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Higgs-boson production through gluon fusion in the 2HDM with electroweak corrections

Laura Jenniches, Christian Sturm*
Universität Würzburg, Institut für Theoretische Physik und Astrophysik,
Lehrstuhl für Theoretische Physik II, Campus Hubland Nord,
Emil-Hilb-Weg 22, 97074 Würzburg, Germany
E-mail: Laura.Jenniches@physik.uni-wuerzburg.de,
Christian.Sturm@physik.uni-wuerzburg.de

Sandro Uccirati
Università di Torino e INFN, 10125 Torino, Italy
E-mail: uccirati@to.infn.it

We discuss the computation of the next-to-leading order electroweak corrections to Higgs-boson production through gluon fusion in the Two-Higgs-Doublet Model. In particular, we focus on the production of a neutral, scalar Higgs boson. We provide results in different renormalization schemes. Our results can also be used in order to describe the corresponding electroweak corrections of the Higgs-boson decay into two gluons at next-to-leading order.

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1. Introduction

After the discovery of a Higgs boson [1, 2] at the Large Hadron Collider (LHC), the precise determination of its properties, both in theory and experiment, is now of central interest. Especially the question of whether the discovered Higgs boson is just the Standard Model (SM) Higgs boson or whether it is part of a more general theory is subject of very active research. Among such extensions of the SM, theories with additional Higgs bosons are of particular interest. Such extensions address open questions of particle physics. They can, for example, contribute to answer the question of the origin of the matter–anti-matter asymmetry in the Universe or the nature of dark matter. In the following, we consider the Two-Higgs-Doublet Model (2HDM), which is already being studied by the ATLAS [3, 4, 5] and CMS [6, 7, 8] collaborations at the LHC. As a result of this, precise theoretical predictions are necessary.

Within this work, we solely focus on the dominant Higgs-boson production mechanism which proceeds via gluon fusion. In particular, we will concentrate on the production of the light and heavy neutral, scalar Higgs boson. The observed Higgs boson can be interpreted as the light, neutral, scalar Higgs boson of this extended Higgs sector. For the gluon fusion process, we study the effect of the 2HDM extension on the Higgs boson production in the context of the calculation of the electroweak (EW) corrections.

In the SM, EW corrections to Higgs-boson production in gluon fusion are known at next-to-leading order (NLO). The light fermion contributions to the SM EW corrections have been calculated in Refs. [9, 10]. The leading EW correction due to a heavy quark at order $\mathscr{O}(G_F m_t^2)$ has been determined in Refs. [11, 12]. Heavy mass expansions of the diagrams which involve the top quark are known from Ref. [13] and, finally, the complete EW corrections have been computed in Refs. [14, 15]. In the SM they amount to 5.2% [14, 15] for the recent value of the top-quark mass of $m_t = 173.1$ GeV [16].

EW corrections to extensions of the SM can be large. For example, in a model with a sequential fourth generation of heavy fermions, the calculation of the EW corrections to Higgs-boson production [17, 18, 12, 11] helped to exclude this model at the LHC.

In the 2HDM, the renormalization of the new parameters as well as the application of the different schemes for the determination of NLO EW corrections to Higgs-boson production and decay processes has been studied in Refs. [19, 20, 21, 22, 23, 24, 25].

2. The model

The two scalar doublets Φ_i $(i = 1, 2)$ of the 2HDM obey the generalized Higgs potential

$$\begin{aligned} V(\Phi_1,\Phi_2) =&\; m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) \\ &+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) \\ &+ \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right], \end{aligned} \tag{2.1}$$

which has five dimensionless couplings λ_i $(i = 1, \ldots, 5)$ and three parameters m_1, m_2 and m_{12}, which have a mass dimension. We consider all parameters to be real, which assures a CP conserving version of the potential.

