

Higher-order radiative corrections for $b\bar{b} \rightarrow H^- W^+$

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I present higher-order radiative corrections from collinear and soft-gluon emission for the associated production of a charged Higgs boson with a W boson. The calculation uses expressions from resummation at next-to-leading-logarithm accuracy. From the resummed cross section I derive analytical formulas at approximate next-to-next-to-leading order and next-to-next-to-next-to-leading order. Total cross sections are presented for the process $b\bar{b} \rightarrow H^- W^+$ at various LHC energies. The transverse momentum and rapidity distributions of the charged Higgs boson are also calculated.

DOI: [10.1103/PhysRevD.97.034002](https://doi.org/10.1103/PhysRevD.97.034002)**I. INTRODUCTION**

Higgs bosons play a central role in both the Standard Model and in searches for new physics. Two-Higgs-doublet models in new physics scenarios, such as the minimal supersymmetric Standard Model, involve charged Higgs bosons in addition to neutral ones. One of the Higgs doublets gives mass to up-type fermions while the other to down-type fermions, with the ratio of the vacuum expectation values for the two doublets denoted by $\tan\beta$. Two charged Higgs bosons, H^+ and H^- , appear in such models.

An important charged Higgs production process at LHC energies is the associated production of a charged Higgs boson with a W boson, which may proceed via the partonic process $b\bar{b} \rightarrow H^- W^+$ or $b\bar{b} \rightarrow H^+ W^-$. This process was studied in Refs. [1–18], and various kinds of radiative corrections were calculated in those works. There is good potential for the LHC to discover charged Higgs bosons via this process, so it is useful to calculate higher-order corrections that may enhance the cross section.

An important set of higher-order corrections is due to soft-gluon emission, dominant near partonic threshold; another is due to collinear gluon emission. These corrections can in principle be resummed, and the resummation formalism can be used to construct approximate higher-order results.

In this paper I present a first study of collinear and soft-gluon resummation for the associated production of a charged Higgs boson with a W boson via b -quark annihilation. Since the charged Higgs boson is presumably very massive, its possible production at the LHC would be a near-threshold process.

I employ the resummation formalism that has been used for several related processes, including charged Higgs production in association with a top quark [19,20], neutral Higgs production via $b\bar{b}$ annihilation [21], W or Z production at large transverse momentum [22], top-quark production in association with a W boson [20,23,24], and top-antitop pair production [23,25].

In the next section I discuss collinear and soft-gluon corrections and present their resummation. Using the expansion of the resummed cross section at next-to-leading order (NLO), next-to-next-to-leading order (NNLO), and next-to-next-to-next-to-leading order (N^3 LO), I derive approximate NLO (aNLO), approximate NNLO (aNNLO), and approximate N^3 LO (aN 3 LO) cross sections. In Sec. III I present results for $H^- W^+$ total cross sections at LHC energies. In Sec. IV I present results for the charged Higgs transverse momentum and rapidity distributions in this process. I conclude in Sec. V.

II. COLLINEAR AND SOFT-GLUON RESUMMATION FOR $b\bar{b} \rightarrow H^- W^+$

For the process $b\bar{b} \rightarrow H^- W^+$, involving bottom quarks in the initial state, I assign the momenta

$$b(p_1) + \bar{b}(p_2) \rightarrow H^-(p_3) + W^+(p_4) \quad (2.1)$$

and define the kinematical variables $s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$, $t_1 = t - m_H^2$, $t_2 = t - m_W^2$, $u = (p_2 - p_3)^2$, $u_1 = u - m_H^2$, and $u_2 = u - m_W^2$, where m_H is the charged Higgs mass and m_W is the W -boson mass while the b -quark mass is taken to be 0. I note that I work in the five-flavor scheme where the b -quark is treated as a parton in the proton.

I also define the variable $s_4 = s + t_1 + u_2$, which measures distance from partonic threshold where there is no energy for additional emission; however, even when $s_4 = 0$ the charged Higgs boson and the W boson are not

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constrained to be produced at rest. I note that identical considerations apply to H^+W^- production.

