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Status of vh@nnlo and Plans

VH subgroup meeting: Plans for YR5

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Part I:
vh@nnlo in a nutshell

vh@nnlo

18 Oct 2012 — WUB/12-20

vh@nnlo — Higgs Strahlung at hadron colliders[1]

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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, $\sigma(pp/p\bar{p} \to HV)$, $V \in \{W, Z\}$. 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.

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

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vh@nnlo-v2: New physics in Higgs Strahlung

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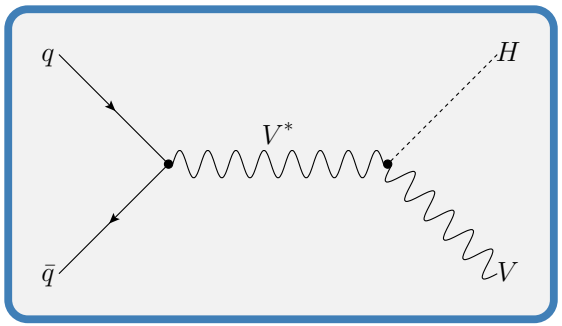
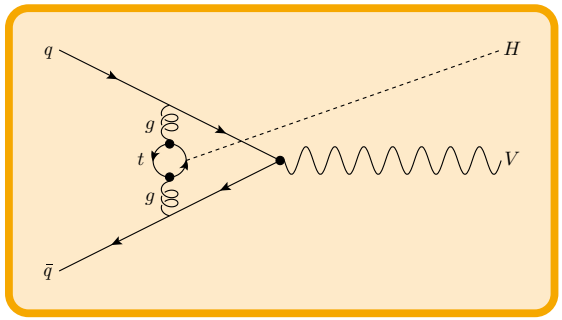
Abstract

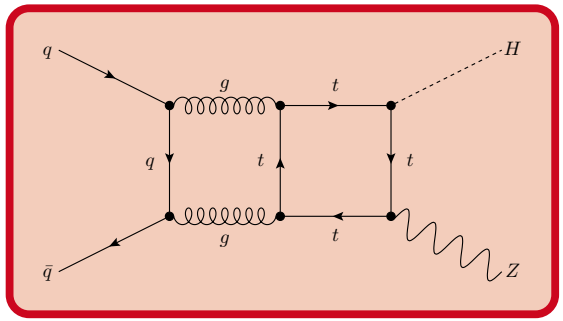
Introducing version 2 of the code vh@nnlo [1], we study the effects of a number of new-physics scenarios on the Higgs-Strahlung process. In particular, the cross section is evaluated within a general 2HDM and the MSSM. While the Drell-Yan-like contributions are consistently taken into account by a simple rescaling of the SM result, the gluon-initiated contribution is supplemented by squark-loop mediated amplitudes, and by the s-channel exchange of additional scalars which may lead to conspicuous interference effects. The latter holds as well for bottom-quark initiated Higgs Strahlung, which is also included in the new version of vh@nnlo. Using an orthogonal rotation of the three Higgs CP eigenstates in the 2HDM and the MSSM, vh@nnlo incorporates a simple means of CP mixing in these models. Moreover, the effect of vector-like quarks in the SM on the gluon-initiated contribution can be studied. Beyond concrete models, vh@nnlo allows to include the effect of higher-dimensional operators on the production of CP-even Higgs bosons. Transverse momentum distributions of the final state Higgs boson and invariant mass distributions of the $V\phi$ final state for the gluon- and bottom-quark initiated contributions can be studied. Distributions for the Drell-Yan-like component of Higgs Strahlung can be included through a link to MCFM. vh@nnlo can also be linked to FeynHiggs and 2HDMC for the calculation of Higgs masses and mixing angles. It can also read these parameters from an SLHA-file as produced by standard spectrum generators. Throughout the manuscript, we highlight new-physics effects in various numerical examples, both at the inclusive level and for distributions.

