Abstract

A numerical program for the evaluation of the inclusive cross section for associated Higgs production with a massive weak gauge boson at hadron colliders is described, $\sigma(pp/p\bar{p} \rightarrow HV)$, $V \in \{W, Z\}$. The calculation is performed in the framework of the Standard Model and includes next-to-next-to-leading order QCD as well as next-to-leading order electro-weak effects.

Keywords: Higgs production; hadron collider; higher orders

PROGRAM SUMMARY

Program Title: vh@nnlo
Distribution format: tar.gz
Programming language: Fortran 77, C++.
Computer: Personal computer.
Operating system: Unix/Linux, Mac OS.
RAM: A few 100 MB.
External routines/libraries: LHAPDF (http://lhapdf.hepforge.org/), CUBA (http://www.feynarts.de/cuba/)
Nature of problem:
Calculation of the inclusive total cross section for associated Higgs- and $W$- or $Z$-boson production at hadron colliders through next-to-next-to-leading order QCD.
Solution method:
Numerical Monte Carlo integration.
Running time:
A few seconds for a single set of parameters.

1The program is available from
http://particle.uni-wuppertal.de/harlander/software/vh@nnlo
1. Introduction

The associated production of a Higgs ($H$) and a weak gauge boson ($V \in \{W, Z\}$), or “Higgs Strahlung” for short, has already proven to be an important process at hadron colliders (see, e.g., Refs. [1, 2, 3]). In the Standard Model (SM), the leading order (LO) amplitude is given by the Feynman diagram shown in Fig. 1(a). We count it as order $g^4$, where $g$ is the weak gauge coupling. Through next-to-leading order (NLO) QCD, $O(g^4\alpha_s)$, it can be represented as the convolution of the production of a virtual gauge boson $V^*$ with the decay rate of $V^*$ into the on-shell gauge boson $V$ and the Higgs boson $H$, schematically: $\sigma_{VH} = \sigma_{V^*} \otimes \Gamma_{V^*\rightarrow VH}$. The precise formula will be given below.

The bulk of the next-to-next-to-leading order (NNLO) QCD corrections, $O(g^4\alpha_s^2)$, is given by the same formula and will be referred to as DY (for “Drell-Yan like”) terms in the following.
Figure 3: A $\mathcal{O}(g^3\lambda_t\alpha_s^2)$ contributions only present for $ZH$ production. Diagram (c) gives rise to the $q\bar{q} \rightarrow ZHg$, $qg \rightarrow ZHq$, and $\bar{q}g \rightarrow ZH\bar{q}$ processes.

Figure 4: Typical diagram for the $ggHZ$ contribution.
At $\mathcal{O}(\alpha_s^2)$, there are contributions to the cross section which cannot be derived from the Drell-Yan process as before. One such class is given by diagrams where the Higgs boson is radiated off a virtual top-quark loop which is inserted either in a real or a virtual gluon line. Sample diagrams are shown in Fig. 2. Apart from that, for $ZH$ production, both the $Z$ and the $H$ can couple to the top-quark loop; examples are shown in Fig. 3. All these diagrams enter the total cross section at $\mathcal{O}(g^3\lambda_t\alpha_s^2)$ through the interference with the LO amplitudes shown in Fig. 1. Although these are not the only contributions induced by top-quark loops, we will refer specifically to these $\mathcal{O}(g^3\lambda_t\alpha_s^2)$ terms as the “top” terms.

For $ZH$ production, yet another top-quark induced contribution enters at $\mathcal{O}(\alpha_s^2)$. Sample diagrams are shown in Fig. 4. They differ from the previous ones in that they contain two initial state gluons. Since this does not occur at lower orders in $\alpha_s$, it is the square of the corresponding amplitude that enters the cross section, rather than the interference with lower order terms. It will be referred to as the “$ggHZ$” contribution in what follows. Note that there are also DY diagrams with $gg$ initial state, but they belong to the double real emission terms (e.g. $gg \rightarrow VHq\bar{q}$), while the $ggHZ$ contribution is a purely virtual correction. In our counting of coupling constants, it enters the cross section at $\mathcal{O}(g^2\lambda_t^2\alpha_s^2)$.

