Associated Higgs-W-Boson Production at Hadron Colliders: A Fully Exclusive QCD Calculation at NNLO

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We consider QCD radiative corrections to standard model Higgs-boson production in association with a W boson in hadron collisions. We present a fully exclusive calculation up to next-to-next-to-leading order (NNLO) in QCD perturbation theory. To perform this NNLO computation, we use a recently proposed version of the subtraction formalism. Our calculation includes finite-width effects, the leptonic decay of the W boson with its spin correlations, and the decay of the Higgs boson into a $b\bar{b}$ pair. We present selected numerical results at the Tevatron and the LHC.

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The search for the Higgs boson or its alternatives in theories beyond the standard model (SM) is the key endeavor of current high-energy colliders. The Tevatron has recently excluded at the 95% C.L. a SM Higgs boson in the mass range $158 < m_H < 173$ GeV [1]. At the LHC the Higgs-boson search has now started. If the LHC will confirm the Tevatron exclusion, the attention will move to the low mass region, where the Higgs-boson search is more difficult.

One of the most important production mechanisms of a light Higgs boson at hadron colliders is the so-called Higgs-strahlung process, i.e., the associated production of the Higgs boson together with a vector boson V ($V = W^{\pm}, Z$). At the Tevatron, this is the main search channel in the low mass region, $m_H \lesssim 140$ GeV, since the lepton(s) from the decay of the vector boson provide the necessary background rejection. At the LHC, this production channel has been considered less promising, due to the large backgrounds. Recent studies [2] have indicated that at large transverse momenta, employing modern jet reconstruction and decomposition techniques, WH and ZH production can be recovered as promising search modes for a light Higgs boson at the LHC.

In order to fully exploit this channel it is important to have accurate theoretical predictions for the production cross section and the associated distributions. Theoretical predictions with high precision demand in turn detailed computations of radiative corrections. The next-to-leading order (NLO) QCD corrections to VH production are the same as those of the Drell-Yan process [3]. Beyond NLO, the QCD corrections differ from those to the Drell-Yan process [4] by contributions where the Higgs boson couples to the gluons through a heavy-quark loop. (In the case of ZH production there are also gluon-gluon-induced terms where both the Z and H bosons couple to a heavy-quark loop [5].) The impact of these additional terms is, however, expected to be rather small. Using the classical result of Ref. [4], the computation of the NNLO inclusive cross section has been completed in Ref. [5]. Also, NLO electroweak corrections have been evaluated [6].

The effect of NNLO QCD radiative corrections on the inclusive cross section is relatively modest [5]. However, it is important to study how QCD corrections impact the accepted cross section and the relevant kinematical distributions. This is particularly true when severe selection cuts are applied, as it typically happens in Higgs-boson searches.

The evaluation of higher-order QCD radiative corrections to hard-scattering processes is well known to be a hard task. The presence of infrared singularities at intermediate stages of the calculation does not allow a straightforward implementation of numerical techniques. In particular, fully differential calculations at the NNLO involve a substantial amount of conceptual and technical complications [7–12]. In e^+e^- collisions, NNLO differential cross sections are known only for two [13,14] and three jet production [15,16]. In hadron-hadron collisions, fully differential cross sections have been computed only in the cases of Higgs-boson production by gluon fusion [17–19] and of the Drell-Yan process [20–22].

In this Letter we focus on WH production and we present the fully exclusive NNLO QCD computation for this process. The calculation is performed by using the subtraction formalism of Ref. [18], and it is based on an extension of the numerical program of Ref. [21]. We include finite-width effects, the leptonic decay of the W boson, with its spin correlations, and the decay of the Higgs boson into a $b\bar{b}$ pair. Only diagrams in which the Higgs boson is radiated by a W boson are considered; i.e., we neglect the contributions in which the Higgs boson couples to a heavy-quark loop. Comparing our results to those of Ref. [23], where NLO predictions for WH + jet, including these additional diagrams, are presented, we expect the neglected contributions to be at the 1% level or smaller. When no cuts are applied, and the W and H are produced on shell, our numerical results agree with those obtained with the program VH@NNLO [5].

In the following we present an illustrative selection of numerical results for WH production at the Tevatron and the LHC. We consider u, d, s, c, b quarks in the initial state and we use the (unitarity constrained) Cabibbo-Kobayashi-Maskawa matrix elements $V_{ud} = 0.974\,28$, $V_{us} = 0.2253$, $V_{ub} = 0.003\,47$, $V_{cd} = 0.2252$, $V_{cs} = 0.973\,45$, $V_{cb} = 0.0410$ from the Particle Data Group (PDG) 2010 [24]. As for the electroweak couplings, we use the so-called G_μ scheme, where the input parameters are G_F, m_Z, m_W. In particular we use the values $G_F = 1.166\,37 \times 10^{-5}\ \mathrm{GeV}^{-2}$, $m_Z = 91.1876$ GeV, $m_W = 80.399$ GeV, and $\Gamma_W = 2.085$ GeV. Throughout the Letter, we consider a SM Higgs boson with mass $m_H = 120$ GeV and width $\Gamma_H = 3.47$ MeV [25]. We compute the $H \to b\bar{b}$ decay at tree level in the massless approximation, and we normalize the $Hb\bar{b}$ Yukawa coupling such that the branching ratio is $\mathrm{BR}(H \to b\bar{b}) = 0.649$ [25]. We use the Martin-Stirling-Thorne-Watt 2008 (MSTW2008) [26] sets of parton distributions, with densities and α_S evaluated at each corresponding order [i.e., we use $(n+1)$ loop α_S at N^{n}LO, with $n = 0, 1, 2$]. The central values of the renormalization and factorization scales are fixed to the value $\mu_R = \mu_F = m_W + m_H$.