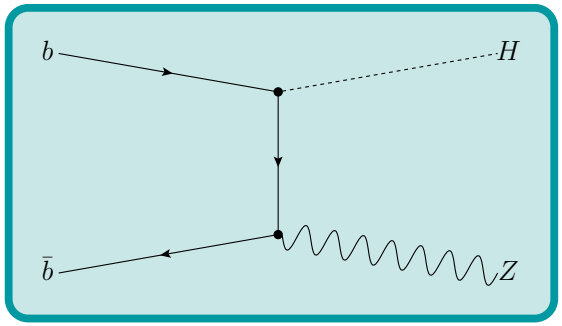
VH cross section with vh@nnlo

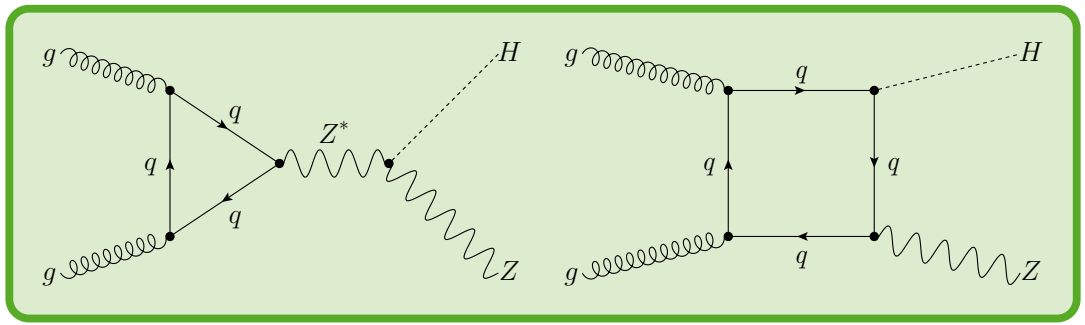
$$\sigma^{VH} = \left(1 + \delta^{VH}_{\mathrm{EW}}\right) \sigma^{VH}_{\mathrm{DY}} + \sigma^{VH}_{\mathrm{I}} + \delta_{VZ} \left(\sigma^{ZH}_{\mathrm{II}} + \sigma_{b\bar{b}\to ZH} + \sigma_{ggZH}\right)$$







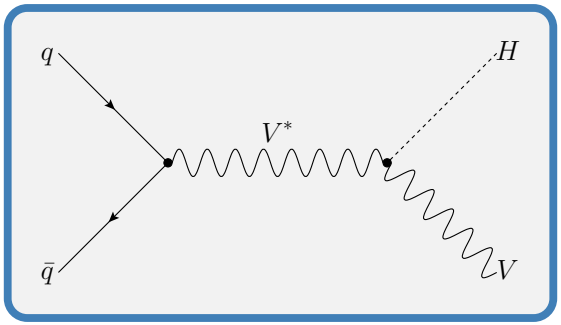




VH cross section with vh@nnlo

Drell-Yan-like contribution

$$\sigma^{VH} = \left(1 + \delta^{VH}_{\mathrm{EW}}\right) \sigma^{VH}_{\mathrm{DY}} + \sigma^{VH}_{\mathrm{I}} + \delta_{VZ} \left(\sigma^{ZH}_{\mathrm{II}} + \sigma_{b\bar{b}\to ZH} + \sigma_{ggZH}\right)$$



- **NNLO QCD** corrections have been computed 20 years ago

  [Brein, Djouadi, Harlander 2004 (arXiv:hep-ph/0307206)]

- `vh@nnlo` implementation is based on `ZWPROD`

  [Hamberg, van Neerven, Matsuura 1991]

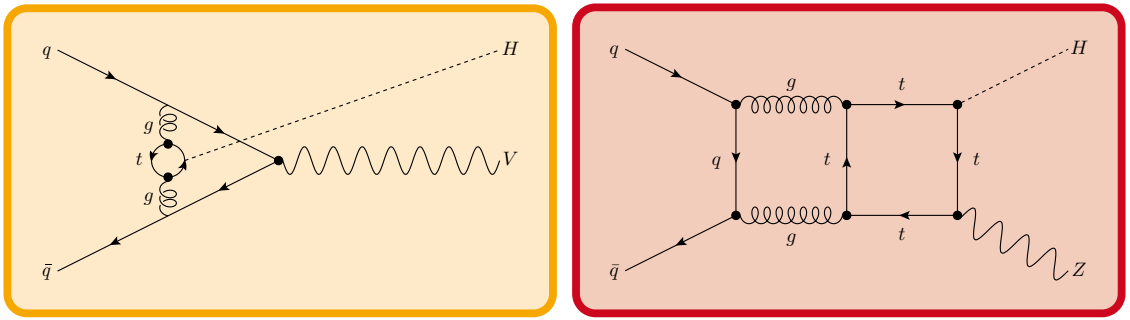
- **NLO EW** corrections (including leptonic vector boson decay)
  - to inclusive process [Ciccolini, Dittmaier, Krämer 2003 (arXiv:hep-ph/0306234)]
  - `HAWK` [Denner, Dittmaier, Kallweit, Mück 2012 (arXiv:1112.5142)]
  - `HAWK 2.0` [Denner, Dittmaier, Kallweit, Mück 2015 (arXiv:1412.5390)]