Radiative corrections, including collinear and soft-gluon corrections, appear at each order in the perturbative expansion of the cross section. The resummation of these corrections in our formalism is performed for the double-differential cross section in single-particle-inclusive (1PI) kinematics, in terms of the variable s_4 . I note that while resummation for colorless final states is well established, previous studies have not been done in 1PI kinematics but have instead used the more inclusive variable $z = M^2/s$, where M is the invariant mass of the final state. Therefore, the present work is distinct from other work on Higgs or other electroweak final states. Using the s_4 resummation introduces several additional new terms in the expressions for the higher-order corrections, as I will discuss later. Furthermore, my 1PI resummation formalism allows the calculation of higher-order soft-gluon contributions to the Higgs transverse momentum and rapidity distributions, something which is not possible with the resummation in invariant mass.

The soft-gluon terms are plus distributions of logarithms of s_4 , $[\ln^k(s_4/m_H^2)/s_4]_+$, with k an integer ranging from 0 to $2n-1$ for the n th order corrections in the strong coupling, α_s . The plus distributions are defined by their integrals with functions f , which in our case involve perturbative coefficients and parton distribution functions (pdf) as discussed later, via the expression

$$\begin{aligned} & \int_0^{s_4^{\max}} ds_4 \left[\frac{\ln^k(s_4/m_H^2)}{s_4} \right]_+ f(s_4) \\ &= \int_0^{s_4^{\max}} ds_4 \frac{\ln^k(s_4/m_H^2)}{s_4} [f(s_4) - f(0)] \\ & \quad + \frac{1}{k+1} \ln^{k+1} \left(\frac{s_4^{\max}}{m_H^2} \right) f(0). \end{aligned} \quad (2.2)$$

In addition, further logarithmic terms of the form $(1/m_H^2) \ln^k(s_4/m_H^2)$, of collinear origin, also appear in the perturbative expansion. These collinear terms are fully known only at leading logarithmic accuracy. In this paper I provide the first analytical and numerical study of such terms in 1PI kinematics with the s_4 variable.

Resummation of collinear and soft-gluon contributions follows from the factorization of the cross section into various functions that describe collinear and soft emission in the partonic process. Taking moments of the partonic scattering cross section, $\hat{\sigma}(N) = \int (ds_4/s) e^{-Ns_4/s} \hat{\sigma}(s_4)$, with N the moment variable, I write a factorized expression in $4-\epsilon$ dimensions:

$$\begin{aligned} \hat{\sigma}^{H^+W^+}(N, \epsilon) &= \left(\prod_{i=b, \bar{b}} J_i(N, \mu, \epsilon) \right) H^{H^+W^+}(\alpha_s(\mu)) \\ & \quad \times S^{H^+W^+} \left(\frac{m_H}{N\mu}, \alpha_s(\mu) \right), \end{aligned} \quad (2.3)$$

where μ is the scale, J_i are jet functions that describe soft and collinear emission from the incoming b and \bar{b} quarks, $H^{H^+W^+}$ is the hard-scattering function, and $S^{H^+W^+}$ is the soft-gluon function for noncollinear soft-gluon emission. The lowest-order cross section is given by the product of the lowest-order hard and soft functions.

The soft function $S^{H^+W^+}$ requires renormalization, and its N dependence can be resummed via renormalization group evolution. Thus, $S^{H^+W^+}$ satisfies the renormalization group equation

$$\left(\mu \frac{\partial}{\partial \mu} + \beta(g_s, \epsilon) \frac{\partial}{\partial g_s} \right) S^{H^+W^+} = -2S^{H^+W^+} \Gamma_S^{H^+W^+}, \quad (2.4)$$

where $g_s^2 = 4\pi\alpha_s$; $\beta(g_s, \epsilon) = -g_s\epsilon/2 + \beta(g_s)$ with $\beta(g_s)$ the QCD beta function; and $\Gamma_S^{H^+W^+}$ is the soft anomalous dimension that controls the evolution of the soft-gluon function $S^{H^+W^+}$.

