PRECISION CALCULATIONS FOR ASSOCIATED WH AND ZH PRODUCTION AT HADRON COLLIDERS

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Abstract
Recently the next-to-next-to-leading order QCD corrections and the electroweak $\mathcal{O}(\alpha)$ corrections to the Higgs-strahlung processes $p\bar{p}/pp \to WH/ZH + X$ have been calculated. Both types of corrections are of the order of 5–10%. In this article the various corrections are briefly discussed and combined into state-of-the-art predictions for the cross sections. The theoretical uncertainties from renormalization/factorization scales and from the parton distribution functions are discussed.

1. INTRODUCTION

At the Tevatron, Higgs-boson production in association with W or Z bosons, $p\bar{p} \to WH/ZH+X$, is the most promising discovery channel for a SM Higgs particle with a mass below about 135 GeV, where decays into $b\bar{b}$ final states are dominant [1, 2]. At the pp collider LHC other Higgs-production mechanisms play the leading role [3], but nevertheless these Higgs-strahlung processes should be observable.

At leading order (LO), the production of a Higgs boson in association with a vector boson, $p\bar{p} \to VH + X, (V = W, Z)$ proceeds through $q\bar{q}$ annihilation [4], $q\bar{q}' \to V^* \to VH$. The next-to-leading order (NLO) QCD corrections coincide with those to the Drell-Yan process and increase the cross section by about 30% [5]. Beyond NLO, the QCD corrections to VH production differ from those to the Drell-Yan process by contributions where the Higgs boson couples to a heavy fermion loop. The impact of these additional terms is, however, expected to be small in general [6]. Moreover, for ZH production the one-loop-induced process $gg \to ZH$ contributes at next-to-next-to-leading order (NNLO). The NNLO corrections corresponding to the Drell-Yan mechanism as well as the $gg \to ZH$ contribution have been calculated in Ref. [7]. These NNLO corrections further increase the cross section by the order of 5–10%. Most important, a successive reduction of the renormalization and factorization scale dependence is observed when going from LO to NLO to NNLO. The respective scale uncertainties are about 20% (10%), 7% (5%), and 3% (2%) at the Tevatron (LHC). At this level of accuracy, electroweak corrections become significant and need to be included to further improve the theoretical prediction. In Ref. [8] the electroweak $\mathcal{O}(\alpha)$ corrections have been calculated; they turn out to be negative and about –5% or –10% depending on whether the weak couplings are derived from G_μ or $\alpha(M_Z^2)$, respectively. In this paper we summarize and combine the results of the NNLO corrections of Ref. [7] and of the electroweak $\mathcal{O}(\alpha)$ corrections of Ref. [8].

The article is organized as follows. In Sects. 2. and 3. we describe the salient features of the QCD and electroweak corrections, respectively. Section 4. contains explicit numerical results on the corrected WH and ZH production cross sections, including a brief discussion of the theoretical uncertainties originating from the parton distribution functions (PDFs). Our conclusions are given in Sect. 5.

2. QCD CORRECTIONS

The NNLO corrections, i.e. the contributions at $\mathcal{O}(\alpha_s^2)$, to the Drell-Yan process $p\bar{p}/pp \to V^* + X$ consist of the following set of radiative corrections:

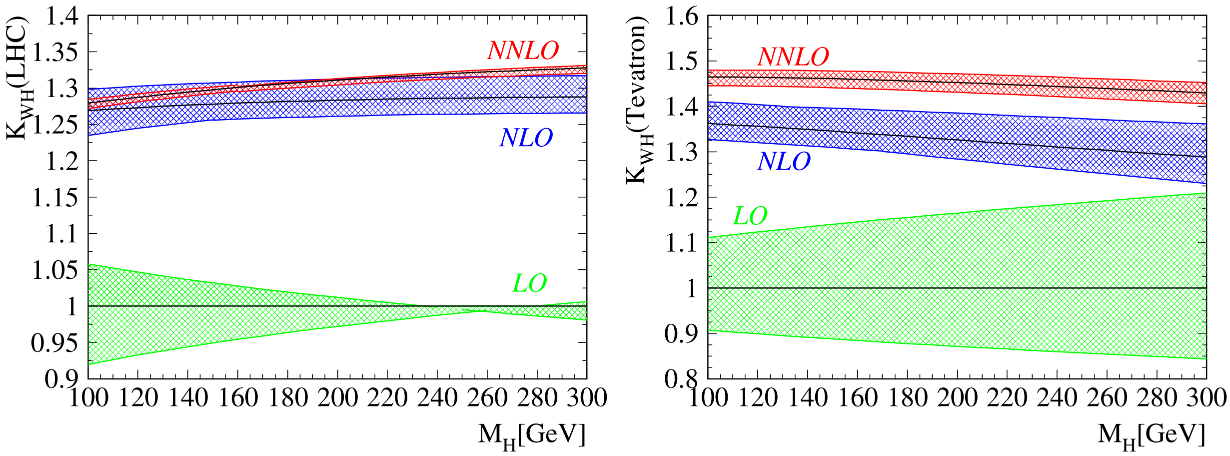

Fig. 1: QCD K-factors for WH production (i.e. from the sum of W^+H and W^-H cross sections) at the LHC (l.h.s.) and the Tevatron (r.h.s.). The bands represent the spread of the cross section when the renormalization and factorization scales are varied in the range $\frac{1}{3}M_{VH} \leq \mu_R\,(\mu_F) \leq 3M_{VH}$, the other scale being fixed at $\mu_F(\mu_R) = M_{VH}$. (Taken from Ref. [7].)

- two-loop corrections to $q\bar{q} \to V^*$, which have to be multiplied by the Born term,
- one-loop corrections to the processes $gq \to qV^*$ and $q\bar{q} \to gV^*$, which have to be multiplied by the tree-level gq and $q\bar{q}$ terms,
- tree-level contributions from $q\bar{q}, qq, qg, gg \to V^* +$ 2 partons in all possible ways; the sums of these diagrams for a given initial and final state have to be squared and added.

These corrections have been calculated a decade ago in Ref. [9] and have recently been updated [10]. They represent a basic building block in the NNLO corrections to VH production. There are, however, two other sources of $\mathcal{O}(\alpha_s^2)$ corrections:

- irreducible two-loop boxes for $q\bar{q}' \to VH$ where the Higgs boson couples via heavy-quark loops to two gluons that are attached to the q line,
- the gluon–gluon-initiated mechanism $gg \to ZH$ [11] at one loop; it is mediated by closed quark loops which induce ggZ and $ggZH$ couplings and contributes only to ZH but not to WH production.

In Ref. [7] the NNLO corrections to VH production have been calculated from the results [10] on Drell-Yan production and completed by the (recalculated) contribution of $gg \to ZH$. The two-loop contributions with quark-loop-induced ggZ or ggH couplings are expected to be very small and have been neglected.

The impact of higher-order (HO) QCD corrections is usually quantified by calculating the K-factor, which is defined as the ratio between the cross sections for the process at HO (NLO or NNLO), with the value of $\alpha_{\rm s}$ and the PDFs evaluated also at HO, and the cross section at LO, with $\alpha_{\rm s}$ and the PDFs consistently evaluated also at LO: $K_{\rm HO} = \sigma_{\rm HO}(p\bar{p}/pp \to VH + X)/\sigma_{\rm LO}(p\bar{p}/pp \to VH + X)$. A K-factor for the LO cross section, $K_{\rm LO}$, may also be defined by evaluating the latter at given factorization and renormalization scales and normalizing to the LO cross sections evaluated at the central scale, which, in our case, is given by $\mu_F = \mu_R = M_{VH}$, where M_{VH} is the invariant mass of the VH system.

The K-factors at NLO and NNLO are shown in Fig. 1 (solid black lines) for the LHC and the Tevatron as a function of the Higgs mass M_H for the process $p\bar{p}/pp \to WH + X$; they are practically the same for the process $p\bar{p}/pp \to ZH + X$ when the contribution of the $gg \to ZH$ component is not included. Inclusion of this contribution adds substantially to the uncertainty of the NNLO prediction for ZH production. This is because $gg \to ZH$ appears at $\mathcal{O}(\alpha_{\rm s}^2)$ in LO.

The scales have been fixed to $\mu_F = \mu_R = M_{VH}$, and the MRST sets of PDFs for each perturbative order (including the NNLO PDFs of Ref. [12]) are used in a consistent manner.

