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Heavy MSSM Higgs production at the LHC and decays to WW, ZZ at higher orders

P. González??[*] S. Palmer?? M. Wiebusch??[†]
K. Williams??

[a]*Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen, D-52056 Aachen, Germany*

[b]*Institute for Theoretical Physics, Karlsruhe Institute of Technology (KIT), D-76128 Karlsruhe, Germany*

[c]*Institute for Theoretical Particle Physics, Karlsruhe Institute of Technology (KIT), D-76128 Karlsruhe, Germany*

[d]*Department of Physics and Astronomy University of Bonn, Nußallee 12, D-53115 Bonn, Germany*

Abstract

In this paper we discuss the production of a heavy scalar MSSM Higgs boson H and its subsequent decays into pairs of electroweak gauge bosons WW and ZZ. We perform a scan over the relevant MSSM parameters, using constraints from direct Higgs searches and several low-energy observables. We then compare the possible size of the $pp \to H \to WW, ZZ$ cross sections with corresponding Standard Model cross sections. We also include the full MSSM vertex corrections to the $H \to WW, ZZ$ decay and combine them with the Higgs propagator corrections, paying special attention to the IR-divergent contributions. We find that the vertex corrections can be as large as -30% in MSSM parameter space regions which are currently probed by Higgs searches at the LHC. Once the sensitivity of these searches reaches two percent of the SM signal strength the vertex corrections can be numerically as important as the leading order and Higgs self-energy corrections and have to be considered when setting limits on MSSM parameters.

[*]email: gonzalez@physik.rwth-aachen.de
[†]email: martin.wiebusch@kit.edu

1 Introduction

The recent discovery of a 126 GeV resonance decaying into photons and (off-shell) Z bosons at the LHC [? ?] opens a new era in particle physics. The next important task for both theorists and experimentalists is to determine the exact nature of that resonance. Currently the measured signals are in statistical agreement with the expectations from a Standard Model (SM) Higgs boson. However, the experimental sensitivity is not yet sufficient to rule out an extended Higgs sector, especially if the (tree-level) couplings of the additional Higgs bosons to electroweak gauge bosons are suppressed. The discovery of additional scalar resonances would give us important clues about the exact mechanism of electroweak symmetry breaking.

In the minimal supersymmetric SM (MSSM) the tree-level couplings of the neutral Higgs bosons to weak gauge bosons are determined by the Higgs mass scale (either M_A, the mass of the pseudoscalar Higgs boson, or $M_{H^\pm}$, the mass of the charged Higgs boson) and $\tan\beta$, the ratio of the vacuum expectation values of the Higgs doublets. At leading order the masses of the Higgs bosons are also determined by these two parameters. For $M_A \gg M_Z$, the so-called decoupling limit [? ?], the heavy scalar Higgs boson H and the pseudoscalar A are almost degenerate and their (effective) couplings to W and Z bosons are strongly suppressed. This makes the search for heavy MSSM Higgs bosons more difficult than the search for a Standard Model Higgs boson with similar mass. However, it is well-known that the masses and couplings of MSSM Higgs bosons receive large corrections at higher orders in perturbation theory [? ? ? ?]. Also, the production rates for Higgs bosons are modified in the MSSM, especially in the $gg \to H, A$ and $b\bar{b} \to H, A$ production modes.

In [?] the production and decays of a pseudoscalar Higgs into electroweak gauge bosons were discussed in a number of different models, including the MSSM. In this paper we answer the question of how large the LHC signal cross sections for $pp \to H \to WW, ZZ$ can become in the MSSM when higher order corrections to both the production and decay processes are taken into account. For this purpose we perform a scan over the relevant MSSM parameters, using experimental constraints from several low-energy observables and direct Higgs searches at LEP, Tevatron and LHC. We do not assume a specific SUSY breaking scenario, but scan directly over the soft SUSY breaking parameters at the electroweak scale. For this scan we make extensive use of the public codes `HiggsBounds 3.8.0` [? ?] and `FeynHiggs 2.7.4` [? ? ? ? ? ? ?].

