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Towards Fully Automated (N)MSSM Calculations

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We review recent progress towards automated (N)MSSM calculations. In the MSSM with complex parameters (cMSSM) a consistent renormalization of all relevant sectors at the one-loop level that can be applied to nearly the full cMSSM parameter space is close to completion. Example calculations for the decay of heavy scalar tops are presented. In the NMSSM, where the technical development is substantially less advanced than in the MSSM, a `FeynArts` model file for all tree-level couplings is reviewed. Example calculations for the NMSSM Higgs production at the LHC with the subsequent decay to two photons are presented. The achieved progress is necessary especially in view of the recently discovered new Higgs-like particle at ~ 125 GeV, which can be interpreted as a Higgs boson in the MSSM or the NMSSM.

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1. Motivation

Two of the most important goals of the experiments at the Large Hadron Collider (LHC) are to identify the origin of electroweak symmetry breaking, and to search for physics effects beyond the Standard Model (SM). The Higgs analyses currently ongoing at the LHC (and previously carried out at the Tevatron) address both those goals. The spectacular discovery of a Higgs-like particle with a mass around $M_H \simeq 125$ GeV, which has been announced by ATLAS and CMS [1, 2], marks a milestone of an effort that has been ongoing for almost half a century and opens a new era of particle physics. Both ATLAS and CMS reported a clear excess around ~ 125 GeV in the two photon channel as well as in the $ZZ^{(*)}$ channel, whereas the analyses in other channels have a lower mass resolution and at present are less significant. The combined sensitivity in each of the experiments reaches about $\sim 5\sigma$. The observed rate in the $\gamma\gamma$ channel turns out to be somewhat above the expectation for a SM Higgs both for ATLAS and CMS. While the statistical significance of this possible deviation from the SM prediction is not sufficient at present to draw a definite conclusion, if confirmed in the future it could be a first indication of a non-SM nature of the new state. The results of the SM Higgs searches at the Tevatron, based on the full dataset collected by CDF and D0 have also just been announced [3], showing a broad excess in the region around $M_H \sim 125$ GeV that reaches a significance of nearly $3\,\sigma$ and would be compatible with a signal at about $M_H \sim 125$ GeV.

The prime task now is clearly to study the properties of the discovered new particle and in particular to test whether the new particle is compatible with the Higgs boson of the SM or whether there are significant deviations from the SM predictions, which would point towards physics beyond the SM. The fact that the observed signal in the $H \to \gamma\gamma$ channel appears to be somewhat stronger than expected in the SM could be a first hint in this direction, although it is statistically not very significant up to now. This result nevertheless serves as a strong motivation for investigating possible alternatives to the SM where a possible signal in the $\gamma\gamma$ channel could be enhanced compared to the SM case.

The extent to which the results of the Higgs searches at the LHC can discriminate between the SM and possible alternatives depends both on the experimental precision with which the properties of a possible signal can be determined and on the detailed nature of the mechanism for electroweak symmetry breaking that is actually realized in nature. One of the leading candidates for physics beyond the SM is supersymmetry (SUSY), which doubles the particle degrees of freedom by predicting two scalar partners for all SM fermions, as well as fermionic partners to all bosons. The most widely studied SUSY framework is the Minimal Supersymmetric Standard Model (MSSM) [4], which keeps the number of new fields and couplings to a minimum. The Higgs sector in particular contains two Higgs doublets, which in the $\mathcal{CP}$ conserving case leads to a physical spectrum consisting of two $\mathcal{CP}$-even, h, H, one $\mathcal{CP}$-odd, A, and two charged Higgs bosons, $H^\pm$.

