

## LHC HIGGS WORKING GROUP\*

## PUBLIC NOTE

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# Predictions for Production Cross Sections of the Higgs Boson at the LHC and HL-LHC

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**Instructions for authors:**

- Add your name on the author list in the appropriate group. Anyone who was/is a convener since we started this work should be listed as such. External people should be listed in the “In collaboration with”. All groups should be alphabetical.
- Add your affiliation(s) and *update* the affiliation list appropriately.
- Please respect the formatting of tables etc by looking at previously committed material.
- Each chapter should serve as a review of the state-of-the-art theory. We should aim to be generous with references, and hence make sure to also cite work that is no longer state-of-the-art, but is now considered important work towards the state-of-the-art.

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**Abstract** This note documents state-of-the-art predictions for the production cross sections of the Higgs Boson at the LHC. Specifically, Standard Model predictions for the LHC with centre-of-mass. energy of 7, 8, 13, 13.6 and 14 TeV are presented.

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## 1 Introduction

Production cross sections for the Higgs boson based on the Standard Model of particle physics were collected in the CERN Yellow Report "Deciphering the Nature of the Higgs Sector" (YR4) (CERN-2017-002) [?]. Since this document became public many advancements in our abilities to predict production cross sections were achieved. Furthermore, the LHC performed measurements at a higher centre-of-mass energy of 13.6 TeV for which YR4 does not contain any predictions. Looking ahead to Run-3 and the High Luminosity phase of the LHC (HL-LHC) and the associated wealth of data that will be collected an update of the HWG recommendation of all production cross sections to reflect the current state of the art is called for. The aim of this note is to document recent advancements and review the ingredients for the prediction of Standard Model predictions for the production cross sections of the Higgs boson at the LHC (similar in spirit as in YR4). Updated numerical predictions for central values of the production cross sections and associated theoretical and parametric uncertainties are the main result of this article. This note supersedes the interpolation of Ref. [?].

For now, instructions and input parameters for the generation of numerical values can be found here: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG136TeVxsec>

## 2 Common setup

Here we describe all input parameters and settings that are common to all predictions presented in this report. In general we have aimed to use physical parameters from the Review of Particle Physics (PDG) [?].

## 2.1 Fermion masses

## 2.2 Gauge boson masses

We use the following on-shell values for the  $W$  and  $Z$  boson masses and widths

$$\begin{aligned} M_W^{\text{OS}} &= 80.379 \text{ GeV}, & \Gamma_W^{\text{OS}} &= 2.085 \text{ GeV} \\ M_Z^{\text{OS}} &= 91.1876 \text{ GeV}, & \Gamma_Z^{\text{OS}} &= 2.4952 \text{ GeV}. \end{aligned} \quad (1)$$

When needed for EW computations they are translated into their pole masses [?] according to

$$M_V = \frac{M_V^{\text{OS}}}{\sqrt{1 + (\Gamma_V^{\text{OS}}/M_V^{\text{OS}})^2}}, \quad \Gamma_V = \frac{\Gamma_V^{\text{OS}}}{\sqrt{1 + (\Gamma_V^{\text{OS}}/M_V^{\text{OS}})^2}}. \quad (2)$$

We use the  $G_\mu$ -scheme [?] to compute the fine structure constant  $\alpha$  from  $G_F$ ,  $M_W^{\text{OS}}$ , and  $M_Z^{\text{OS}}$

$$\alpha = \frac{\sqrt{2}}{\pi} G_F (M_W^{\text{OS}})^2 \sin^2 \theta_W, \quad \sin^2 \theta_W = 1 - \frac{(M_W^{\text{OS}})^2}{(M_Z^{\text{OS}})^2}, \quad G_F = 1.16638 \cdot 10^{-5} \text{ GeV}^2. \quad (3)$$

This yields a value

$$\alpha = 0.007565210. \quad (4)$$

## 2.3 PDF and $\alpha_s$

Following the PDF4LHC recommendation [?] we use PDF4LHC21\_40 PDF set for all predictions. The value of the strong coupling,  $\alpha_s$ , is given at the  $Z$  boson mass

$$\alpha_s(M_Z) = 0.1180 \pm 0.001. \quad (5)$$

We estimate the  $\alpha_s$  and PDF uncertainties following the same recommendation. The 4-flavour version of the PDF is used whenever a calculations is performed in the 4-flavour scheme. The above combined PDF sets do not contain any photon content. When computing photon initiate processes we instead use the LUXqed17\_plus\_PDF4LHC15\_nnlo\_100 [?] set for the photon *only*. This is not fully consistent as the presence of the photon in the PDF inevitably impacts the distributions of all the other partons. However, since the photon-initiated component is typically very small, this inconsistency is expected to be fully contained within other theoretical uncertainties.