The NLO K-factor is practically constant at the LHC, increasing only from $K_{\rm NLO} = 1.27$ for $M_H = 110$ GeV to $K_{\rm NLO} = 1.29$ for $M_H = 300$ GeV. The NNLO contributions increase the K-factor by a mere 1% for the low M_H value and by 3.5% for the high value. At the Tevatron, the NLO K-factor is somewhat higher than at the LHC, enhancing the cross section between $K_{\rm NLO} = 1.35$ for $M_H = 110$ GeV and $K_{\rm NLO} = 1.3$ for $M_H = 300$ GeV with a monotonic decrease. The NNLO corrections increase the K-factor uniformly by about 10%. Thus, these NNLO corrections are more important at the Tevatron than at the LHC.

The bands around the K-factors represent the cross section uncertainty due to the variation of either the renormalization or factorization scale from $\frac{1}{3}M_{VH} \leq \mu_F\,(\mu_R) \leq 3M_{VH}$, with the other scale fixed at $\mu_R\,(\mu_F) = M_{VH}$; the normalization is provided by the production cross section evaluated at scales $\mu_F = \mu_R = M_{VH}$. As can be seen, except from the accidental cancellation of the scale dependence of the LO cross section at the LHC, the decrease of the scale variation is strong when going from LO to NLO and then to NNLO. For $M_H = 120$ GeV, the uncertainty from the scale choice at the LHC drops from 10% at LO, to 5% at NLO, and to 2% at NNLO. At the Tevatron and for the same Higgs boson mass, the scale uncertainty drops from 20% at LO, to 7% at NLO, and to 3% at NNLO. If this variation of the cross section with the two scales is taken as an indication of the uncertainties due to the not yet calculated higher-order corrections, one concludes that once the NNLO QCD contributions are included in the prediction, the QCD corrections to the cross section for the $p\bar{p}/pp \to VH + X$ process are known at the rather accurate level of 2 to 3% relative to the LO.

3. ELECTROWEAK CORRECTIONS

The calculation of the electroweak $\mathcal{O}(\alpha)$ corrections, which employs established standard techniques, is described in detail in Ref. [8]. The virtual one-loop corrections involve a few hundred diagrams, including self-energy, vertex, and box corrections. In order to obtain IR-finite corrections, real-photonic bremsstrahlung has to be taken into account. In spite of being IR finite, the $\mathcal{O}(\alpha)$ corrections involve logarithms of the initial-state quark masses which are due to collinear photon emission. These mass singularities are absorbed into the PDFs in exactly the same way as in QCD, viz. by $\overline{\rm MS}$ factorization. As a matter of fact, this requires also the inclusion of the corresponding $\mathcal{O}(\alpha)$ corrections into the DGLAP evolution of these distributions and into their fit to experimental data. At present, this full incorporation of $\mathcal{O}(\alpha)$ effects in the determination of the quark distributions has not been performed yet. However, an approximate inclusion of the $\mathcal{O}(\alpha)$ corrections to the DGLAP evolution shows [13] that the impact of these corrections on the quark distributions in the $\overline{\rm MS}$ factorization scheme is well below 1%, at least in the x range that is relevant for associated VH production at the Tevatron and the LHC. This is also supported by a recent analysis of the MRST collaboration [14] who took into account the $\mathcal{O}(\alpha)$ effects to the DGLAP equations.

The size of the $\mathcal{O}(\alpha)$ corrections depends on the employed input-parameter scheme for the coupling α. This coupling can, for instance, be derived from the fine-structure constant $\alpha(0)$, from the effective running QED coupling $\alpha(M_Z^2)$ at the Z resonance, or from the Fermi constant G_μ via $\alpha_{G_\mu} = \sqrt{2}G_\mu M_W^2 s_W^2/\pi$. The corresponding schemes are known as $\alpha(0)$-, $\alpha(M_Z^2)$-, and G_μ-scheme, respectively. In contrast to the $\alpha(0)$-scheme, where the $\mathcal{O}(\alpha)$ corrections are sensitive to the non-perturbative regime of the hadronic vacuum polarization, in the $\alpha(M_Z^2)$- and G_μ-schemes these effects are absorbed into the coupling constant α. In the G_μ-scheme large renormalization effects induced by the ρ-parameter are absorbed in addition via α_{G_μ}. Thus, the G_μ-scheme is preferable over the two other schemes (at least over the $\alpha(0)$-scheme).