In order to arrive at the mass eigenstates of the physical Higgs bosons, one has to diagonalize the scalar sector by two rotation matrices with two mixing angles α and β. In the 2HDM, one has a light and a heavy neutral, scalar Higgs boson, H_l and H_h, a pseudoscalar Higgs boson, H_a, and two charged Higgs bosons, $H^{\pm}$. As free parameters, one has in addition to the two mixing angles α and β the masses of the new Higgs bosons as well as the soft-breaking scale M_{sb}. The latter is related to the parameter m_{12} of the Higgs potential in Eq. (2.1). For convenience we use $\cos(\alpha-\beta) \equiv c_{\alpha\beta}$ and $\tan\beta \equiv t_\beta$ as free parameters instead of the mixing angles α and β. In the so called alignment limit ($c_{\alpha\beta} = 0$) the light Higgs boson H_l has SM-like couplings to fermions and gauge bosons. The decoupling limit is defined by the alignment limit with all heavy new mass scales taken to be much larger than the EW scale.

Considering the production of a scalar, neutral Higgs boson in the 2HDM through gluon fusion, the leading order (LO) process $gg \to H_l$ or H_h is already a one-loop diagram (Fig. 1).

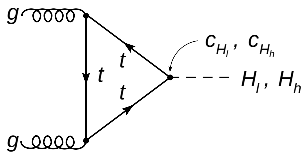

Figure 1: LO Higgs-boson production through gluon (g) fusion mediated through a top-quark (t) loop.

Compared to the corresponding SM Higgs-boson production process, only the coupling of the Higgs boson to fermions is modified in Fig. 1 by a factor $c_{H_l} = c_{\alpha\beta}/t_\beta - s_{\alpha\beta}$ for the production of the light Higgs boson H_l and by a factor $c_{H_h} = s_{\alpha\beta}/t_\beta - c_{\alpha\beta}$ for the production of a heavy Higgs boson H_h. These factors are sensitive to the precise value of the mixing angles α and β. Depending on their value, these angles can decrease or increase the Higgs-boson production cross section compared to the SM process.

The computation of the two-loop EW corrections is involved. For that purpose, we define the NLO EW percentage correction $\delta_{\mathrm{EW}}^{\mathrm{NLO}}$ with respect to the LO cross section $\hat{\sigma}^{\mathrm{LO}}$ by

$$\hat{\sigma}^{\mathrm{NLO}} = \hat{\sigma}^{\mathrm{LO}}(1+\delta_{\mathrm{EW}}^{\mathrm{NLO}}), \tag{2.2}$$

where we replace the superscript NLO by the name of the renormalization scheme of the mixing angles which we use in the following.

3. Calculation and results

We generate the amplitudes for our two-loop diagrams with `QGRAF` [26] and the Feynman rules with `FeynRules` [27]. The output of both programs is then processed by `QGS`, an extension of `GraphShot (GS)` [28], which was used for the corresponding SM calculations. `QGS` is a `FORM` [29, 30] based program which performs all necessary algebraic manipulations of the amplitude. The amplitude is integrated numerically using in-house Fortran routines based on extensions of the techniques described in Ref. [15].

For the renormalization of the mixing angles we use different schemes. In order to perform a gauge-independent and consistent $\overline{\mathrm{MS}}$ renormalization of the mixing angles (and the soft-breaking scale M_{sb}) the FJ tadpole scheme [31] has been extended to arbitrary theories with spontaneous symmetry breaking and in particular to the 2HDM [21], which allows for a proper treatment of the Higgs-tadpole contributions. For an application of the FJ tadpole scheme in the 2HDM see also Ref. [20]. The percentage correction of Eq. (2.2) becomes dependent on the renormalization scale μ for an $\overline{\mathrm{MS}}$ renormalization of the mixing angles. The scale dependent part for the process $gg \to H_l$ in the alignment limit ($c_{\alpha\beta} = 0$) reads [21]