„Status of Electroweak Corrections and Plans”

VH cross section with vh@nnlo

Top-mediated contributions

$$\sigma^{VH} = \left(1 + \delta^{VH}_{\mathrm{EW}}\right) \sigma^{VH}_{\mathrm{DY}} + \sigma^{VH}_{\mathrm{I}} + \delta_{VZ} \left(\sigma^{ZH}_{\mathrm{II}} + \sigma_{b\bar{b}\to ZH} + \sigma_{ggZH}\right)$$

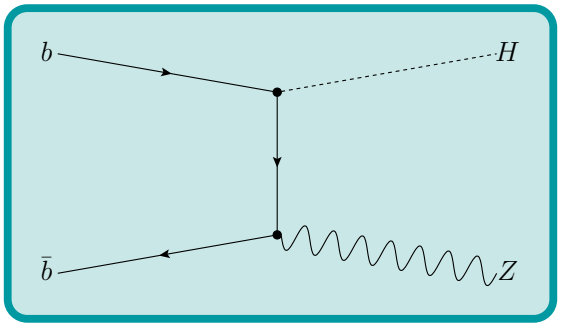


- top-quark mediated effects with a direct **Higgs-to-top Yukawa coupling** [Brein, Harlander, Wiesemann, Zirke 2012 (arXiv:1111.0761)]
- corrections of the order of $1 - 3\%$ at LHC energies

VH cross section with vh@nnlo

Bottom-induced contribution

$$\sigma^{VH} = \left(1 + \delta^{VH}_{\mathrm{EW}}\right) \sigma^{VH}_{\mathrm{DY}} + \sigma^{VH}_{\mathrm{I}} + \delta_{VZ} \left(\sigma^{ZH}_{\mathrm{II}} + \sigma_{b\bar{b}\to ZH} + \sigma_{ggZH}\right)$$

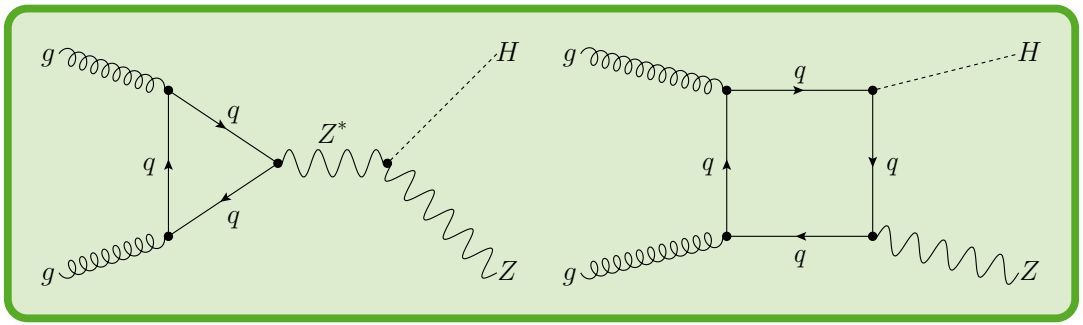


- only $b\bar{b}$-initiated contributions with a direct **Higgs-to-bottom Yukawa coupling**
- implemented at LO in QCD with massless bottom quarks but non-zero Yukawa coupling
- contribution negligible in SM (effects at permille level)

VH cross section with vh@nnlo

Gluon-induced contribution

$$\sigma^{VH} = \left(1 + \delta^{VH}_{\mathrm{EW}}\right)\sigma^{VH}_{\mathrm{DY}} + \sigma^{VH}_{\mathrm{I}} + \delta_{VZ}\left(\sigma^{ZH}_{\mathrm{II}} + \sigma_{b\bar{b}\to ZH} + \sigma_{ggZH}\right)$$



$$\sigma_{ggZH} = K^{\infty}_{\mathrm{NLO}}\sigma^{\mathrm{LO}}_{gg\to ZH} + \sigma^{\mathrm{NLL-NLO}}_{gg\to ZH}$$

- $K^{\infty}_{\mathrm{NLO}}$ is the **NLO K-factor** in the heavy top limit

  [Altenkamp, Dittmaier, Harlander, Rzehak, Zirke 2013 (arXiv:1211.5015)]