The evolution of the soft and jet functions provides resummed expressions for the cross section [19–25]. For H^+W^+ production the resummed partonic cross section in moment space is given by

$$\begin{aligned} \hat{\sigma}_{\text{res}}^{H^+W^+}(N) &= \exp \left[\sum_{i=b, \bar{b}} E_i(N_i) \right] H^{H^+W^+}(\alpha_s(\sqrt{s})) \\ & \quad \times S^{H^+W^+}(\alpha_s(\sqrt{s}/\tilde{N}')) \\ & \quad \times \exp \left[2 \int_{\sqrt{s}}^{\sqrt{s}/\tilde{N}'} \frac{d\mu}{\mu} \Gamma_S^{H^+W^+}(\alpha_s(\mu)) \right]. \end{aligned} \quad (2.5)$$

The first exponent [26,27] in Eq. (2.5) resums soft and collinear corrections from the incoming b and \bar{b} quarks and is well known (see [20,21,23] for details). Since the resummation is performed in 1PI kinematics, I have $N_b = N(-u_2/m_H^2)$ and $N_{\bar{b}} = N(-t_2/m_H^2)$, and this generates logarithms involving t_2 and u_2 in the fixed-order expansions. This is an important point, as no such terms appear in invariant-mass resummations, for which $N_b = N_{\bar{b}} = N$.

The specific forms of the expressions for the individual terms in Eq. (2.5) depend on the gauge, although the overall result for the resummed cross section of course does not. In Feynman gauge the one-loop soft anomalous dimension for $b\bar{b} \rightarrow H^+W^+$ vanishes; in axial gauge it is $(\alpha_s/\pi)C_F$, where $C_F = (N_c^2 - 1)/(2N_c)$ with $N_c = 3$ the number of colors. I calculate the soft-gluon corrections at next-to-leading-logarithm accuracy. However, as mentioned previously, only the leading collinear corrections are fully known.

I expand the resummed cross section, Eq. (2.5), in α_s , and then I invert to momentum space. I provide explicit analytical results through third order for the collinear and soft-gluon corrections.

The NLO collinear and soft-gluon corrections from the resummation are

$$\begin{aligned} \frac{d^2 \hat{\sigma}^{(1)}}{dt du} = & \frac{\pi \alpha^2 m_i^4 \cot^2 \beta}{48 \sin^4 \theta_W m_W^4 s^2 t_1^2} (m_W^2 s + t_2 u_2) \frac{\alpha_s(\mu_R)}{\pi} C_F \left\{ -\frac{4}{m_H^2} \ln \left(\frac{s_4}{m_H^2} \right) + 4 \left[\frac{\ln(s_4/m_H^2)}{s_4} \right]_+ - 2 \left[\ln \left(\frac{t_2 u_2}{m_H^4} \right) + \ln \left(\frac{\mu_F^2}{s} \right) \right] \left[\frac{1}{s_4} \right]_+ \right. \\ & \left. + \left[\ln \left(\frac{t_2 u_2}{m_H^4} \right) - \frac{3}{2} \right] \ln \left(\frac{\mu_F^2}{m_H^2} \right) \delta(s_4) \right\}, \end{aligned} \quad (2.6)$$

where $\alpha = e^2/(4\pi)$, θ_W is the weak mixing angle, μ_R is the renormalization scale, and μ_F is the factorization scale. I note that the logarithmic terms involving the variables t_2 and u_2 in the above expression arise from the 1PI nature of our resummation and would not appear in an invariant-mass resummation.