$$\delta_{\mathrm{EW}}^{\overline{\mathrm{MS}},\mu-\mathrm{dep.}} = \frac{G_F\sqrt{2}}{8\pi^2 t_\beta^2 M_{H_h}^2 (M_{H_h}^2 - M_{H_l}^2)} \Big\{ 6m_t^2(M_{H_h}^2 M_{H_l}^2 - 4M_{sb}^2 m_t^2) + (1-t_\beta^2)(M_{H_h}^2 - M_{sb}^2)\Big[3M_{H_h}^2 M_{H_l}^2 + M_{sb}^2(M_{H_a}^2 + 2M_{H^\pm}^2 - 3M_{H_h}^2)\Big]\Big\} \ln\frac{\mu^2}{M_{H_l}^2}, \quad (3.1)$$

where M_{H_l}, M_{H_h}, M_{H_a}, $M_{H^\pm}$ are the masses of the Higgs bosons, m_t is the on-shell top-quark mass and G_F is the Fermi-coupling constant. Depending on the values of t_β and the mass parameters, the coefficient of the scale dependent logarithm can become large or small, which can lead to a large or a small scale dependence. We name the corresponding complete percentage correction $\delta_{\mathrm{EW}}^{\overline{\mathrm{MS}}}$. For the central value of the renormalization scale μ_0, we choose the average of all Higgs-boson masses and the soft-breaking scale, if it is different from zero; cf. Ref. [21] for a different choice of μ_0.

Next to the scale-dependent $\overline{\mathrm{MS}}$ renormalization of the mixing angles, we also present results for scale-independent schemes, where we evaluate either two-point functions of the scalar mixing self-energies or a physical process at particular values of the external momenta in order to impose a renormalization condition. In the 2HDM, scale- and gauge-independent schemes which rely on the pinch technique or the background-field method have been introduced in Refs. [20, 24]. Scale independence of the rotation matrices arises for two different choices of the momentum of the two-point functions, i.e. on-shell and for the particular value of the external momentum p^* [32, 33]. We denote the corresponding percentage corrections in the following with $\delta_{\mathrm{EW}}^{\mathrm{OS}}$ and $\delta_{\mathrm{EW}}^{p^*}$, respectively.

Finally, we also study a process dependent renormalization of the mixing angles by requiring that the purely NLO weak corrections to the partial decay width of the two processes $H_h \to \tau^+\tau^-$

BP	$\delta_{\mathrm{EW}}^{\mathrm{OS}}$	$\delta_{\mathrm{EW}}^{p^*}$	$\delta_{\mathrm{EW}}^{\mathrm{proc}}$	$\delta_{\mathrm{EW}}^{\overline{\mathrm{MS}}}$
2_{1A}	5.3	6.3	10.1	-0.6 ∓ 9.8
2_{1B}	3.8	4.8	4.5	-7.0 ∓ 10.0
2_{1C}	4.3	4.4	9.9	12.7 ∓ 0.6
2_{1D}	2.9	3.5	4.1	14.5 ∓ 0.6
3_{A1}	4.1	4.0	4.5	11.8 ∓ 8.1

BP	$\delta_{\mathrm{EW}}^{\mathrm{OS}}$	$\delta_{\mathrm{EW}}^{p^*}$	$\delta_{\mathrm{EW}}^{\mathrm{proc}}$	$\delta_{\mathrm{EW}}^{\overline{\mathrm{MS}}}$
2_{2A}	1.7	1.8	1.5	0.6 ± 0.0
3_{B1}	3.9	3.8	3.9	7.2 ∓ 4.0
3_{B2}	3.7	3.7	3.5	-8.3 ± 0.4
4_3	4.3	4.3	3.8	12.6 ∓ 2.1
4_4	4.4	4.4	3.8	10.3 ± 0.4
4_5	3.6	3.6	2.6	4.5 ± 10.0
a-1	4.4	4.7	4.8	-3.8 ∓ 25.4
b-1	4.8	4.5	5.4	-0.5 ∓ 6.2

Table 1: Percentage EW correction for the process $gg \to H_l$ for different BPs for different renormalizations of the mixing angles of the 2HDM. For the $\overline{\mathrm{MS}}$ result, the lower (upper) sign of the uncertainty corresponds to decreasing (increasing) the central renormalization scale μ_0 to $\mu_0/2$ ($2\mu_0$). No running of the $\overline{\mathrm{MS}}$ renormalized parameters is taken into account.