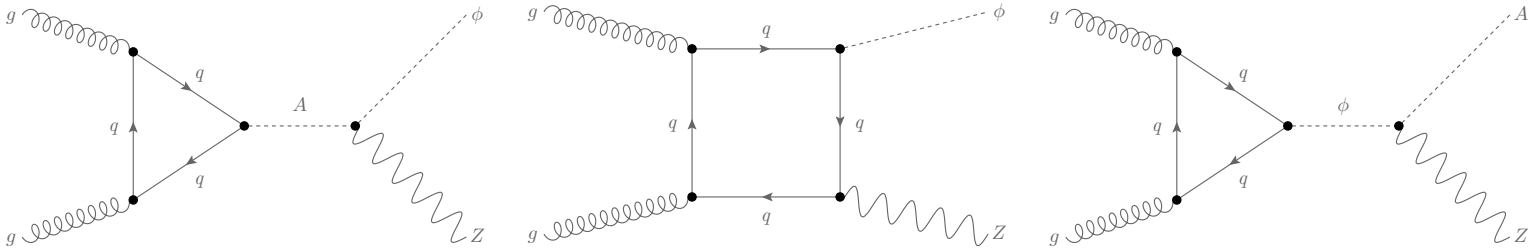
- $\sigma^{\mathrm{NLL-NLO}}_{gg\to ZH}$ contains **NLL soft-gluon resummation** effects

  [Harlander, Kulesza, Theeuwes 2014 (arXiv:1410.0217)]

Beyond the Standard Model

Theories **beyond the Standard Model** in `vh@nnlo`:

- Two-Higgs-Doublet Model (**2HDM**)



- Next-to-Minimal Two-Higgs-Doublet Model (**N2HDM**) [not public]
- Minimal Supersymmetric Standard Model (**MSSM**)
- **CP-mixing** effects for 2HDM, N2HDM and MSSM
- **higher-dimensional operators**
- effects of **vector-like quarks**

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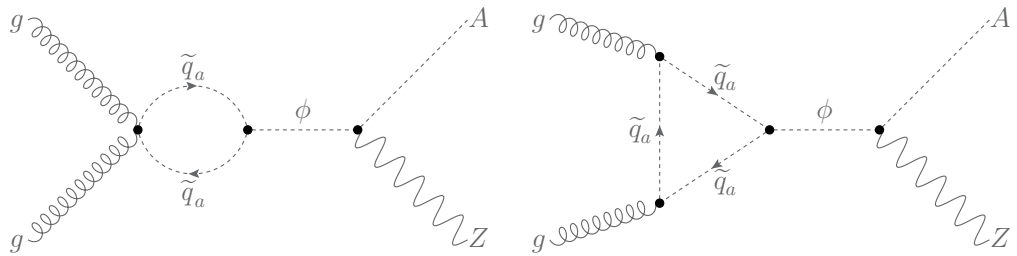

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$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} h \\ H \\ A \end{pmatrix}$$

- **higher-dimensional operators**
- effects of **vector-like quarks**

Beyond the Standard Model

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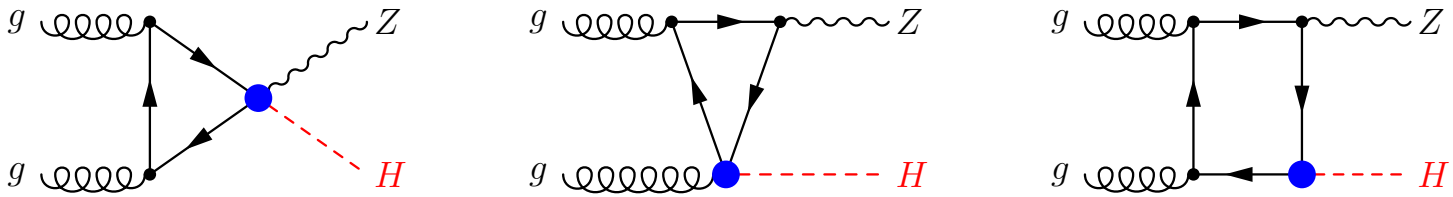