We start the presentation of our results by considering WH production at the Tevatron ($p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV). We use the following cuts (see, e.g., Ref. [27]). We require the charged lepton to have transverse momentum $p_T^l > 20$ GeV and pseudorapidity $|\eta_l| < 2$, and the missing transverse momentum of the event to fulfil $p_T^{\mathrm{miss}} > 20$ GeV. Jets are reconstructed with the k_T algorithm with $R = 0.4$ [28]. We require exactly two jets with $p_T > 20$ GeV and $|\eta| < 2$, and at least one of them has to be a b jet, with $|\eta| < 1$.

In Table I we report the accepted cross section (throughout the Letter the errors on the values of the cross sections and the error bars in the plots refer to an estimate of the numerical errors in the Monte Carlo integration) at LO, NLO, and NNLO in the case of three different scale choices around the central value $\mu_F = \mu_R = m_W + m_H$. The impact of NLO (NNLO) corrections ranges from +13% to +30% (− 1% to +4%), depending on the scale choice. The scale dependence is at the level of about ±1% both at NLO and NNLO.

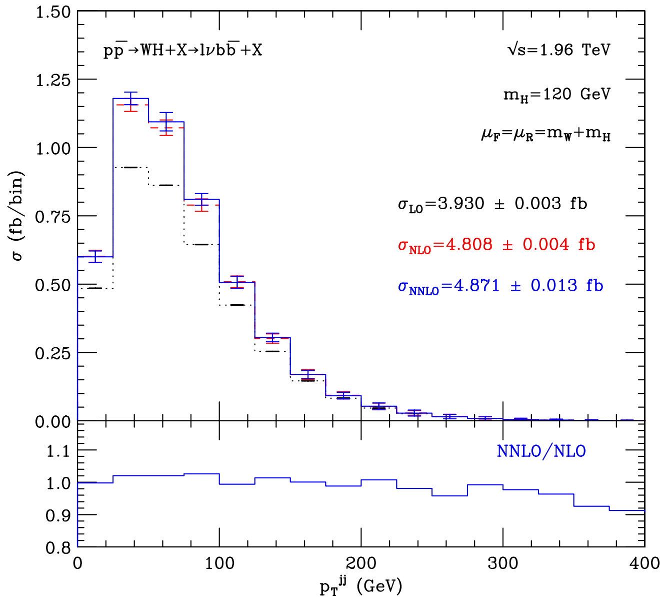

FIG. 1 (color online). Transverse-momentum spectrum of the dijet system for $p\bar{p} \to WH + X \to l\nu b\bar{b} + X$ at the Tevatron at LO (dots), NLO (dashes), and NNLO (solid). The applied cuts are described in the text.

In Fig. 1 we show the transverse-momentum spectrum of the dijet system at LO, NLO, NNLO. The lower panel of the figure shows the NNLO to NLO ratio. We see that the shape of the spectrum is rather stable, when going from NLO to NNLO, within the statistical uncertainties.

We now consider WH production at the LHC ($\sqrt{s} = 14$ TeV). We follow the selection strategy of Ref. [2] (see also [29]): the Higgs boson is searched for at large transverse momenta through its decay into a collimated $b\bar{b}$ pair. We require the charged lepton to have $p_T^l > 30$ GeV and $|\eta_l| < 2.5$, and the missing transverse momentum of the event to fulfil $p_T^{\mathrm{miss}} > 30$ GeV. We also require the W boson to have $p_T^W > 200$ GeV. Jets are reconstructed with the Cambridge-Aachen algorithm [30], with $R = 1.2$. One of the jets (fat jet) must have $p_T^J > 200$ GeV and $|\eta_J| < 2.5$ and must contain the $b\bar{b}$ pair. There should not be other jets with $p_T > 20$ GeV and $|\eta| < 5$.

In Table II we report the corresponding accepted cross sections at LO, NLO, and NNLO. We see that the impact of NLO and NNLO corrections is negative and larger than at

TABLE I. Cross sections for $p\bar{p} \to WH + X \to l\nu_l b\bar{b} + X$ at the Tevatron. The applied cuts are described in the text.

σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = (m_W + m_H)/2$	4.266 ± 0.003	4.840 ± 0.005	4.788 ± 0.013
$\mu_F = \mu_R = m_W + m_H$	3.930 ± 0.003	4.808 ± 0.004	4.871 ± 0.013
$\mu_F = \mu_R = 2(m_W + m_H)$	3.639 ± 0.002	4.738 ± 0.004	4.908 ± 0.010

TABLE II. Cross sections for $pp \to WH + X \to l\nu_l b\bar{b} + X$ at the LHC. The applied cuts are described in the text.

σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = (m_W + m_H)/2$	2.640 ± 0.002	1.275 ± 0.003	1.193 ± 0.017
$\mu_F = \mu_R = m_W + m_H$	2.617 ± 0.003	1.487 ± 0.003	1.263 ± 0.014
$\mu_F = \mu_R = 2(m_W + m_H)$	2.584 ± 0.003	1.663 ± 0.002	1.346 ± 0.013

the Tevatron. The NLO (NNLO) effect ranges from -52% to -36% (-6% to -19%), depending on the scale choice. The scale dependence goes from about $\pm 13\%$ at NLO to about $\pm 6\%$ at NNLO. The NLO and NNLO accepted cross sections are compatible within the scale uncertainties.

In Fig. 2 we show the transverse-momentum spectrum of the fat jet at LO, NLO, and NNLO. The lower panel shows the NNLO to NLO ratio. We see that the shape of the distribution is relatively stable when going from NLO to NNLO.

We add a few comments on the different impact of QCD radiative corrections at the Tevatron and at the LHC [31]. At the Tevatron, the invariant mass of the WH system is $M_{WH} \sim m_W + m_H$. The typical scale of the accompanying QCD radiation is of the order of about $\langle 1 - z \rangle M_{WH}$, where $\langle 1 - z \rangle = \langle 1 - M_{WH}^2/\hat{s} \rangle$ is the average distance from the partonic threshold. The effect of the veto on additional jets is thus marginal if the jet veto scale p_T^{veto} is of the order of $\langle 1 - z \rangle M_{WH}$. In this case the perturbative expansion appears under good control. The situation at the LHC is different in two respects. First, the invariant mass of the

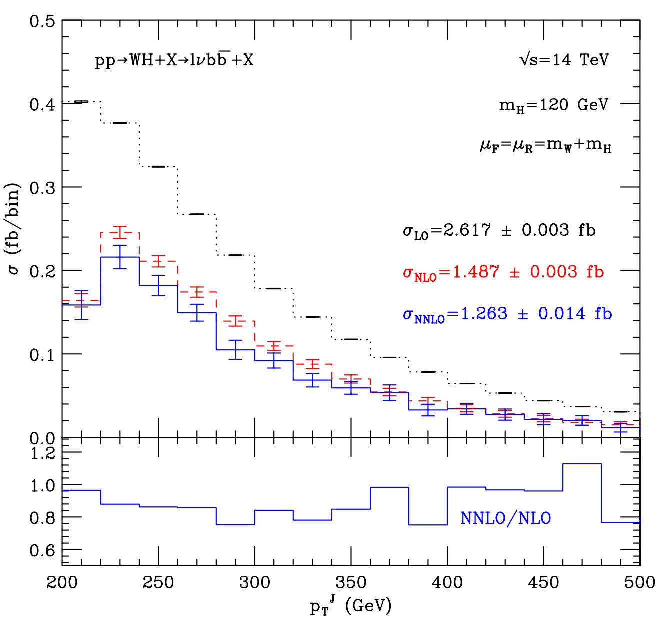

FIG. 2 (color online). Transverse-momentum spectra of the fat jet for $pp \to WH + X \to l\nu b\bar{b} + X$ at the LHC at LO (dots), NLO (dashes), and NNLO (solid). The applied cuts are described in the text.

WH system is larger, due to the high p_T required for the W and the Higgs-boson candidate. Second, the typical distance from the partonic threshold is larger, i.e., $\langle 1 - z \rangle$ is larger than at the Tevatron, due to the increased $\sqrt{s}$. As a consequence, a stringent veto on the radiation recoiling against the WH system spoils the cancellation of the infrared singularities in real and virtual corrections, and contributions enhanced by the logarithm of the ratio $(1 - z)M_{WH}/p_T^{\mathrm{veto}}$ are definitely relevant. We have checked that the reduction in the accepted cross section is in fact due to the jet veto, the impact of QCD corrections being positive if the jet veto is removed.

We have illustrated a calculation of the NNLO cross section for WH production in hadron collisions. The calculation is implemented in a parton level event generator and allows us to apply arbitrary kinematical cuts on the W and H decay products as well as on the accompanying QCD radiation. We have studied the impact of NNLO QCD corrections in two typical cases at the Tevatron and the LHC. At the Tevatron, the perturbative expansion appears under good control. At the LHC, by searching for events where the Higgs boson is boosted at high p_T, the impact of QCD corrections is more sizable, and the stability of the fixed-order calculation is challenged. More detailed studies, along the lines of Refs. [32,33], are needed in order to assess the relevance of these fixed-order perturbative result.

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