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and $H_a \to \tau^+\tau^-$ are equal to the LO result [20]. The corresponding percentage corrections in this scheme will be called $\delta_{\rm EW}^{\rm proc}$.

The LHC Higgs cross section working group (LHCHXSWG) has collected several benchmark points (BPs) [34]. For their precise values we refer to Ref. [34]. In the following, we consider selected BPs of the LHCHXSWG as well as two BPs (a-1, b-1) from Ref. [35]. In Tab. 1 we summarize the results for the NLO EW percentage corrections of the process $gg \to H_l$ for the individual BPs in the different renormalization schemes. In general, the corrections are of moderate size and comparable to the correction in the SM. In addition, for the results of the production of a heavy Higgs-boson through the process $gg \to H_h$, we refer to [36]. Here, depending on the individual BPs, the corrections can become very large.

In Fig. 2, we study the dependence of the percentage correction on the heavy Higgs-boson mass M_{H_h} for the process $gg \to H_l$ in the alignment limit ($c_{\alpha\beta} = 0$). All other new, mass-scale dependent parameters have been set to 700 GeV and $t_\beta = 2$. The percentage correction is shown for different renormalization schemes and compared to the SM result.

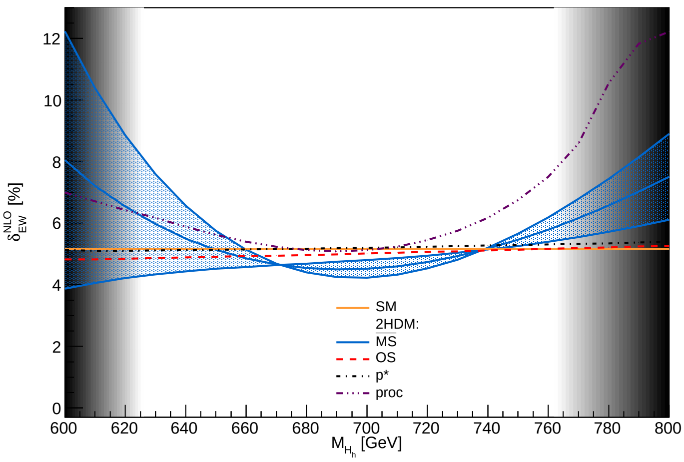

Figure 2: The percentage correction as a function of the heavy Higgs-boson mass is shown. The M_{H_h} independent result of the SM is given by the yellow, solid, horizontal line. All other lines correspond to results for the 2HDM in different schemes. The blue shaded band is the result for the $\overline{\rm MS}$ renormalization of the mixing angles, where the renormalization scale has been varied between $\mu_0/2$ and $2\mu_0$. No running of the $\overline{\rm MS}$ renormalized parameters is taken into account.

The grey shaded band shows the region where at least one of the parameters $\lambda_i/(4\pi)$ of Eq. (2.1) becomes larger than 0.5. There, one slowly starts to enter the non-perturbative regime.

4. Summary and conclusion

We have discussed the computation of the two-loop EW corrections to neutral, scalar Higgs-boson production through gluon fusion in the 2HDM. We can determine the EW percentage corrections for essentially any scenario of the new Higgs-boson masses, the soft-breaking scale and the mixing angles. In particular, we have computed the EW percentage corrections for benchmark

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points collected by the LHC Higgs cross section working group. We provide our results in different renormalization schemes, which allows to assess the theory uncertainty due to unknown higher order corrections. The size of the EW correction for the production of a light Higgs boson through gluon fusion for the different benchmark points is of moderate size and mainly comparable to the one in the SM. The results will be valuable for experimental studies of the 2HDM at the LHC. Our results can also be directly applied to the corresponding partial Higgs-boson decay widths into two gluons.