The NNLO collinear and soft-gluon corrections from the resummation are

$$\begin{aligned} \frac{d^2 \hat{\sigma}^{(2)}}{dt du} = & \frac{\pi \alpha^2 m_i^4 \cot^2 \beta}{48 \sin^4 \theta_W m_W^4 s^2 t_1^2} (m_W^2 s + t_2 u_2) \frac{\alpha_s^2(\mu_R)}{\pi^2} C_F \left\{ -8C_F \frac{1}{m_H^2} \ln^3 \left(\frac{s_4}{m_H^2} \right) + 8C_F \left[\frac{\ln^3(s_4/m_H^2)}{s_4} \right]_+ \right. \\ & + \left[-12C_F \left(\ln \left(\frac{t_2 u_2}{m_H^4} \right) + \ln \left(\frac{\mu_F^2}{s} \right) \right) - \frac{11}{3} C_A + \frac{2}{3} n_f \right] \left[\frac{\ln^2(s_4/m_H^2)}{s_4} \right]_+ \\ & + \left[4C_F \ln^2 \left(\frac{\mu_F^2}{m_H^2} \right) + C_F \left(12 \ln \left(\frac{t_2 u_2}{m_H^4} \right) + 8 \ln \left(\frac{m_H^2}{s} \right) - 6 \right) \ln \left(\frac{\mu_F^2}{m_H^2} \right) + \left(\frac{11}{3} C_A - \frac{2}{3} n_f \right) \ln \left(\frac{\mu_R^2}{m_H^2} \right) \right] \left[\frac{\ln(s_4/m_H^2)}{s_4} \right]_+ \\ & \left. + \left[\left(-2C_F \ln \left(\frac{t_2 u_2}{m_H^4} \right) + 3C_F + \frac{11}{12} C_A - \frac{n_f}{6} \right) \ln^2 \left(\frac{\mu_F^2}{m_H^2} \right) - \left(\frac{11}{6} C_A - \frac{n_f}{3} \right) \ln \left(\frac{\mu_F^2}{m_H^2} \right) \ln \left(\frac{\mu_R^2}{m_H^2} \right) \right] \left[\frac{1}{s_4} \right]_+ \right\}, \end{aligned} \quad (2.7)$$

where $C_A = N_c$, and $n_f = 5$ is the number of light-quark flavors. Again, the logarithmic terms involving the variables t_2 and u_2 in the above expression arise from the 1PI nature of the resummation.

Equation (2.7) can be written more compactly as

$$\frac{d^2 \hat{\sigma}^{(2)}}{dt du} = F_{\text{LO}} \frac{\alpha_s^2}{\pi^2} \left\{ -C_3^{(2)} \frac{1}{m_H^2} \ln^3 \left(\frac{s_4}{m_H^2} \right) + \sum_{k=0}^3 C_k^{(2)} \left[\frac{\ln^k(s_4/m_H^2)}{s_4} \right]_+ \right\}, \quad (2.8)$$

where F_{LO} denotes the overall leading-order factor and the $C_k^{(2)}$ are coefficients of the logarithms, and they can be read off by comparing Eq. (2.8) with Eq. (2.7), e.g. $C_3^{(2)} = 8C_F^2$. This compact form for the aNNLO corrections will be useful in the next section.

Finally, one can consider the contribution of even higher-order corrections, although not all logarithms can be determined. The N³LO collinear and soft-gluon corrections from the resummation are

$$\frac{d^2 \hat{\sigma}^{(3)}}{dt du} = F_{\text{LO}} \frac{\alpha_s^3}{\pi^3} \left\{ -C_5^{(3)} \frac{1}{m_H^2} \ln^5 \left(\frac{s_4}{m_H^2} \right) + \sum_{k=0}^5 C_k^{(3)} \left[\frac{\ln^k(s_4/m_H^2)}{s_4} \right]_+ \right\}, \quad (2.9)$$

where the $C_k^{(3)}$ are coefficients of the logarithms. I have $C_5^{(3)} = 8C_F^3$,

$$C_4^{(3)} = -20C_F^3 \left[\ln \left(\frac{t_2 u_2}{m_H^4} \right) + \ln \left(\frac{\mu_F^2}{s} \right) \right] - \frac{10}{3} \beta_0 C_F^2, \quad (2.10)$$