- effects of **vector-like quarks**

Beyond the Standard Model

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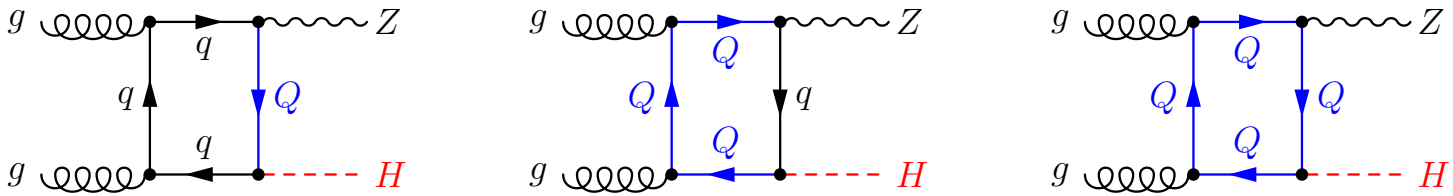

Part II:

Inclusive cross sections for VH production

WH cross section with leptonic decay

$pp \to WH \to \ell\nu H$

Inclusive cross section at **NNLO QCD + NLO EW**

$$\sigma(pp \to WH \to \ell\nu H) = \left((1+\delta_{\mathrm{EW}}^{\ell\nu H})\sigma_{\mathrm{DY}}^{WH} + \sigma_{\mathrm{I}}^{WH}\right) \times \mathrm{Br}^{\mathrm{LO}}(W \to \ell\nu) + \sigma_{\gamma}^{\ell\nu H}$$

Parameter scan

- center of mass energies: $\sqrt{s} \in \{7, 8, 13, 13.6, 14\}$ TeV
- Higgs masses: $M_H \in \{120, 122, 124, 124.6, 124.8, 125, 125.09, 125.2, 125.3, 125.38, 125.6, 126, 128, 130\}$ GeV

WH cross section with leptonic decay

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Parameter scan

- center of mass energies: $\sqrt{s} \in \{7, 8, 13, 13.6, 14\}$ TeV
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`vh@nnlo`

- central scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = M_{WH}$
- PDF set: `PDF4LHC21_40`

`HAWK 2.0`

- PDF set for computing δ_{EW}: `PDF4LHC21_40`
- PDF set for computing σ_{γ}: `LUXqed17_plus_PDF4LHC15_nnlo_100`

Uncertainty estimate

$pp \to WH \to \ell\nu H$

Uncertainties have been computed following the recommendations for „Higgs Production Cross Section for Run III"

1. **QCD scale uncertainty**: 7-point scale variation

$$\frac{1}{3} M_{WH} < \mu_{\mathrm{R}}, \mu_{\mathrm{F}} < 3 M_{WH} \quad \wedge \quad \frac{1}{3} < \frac{\mu_{\mathrm{R}}}{\mu_{\mathrm{F}}} < 3$$

2. **PDF uncertainty**: following the PDF4LHC recommendation for a symmetric Hessian PDF set
3. α_s **uncertainty**: we have varied $\alpha_s(M_Z) = 0.1180 \pm 0.0010$ (as provided by the PDF set)

Note: Uncertainties have not been computed for the photon induced contribution σ_γ.

VH cross section values

$$\sqrt{s} = 13.6\,\text{TeV}\,, \qquad M_H = 125.09\,\text{GeV}$$

	σ [pb]	scale [%]	PDF [%]	α_s [%]	PDF+α_s [%]
$\ell^+\nu H$	0.10180	$^{+0.49}_{-0.74}$	1.69	0.54	1.78
$\ell^-\bar{\nu}H$	0.064475	$^{+0.42}_{-0.66}$	1.73	0.54	1.81
W^+H	0.89750	$^{+0.51}_{-0.77}$	1.76	0.57	1.85
W^-H	0.56684	$^{+0.43}_{-0.69}$	1.81	0.57	1.90

	σ [pb]	scale [%]	PDF [%]	α_s [%]	PDF+α_s [%]
$\ell^+\ell^- H$	0.032152	$^{+3.90}_{-3.27}$	1.52	0.50	1.60
$\nu\bar{\nu}H$	0.19111	$^{+3.89}_{-3.26}$	1.52	0.50	1.60
ZH	0.95187	$^{+3.92}_{-3.28}$	1.53	0.50	1.61

Part III:
Beyond vh@nnlo

Beyond vh@nnlo

Production cross section at N^{3}LO

- inclusive cross section and invariant mass distribution for DY-like contributions available in literature [Baglio, Duhr, Mistlberger, Szafron 2022 (arXiv:2209.06138)]
- public code `n3loxs` available

Fully-differential cross sections at NNLO

fully-differential cross sections at NNLO (including various decay channels of the Higgs and/or vector boson)

- for WH production [Ferrera, Grazzini, Tramontano 2014 (arXiv:1312.1669)]
- for ZH production [Ferrera, Grazzini, Tramontano 2015 (arXiv:1407.4747)]
- for VH production [Ferrera, Somogyi, Tramontano 2018 (arXiv:1705.10304)]
- with Nested Soft-Collinear Subtraction [Caola, Melnikov, Röntsch 2019 (arXiv:1902.02081)]
  - we also have an implementation based on Nested Soft-Collinear Subtraction for fully-differential VH cross sections
- many more ...