## 3 ggF

## 4 VBF

The results are combined according to

$$\sigma^{\text{VBF}} = \sigma_{\text{N3LO}}^{\text{DIS}} (1 + \delta_{\text{EW}}) + \sigma_\gamma \quad (6)$$

and the theory uncertainties are computed as

$$\Delta_{\text{TU}} = \max \{0.5\%, \delta_{\text{EW}}^2\} + \frac{|\sigma_{\text{nf}}| + |\sigma_{\text{s/t/u}}|}{\sigma^{\text{VBF}}} \% \quad (7)$$

for  $\sqrt{s} = \{13, 13.6, 14\}$  TeV. For the legacy numbers corresponding to  $\sqrt{s} = \{7, 8\}$  TeV the non-factorisable contribution,  $\sigma_{\text{nf}}$ , was not computed, and we instead set

$$\Delta_{\text{TU}} = \max \left[ \max \{0.5\%, \delta_{\text{EW}}^2\} + \frac{|\sigma_{\text{s/t/u}}|}{\sigma^{\text{VBF}}} \%, 1.0\% \right]. \quad (8)$$

In fact, in this case it always corresponds to 1%.

**5**   **VH**

**6**    **$t\bar{t}H$  and  $tH$**

**7**    **$b\bar{b}H$**

**8**   **Conclusions**

**Acknowledgments**

This work was done on behalf of the LHCHWG.

## A Reference tables

### A.1 ggF

### A.2 VBF

Table 1: Total VBF cross sections in the SM for a LHC CM energy of  $\sqrt{s} = 7$  TeV, including QCD and EW corrections and their uncertainties for different Higgs-boson masses  $M_H$ . For more details see section 4.

$M_H[\text{GeV}]$	$\sigma^{\text{VBF}}[\text{fb}]$	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF}/\alpha_s/\text{PDF}\oplus\alpha_s}[\%]$	$\Delta_{\text{TU}}[\%]$	$\sigma_{\text{N3LO}}^{\text{DIS}}[\text{fb}]$	$\delta_{\text{EW}}[\%]$	$\sigma_\gamma[\text{fb}]$	$\sigma_{\text{nf}}[\text{fb}]$	$\sigma_{\text{s/t/u}}[\text{fb}]$
120.00	1310	$^{+0.067}_{-0.050}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1360	-4.4	9.7	—	-5.3
122.00	1285	$^{+0.065}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1333	-4.4	9.6	—	-5.0
124.00	1261	$^{+0.064}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1309	-4.4	9.5	—	-4.7
124.60	1254	$^{+0.064}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1301	-4.3	9.5	—	-4.6
124.80	1252	$^{+0.064}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1299	-4.3	9.4	—	-4.6
125.00	1249	$^{+0.064}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1296	-4.3	9.4	—	-4.5
125.09	1248	$^{+0.063}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1295	-4.3	9.4	—	-4.5
125.20	1247	$^{+0.063}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1294	-4.3	9.4	—	-4.5
125.30	1246	$^{+0.063}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1293	-4.3	9.4	—	-4.4
125.38	1245	$^{+0.063}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1292	-4.3	9.4	—	-4.4
125.60	1242	$^{+0.063}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1289	-4.3	9.4	—	-4.4
126.00	1238	$^{+0.063}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1284	-4.3	9.4	—	-4.4
128.00	1215	$^{+0.061}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1260	-4.3	9.2	—	-4.1
130.00	1192	$^{+0.060}_{-0.051}$	$\pm 2.3/\pm 0.3/\pm 2.4$	$\pm 1.0$	1237	-4.3	9.1	—	-3.8

Table 2: Total VBF cross sections in the SM for a LHC CM energy of  $\sqrt{s} = 8$  TeV, including QCD and EW corrections and their uncertainties for different Higgs-boson masses  $M_H$ . For more details see section 4.