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References

[1] ATLAS collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett.* **B716** (2012) 1–29, [1207.7214].

[2] CMS collaboration, S. Chatrchyan et al., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett.* **B716** (2012) 30–61, [1207.7235].

[3] ATLAS collaboration, G. Aad et al., *Constraints on new phenomena via Higgs boson couplings and invisible decays with the ATLAS detector*, *JHEP* **11** (2015) 206, [1509.00672].

[4] C. T. Potter, *ATLAS Searches for Beyond the Standard Model Higgs Bosons*, in *Meeting of the APS Division of Particles and Fields (DPF 2013) Santa Cruz, California, USA, August 13-17, 2013*, 2013, 1310.0515, https://inspirehep.net/record/1256470/files/arXiv:1310.0515.pdf.

[5] ATLAS collaboration, *Search for Higgs bosons in Two-Higgs-Doublet models in the $H \to WW \to e\nu\mu\nu$ channel with the ATLAS detector*, ATLAS-CONF-2013-027.

[6] CMS collaboration, V. Khachatryan et al., *Search for neutral resonances decaying into a Z boson and a pair of b jets or τ leptons*, *Phys. Lett.* **B759** (2016) 369–394, [1603.02991].

[7] CMS collaboration, V. Khachatryan et al., *Search for a low-mass pseudoscalar Higgs boson produced in association with a $b\bar{b}$ pair in pp collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett.* **B758** (2016) 296–320, [1511.03610].

[8] CMS collaboration, V. Khachatryan et al., *Searches for heavy Higgs bosons in two-Higgs-doublet models and for tch decay using multilepton and diphoton final states in pp collisions at 8 TeV*, *Phys. Rev.* **D90** (2014) 112013, [1410.2751].

[9] U. Aglietti, R. Bonciani, G. Degrassi and A. Vicini, *Two loop light fermion contribution to Higgs production and decays*, *Phys. Lett.* **B595** (2004) 432–441, [hep-ph/0404071].

[10] U. Aglietti, R. Bonciani, G. Degrassi and A. Vicini, *Master integrals for the two-loop light fermion contributions to $gg \to H$ and $H \to \gamma\gamma$*, *Phys. Lett.* **B600** (2004) 57–64, [hep-ph/0407162].

[11] A. Djouadi, P. Gambino and B. A. Kniehl, *Two loop electroweak heavy fermion corrections to Higgs boson production and decay*, *Nucl. Phys.* **B523** (1998) 17–39, [hep-ph/9712330].

[12] A. Djouadi and P. Gambino, *Leading electroweak correction to Higgs boson production at proton colliders*, *Phys. Rev. Lett.* **73** (1994) 2528–2531, [hep-ph/9406432].

[13] G. Degrassi and F. Maltoni, *Two-loop electroweak corrections to Higgs production at hadron colliders*, *Phys. Lett.* **B600** (2004) 255–260, [hep-ph/0407249].

[14] S. Actis, G. Passarino, C. Sturm and S. Uccirati, *NLO Electroweak Corrections to Higgs Boson Production at Hadron Colliders*, *Phys. Lett.* **B670** (2008) 12–17, [0809.1301].

[15] S. Actis, G. Passarino, C. Sturm and S. Uccirati, *NNLO Computational Techniques: The Cases $H \to \gamma\gamma$ and $H \to gg$*, *Nucl. Phys.* **B811** (2009) 182–273, [0809.3667].

[16] Particle Data Group collaboration, C. Patrignani et al., *Review of Particle Physics*, *Chin. Phys.* **C40** (2016) 100001.

[17] G. Passarino, C. Sturm and S. Uccirati, *Complete Electroweak Corrections to Higgs production in a Standard Model with four generations at the LHC*, *Phys. Lett.* **B706** (2011) 195–199, [1108.2025].

