HIGLU and HDECAY: Programs for Higgs Boson Production at the LHC and Higgs Boson Decay Widths

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Abstract

The total cross section for Higgs boson production via the dominant gluon fusion mechanism including NLO [two-loop] QCD corrections can be calculated numerically with the program HIGLU. The QCD corrections are included for arbitrary Higgs and quark masses and increase the cross section at the LHC by up to a factor of 2. The source code HIGLU provides the evaluation of the production of the Standard Model [SM] Higgs boson as well as the neutral Higgs bosons of the minimal supersymmetric extension [MSSM].

The program HDECAY determines the decay widths and branching ratios of the Higgs bosons within the SM and the MSSM, including the dominant higher-order corrections. The latter are dominated by QCD corrections and two-loop corrections to the couplings and Higgs masses of the MSSM. The program includes all decay modes with branching ratios larger than $10^{-4}$. Moreover, below-threshold decays with off-shell top quarks, gauge and Higgs bosons are implemented. In addition the program is able to calculate the branching ratios of the MSSM Higgs bosons into supersymmetric particles, which can be dominant.

*Talk given at the AIHENP’96 Workshop, Lausanne, September 1996.
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1. Introduction

At the future CERN hadron collider, the LHC, the Higgs boson will be produced primarily via the gluon fusion mechanism for the entire relevant Higgs mass range within the Standard Model [SM] as well as its minimal supersymmetric extension [MSSM]. The two-loop QCD corrections to the production cross sections of scalar [CP-even] as well as pseudoscalar [CP-odd] Higgs bosons have been calculated in [3] for heavy squarks. The QCD corrections are significant for the theoretical prediction of the cross sections leading to an increase by up to a factor of 2 compared with the lowest-order results. Recently, the leading part of the pure QCD corrections to the squark loop contributions to MSSM Higgs boson production have also been evaluated by means of low-energy theorems in the limit of heavy gluinos [4]. The squark loops are sizeable for squark masses below $\sim 400$ GeV. The corrections are of the same magnitude as the corrections to the quark loops so that the $K$ factors are only slightly changed by the inclusion of the squark loops.

The program HIGLU provides the calculation of the total Higgs production cross sections including next-to-leading order QCD corrections to the heavy quark loops. Various input parameters can be chosen from an input file, including a flag specifying

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the model. Possible options are the Standard Model, its minimal supersymmetric extension, and a general Higgs model by initializing the Higgs Yukawa couplings appropriately. The program includes the contribution of the top and bottom quarks in the loops that generate the Higgs couplings to gluons. Within the Standard Model, as well as in most of the parameter space of the MSSM, these contributions provide an excellent approximation for all practical cases. Moreover, the program allows the calculation of the decay widths of Higgs bosons into gluons including next-to-leading order QCD corrections. The gluonic decay mode plays a significant rôle in the intermediate mass range at future $e^+e^-$ colliders.

The search for Higgs bosons at the LHC mainly proceeds via looking for $ZZ$, $W^+W^-$ and $\gamma\gamma$ final states as decay products of the SM Higgs particle and in addition for Higgs boson pairs in the case of the MSSM Higgs bosons. Thus it is of vital importance to have reliable predictions for the branching ratios of the Higgs bosons in both models. These are determined by the program HDECAY including all relevant higher-order corrections, which are dominated by QCD corrections and the two-loop corrections to the MSSM Higgs masses and couplings arising from the large top mass. HDECAY calculates all decay modes with branching ratio larger than $10^{-4}$ and includes below-threshold decays involving off-shell top quarks, gauge and Higgs bosons in the final states. Moreover, all decay modes of the MSSM Higgs bosons into SUSY particles are contained in the program, which can be dominant for Higgs masses below the $t\bar{t}$-threshold.

The source codes of the programs are written in FORTRAN. They have been tested on computers running under different operating systems. The numerical phase space integration of HIGLU is performed by using the VEGAS package for integrals of dimension up to 3. Parton distributions can be attached to HIGLU in any desirable way by adjusting the corresponding subroutine. As standard parametrization, the program contains the GRV sets.