Going beyond the MSSM, this model has a simple extension in the Next-to-Minimal Supersymmetric Standard Model (NMSSM), see e.g. Ref. [5] for reviews. A particularly appealing motivation for considering the NMSSM is that it provides a solution for naturally associating an adequate scale to the μ parameter appearing in the MSSM superpotential [6, 7]. In the NMSSM, the introduction of a new singlet superfield that only couples to the Higgs sector gives rise to an effective μ-term, generated in a similar way as the Yukawa mass terms of fermions through its

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vacuum expectation value. The new field must be a gauge singlet, since the parameter μ carries no $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{I}} \times U(1)_{\mathrm{Y}}$ quantum numbers. This effective μ-term is linked dynamically to the electroweak scale. The additional degrees of freedom from the singlet add to the NMSSM particle spectrum. In the case where $\mathscr{CP}$ is conserved, the states in the Higgs sector can now be classified as three $\mathscr{CP}$-even Higgs bosons, h_i ($i = 1,2,3$), two $\mathscr{CP}$-odd Higgs bosons, a_j ($j = 1,2$), and the charged Higgs boson pair $H^{\pm}$. In addition, the SUSY partner of the singlet Higgs (called the singlino) extends the neutralino sector (to a total of five neutralinos).

In order to investigate the impact of the Higgs search results at the LHC on possible scenarios of new physics, precise theoretical predictions both within the SM and possible alternatives of it are needed. In particular, if small deviations from the SM predictions are probed it is crucial to treat the considered model of new physics at the same level of precision to enable an accurate analysis and comparison. In the MSSM Higgs sector higher-order contributions are known to give numerically large effects (see, e.g., Refs. [8, 9]), and the same also holds for the NMSSM (see, e.g., Ref. [10]). For many observables it is therefore necessary to include corrections beyond leading order in the perturbative expansion to obtain reliable results. The calculation of loop diagrams, often involving a large number of fields, is a tedious and error-prone task if done by hand. This is true in particular for theories beyond the SM where the number of fields is significantly increased. For one-loop calculations, as will be the focus in the following, computer methods with a high degree of automatization have been devised to simplify the work. However, most of the available tools so far have focused on calculations either in the SM or the MSSM with external SM particles.

Here we review recent progress in the MSSM involving especially the inclusion of the renormalization into the automated frameworks, and in the NMSSM, focusing on the correct inclusion of Feynman rules into the automated frameworks. The general framework considered here is based on the codes `FeynArts` [11, 12] and `FormCalc` [13] (including the `LoopTools` package).

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2. The MSSM

2.1 Progress for renormalization

The tree-level Feynman rules of the MSSM are by now well under control [12]. More recently also the extension to the MSSM with complex parameters (cMSSM) has been completed and is included in the `FeynArts` package. Concerning the renormalization, however, most calculations in the past chose a prescription that was tailored to one specific calculation or even one specific part of the (c)MSSM parameter space. Since the values of the SUSY parameters realized in nature are unknown (*if* SUSY is realized in nature), at the current state scans over large parts of the cMSSM parameter space are necessary. Furthermore, many processes have to be evaluated simultaneously. Both requirements make a *complete* renormalization of the cMSSM necessary that is valid over the *full* (or at least “large parts”) of the cMSSM parameter space. Only with such a renormalization at hand fully automated calculations in the cMSSM will be possible. Evidently, calculations at n-loop require an n-loop renormalization, where we will focus on the one-loop case.

Substantial progress in this direction has been made over the last years[1]. A full one-loop renormalization of the Higgs sector of the cMSSM was presented in Ref. [17]. The corresponding

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[1] For alternative approaches see Refs. [14, 15, 16].

results for Higgs-boson masses and couplings are implemented into the code `FeynHiggs` [18, 19, 20, 17]. First investigations in the scalar fermion sector in the MSSM in our approach were published in Refs. [21, 22], while corresponding results for other sectors of the MSSM can be found in Refs. [23, 24]. More systematic analyses in the cMSSM for the scalar top/bottom sector are given in Refs. [25], where a "preferred scheme" for that sector was suggested.