The NLO QCD corrections have been known for a long time [4]. The DY NNLO corrections, based on the NNLO results for the actual Drell-Yan process [5, 6] and including the $ggHZ$ terms [7], were first presented in Ref. [8]. The top effects were subsequently evaluated in Ref. [9]. For a Higgs mass of $M_H = 125$ GeV, inclusion of the NLO corrections enhances the total inclusive cross section for $WH$ production by about 31% (27%, 41%) at the LHC8 (LHC14, Tevatron); the effect of the NNLO DY terms is an additional 3% (3%, 10%), and the top effects amount to about 1% in all three cases. For $ZH$ production, these numbers are very similar; the additional $ggHZ$ component amounts to about 5% (9%, 0.2%).

These numbers show that the numerical effect of the NNLO DY corrections is rather small; however, including them significantly reduces the theoretical uncertainty due to scale variations [8], in particular for the $WH$ process. For $ZH$ production, on the other hand, the fact that the $ggHZ$ terms are separately finite, gauge independent, and proportional to $\alpha_s^2(\mu)$ introduces an additional and significant amount of theory uncertainty (see also Refs. [10, 11]).

Currently, the program $vh@nnlo$ includes the DY, the top, and the $ggHZ$
contributions at $\mathcal{O}(\alpha_s^2)$. Electro-weak corrections to the Higgs Strahlung process are of the order of 5% and thus larger than the QCD scale uncertainty \[12, 13\]. Since they do not depend on any of the QCD parameters like PDFs or the strong coupling, we included them in $\text{vh@nnlo}$ in the form of a correction factor by linearly interpolating the numbers given in Ref.\[14\].

Note that $\text{vh@nnlo}$ only evaluates the total inclusive cross section; kinematical distributions, for example in the Higgs’ transverse momentum or rapidity cannot be calculated with this program. We refer the reader to Refs. \[15, 16, 17\] (and references therein) for that purpose.

2. Description of the program

2.1. Structure

This section describes the internal structure of $\text{vh@nnlo}$.

2.1.1. DY terms

The core of the program consists of the Fortran 77 code $\text{zwprod}$ by W. van Neerven which is publicly available from Ref. \[18\]. It evaluates the production of an off-shell weak gauge boson $V^*$ of invariant mass $q^2$ through NNLO QCD by implementing the results for the partonic cross section $\hat{\sigma}_{V^*\alpha\beta}$ for the process $\alpha\beta \rightarrow V^* + X$ ($\alpha, \beta \in \{q, \bar{q}, g\}$) of Refs. \[5, 6\] and integrating them over the parton density functions $\phi_{\alpha/p}$:

$$
\sigma_{pp'}^{V^*}(q^2, s) \equiv \frac{1}{s} \sum_{\alpha, \beta \in \{q, \bar{q}, g\}} \int_{q^2}^{s} d\hat{s} \cdot \hat{\sigma}_{V^*\alpha\beta}(q^2, \hat{s}, \mu_F) \\
\times \left[ \frac{\phi_{\alpha/p}(\hat{s}/s, \mu_F) \phi_{\beta/p'}(\hat{s}/\hat{s}, \mu_F)}{1 + \delta_{\alpha\beta}} \right], \quad p' \in \{p, \bar{p}\}.
$$