$$C_3^{(3)} = -64C_F^3 \zeta_2 + 8C_F^3 \ln \left(\frac{\mu_F^2}{m_H^2} \right) \left[2 \ln \left(\frac{\mu_F^2}{m_H^2} \right) + 4 \ln \left(\frac{m_H^2}{s} \right) + 5 \ln \left(\frac{t_2 u_2}{m_H^4} \right) - \frac{3}{2} \right] + 4C_F^2 \beta_0 \left[\frac{2}{3} \ln \left(\frac{\mu_F^2}{m_H^2} \right) + \ln \left(\frac{\mu_R^2}{m_H^2} \right) \right], \quad (2.11)$$

$$\begin{aligned} C_2^{(3)} = & 160C_F^3 \zeta_3 - 4C_F^3 \ln^3 \left(\frac{\mu_F^2}{m_H^2} \right) - 12C_F^3 \ln^2 \left(\frac{\mu_F^2}{m_H^2} \right) \left[2 \ln \left(\frac{t_2 u_2}{m_H^4} \right) + \ln \left(\frac{m_H^2}{s} \right) - \frac{3}{2} \right] + 96C_F^3 \zeta_2 \left[\ln \left(\frac{t_2 u_2}{m_H^4} \right) + \ln \left(\frac{\mu_F^2}{s} \right) \right] \\ & - 6\beta_0 C_F^2 \ln \left(\frac{\mu_F^2}{m_H^2} \right) \ln \left(\frac{\mu_R^2}{m_H^2} \right) + \frac{3}{2} \beta_0 C_F^2 \ln^2 \left(\frac{\mu_F^2}{m_H^2} \right), \end{aligned} \quad (2.12)$$

$$\begin{aligned} C_1^{(3)} = & -160C_F^3 \zeta_3 \ln \left(\frac{\mu_F^2}{m_H^2} \right) + 4C_F^3 \ln^3 \left(\frac{\mu_F^2}{m_H^2} \right) \left[\ln \left(\frac{t_2 u_2}{m_H^4} \right) - \frac{3}{2} \right] + C_F^2 \beta_0 \ln^2 \left(\frac{\mu_F^2}{m_H^2} \right) \left[2 \ln \left(\frac{\mu_R^2}{m_H^2} \right) - \ln \left(\frac{\mu_F^2}{m_H^2} \right) \right] - 40C_F^3 \zeta_2 \ln^2 \left(\frac{\mu_F^2}{m_H^2} \right) \\ & - 24C_F^3 \zeta_2 \ln^2 \left(\frac{\mu_F^2}{m_H^2} \right) \left[4 \ln \left(\frac{t_2 u_2}{m_H^4} \right) + \frac{10}{3} \ln \left(\frac{m_H^2}{s} \right) - 1 \right]. \end{aligned} \quad (2.13)$$

In the above expressions, $\beta_0 = (11C_A - 2n_f)/3$. Once again, the logarithmic terms involving the variables t_2 and u_2 in the above expression arise from the details of the 1PI resummation.

III. TOTAL CROSS SECTIONS FOR $H^- W^+$ PRODUCTION

I consider proton-proton collisions with momenta $p(p_A) + p(p_B) \rightarrow H^-(p_3) + W^+(p_4)$. In analogy to the partonic variables defined in Sec. II, I define the hadronic kinematical variables $S = (p_A + p_B)^2$, $T = (p_A - p_3)^2$, $T_1 = T - m_H^2$, $T_2 = T - m_W^2$, $U = (p_B - p_3)^2$, and $U_1 = U - m_H^2$. The hadronic variables are related to the partonic variables via $p_1 = x_1 p_A$ and $p_2 = x_2 p_B$, where x_1 and x_2 are the fractions of the momentum carried by the partons in protons A and B , respectively.