Eventually the full renormalization of the cMSSM was developed and applied to sample calculations to study the size of one-loop corrections [26, 27, 28, 29, 30]. Particular emphasis was put on the requirement that the one-loop corrections stay "small" over the full allowed parameter range. The renormalization by now includes the scalar fermion sector, the remaining colored sector, the chargino/neutralino sector and the Higgs sector (as well as the SM part of the MSSM). In principle this is sufficient to evaluate all currently relevant processes at the one-loop level. The examples evaluated include scalar top decays [26], scalar tau decays [28], gluino decays [27] as well as non-hadronic chargino [29] and neutralino decays [30]. These evaluations are complete at the one-loop level, including hard and soft QED and QCD radiation.

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2.2 Example of application

In view of the recent discovery of a particle compatible with a SM-like Higgs boson we show a few example results for heavy scalar top decays, evaluated in the above described framework, involving the neutral and the charged Higgs bosons of the MSSM.

The examples, taken from Ref. [26], are shown in two numerical scenarios, S1 and S2, where the parameters are given in Tab. 1. The results shown in this section consist of "tree", which denotes the tree-level value and of "full", which is the partial decay width including *all* one-loop corrections; "abs" also includes the "absorptive contributions", see Ref. [26] for details.

Scen.	$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_2}$	μ	A_t	A_b	M_1	M_2	M_3
S1	20	150	650	$0.4\,m_{\tilde{t}_2}$	$0.7\,m_{\tilde{t}_2}$	200	800	400	200	300	350
S2	20	180	1200	$0.6\,m_{\tilde{t}_2}$	$0.8\,m_{\tilde{t}_2}$	300	1800	1600	150	200	400

Table 1: MSSM parameters for the initial numerical investigation; all masses are in GeV. $\tan\beta$ is the ratio of the two vacuum expectation values, $M_{H^\pm}$ denotes the mass of the charged Higgs boson, $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$ are the stop- and sbottom masses, μ the Higgs mixing parameter, A_t and A_b the trilinear couplings of Higgs bosons to stops and sbottoms, respectively, and M_1, M_2, M_3 are the gaugino soft SUSY-breaking parameters.

The parameters are chosen such that the production of $\tilde{t}_2$ at the ILC(1000), i.e. with $\sqrt{s} =$ 1000 GeV, via $e^+e^- \to \tilde{t}_1^\dagger\tilde{t}_2$ will be possible. The clean environment of the ILC would permit a detailed study of the scalar top decays. For the parameters in Tab. 1 we find $\sigma(e^+e^- \to \tilde{t}_1^\dagger\tilde{t}_2) \approx$ 1.4 fb, i.e. an integrated luminosity of $\sim 1\,\mathrm{ab}^{-1}$ would yield about 1400 $\tilde{t}_2$. The ILC environment would result in an accuracy of the relative branching ratio close to the statistical uncertainty: a BR of 30% could be determined to $\sim$ 6% for the $m_{\tilde{t}_2}$ values in Tab. 1. Depending on the combination of allowed decay channels a determination of the branching ratios at the few per-cent level might be achievable in the high-luminosity running of the ILC(1000).

In Fig. 1 we show the results for the various decay widths as a function of φ_{A_t}. In the figure we show $\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_1)$ (first), $\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_2)$ (second), $\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_3)$ (third) and $\Gamma(\tilde{t}_2 \to \tilde{b}_1 H^+)$ (fourth