The DY terms of the inclusive total cross section for $VH$ production are then obtained by folding this expression with the decay rate of the off-shell vector boson $d\Gamma$:

$$
\sigma_{pp'}^{DY}(s, M_H^2, M_V^2) = \int_{(M_H+M_V)^2}^{s} dq^2 \cdot \sigma_{pp'}^{V^*}(q^2, s) \frac{d\Gamma(M_H^2, M_V^2; q^2)}{dq^2},
$$

where

$$
\frac{d\Gamma(M_H^2, M_V^2; q^2)}{dq^2} = GFM_V^4 \frac{\lambda^{1/2}(M_V^2, M_H^2; q^2)}{2\sqrt{2}\pi^2} \left( 1 + \frac{\lambda(M_V^2, M_H^2; q^2)}{M_V^2/q^2} \right),
$$
and
\[ \lambda(x, y, z) \equiv \left( 1 - \frac{x}{z} - \frac{y}{z} \right)^2 - 4 \frac{xy}{z}. \] (4)

In vh@nnlo, the program zwprod is modified in such a way that it performs the three integrations of Eq. (1) and (2) simultaneously using the Vegas algorithm \cite{19} as implemented in the CUBA library \cite{20}.

For the PDFs, vh@nnlo links the LHAPDF library \cite{21} which allows one to switch between different PDF sets conveniently. Neither LHAPDF nor CUBA are part of the distribution of vh@nnlo; they have to be installed separately.

2.1.2. \textsl{ggHZ terms}

The \textsl{ggHZ} terms of order \( O(g^2 \lambda^2 \alpha_s^2) \) are calculated by a routine that was generated with the help of FeynArts \cite{22}. Due to the top-quark loop, one arrives at massive box integrals that are evaluated using a slightly modified version of the LoopTools/FF library \cite{23, 24} which is included in the distribution of vh@nnlo. For the PDFs, again LHAPDF \cite{21} is used.

2.1.3. \textsl{top terms}

The \textsl{top} contributions of order \( O(g^3 \lambda \alpha_s^2) \) are evaluated by a C++ routine. The calculation is based on the heavy-top limit which was shown to work well within the overall available accuracy \cite{9}. Folding the partonic differential cross section with the PDFs and integrating it over the phase space requires a three (six) dimensional numerical integration for the virtual (real) contribution, which is again performed using LHAPDF and the CUBA implementation of VEGAS.

2.1.4. \textsl{Electro-weak corrections}

As already mentioned above, electro-weak corrections are implemented in the form of a two-dimensional grid spanning over the values \( M_H \in [80, 200] \) GeV in steps of 5 GeV, \( M_H \in [200, 300] \) GeV in steps of 10 GeV, and \( \sqrt{s} \in \{7, 8, 9, 10, 14\} \) TeV. The correction factor is very flat; at intermediate values it is therefore obtained by linear interpolation.
2.1.5. Total cross section

In summary, the individual orders of the inclusive Higgs Strahlung cross section are calculated as follows:

\[
\begin{align*}
\sigma_{\text{LO}} &= (1 + \delta_{\text{EW}})\sigma_{\text{LO}}^{\text{DY}}, \\
\sigma_{\text{NLO}} &= (1 + \delta_{\text{EW}})\sigma_{\text{NLO}}^{\text{DY}}, \\
\sigma_{\text{NNLO}} &= (1 + \delta_{\text{EW}})\sigma_{\text{NNLO}}^{\text{DY}} + \sigma^{\text{ggHZ}} + \sigma^{\text{top}},
\end{align*}
\]

(5)

where \(\delta_{\text{EW}}\) denotes the electro-weak correction factor.

2.2. Installation and compilation

2.2.1. Installation

Unpacking the tar ball will create the following directory structure:

```
vh@nnlo/
infiles/
mainfiles/
manual/
output/
source/
x/
```

\textit{vh@nnlo}: this will also be referred to as the root directory of \textit{vh@nnlo}. It contains the file \texttt{README} which briefly describes the most important topics for installation, compilation, and operation of the program \textit{vh@nnlo}.

\textit{source}: contains both the sources of \textit{vh@nnlo}, as well as the main \texttt{Makefile} and a very simple compilation script named \texttt{vh@nnlo\_install}.