The hadronic total cross section can be written as

$$\sigma^{H^- W^+} = \int_{T^{\min}}^{T^{\max}} dT \int_{U^{\min}}^{U^{\max}} dU \int_{x_2^{\min}}^1 dx_2 \times \int_0^{s_4^{\max}} ds_4 \frac{x_1 x_2}{x_2 S + T_1} \phi(x_1) \phi(x_2) \frac{d^2 \hat{\sigma}}{dt du}, \quad (3.1)$$

where the ϕ denotes the pdf; $x_1 = (s_4 - m_H^2 + m_W^2 - x_2 U_1) / (x_2 S + T_1)$; $T^{\min} = -(1/2)(S - m_H^2 - m_W^2) \pm (1/2)[(S - m_H^2 - m_W^2)^2 - 4m_H^2 m_W^2]^{1/2}$; $U^{\max} = m_H^2 + S m_H^2 / T_1$ and $U^{\min} = -S - T_1 + m_W^2$; $x_2^{\min} = -T_2 / (S + U_1)$; and $s_4^{\max} = x_2(S + U_1) + T_2$.

Specifically, using the properties of plus distributions, Eq. (2.2), and the compact form of Eq. (2.8), the aNNLO corrections to the total cross section, Eq. (3.1), can be written as

$$\sigma_{H^- W^+}^{(2)} = \frac{\alpha_s^2}{\pi^2} \int_{T^{\min}}^{T^{\max}} dT \int_{U^{\min}}^{U^{\max}} dU \int_{x_2^{\min}}^1 dx_2 \phi(x_2) \frac{x_2}{x_2 S + T_1} \times \left\{ - \int_0^{s_4^{\max}} ds_4 \frac{1}{m_H^2} \ln^3 \left(\frac{s_4}{m_H^2} \right) F_{\text{LO}} C_3^{(2)} x_1 \phi(x_1) + \sum_{k=0}^3 \left[\int_0^{s_4^{\max}} ds_4 \frac{1}{s_4} \ln^k \left(\frac{s_4}{m_H^2} \right) (F_{\text{LO}} C_k^{(2)} x_1 \phi(x_1) - F_{\text{LO}}^{\text{el}} C_k^{(2)\text{el}} x_1^{\text{el}} \phi(x_1^{\text{el}})) + \frac{1}{k+1} \ln^{k+1} \left(\frac{s_4^{\max}}{m_H^2} \right) F_{\text{LO}}^{\text{el}} C_k^{(2)\text{el}} x_1^{\text{el}} \phi(x_1^{\text{el}}) \right] \right\}, \quad (3.2)$$

where x_1^{el} , $F_{\text{LO}}^{\text{el}}$, and $C_k^{(2)\text{el}}$ denote the elastic variables, i.e. these quantities with $s_4 = 0$. Analogous results can be written for the aNLO and aN³LO corrections.

I now present results for the total $H^- W^+$ cross section at LHC energies using MMHT2014 NNLO pdf [28]. For convenience I set $\tan\beta = 1$, but it is easy to rescale the results for any value of $\tan\beta$.

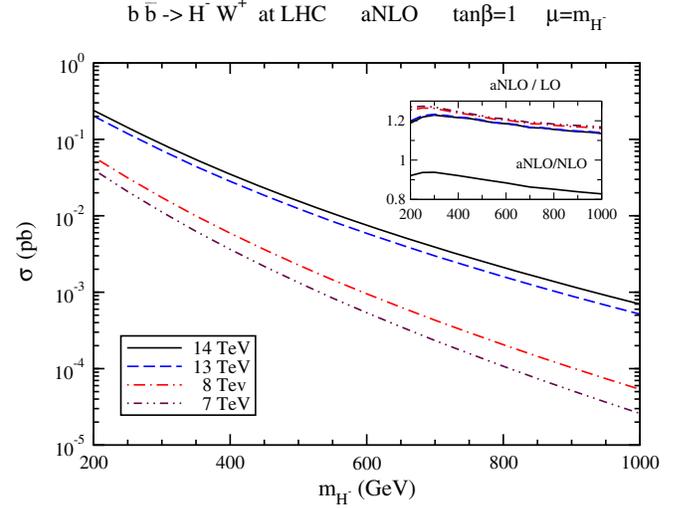


FIG. 1. The aNLO cross sections for $b\bar{b} \rightarrow H^- W^+$ at the LHC with $\sqrt{S} = 7, 8, 13,$ and 14 TeV.