$M_H[\text{GeV}]$	$\sigma^{\text{VBF}}[\text{fb}]$	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF}/\alpha_s/\text{PDF}\oplus\alpha_s}[\%]$	$\Delta_{\text{TU}}[\%]$	$\sigma_{\text{N3LO}}^{\text{DIS}}[\text{fb}]$	$\delta_{\text{EW}}[\%]$	$\sigma_\gamma[\text{fb}]$	$\sigma_{\text{nf}}[\text{fb}]$	$\sigma_{\text{s/t/u}}[\text{fb}]$
120.00	1687	$^{+0.082}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1754	-4.6	13.2	—	-6.2
122.00	1657	$^{+0.081}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1722	-4.6	13.0	—	-5.9
124.00	1627	$^{+0.081}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1691	-4.5	12.9	—	-5.5
124.60	1618	$^{+0.081}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1681	-4.5	12.8	—	-5.5
124.80	1615	$^{+0.081}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1678	-4.5	12.8	—	-5.5
125.00	1612	$^{+0.081}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1675	-4.5	12.8	—	-5.4
125.09	1611	$^{+0.081}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1674	-4.5	12.8	—	-5.4
125.20	1609	$^{+0.081}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1672	-4.5	12.8	—	-5.4
125.30	1608	$^{+0.081}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1671	-4.5	12.8	—	-5.4
125.38	1607	$^{+0.080}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1669	-4.5	12.8	—	-5.4
125.60	1604	$^{+0.080}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1666	-4.5	12.8	—	-5.3
126.00	1598	$^{+0.080}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1660	-4.5	12.7	—	-5.2
128.00	1569	$^{+0.079}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1630	-4.5	12.6	—	-4.9
130.00	1542	$^{+0.079}_{-0.061}$	$\pm 2.3/\pm 0.3/\pm 2.3$	$\pm 1.0$	1601	-4.5	12.4	—	-4.6

### A.3 VH

### A.4 ttH

### A.5 bbH

Table 3: Total VBF cross sections in the SM for a LHC CM energy of  $\sqrt{s} = 13$  TeV, including QCD and EW corrections and their uncertainties for different Higgs-boson masses  $M_H$ . For more details see section 4.

$M_H[\text{GeV}]$	$\sigma^{\text{VBF}}[\text{fb}]$	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF}/\alpha_s/\text{PDF}\oplus\alpha_s}[\%]$	$\Delta_{\text{TU}}[\%]$	$\sigma_{\text{N3LO}}^{\text{DIS}}[\text{fb}]$	$\delta_{\text{EW}}[\%]$	$\sigma_\gamma[\text{fb}]$	$\sigma_{\text{nf}}[\text{fb}]$	$\sigma_{\text{s/t/u}}[\text{fb}]$
120.00	3967	$^{+0.13}_{-0.091}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4148	-5.2	36.1	-8.9	-11.5
122.00	3905	$^{+0.13}_{-0.092}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4082	-5.2	35.8	-8.5	-10.6
124.00	3844	$^{+0.13}_{-0.092}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4017	-5.2	35.4	-8.2	-10.2
124.60	3825	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3998	-5.2	35.3	-8.1	-10.0
124.80	3819	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3992	-5.2	35.3	-8.1	-10.0
125.00	3813	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3985	-5.2	35.2	-8.0	-10.0
125.09	3811	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3982	-5.2	35.2	-8.0	-10.0
125.20	3807	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3979	-5.2	35.2	-8.0	-10.0
125.30	3804	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3976	-5.2	35.2	-8.0	-9.9
125.38	3802	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3973	-5.2	35.2	-8.0	-9.8
125.60	3795	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3966	-5.2	35.1	-8.0	-9.7
126.00	3784	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	3954	-5.2	35.1	-7.9	-9.6
128.00	3725	$^{+0.13}_{-0.093}$	$\pm 2.2/\pm 0.4/\pm 2.2$	$\pm 1.0$	3892	-5.2	34.7	-7.7	-9.2
130.00	3667	$^{+0.13}_{-0.094}$	$\pm 2.2/\pm 0.3/\pm 2.2$	$\pm 0.9$	3831	-5.2	34.3	-7.5	-8.6

Table 4: Total VBF cross sections in the SM for a LHC CM energy of  $\sqrt{s} = 13.6$  TeV, including QCD and EW corrections and their uncertainties for different Higgs-boson masses  $M_H$ . For more details see section 4.