\textit{x}: should be empty upon first installation. It will contain the executable once \textit{vh@nnlo} is compiled.

\textit{output}: a directory to store output files.

\textit{infiles}: a directory to store input files.

\textit{manual}: contains this manual.

\textit{mainfiles}: a directory to store the main program. Currently, it contains only the file \texttt{main.f}.
2.2.2. Compilation

Before compiling, it might be necessary to adjust some of the library paths in source/Makefile.

Full compilation is most easily done by saying

./vh@nnlo_install

in the directory source. This will compile the LoopTools/FF library, and the ggHZ, DY, and top components of the calculation. The main executable x.main will be copied to the directory x and should be called from the root directory of vh@nnlo.

Sometimes it is obvious that the ggHZ component does not contribute to the cross section. This is true for WH production, for example, or if only the NLO result is needed. In that case, one may work with only a subset of the code and exclude, for example, the LoopTools/FF library from the compilation. Instead of running the installation script, one may then simply say

make GGHZ=no

in the source directory.

2.3. Operation

2.3.1. Input

vh@nnlo is controlled by a single input file. An example named in.init is included in the distribution in the directory infiles. It is structured like an SLHA input file [25], but is not SLHA compatible (it uses its own Blocks, for example). The content of in.init as contained in the distribution is:
Block REAL
1  8.000000D+03 # sqrt(s) [GeV]
2  125.0000D+00 # mh [GeV]
3  0.100000D+01 # muR/q
4  0.100000D+01 # muF/q
8  172.5d0    # mt [GeV]
9  4.75d0     # mb [GeV]
11 0.911876D+02 # Mz [GeV]
12 0.803980D+02 # Mw [GeV]
13 0.249520D+01 # GammaZ [GeV]
14 0.214100D+01 # GammaW [GeV]
15 0.116637D-04 # GFermi [1/GeV^2]
18 0.508000D-01 # sin^2(thetaC)

Block INTEGER
1  1 # [1:pp][2:ppbar]
2  2 # [0:LO][1:NLO][2:NNLO] (adjust PDF set as well!)
3  1 # [0:WH][1:ZH]
4  0 # PDF number
5  5 # nf
6  1 # [0:w/o][1:with] electro-weak corrections

Block CHAR
1 MSTW2008nnlo68cl.LHgrid # PDF set

It is divided into “Blocks” that are characterized by the type of the input variables they contain (REAL*8, INTEGER, and CHARACTER). Each line inside a Block consists of (from left to right)

- at least one whitespace character
- a label of type INTEGER
- the value of the input variable
- (optionally) a comment, introduced by a hash symbol (#)

Quite generally, vh@nnlo will ignore any text to the right of the hash symbol #.

In the following, the individual input parameters are described in more detail. All masses, energies, and decay widths are to be given in GeV.
Block REAL — input variables of type REAL*8

1 — $\sqrt{s}$, the hadronic center-of-mass energy

2 — $M_H$, the mass of the Higgs boson

3 — $\mu_R/\sqrt{q^2}$, the renormalization scale relative to $\sqrt{(p_V + p_H)^2}$

   $p_V$ and $p_H$ are the 4-momenta of the final state weak gauge boson and the Higgs, respectively. At LO, $q^2 = (p_V + p_H)^2$ is thus the square of the partonic center-of-mass energy.

4 — $\mu_F/\sqrt{q^2}$, the factorization scale relative to $\sqrt{(p_V + p_H)^2}$

   See entry 3.

8 — $M_t$, the on-shell top quark mass

9 — $M_b$, the on-shell bottom quark mass

11 — $M_Z$, the $Z$ boson mass

12 — $M_W$, the $W$ boson mass

13 — $\Gamma_Z$, the $Z$ boson decay width

14 — $\Gamma_W$, the $W$ boson decay width

15 — $G_F$, the Fermi constant (in GeV$^{-2}$)

   Note that the electro-weak couplings $g, g'$ are expressed in terms of $G_F, M_W,$ and $M_Z$; in particular, we use $G_F = \pi\alpha_{\text{QED}}/(\sqrt{2}M_W^2 \sin^2 \theta_W)$ and $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$.