Figure 2 shows the relative size of the $\mathcal{O}(\alpha)$ corrections as a function of the Higgs-boson mass for $p\bar{p} \to W^+H + X$ and $p\bar{p} \to ZH + X$ at the Tevatron. The numerical results have been obtained

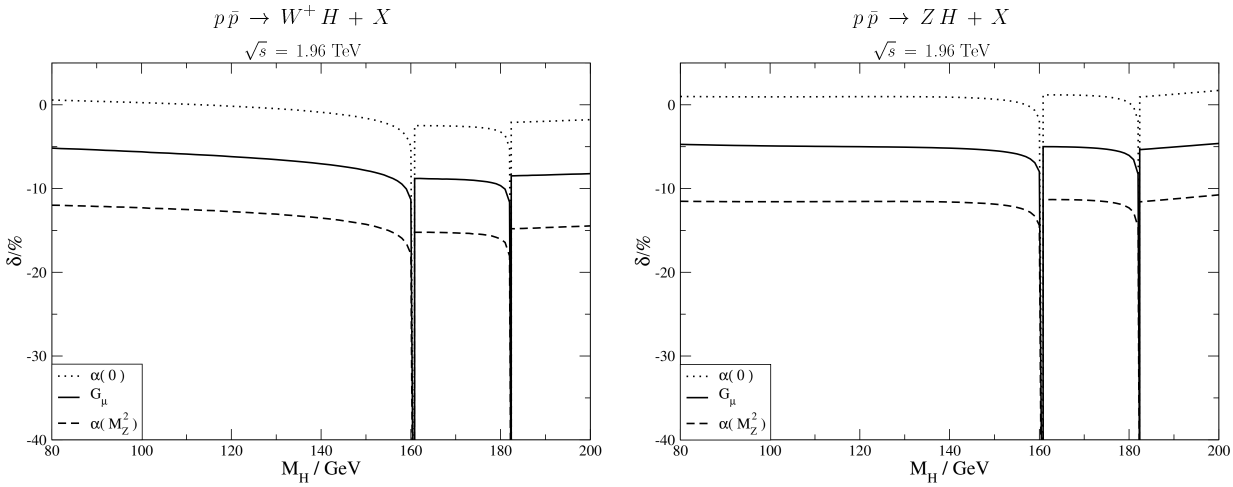

Fig. 2: Relative electroweak correction δ as a function of M_H for the total cross section of $p\bar{p} \to W^+H + X$ (l.h.s.) and $p\bar{p} \to ZH + X$ (r.h.s.) at the Tevatron in various input-parameter schemes. (Taken from Ref. [8].)

using the CTEQ6L1 [15] parton distribution function, but the dependence of the relative electroweak correction δ displayed in Fig. 2 on the PDF is insignificant. Results are presented for the three different input-parameter schemes. The corrections in the G_μ- and $\alpha(M_Z^2)$-schemes are significant and reduce the cross section by 5–9% and by 10–15%, respectively. The corrections in the $\alpha(0)$-scheme differ from those in the G_μ-scheme by $2\Delta r \approx 6\%$ and from those in the $\alpha(M_Z^2)$-scheme by $2\Delta\alpha(M_Z^2) \approx 12\%$. The quantities Δr and $\Delta\alpha(M_Z^2)$ denote, respectively, the radiative corrections to muon decay and the correction describing the running of $\alpha(Q^2)$ from $Q = 0$ to M_Z (see Ref. [8] for details). The fact that the relative corrections in the $\alpha(0)$-scheme are rather small results from accidental cancellations between the running of the electromagnetic coupling, which leads to a contribution of about $2\Delta\alpha(M_Z^2) \approx +12\%$, and other (negative) corrections of non-universal origin. Thus, corrections beyond $\mathcal{O}(\alpha)$ in the $\alpha(0)$-scheme cannot be expected to be suppressed as well. In all schemes, the size of the corrections does not depend strongly on the Higgs-boson mass.

For the LHC the corrections are similar in size to those at the Tevatron and reduce the cross section by 5–10% in the G_μ-scheme and by 12–17% in the $\alpha(M_Z^2)$-scheme (see Figs. 13 and 14 in Ref. [8]).