$M_H[\text{GeV}]$	$\sigma^{\text{VBF}}[\text{fb}]$	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF}/\alpha_s/\text{PDF}\oplus\alpha_s}[\%]$	$\Delta_{\text{TU}}[\%]$	$\sigma_{\text{N3LO}}^{\text{DIS}}[\text{fb}]$	$\delta_{\text{EW}}[\%]$	$\sigma_\gamma[\text{fb}]$	$\sigma_{\text{nf}}[\text{fb}]$	$\sigma_{\text{s/t/u}}[\text{fb}]$
120.00	4276	$^{+0.13}_{-0.093}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4473	-5.3	39.4	-9.2	-11.9
122.00	4210	$^{+0.13}_{-0.094}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4403	-5.3	39.0	-8.8	-11.4
124.00	4144	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4334	-5.3	38.6	-8.5	-10.9
124.60	4125	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4313	-5.3	38.5	-8.4	-10.8
124.80	4118	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4307	-5.3	38.5	-8.4	-10.7
125.00	4112	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4300	-5.3	38.5	-8.3	-10.7
125.09	4109	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4297	-5.3	38.4	-8.3	-10.7
125.20	4106	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4293	-5.3	38.4	-8.3	-10.6
125.30	4102	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4290	-5.3	38.4	-8.3	-10.5
125.38	4100	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4287	-5.3	38.4	-8.3	-10.4
125.60	4093	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4280	-5.3	38.3	-8.3	-10.4
126.00	4080	$^{+0.13}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4266	-5.3	38.3	-8.2	-10.3
128.00	4018	$^{+0.13}_{-0.096}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 0.9$	4200	-5.2	37.9	-8.0	-9.8
130.00	3956	$^{+0.13}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 0.9$	4135	-5.2	37.5	-7.8	-9.1

Table 5: Total VBF cross sections in the SM for a LHC CM energy of  $\sqrt{s} = 14$  TeV, including QCD and EW corrections and their uncertainties for different Higgs-boson masses  $M_H$ . For more details see section 4.

$M_H[\text{GeV}]$	$\sigma^{\text{VBF}}[\text{fb}]$	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF}/\alpha_s/\text{PDF}\oplus\alpha_s}[\%]$	$\Delta_{\text{TU}}[\%]$	$\sigma_{\text{N}^3\text{LO}}^{\text{DIS}}[\text{fb}]$	$\delta_{\text{EW}}[\%]$	$\sigma_\gamma[\text{fb}]$	$\sigma_{\text{nf}}[\text{fb}]$	$\sigma_{\text{s/t/u}}[\text{fb}]$
120.00	4486	$^{+0.14}_{-0.094}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4694	-5.3	41.7	-9.9	-12.4
122.00	4416	$^{+0.14}_{-0.095}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4620	-5.3	41.3	-9.5	-11.9
124.00	4348	$^{+0.14}_{-0.096}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4549	-5.3	40.8	-9.1	-11.2
124.60	4328	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4527	-5.3	40.7	-9.0	-11
124.80	4322	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4520	-5.3	40.7	-9.0	-11
125.00	4315	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4513	-5.3	40.7	-8.9	-10.9
125.09	4312	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4510	-5.3	40.6	-8.9	-10.9
125.20	4308	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4506	-5.3	40.6	-8.9	-10.9
125.30	4305	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4503	-5.3	40.6	-8.9	-10.8
125.38	4302	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4500	-5.3	40.6	-8.9	-10.8
125.60	4295	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4492	-5.3	40.5	-8.9	-10.6
126.00	4282	$^{+0.14}_{-0.097}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4478	-5.3	40.5	-8.8	-10.5
128.00	4216	$^{+0.14}_{-0.098}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4409	-5.3	40	-8.6	-10
130.00	4152	$^{+0.14}_{-0.099}$	$\pm 2.1/\pm 0.4/\pm 2.2$	$\pm 1.0$	4342	-5.3	39.7	-8.4	-9.5