18 — $\sin^2 \theta_C$, the Cabbibo angle

   Mixing of the first and second quark generation with the third generation is neglected, i.e. $v_h@nnlo$ assumes $V_{qT} = \delta_{qT}$, $q \in \{d,s,b\}$. The error introduced by this approximation is completely negligible.
Block INTEGER — *input variables of type INTEGER*
1 — *collider type: 1 \( \equiv pp \), 2 \( \equiv p\bar{p} \)
2 — *order of calculation: 0 \( \equiv LO \), 1 \( \equiv NLO \), 2 \( \equiv NNLO \)*
This parameter affects only the order of \( \alpha_s \) that is taken into account for the partonic cross section. It has no influence on the order at which \( \alpha_s \) or the PDFs are *evolved*. This is determined by the choice of the PDF set (Block CHAR, entry 1).
3 — *type of process: 0 \( \equiv WH \), 1 \( \equiv ZH \)*
4 — *number of the PDF set member*
Modern PDF sets usually provide a means to evaluate the corresponding uncertainties. For this, they contain several “member” PDFs within one set. The set itself is specified in Block CHAR, entry 1, see below.
5 — *number of flavors taking into account in the running of \( \alpha_s \)*
6 — *include electro-weak correction factor: 0 \( \equiv no \), 1 \( \equiv yes \)*

Block CHAR — *input variables of type CHARACTER*
1 — *the name of the PDF set as defined in LHAPDF*
The perturbative order of the PDF set will determine the order of the DGLAP evolution of the PDFs, and also the order to which \( \alpha_s \) is evolved from \( M_Z \) to \( \mu_R \).

In order to run the program with this input file, say

```
x/x.main infiles/in.init
```

in the main directory of `vh@nnlo`.

### 2.3.2. Output

The input file of section 2.3.1 will lead to the following output, written to the file output/out.vh:

```
# -----------------------
# +++ vh@nnlo version 1.20 +++
# Authors: T. Zirke and R.V. Harlander (Drell-Yan part)
# 0. Brein (ggHZ part)
# Based on zwprod.f by W. van Neerven and the paper
# 0. Brein, A. Djouadi, R.V. Harlander,
# Phys.Lett. B579 (2004) 149, hep-ph/0307206.
# Uses LoopTools by T. Hahn and FF by J. van Oldenborgh.
# -----------------------
```
# In addition, please cite the following papers:
# Han:1991ia
# Hamberg:1991np
# Harlander:2002wh
# Brein:2003wg
# Ciccolini:2003jy
# Kniehl:1990iv
# -----------------------

**Block REAL**

| Block | Value          | Description                  |
|-------|----------------|------------------------------|
| 1     | 0.800000D+04   | \( \sqrt{s} \) [GeV]        |
| 2     | 0.125000D+03   | \( m_h \) [GeV]             |
| 3     | 0.100000D+01   | \( \mu_R/q \)                |
| 4     | 0.100000D+01   | \( \mu_F/q \)                |
| 8     | 0.172500D+03   | \( M_t \) [GeV]             |
| 9     | 0.475000D+01   | \( M_b \) [GeV]             |
| 11    | 0.911876D+02   | \( M_Z \) [GeV]             |
| 12    | 0.803980D+02   | \( M_W \) [GeV]             |
| 13    | 0.249520D+01   | \( \Gamma_Z \) [GeV]        |
| 14    | 0.214100D+01   | \( \Gamma_W \) [GeV]        |
| 15    | 0.116637D-04   | \( G_{\text{Fermi}} \) [GeV]|
| 16    | 0.755625D-02   | \( \alpha_{\text{QED}} \)  |
| 17    | 0.222646D+00   | \( \sin^2(\theta_W) \)     |
| 18    | 0.508000D-01   | \( \sin^2(\theta_C) \)     |

