $\mathcal{S}_h$ described above. The results in both RS cannot be distinguished from each other. It is worth mentioning that this decay channel is very sensitive to the relative CP phase between the neutralinos and the Higgs boson, leading to a strong p-wave suppression for negative M_1. In the lower panel we show the relative difference $\Delta\Gamma/\Gamma$, defined as the ratio between the one-loop corrections and the tree-level result. Here we can appreciate a small difference between our RS and RSII for $\varphi_{M_1} \neq 0, \pi/2$. This difference, which is to be expected, is of the sub-percent order and is compatible with being of higher order.

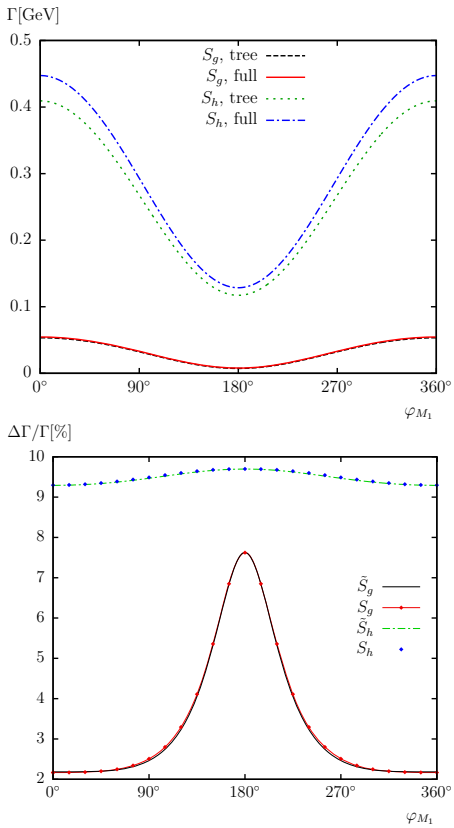

Figure 2: $\Gamma(\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_1)$. Tree-level ("tree") and full one-loop ("full") corrected decay widths are shown with the parameters chosen according to Sec. 5, with φ_{M_1} varied. The upper plot shows the decay width, the lower plot shows the relative size of the corrections. Here $\tilde{\mathcal{S}}_g$ and $\tilde{\mathcal{S}}_h$ refer to the results obtained with the renormalization scheme RSII.

6. Conclusions

The new model file presented in [9] includes the consistent renormalization of all sectors of the cMSSM, not including non-minimal Flavor Violation (FV) effects.

Here we have reviewed the consistent renormalization of all relevant sectors of the cMSSM. We have described in more detail the renormalization of the chargino/neutralino sector, where we have discussed the possible choices of on-shell renormalization scheme conditions and their numerical stability for different regions of parameter space. We have also discussed the inclusion of the renormalization procedure in a `FeynArts`/`FormCalc` package which has recently become publicly available. A comparison of renormalization schemes in the chargino/neutralino sector, and an automated setup to implement the optimal scheme is also discussed. Here we have found both schemes to be equivalent in the limit of real parameters, where we obtain full agreement, while small differences arise when parameters are allowed to become complex. These differences are due to the different treatment of the phases of the renormalized MSSM parameters and are of higher order in perturbation theory. The consistency of these results lead to the conclusion that both RS are equivalent at the one-loop level.

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