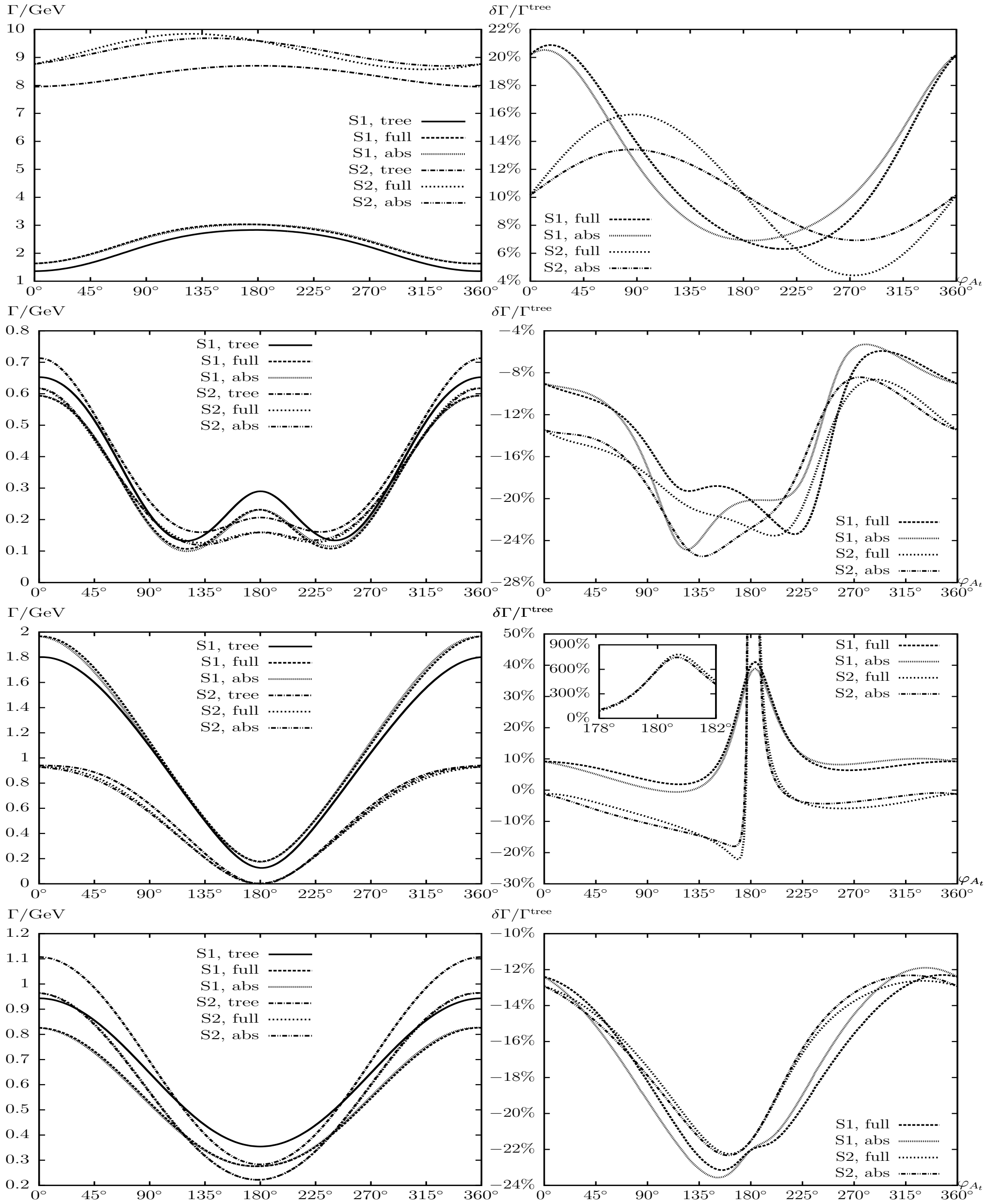

Figure 1: Tree-level ("tree") and full one-loop ("full") corrected partial decay widths are shown with φ_{A_t} varied [26]. Also shown are the full one-loop corrected partial decay widths including absorptive contributions ("abs"). First row: $\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_1)$, second row: $\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_2)$, third row: $\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_3)$, fourth row: $\Gamma(\tilde{t}_2 \to \tilde{b}_1 H^+)$.