**Block INTEGER**

| Block | Value | Description |
|-------|-------|-------------|
| 1     | 1     | [1:pp][2:ppbar] |
| 2     | 2     | [0:LO][1:NLO][2:NNLO] |
| 3     | 1     | [0:WH][1:ZH] |
| 4     | 0     | PDF number |
| 5     | 5     | \( n_f \) |
| 6     | 1     | [0:w/o][1:with] electro-weak corrections |

**Block CHAR**

| Block | Value | Description |
|-------|-------|-------------|
| 1     | MSTW2008nnlo68cl.LHgrid | # PDF set |

**Block SIGMA**

| Block | Value          | Description          |
|-------|----------------|----------------------|
| 1     | 0.398313D+00   | \( \sigma(\text{all}) \) [pb] |
| 10    | 0.117070D+00   | \( \alpha_s(m_Z) \)  |
| 11    | 0.399203D+00   | \( \sigma(\text{DY}) \) [pb] |
| 12    | 0.154259D-01   | \( \sigma(\text{gg\rightarrow HZ}) \) [pb] |
| 13    | -.510000D+01   | \( \Delta_{\text{EW}} \) [%] |
| 14    | 0.404315D-02   | \( \sigma(\text{top}) \) [pb] |
One observes that \texttt{vh@nnlo} includes the input to the output file, and adds a new Block, named SIGMA. Its entries are given as follows:

\textbf{Block SIGMA} — output of \texttt{vh@nnlo}

- 1 — \(\sigma_{\text{tot}}\), the total inclusive cross section, including all corrections requested in the input file
- 10 — \(\alpha_s(M_Z)\), the input value for the strong coupling constant, defined by the PDF set
- 11 — \(\sigma^{\text{DY}}\), the DY part of the cross section
- 12 — \(\sigma^{\text{ggHZ}}\), the \(\text{ggHZ}\) component of the cross section
- 13 — \(\delta_{\text{EW}}\), the electro-weak correction factor
- 14 — \(\sigma^{\text{top}}\), the top component of the cross section

Note that \texttt{vh@nnlo} will output the results only up to the order requested in the input file. Thus, for example, \(\sigma^{\text{ggHZ}}\) and \(\sigma^{\text{top}}\) (entries 12 and 14) will be zero unless the requested order of the calculation is NNLO (i.e. Block INTEGER, entry 2 is equal to 2).

2.3.3. Citations

\texttt{vh@nnlo} collects a number of results which need to be acknowledged in a proper way. It is insufficient for the user of \texttt{vh@nnlo} to simply refer to this manual without explicitly referencing the relevant literature that entered into the calculation. In order to facilitate this task, \texttt{vh@nnlo} outputs a list of “texkeys” in the header of the output file which have to be referenced (see Section 2.3.2). The full references can be obtained with these texkeys from the \texttt{INSPIRE} [26] database using the \texttt{find texkey} command.

2.3.4. Parameter scans

The input file described in section 2.3.1 defines one single set of parameters. In order to perform parameter scans, one could modify the main program \texttt{mainfiles/main.f}. However, we recommend leaving the Fortran code of \texttt{vh@nnlo} untouched, and rather operate with scripts such as \texttt{slharoutines} which are available from Ref. [27].

3. Conclusions

\texttt{vh@nnlo} is a program that collects the most up-to-date results for inclusive production of Higgs bosons in association with a weak gauge boson in the SM. Individual perturbative contributions can be separately considered.
Various parameters can be adjusted. In particular, parton densities can be easily changed through the use of the LHAPDF library.

We hope that the program will be useful for Higgs physics at the LHC.

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