In Fig. 1 I plot the aNLO cross sections for $b\bar{b} \rightarrow H^- W^+$ in proton-proton collisions at the LHC versus charged Higgs mass for energies of 7, 8, 13, and 14 TeV. The cross sections vary greatly with charged Higgs mass, falling by 3 orders of magnitude over the mass range at each energy. I also observe an order of magnitude or so increase in the cross section at 13 and 14 TeV relative to 7 and 8 TeV.

The inset plot of Fig. 1 shows the K factors, i.e. the ratios of cross sections at various orders. The four lines at the top of the inset plot show the aNLO/LO ratios for the four LHC energies. The corrections are clearly very significant for all LHC energies. I also note that the K factors at different energies are rather similar and are slightly higher for smaller energies.

It is also important to determine how much of the full NLO corrections [6] are accounted for by the soft and collinear contributions. The lower line in the inset plot of Fig. 1 shows the aNLO/NLO ratio at 14 TeV energy. I see that the ratio is close to 1 for smaller charged Higgs masses and that it remains above 0.9 up to a mass of 500 GeV, indicating that the soft and collinear gluon corrections are dominant and provide numerically the majority of the NLO corrections. The ratio remains well above 0.8 through 1000 GeV, showing that the collinear and soft-gluon corrections are still large and significant.

In Fig. 2 I plot the aNNLO cross sections for $b\bar{b} \rightarrow H^- W^+$ versus charged Higgs mass for LHC energies of 7, 8, 13, and 14 TeV. Again, I observe a large increase in the cross section at 13 and 14 TeV relative to 7 and 8 TeV, and a large dependence of the cross section on the mass of the charged Higgs boson between 200 and 1000 GeV at each energy. The inset plot shows the aNNLO/LO K factors.

I note that the leading collinear terms by themselves make a significant contribution to the total collinear plus soft corrections. For example, for 200 GeV charged Higgs

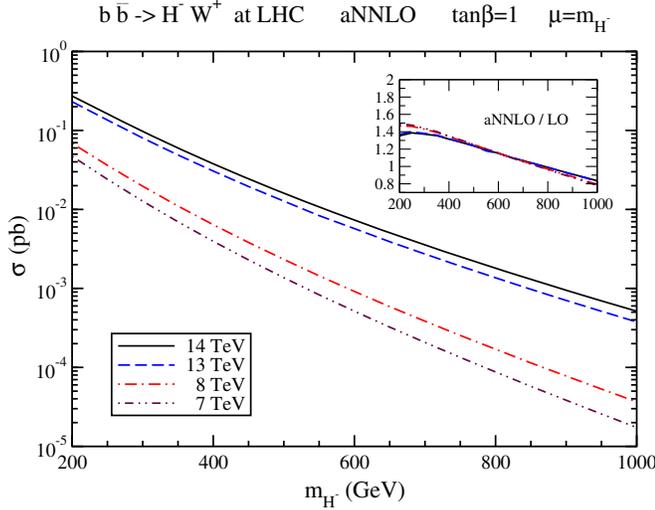


FIG. 2. The aNNLO cross sections for $b\bar{b} \rightarrow H^- W^+$ at the LHC with $\sqrt{S} = 7, 8, 13,$ and 14 TeV.

mass at 13 TeV energy, they amount to 20% of the aNNLO corrections.

Theoretical uncertainties arise from scale variation as well as from pdf uncertainties. Scale variation by a factor of 2 around the central scale $\mu = m_H$ produces a moderate uncertainty, $\pm 15\%$ at 13 TeV LHC energy for a 500 GeV charged Higgs, with similar numbers at other energies. The uncertainties from the pdf are smaller, $\pm 5\%$ at 13 TeV for a 500 GeV charged Higgs.