In Ref. [8] the origin of the electroweak corrections was further explored by separating gauge-invariant building blocks. It turns out that fermionic contributions (comprising all diagrams with closed fermion loops) and remaining bosonic corrections partly compensate each other, but the bosonic corrections are dominant. The major part of the corrections is of non-universal origin, i.e. the bulk of the corrections is not due to coupling modifications, photon radiation, or other universal effects.

Figure 3 shows the K-factor after inclusion of both the NNLO QCD and the $\mathcal{O}(\alpha)$ electroweak corrections for $p\bar{p}/pp \to WH + X$ and $p\bar{p}/pp \to ZH + X$ at the Tevatron and the LHC. The larger uncertainty band for the ZH production process at the LHC is due to the contribution of $gg \to HZ$.

4. CROSS-SECTION PREDICTIONS

Figure 4 shows the predictions for the cross sections of WH and ZH production at the LHC and the Tevatron, including the NNLO QCD and electroweak $\mathcal{O}(\alpha)$ corrections as discussed in the previous sections. At the LHC the process $gg \to ZH$ adds about 10% to the ZH production cross section, which is due to the large gluon flux; at the Tevatron this contribution is negligible.

Finally, we briefly summarize the discussion [8] of the uncertainty in the cross-section predictions

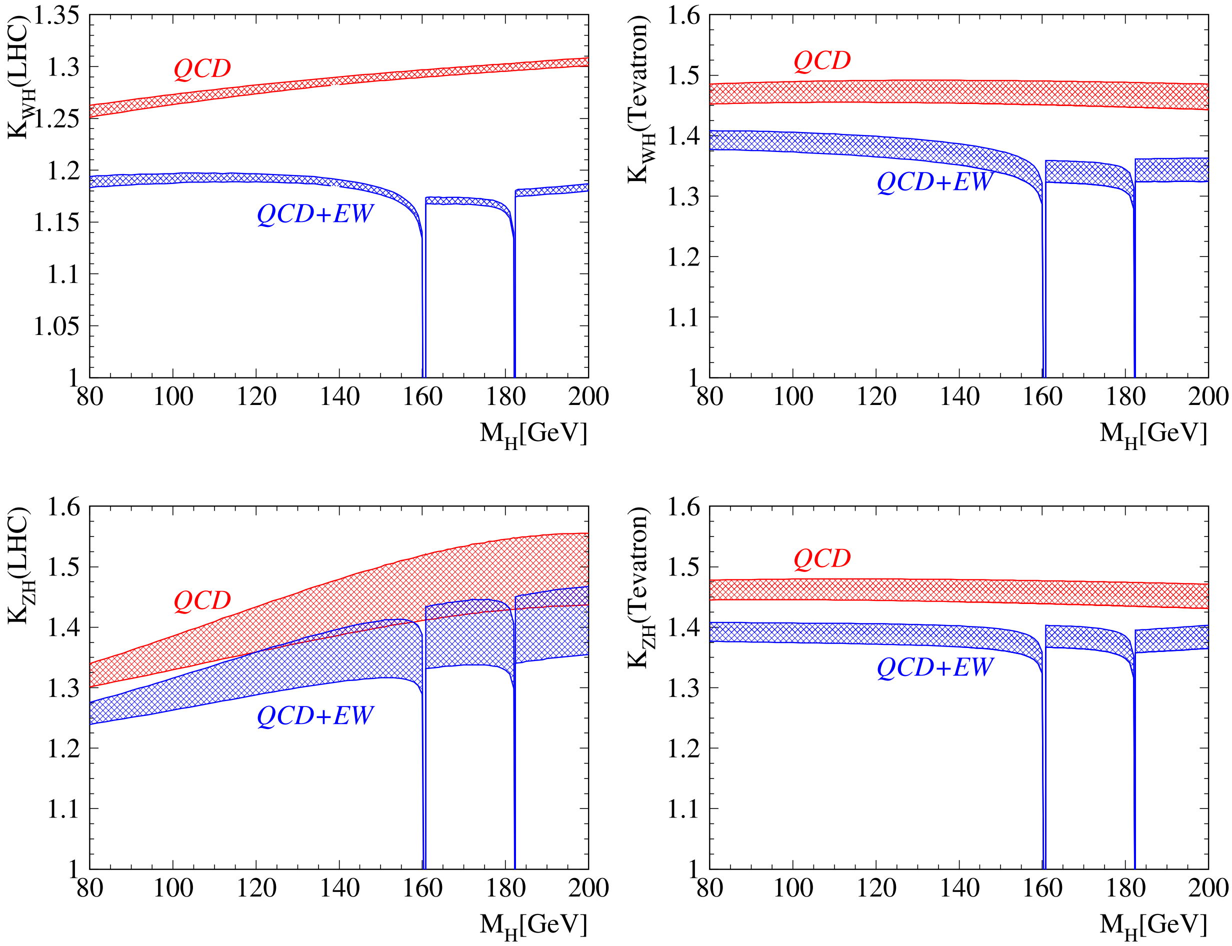

Fig. 3: K-factors for WH production and ZH production at the LHC (l.h.s.) and the Tevatron (r.h.s.) after inclusion of the NNLO QCD and electroweak $\mathcal{O}(\alpha)$ corrections. Theoretical errors as described in Figure 1.

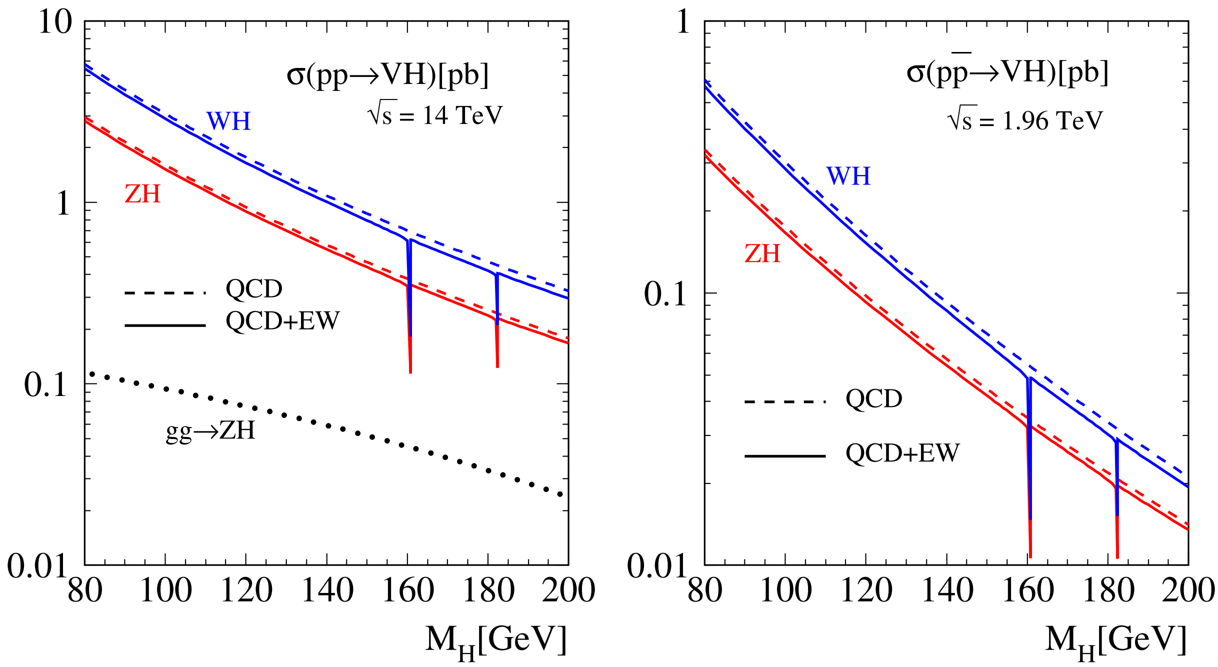

Fig. 4: Cross-section predictions (in the G_μ-scheme) for WH and ZH production at the LHC (l.h.s.) and the Tevatron (r.h.s.), including NNLO QCD and electroweak $\mathcal{O}(\alpha)$ corrections.