The Higgs–gauge-boson couplings are implemented in `FeynHiggs` in the *improved Born-approximation*, i.e. taking into account higher order corrections from Higgs self-energies but no genuine vertex corrections. The MSSM vertex corrections for both the WW and ZZ final state were calculated in [?], although for the WW final state only fermion and sfermion contributions were considered. For our analysis we performed an independent calculation of all one-loop vertex corrections and found agreement with [?]. We then extended the analysis of the $H \to WW$ case to the complete MSSM corrections, including the IR divergent contributions and the corresponding real emission graphs. Our scan shows that the vertex corrections typically lie between -10% and -30% in MSSM parameter space regions where the $H \to WW, ZZ$ channels should still be observable at the LHC.

The case of off-shell decays of the light MSSM Higgs-boson h was discussed in [**?**], where a calculation of the process $h \to W^*W^*, Z^*Z^* \to 4f$ (four fermions) was presented. In this paper we examine the possibility of calculating the single off-shell processes $H \to WW^* \to Wff'$ and $H \to ZZ^* \to Wff'$ process in an effective coupling approximation, i.e. by re-scaling the corresponding SM decay rates. Such an approximation can be useful in parameter scans or fits, where off-shell decays of the heavy MSSM Higgs boson may be of interest, but a numerical integration of the full four-particle phase space is not feasible. We discuss the quality of the approximation and address the issue of infrared divergences in this approach.

In Section **??** we introduce our notation and explain the combination of the vertex corrections with the self-energy corrections calculated by `FeynHiggs`. In Section **??** we give the details of the parameter scan and discuss the experimental constraints that were used in it. The numerical results of the scan and the quality of the effective coupling approximation are discussed in Section **??**. Our conclusions are given in Section **??**.

2 Details of the calculation

2.1 Notation and conventions

In the MSSM, the Higgs sector contains two scalar doublets, which give five physical Higgs bosons. At lowest order, the Higgs sector is $\mathcal{CP}$-conserving, containing two charged Higgs bosons, $H^\pm$, two neutral $\mathcal{CP}$-even Higgs bosons, h and H, and the $\mathcal{CP}$-odd Higgs A. Two independent parameters characterise the Higgs sector, normally taken as M_A and $\tan\beta$, where $\tan\beta$ is the ratio of the vacuum expectation values of the Higgs doublets. Higher order corrections lead to large corrections to the Higgs masses and mixing angle α, and can induce $\mathcal{CP}$-violation and mixing between the three neutral Higgs bosons h, H and A [**? ? ?**] if complex SUSY-breaking parameters are allowed.[1]

2.2 Higgs propagator corrections

Higgs propagator corrections can be extremely important numerically, especially in the non-decoupling regions of the SUSY parameter space, and are in addition needed in order to ensure correct on-shell properties of S-matrix elements involving external Higgs

[1] In the case of $\mathcal{CP}$-violation, it is usual to take $M_{H^\pm}$ as input parameter instead of M_A because, in the $\mathcal{CP}$-violating case the pseudoscalar Higgs boson A mixes with the $\mathcal{CP}$-even neutral Higgs bosons.

bosons – i.e. unit residue and vanishing mixing between different Higgs bosons on mass shell. These corrections can be included by using finite wave function normalisation factors. In the case where these factors are applied to a tree level decay amplitude we speak of an *improved Born approximation*. In the following, quantities computed in this approximation are denoted with a subscript 'imp.B'. An amplitude $\mathcal{A}_{H,\text{imp.B}}$ in the improved Born approximation with an external Higgs boson H can receive corrections from three tree-level amplitudes $\mathcal{A}_{h,\text{tree}}$, $\mathcal{A}_{H,\text{tree}}$ and $\mathcal{A}_{A,\text{tree}}$ involving the three neutral Higgs states:

$$\mathcal{A}_{H,\text{imp.B}} = \mathbf{Z}_{Hh}\mathcal{A}_{h,\text{tree}} + \mathbf{Z}_{HH}\mathcal{A}_{H,\text{tree}} + \mathbf{Z}_{HA}\mathcal{A}_{A,\text{tree}} \tag{1}$$

The matrix $\mathbf{Z}$ has been defined in Ref. [? ?] and is non-unitary. When no $\mathcal{CP}$-violation is present mixing occurs only between the $\mathcal{CP}$-even states, but when complex parameters are allowed mixing between all three neutral states needs to be considered.[2] The program `FeynHiggs 2.7.4` [? ? ? ? ? ? ?] has been used to calculate both the corrected Higgs boson masses and the wave function normalisation $\mathbf{Z}$-factors. `FeynHiggs` includes the complete one-loop corrections as well as the dominant two-loop contributions in the MSSM with real and complex parameters.