2. Processes

2.1. $pp \to \Phi^0 + X$

The hadron cross section of Higgs boson production via gluon fusion $gg \to \Phi^0$ ($\Phi^0 = \mathcal{H}, A$) including [two-loop] QCD corrections, can be cast into the form

$$\sigma(pp \to \Phi^0 + X) = \sigma_{LO} + \Delta\sigma_{\text{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{\bar{q}q}. \quad (1)$$

The lowest-order cross sections $\sigma_{LO}^\Phi$ can be found in Refs. The term $\Delta\sigma_{\text{virt}}$ parametrizes the infrared regularized virtual two-loop corrections and the terms $\Delta\sigma_{ij}^\Phi$ ($i, j = g, q, \bar{q}$) the individual collinear regularized real one-loop corrections.

$^b$The scalar [CP-even] Higgs particles will generically be denoted by $\mathcal{H}$, the pseudoscalar [CP-odd] by $A$ and all the neutral Higgs bosons by $\Phi^0$. The MSSM Higgs particles, including the charged ones, will be denoted by $\Phi$. 

2
corresponding to the subprocesses

\[ gg \rightarrow \Phi^0 g, \quad gq \rightarrow \Phi^0 q, \quad q\bar{q} \rightarrow \Phi^0 g. \]

Their expressions can be found in Refs. 3–5.

The calculation of the [two-loop] virtual corrections requires the evaluation of massive two-loop three-point functions depending on one free parameter, the ratio of the Higgs and heavy quark masses. The five-dimensional Feynman integrals have been analytically reduced to one-dimensional integrals; they are numerically integrated by an adaptive Romberg integration. The regularization of UV, IR and collinear divergences is performed in \( n = 4 - 2\epsilon \) dimensions. The UV singularities are absorbed in the strong coupling \( \alpha_s \) and the on-shell quark mass \( m_Q \). The infrared singularities of the virtual corrections cancel against the corresponding singularities of the real corrections of the subprocesses given in Eq. (2). The left-over collinear poles are mapped into the renormalized NLO parton densities. The renormalization and factorization schemes have been chosen as the \( \overline{\text{MS}} \) scheme.

The program HIGLU calculates the five terms in Eq. (3) contributing to the total cross section separately, as well as their sum, for all kinds of neutral Higgs bosons \( \Phi^0 \).

### 2.2. \( \Phi^0 \rightarrow gg \)

The decay widths of Higgs bosons \( \Phi^0 \) into gluons up to next-to-leading order are given by

\[
\Gamma(\Phi^0 \rightarrow gg(g), gqq) = \Gamma_{LO}(\Phi^0 \rightarrow gg) \left[ 1 + E_{\Phi^0} \frac{\alpha_s}{\pi} \right]
\]

\[
E_{\Phi^0} = E_{\Phi^0_{\text{virt}}} + E_{\Phi^0_{ggg}} + N_F E_{\Phi^0_{gq\bar{q}}},
\]

The coefficient \( E_{\Phi^0_{\text{virt}}} \) denotes the infrared-regularized virtual two-loop corrections, \( E_{\Phi^0_{ggg}} \) and \( E_{\Phi^0_{gq\bar{q}}} \) the infrared and collinear regularized real one-loop corrections. The analytical formulae of these contributions can be obtained from the gluon fusion process by crossing and are given in Refs. 3, 4, 13. The parameter \( N_F \) fixes the number of light external flavors produced in the decay \( \Phi^0 \rightarrow gq\bar{q} \), which has to be identified with the number of flavors contributing to the QCD \( \beta \) function in order to map large logarithms into the running strong coupling \( \alpha_s(\mu^2) \). This issue is important, if bottom and charm quarks will not be included as external flavors in the gluonic decay mode, but added to the \( b\bar{b} \) and \( c\bar{c} \) decay channels: in order to avoid large logarithms in the perturbative expansion, the strong coupling has to be evolved with three light flavors instead of five at scales above the heavy-quark thresholds. The program HIGLU evaluates this decay mode, including the full mass dependence. The program HDECAY on the other hand only contains the leading part in the heavy-quark mass limit, which is a reliable approximation in all relevant cases. The gluonic branching ratios reach values of about 10–20% in the intermediate mass ranges and are thus significant for phenomenological analyses.
2.3. $\Phi^0 \rightarrow Qar{Q}$, $H^+ \rightarrow Uar{D}$

The expressions for decay widths of Higgs bosons into heavy-quark pairs can be found in Ref. 14. In order to absorb large logarithms in the limit $M_\Phi \gg m_Q$, one has to introduce the running $\overline{MS}$ mass for the heavy quarks in the final states, which has to be evaluated at the scale of the corresponding Higgs boson mass $M_\phi$. This definition leads to a well-behaved perturbative expansion in the case of charm and bottom quarks above the thresholds. The running $\overline{MS}$ mass is calculated from the value of the pole mass by means of the relation given in Ref. 15. A flag is provided for the choice of the NLO or NNLO formula of this relation, which is important in particular for the charm-quark mass, because of a bad convergence of the perturbative expansion at scales of the order of the charm mass. The $\overline{MS}$ mass characterizes the preferred input parameter, because it can be obtained directly from fits to QCD sum rules.