row) as a function of φ_{A_t} for the parameters in Tab. 1, where the left (right) column displays the (relative one-loop correction to the) decay width. While $\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_1)$ in S2 is of $\mathcal{O}(9\,\text{GeV})$, the other decay widths shown are of $\mathcal{O}(1\,\text{GeV})$. The variation with φ_{A_t} can be seen to be very large, of $\mathcal{O}(50\%)$. The size of the one-loop corrections, as shown in the right column, is also sizable, of $\mathcal{O}(\pm 20\%)$ and exhibit a strong variation with φ_{A_t}. The effects of the "absorptive contributions" are

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clearly visible, especially for $\tilde{t}_2 \to \tilde{t}_1 h_1$. Consequently, the full one-loop corrections must be taken into account in a reliable predictions of Higgs-boson properties as well as for a determination of the complex phase of A_t from scalar top decays.

3. The NMSSM

3.1 Deriving the tree-level model file

In the NMSSM the available tools are much less developed than in the MSSM. Here we are concerned with the development of the *tree-level* model file for `FeynArts`/`FormCalc`, which is the first step towards fully automated NMSSM calculations (see also Ref. [31]). A few public codes already exist for numerical NMSSM calculations. The by far most widely used is `NMSSMTools` [32], which consists of sub-packages to calculate the NMSSM spectrum, constraints on the parameter space, as well as Higgs decays and decay modes of sparticles [33]. Recently also an extension applicable to the NMSSM of the program `SPheno` [34] became available, which makes use of model implementations generated with `SARAH` [35].

We have implemented, with the help of the programs `SARAH` [35] and (for cross-checks) `FeynRules` [36], the NMSSM as a model file that can be used with the program `FeynArts` [11]. As a check of this framework we have evaluated $\mathcal{O}(50)$ $1 \to 2$ and $\mathcal{O}(100)$ $2 \to 2$ processes in the NMSSM that are induced at the one-loop level and have verified their UV- and IR-finiteness.

3.2 Example of application

Since the NMSSM extends the MSSM in the Higgs and the neutralino sectors, differences to the MSSM are best probed in these two sectors. Here we review results obtained for the Higgs sector of the NMSSM [37]. As a first step processes were investigated that have their first non-vanishing contribution at the one-loop level. The one-loop predictions for those processes therefore correspond to the leading-order contributions, which are IR- and also UV-finite without renormalization (for a recent discussion of the renormalization of the NMSSM Higgs sector, see [31]).

Inspired by the possible indications for an excess above the SM in the $\gamma\gamma$ channel, we review [37] the predictions for an NMSSM Higgs bosons for the production in gluon fusion and the decay into two photons including an analysis of a potential enhancements over the SM prediction. For the latter the quantity

$$R^{h_i}_{\gamma\gamma} = \frac{\sigma(pp \to h_i) \times \mathrm{BR}(h_i \to \gamma\gamma)}{\sigma(pp \to H_{\mathrm{SM}}) \times \mathrm{BR}(H_{\mathrm{SM}} \to \gamma\gamma)} \approx \frac{\Gamma(h_i \to gg) \times \mathrm{BR}(h_i \to \gamma\gamma)}{\Gamma(H_{\mathrm{SM}} \to gg) \times \mathrm{BR}(H_{\mathrm{SM}} \to \gamma\gamma)} \tag{3.1}$$

was evaluated (see Ref. [37] for details) for the parameters as specified in Tab. 2.

The results for $R^{h_1}_{\gamma\gamma}$ and $R^{h_2}_{\gamma\gamma}$ from the scan over the NMSSM parameter space are shown in Fig. 2. Looking first at h_1, the left plot shows that a sizable enhancement over the SM rate is possible over the whole mass range from $m_{h_1} = 80$ GeV to $m_{h_1} = 130$ GeV. For the range of Higgs masses around ~ 125 GeV points with a significant enhancement $R^{h_1}_{\gamma\gamma} \lesssim 2$ are observed. Turning to h_2, shown in the right plot, the results for $R^{h_2}_{\gamma\gamma}$ are similar to those for $R^{h_1}_{\gamma\gamma}$ in the common mass range; the observed maximal enhancement is $R^{h_2}_{\gamma\gamma} \lesssim 2$ for m_{h_2} in the range of $M_{h_2} \sim 125$ GeV.