Since the Higgs propagator corrections are universal, they can in principle be applied to the loop diagrams as well as the tree-level diagrams. Denoting the one-loop vertex corrections to the decay amplitudes of the tree-level mass eigenstates h, H and A as $\Delta\mathcal{A}_h$, $\Delta\mathcal{A}_H$ and $\Delta\mathcal{A}_A$, respectively, we define the *improved vertex corrections* for the physical mass eigenstate as

$$\Delta\mathcal{A}_{\text{imp}} = \mathbf{Z}_{Hh}\Delta\mathcal{A}_h + \mathbf{Z}_{HH}\Delta\mathcal{A}_H + \mathbf{Z}_{HA}\Delta\mathcal{A}_A \quad . \tag{2}$$

When computing interferences between the tree-level and one-loop vertex diagrams, improved versions can be used for neither, the tree-level or both of the factors. This provides an easy method of including (potentially large) higher-order corrections in our calculations. In the $\mathcal{CP}$-violating case, applying the propagator corrections at loop level could give rise to interesting effects as it allows the $\mathcal{CP}$-odd Higgs boson, A (which of course does not couple to the gauge bosons at tree level), to be taken into account.

In any case, applying the Higgs propagator corrections means that we are mixing perturbative orders and could potentially miss cancellations found at higher orders. However, estimations of the uncertainties from unknown higher order corrections (see [? ? ?]) indicate that the $\mathbf{Z}$-factors do indeed give rise to a leading contribution which is not expected to be numerically compensated by the remaining 2-loop pieces. Since the effect of applying the Higgs propagator corrections at loop level is significant (as we shall show), we choose to follow this method.

[2] For the $H \to VV$ decays considered in this paper, $\mathcal{A}_A^{\text{tree}}$ is of course zero.

2.3 Comparing the SM and MSSM

In this paper we are interested in MSSM scenarios that lead to relatively large $pp \to H \to VV$ signals ($VV = WW, ZZ$). Hence, we define the ratios

$$R_{VV} = \frac{\sigma_H^{\rm MSSM} \cdot {\rm BR}(H \to VV)^{\rm MSSM}}{\sigma_H^{\rm SM} \cdot {\rm BR}(H \to VV)^{\rm SM}} = \frac{\sigma_H^{\rm MSSM}}{\sigma_H^{\rm SM}} \cdot \frac{\Gamma_H^{\rm SM}}{\Gamma_H^{\rm MSSM}} \cdot \rho_{VV} \quad ,$$
$$\rho_{VV} = \frac{\Gamma(H \to VV)^{\rm MSSM}}{\Gamma(H \to VV)^{\rm SM}} \quad . \tag{3}$$

where σ_H denotes the LHC production cross section for the Higgs H, ${\rm BR}(H \to VV)$ and $\Gamma(H \to VV)$ are the branching ratio and partial decay width into vector bosons V ($V = W, Z$) and Γ_H is the total decay width of the Higgs boson H. The superscript 'MSSM' indicates that the corresponding quantity is evaluated in the MSSM, with H being the heavy scalar MSSM Higgs boson. The superscript 'SM' means that the quantity is evaluated in the SM, with H being a SM Higgs boson with the same mass as the heavy MSSM Higgs boson. At leading order the ratios R_{VV} and ρ_{VV} are the same for $V = W$ and $V = Z$, since the ratio between the Standard Model and MSSM couplings is the same for both HWW and HZZ. From the definitions of Eq. (**??**) it is obvious that the $pp \to H \to VV$ cross sections and $H \to VV$ partial widths within the MSSM can be obtained by scaling the corresponding SM quantities with R_{VV} or ρ_{VV}.