Backup

WH cross section

$pp \to WH$

Inclusive cross section at **NNLO QCD + NLO EW**

$$\sigma(pp \to WH) = (1 + \delta_{\mathrm{EW}}^{WH})\sigma_{\mathrm{DY}}^{WH} + \sigma_{\mathrm{I}}^{WH}$$

with

$$\delta_{\mathrm{EW}}^{WH} = (1 + \delta_{\mathrm{EW}}^{\ell\nu H})\frac{\mathrm{Br}^{\mathrm{LO}}(W \to \ell\nu)}{\mathrm{Br}^{\mathrm{NLO}}(W \to \ell\nu)} - 1$$

Note: Photon induced contribution has not been included.

BACKUP

ZH cross section with leptonic decay

$pp \to ZH \to \ell\ell Z$

Inclusive cross section at **NNLO QCD + NLO EW**

$$\sigma(pp \to ZH \to \ell\ell H) = \left((1+\delta_{\mathrm{EW}}^{\ell\ell H})\sigma_{\mathrm{DY}}^{ZH} + \sigma_{\mathrm{I}}^{ZH} + \sigma_{\mathrm{II}}^{ZH} + \sigma_{ggZH}\right) \times \mathrm{Br}^{\mathrm{LO}}(Z \to \ell\ell) + \sigma_{\gamma}^{\ell\ell H}$$

vh@nnlo

- central scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = M_{ZH}$
- PDF set: `PDF4LHC21_40`

HAWK 2.0

- PDF set for computing δ_{EW}: `PDF4LHC21_40`
- PDF set for computing σ_{γ}: `LUXqed17_plus_PDF4LHC15_nnlo_100`

BACKUP

Uncertainty estimate

$pp \to ZH \to \ell\ell H$

Uncertainties have been computed following the recommendations for „Higgs Production Cross Section for Run III"

1. **QCD scale uncertainty**: 7-point scale variation

$$\frac{1}{3} M_{ZH} < \mu_{\mathrm{R}}, \mu_{\mathrm{F}} < 3 M_{ZH} \quad \wedge \quad \frac{1}{3} < \frac{\mu_{\mathrm{R}}}{\mu_{\mathrm{F}}} < 3$$

2. **PDF uncertainty**: following the PDF4LHC recommendation for a symmetric Hessian PDF set
3. α_s **uncertainty**: we have varied $\alpha_s(M_Z) = 0.1180 \pm 0.0010$ (as provided by the PDF set)

Note: Only QCD scale uncertainty, but no PDF and α_s uncertainties, have been computed for the resummation contribution $\sigma^{\mathrm{NLL-NLO}}_{gg \to ZH}$. Moreover, uncertainties have not been computed for the photon induced contribution σ_γ.

BACKUP

ZH cross section with leptonic decay

$pp \to ZH \to \ell\ell H$

Inclusive cross section at **NNLO QCD + NLO EW**

$$\sigma(pp \to ZH) = (1 + \delta_{\mathrm{EW}}^{ZH})\sigma_{\mathrm{DY}}^{ZH} + \sigma_{\mathrm{I}}^{ZH} + \sigma_{\mathrm{II}}^{ZH} + \sigma_{ggZH}$$

with

$$\delta_{\mathrm{EW}}^{ZH} = \frac{1}{2}\left[(1 + \delta_{\mathrm{EW}}^{\ell\ell H})\frac{\mathrm{Br}^{\mathrm{LO}}(Z \to \ell\ell)}{\mathrm{Br}^{\mathrm{NLO}}(Z \to \ell\ell)} - 1 + (1 + \delta_{\mathrm{EW}}^{\nu\nu H})\frac{\mathrm{Br}^{\mathrm{LO}}(Z \to \nu\nu)}{\mathrm{Br}^{\mathrm{NLO}}(Z \to \nu\nu)} - 1\right]$$

Note: Photon induced contribution has not been included.

BACKUP