Table 1: Total cross sections (in fb) at the Tevatron ($\sqrt{s} = 1.96$ TeV) including NLO QCD and electroweak corrections in the G_μ-scheme for different sets of PDFs. The results include an estimate of the uncertainty due to the parametrization of the PDFs as obtained with the CTEQ6 [15] and MRST2001 [17] eigenvector sets. The renormalization and factorization scales have been set to the invariant mass of the Higgs–vector-boson pair, $\mu = \mu_0 = M_{VH}$. (Taken from Ref. [8].)

	$p\bar{p} \to WH + X$		$p\bar{p} \to ZH + X$	
M_H/GeV	CTEQ6M [15]	MRST2001 [17]	CTEQ6M [15]	MRST2001 [17]
100.00	268.5(1) $\pm$ 11	269.8(1) $\pm$ 5.2	158.9(1) $\pm$ 6.4	159.6(1) $\pm$ 2.0
120.00	143.6(1) $\pm$ 6.0	143.7(1) $\pm$ 3.0	88.20(1) $\pm$ 3.6	88.40(1) $\pm$ 1.1
140.00	80.92(1) $\pm$ 3.5	80.65(1) $\pm$ 1.8	51.48(1) $\pm$ 2.1	51.51(1) $\pm$ 0.66
170.00	36.79(1) $\pm$ 1.7	36.44(1) $\pm$ 0.91	24.72(1) $\pm$ 1.0	24.69(1) $\pm$ 0.33
190.00	22.94(1) $\pm$ 1.1	22.62(1) $\pm$ 0.60	15.73(1) $\pm$ 0.68	15.68(1) $\pm$ 0.21

Table 2: Same as in Table 1, but for the LHC ($\sqrt{s} = 14$ TeV) (Taken from Ref. [8].)

	$pp \to WH + X$		$pp \to ZH + X$	
M_H/GeV	CTEQ6M [15]	MRST2001 [17]	CTEQ6M [15]	MRST2001 [17]
100.00	2859(1) $\pm$ 96	2910(1) $\pm$ 35	1539(1) $\pm$ 51	1583(1) $\pm$ 19
120.00	1633(1) $\pm$ 55	1664(1) $\pm$ 21	895(3) $\pm$ 30	9217(3) $\pm$ 11
140.00	989(3) $\pm$ 34	1010(1) $\pm$ 12	551(2) $\pm$ 19	568.1(2) $\pm$ 6.7
170.00	508(1) $\pm$ 18	519.3(1) $\pm$ 6.3	290(1) $\pm$ 10	299.4(1) $\pm$ 3.6
190.00	347(1) $\pm$ 12	354.7(2) $\pm$ 4.3	197.8(1) $\pm$ 6.9	204.5(1) $\pm$ 2.5

due to the error in the parametrization of the parton densities (see also [16]). To this end the NLO cross section evaluated using the default CTEQ6 [15] parametrization with the cross section evaluated using the MRST2001 [17] parametrization are compared. The results are collected in Tables 1 and 2. Both the CTEQ and MRST parametrizations include parton-distribution-error packages which provide a quantitative estimate of the corresponding uncertainties in the cross sections.[1] Using the parton-distribution-error packages and comparing the CTEQ and MRST2001 parametrizations, we find that the uncertainty in predicting the WH and ZH production processes at the Tevatron and the LHC due to the parametrization of the parton densities is less than approximately 5%.

5. CONCLUSIONS

After the inclusion of QCD corrections up to NNLO and of the electroweak $\mathcal{O}(\alpha)$ corrections, the cross-section predictions for WH and ZH production are by now the most precise for Higgs production at hadron colliders. The remaining uncertainties should be dominated by renormalization and factorization scale dependences and uncertainties in the parton distribution functions, which are of the order of 3% and 5%, respectively. These uncertainties may be reduced by forming the ratios of the associated Higgs-production cross section with the corresponding Drell-Yan-like W- and Z-boson production channels, i.e. by inspecting $\sigma_{p\bar{p}/pp \to VH+X}/\sigma_{p\bar{p}/pp \to V+X}$, rendering their measurements particularly interesting at the Tevatron and/or the LHC.

[1] In addition, the MRST [18] parametrization allows to study the uncertainty of the NLO cross section due to the variation of α_s. For associated WH and ZH hadroproduction, the sensitivity of the theoretical prediction to the variation of α_s ($\alpha_\mathrm{s}(M_Z^2) = 0.119 \pm 0.02$) turns out to be below 2%.

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