If the Higgs mass M_H is below the VV threshold the Higgs boson H may still decay into Vff' (with f and f' being light fermions) via an off-shell vector boson V^*. If new-physics contributions to the Vff' vertex and non-factorisable contributions are neglected, the corresponding ratios of partial widths or cross sections times branching ratios do not depend on the fermions f and f'. For off-shell decays we therefore define $R_{Vff'}$ and $\rho_{Vff'}$ as ratios of differential cross sections and partial widths:

$$\rho_{Vff'}(M_{ff'}) = \frac{\partial\Gamma(H \to VV^* \to Vff')^{\rm MSSM}/\partial M_{ff'}}{\partial\Gamma(H \to VV^* \to Vff')^{\rm SM}/\partial M_{ff'}}$$
$$R_{Vff'}(M_{ff'}) = \frac{\sigma_H^{\rm MSSM}}{\sigma_H^{\rm SM}} \cdot \frac{\Gamma_H^{\rm SM}}{\Gamma_H^{\rm MSSM}} \cdot \rho_{Vff'}(M_{ff'}) \quad , \tag{4}$$

where $M_{ff'}$ denotes the invariant mass of the ff' pair. *Differential* $pp \to H \to Vff'$ cross sections time branching ratios and *differential* $H \to Vff'$ partial widths within the MSSM may thus be obtained by scaling the corresponding SM quantities with $R_{Vff'}$ and $\rho_{Vff'}$. Usually, $\rho_{Vff'}$ is only weakly dependent on $M_{ff'}$. We may then approximate $\rho_{Vff'}(M_{ff'})$ as a constant,

$$\rho_{Vff'}(M_{ff'}) \approx \rho_{Vff'}(M_H - M_V) \equiv \rho_{Vff'} \quad , \tag{5}$$

and calculate *integrated* MSSM cross sections and partial widths by scaling corresponding SM quantities with the appropriate factors. This approximation is what we call the *effective coupling approximation*, since higher order corrections to the HVV vertex have been absorbed into an effective coupling constant.

The principle behind this effective coupling approximation is the same as that used by the Higgs Cross Section Working Group when working in the MSSM. In order to include all known higher order corrections (some of which are known only in the SM, not the MSSM), the Working Group takes SM 'building blocks' and dresses them with the appropriate MSSM coupling factors, as described in [**?**].

2.4 Higher-order corrections and form factors

We can incorporate the corrections to the HVV vertex by calculating an effective HVV coupling resulting from the loop and counterterm diagrams. The structure of this coupling for on-shell particles is [**? ? ?**]

$$T^{\mu\nu}(q_1, q_2) = A(q_1, q_2) g^{\mu\nu} + B(q_1, q_2) q_1^\mu q_2^\nu + C(q_1, q_2) \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma} \quad . \tag{6}$$

Here, q_1 and q_2 are the momenta of the electroweak gauge bosons, and A, B and C are Lorentz invariant form factors. For off-shell particles, the coupling can have a more complicated structure, but if the gauge bosons decay into massless fermions the only relevant form factors are A, B and C. At tree level, only the formfactor A has a non-zero value in both the SM and the MSSM:

$$A^{\mathrm{SM}}_{H_{\mathrm{SM}}WW} = \frac{i\, e M_W}{\sin\theta_W} \quad , \quad A^{\mathrm{SM}}_{H_{\mathrm{SM}}ZZ} = \frac{i\, e M_W}{\sin\theta_W \cos^2\theta_W} \tag{7}$$

$$A^{\mathrm{MSSM}}_{hVV} = A^{\mathrm{SM}}_{H_{\mathrm{SM}}VV} \sin(\beta-\alpha) \quad , \quad A^{\mathrm{MSSM}}_{HVV} = A^{\mathrm{SM}}_{H_{\mathrm{SM}}VV} \cos(\beta-\alpha) \quad , VV = WW, ZZ \tag{8}$$

At lowest order the MSSM formfactor A representing the coupling of the light $\mathcal{CP}$-even Higgs boson differs from the SM value of A by a factor of $\sin(\beta-\alpha)$, which tends to 1 in the decoupling regime, i.e. for $M_A \gg M_Z$. Higher order diagrams, however, lead to different contributions to A in the Standard Model and MSSM, and can result in non-zero values for B and C.

For the calculation of the form factors we employ a mixed renormalisation scheme where the electroweak sector is renormalised on-shell [**?**], while the Higgs sector is renormalised using a hybrid scheme where the Higgs fields are renormalised in the $\overline{DR}$ scheme and M_A is renormalised on-shell, as described in [**?**]. We parameterise our results in terms of $\alpha(M_Z)$ and calculate the charge renormalisation constant accordingly – i.e.

$$\delta Z_e \to \delta Z_e - \frac{1}{2}\Delta\alpha \tag{9}$$

For Higgs bosons inside loops we use the physical masses and the unitary Higgs mixing matrix calculated by `FeynHiggs`, as described in [**?**].