In the limit $M_\Phi \gg m_Q$ the QCD corrections are known up to NNLO. At the threshold, mass effects are important. Thus we have included the full massive NLO QCD corrections in the program HDECAY, which are smoothly interpolated with the NNLO expressions in the large-Higgs mass range. The QCD corrections reduce the decay widths significantly. Electroweak corrections are small and hence neglected in the program. The $b\bar{b}$ decay mode dominates in the intermediate neutral Higgs mass range, if decays into SUSY particles are kinematically forbidden, except for the heavy scalar MSSM Higgs particle $H$ for small $\tan \beta$. The decays into $c\bar{c}$ and $\tau^+\tau^-$ pairs can reach branching ratios of about 10%. Above threshold the $t\bar{t}$ decay modes are dominating in the MSSM. Charged MSSM Higgs bosons predominantly decay into $\tau\nu$ and $tb$ pairs, if SUSY particle decays are impossible. For top quarks in the final states, HDECAY also takes into account below-threshold decays into off-shell top quarks, which are smoothly interpolated with the on-shell regime.

2.4. $\Phi^0 \rightarrow \gamma\gamma$

The photonic decay widths of the neutral Higgs particles are built-up by charged-particle loop contributions from fermions and $W$ bosons in the SM and in addition from charged Higgs particles, charginos and sfermions in the MSSM. The expressions can be found in Ref. 3. The QCD corrections are moderate and thus neglected in the program HDECAY. The photonic branching ratios reach values of about $10^{-3}$. These decay modes are important for the Higgs search at the LHC.

2.5. $\mathcal{H} \rightarrow WW, ZZ$

The expressions for the scalar decay widths into $W$ and $Z$ boson pairs can be found in Ref. 19. They are the dominant decay modes of the SM Higgs boson for Higgs masses $M_\mathcal{H} \gtrsim 140$ GeV. In the MSSM they are only important for small $\tan \beta$. The program HDECAY includes below-threshold decays into off-shell $W$ and $Z$ bosons, which are interpolated with the expressions of the on-shell range.
Electroweak corrections are small in the relevant Higgs mass ranges and neglected in HDECAY.

2.6. Decays into Higgs particles

The decay widths of the MSSM Higgs bosons into lighter Higgs particles are given in Ref. The decay mode $H \rightarrow hh$ is dominant below the $t\bar{t}$-threshold for small $\tan\beta$. In parts of the mass ranges, the decay modes $A \rightarrow Zh$ and $H^{\pm} \rightarrow W^{\pm} h$ are dominating. HDECAY also includes below-threshold decays into off-shell $Z$ and Higgs bosons and interpolates these contributions with the on-shell regime. The dominant corrections are contained in the two-loop-corrected MSSM couplings.

2.7. Decays into SUSY particles

The partial decay widths into neutralinos, charginos and sfermions are given in Ref. Their branching ratios can amount up to about 100% below the top threshold for small $\tan\beta$ and remain significant above. HDECAY evaluates all these partial decay widths within the MSSM, in which they are completely fixed by two MSSM parameters, $\mu$ and $M_2$.

3. Input and Ouput

All masses, couplings and MSSM parameters can be defined in separate input files for both programs HIGLU and HDECAY. Moreover, there are a few flags to allow a choice of the kind of process, and of the conventions for the parameters involved in the different processes. Thus the two programs provide a very flexible and convenient usage, fitting to all options of phenomenological relevance.

The program HIGLU writes all chosen input parameters as well as the results obtained by VEGAS integrations including the individual parts of the QCD corrections to the file unit 99.

HDECAY produces many output files containing the results for the Higgs branching ratios and total decay widths in table format. These can easily be read by other FORTRAN programs, which need the values for the Higgs branching ratios and decay widths.

Acknowledgements

I would like to thank A. Djouadi, P.M. Zerwas, J. Kalinowski and D. Graudenz for their fruitful collaboration. Special thanks go to A. Djouadi for a critical reading of the manuscript and useful discussions.

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