Comparing the results for $R^{h_i}_{\gamma\gamma}$ to the limits most recent limits from ATLAS (solid red) and CMS (dashed red) [1, 2] (where the 2011 LHC limits are shown in green), it is clearly visible that

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Parameter	Minimum	Maximum	
$A_t = A_b = A_\tau$	$-2\,400$	$2\,400$	GeV
μ_{eff}	150	250	GeV
$M_{H^\pm}$	500	$1\,000$	GeV
$\tan\beta$	2.6	6	
λ	0.5	0.7	
K	0.3	0.5	
A_κ	-100	-5	GeV

Table 2: Parameter ranges used for the scan of $R^{h_i}_{\gamma\gamma}$ in the NMSSM. $\mu_{\text{eff}} = \lambda v_s$, with v_s being the vev of the additional singlet. λ, A_κ and $\kappa = K\lambda$ are new parameters entering in the NMSSM Higgs potential.

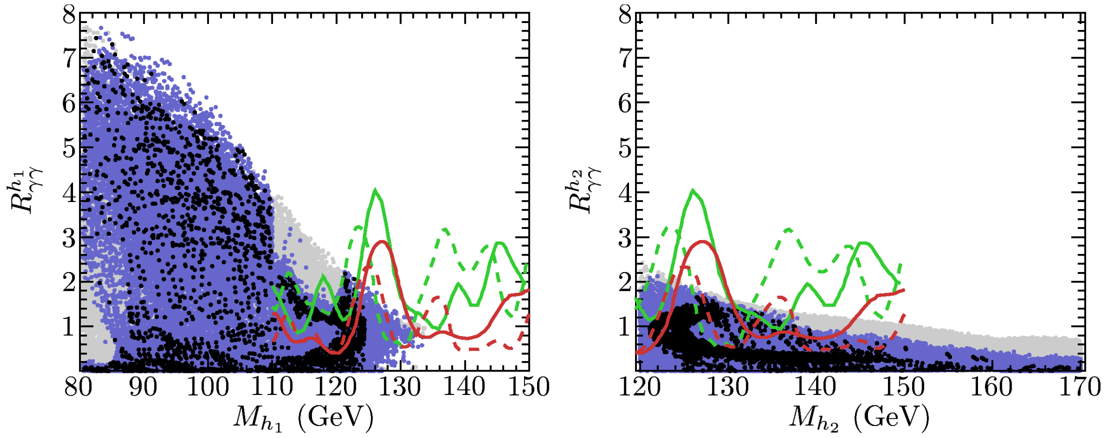

Figure 2: Results from the NMSSM parameter scan on the ratio $R^{h_i}_{\gamma\gamma}$ for the two lightest Higgs bosons h_1 (left) and h_2 (right) [37]. The blue (dark) points satisfy direct Higgs search limits from colliders (from `HiggsBounds` 3.6.1 [38]) while the black points are in agreement with all theoretical and experimental constraints (see Ref. [37]. The green lines show exclusion limits on this channel at 95% CL from 2011 LHC data from ATLAS [39] (solid) and from CMS [40] (dashed). The red lines are the new limits from ATLAS (solid) and CMS (dashed) taken from [1, 2].

the NMSSM can produce points with an enhancement compatible with an excess over the SM rate for Higgs production in the mass region around 125 GeV. The results of Fig. 2 show that such observed excess over the SM rate for Higgs production in the $\gamma\gamma$ channel is well compatible with both h_1 or h_2 production in the NMSSM.

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