[18] A. Denner, S. Dittmaier, A. Mück, G. Passarino, M. Spira, C. Sturm et al., *Higgs Production and Decay with a Fourth Standard-Model-Like Fermion Generation*, *Eur. Phys. J.* **C72** (2012) 1992, [1111.6395].

[19] S. Kanemura, M. Kikuchi and K. Yagyu, *Fingerprinting the extended Higgs sector using one-loop corrected Higgs boson couplings and future precision measurements*, *Nucl. Phys.* **B896** (2015) 80–137, [1502.07716].

[20] M. Krause, R. Lorenz, M. Mühlleitner, R. Santos and H. Ziesche, *Gauge-independent Renormalization of the 2-Higgs-Doublet Model*, *JHEP* **09** (2016) 143, [1605.04853].

[21] A. Denner, L. Jenniches, J.-N. Lang and C. Sturm, *Gauge-independent $\overline{MS}$ renormalization in the 2HDM*, *JHEP* **09** (2016) 115, [1607.07352].

[22] M. Krause, M. Mühlleitner, R. Santos and H. Ziesche, *Higgs-to-Higgs boson decays in a 2HDM at next-to-leading order*, *Phys. Rev.* **D95** (2017) 075019, [1609.04185].

[23] L. Altenkamp, S. Dittmaier and H. Rzehak, *Renormalization schemes for the Two-Higgs-Doublet Model and applications to $h \to WW/ZZ \to 4$ fermions*, *JHEP* **09** (2017) 134, [1704.02645].

[24] A. Denner, J.-N. Lang and S. Uccirati, *NLO electroweak corrections in extended Higgs Sectors with* RECOLA2, *JHEP* **07** (2017) 087, [1705.06053].

[25] L. Altenkamp, S. Dittmaier and H. Rzehak, *Precision calculations for $h \to WW/ZZ \to 4$ fermions in the Two-Higgs-Doublet Model with* PROPHECY4F, 1710.07598.

[26] P. Nogueira, *Automatic Feynman graph generation*, *J. Comput. Phys.* **105** (1993) 279–289.

[27] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr and B. Fuks, FeynRules 2.0 *- A complete toolbox for tree-level phenomenology*, *Comput. Phys. Commun.* **185** (2014) 2250–2300, [1310.1921].

[28] S. Actis, A. Ferroglia, G. Passarino, M. Passera, C. Sturm and S. Uccirati, GraphShot *a* Form *package for automatic generation and manipulation of one- and two-loop Feynman diagrams*, *unpublished* .

[29] J. A. M. Vermaseren, *New features of* FORM, math-ph/0010025.

[30] J. Kuipers, T. Ueda, J. A. M. Vermaseren and J. Vollinga, FORM *version 4.0*, *Comput. Phys. Commun.* **184** (2013) 1453–1467, [1203.6543].

[31] J. Fleischer and F. Jegerlehner, *Radiative Corrections to Higgs Decays in the Extended Weinberg-Salam Model*, *Phys. Rev.* **D23** (1981) 2001–2026.

[32] J. R. Espinosa and I. Navarro, *Scale independent mixing angles*, *Phys. Rev.* **D66** (2002) 016004, [hep-ph/0109126].

[33] J. R. Espinosa and Y. Yamada, *Scale independent and gauge independent mixing angles for scalar particles*, *Phys. Rev.* **D67** (2003) 036003, [hep-ph/0207351].

[34] LHC Higgs Cross Section Working Group collaboration, D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, 1610.07922.

[35] J. Baglio, O. Eberhardt, U. Nierste and M. Wiebusch, *Benchmarks for Higgs Pair Production and Heavy Higgs boson Searches in the Two-Higgs-Doublet Model of Type II*, *Phys. Rev.* **D90** (2014) 015008, [1403.1264].

[36] L. Jenniches, C. Sturm and S. Uccirati, *Electroweak corrections to Higgs-boson production through gluon fusion in the 2HDM*, *in preparation*.