I find that results using other pdf sets are very similar. If one uses the CT14 NNLO pdf [29], the results are essentially the same.

I note that the aN³LO corrections are incomplete and that their numerical contributions are typically small relative to the aNLO and aNNLO corrections. For example, for 300 GeV charged Higgs mass at 13 TeV energy, the aNLO corrections contribute a 23% enhancement, the aNNLO corrections an additional 14% enhancement, and the aN³LO corrections a further 2% enhancement. The fact that the aN³LO corrections are much smaller than the corrections at previous orders is an indication of perturbative convergence and is also in line with related results for Higgs production and top-quark production (see e.g. [25]). Since the uncertainty due to unknown terms at aN³LO can be of the order of the size of these corrections, I do not study them further. I also note that there are no pdf available at N³LO for such calculations, and the effect of such pdf may also be non-negligible.

IV. CHARGED HIGGS p_T AND RAPIDITY DISTRIBUTIONS

I continue with the charged Higgs p_T and rapidity distributions. The charged Higgs p_T distribution is given by

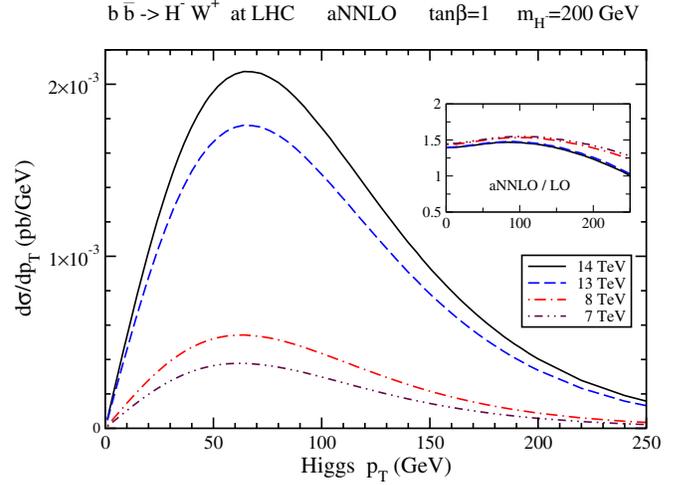


FIG. 3. The aNNLO charged Higgs p_T distributions for $b\bar{b} \rightarrow H^- W^+$ at the LHC with $\sqrt{S} = 7, 8, 13,$ and 14 TeV, and $m_H = 200$ GeV.

$$\frac{d\sigma}{dp_T} = 2p_T \int_{Y^{\min}}^{Y^{\max}} dY \int_{x_2^{\min}}^1 dx_2 \times \int_0^{s_4^{\max}} ds_4 \frac{x_1 x_2 S}{x_2 S + T_1} \phi(x_1) \phi(x_2) \frac{d^2 \hat{\sigma}}{dt du}, \quad (4.1)$$

where $T_1 = -\sqrt{S}(m_H^2 + p_T^2)^{1/2} e^{-Y}$, $U_1 = -\sqrt{S}(m_H^2 + p_T^2)^{1/2} e^Y$, $Y^{\min} = \pm(1/2) \ln[(1 + \beta_T)/(1 - \beta_T)]$ with $\beta_T = [1 - 4(m_H^2 + p_T^2)S/(S + m_H^2 - m_W^2)^2]^{1/2}$, and the other quantities are defined in Sec. III. I note that the total cross section can also be calculated by integrating the p_T distribution, $d\sigma/dp_T$, over p_T from 0 to $p_T^{\max} = [(S - m_H^2 - m_W^2)^2 - 4m_H^2 m_W^2]^{1/2} / (2\sqrt{S})$, and I have checked for consistency that I get the same numerical results as in Sec. III.

In Fig. 3 I plot the aNNLO p_T distributions, $d\sigma/dp_T$, of the charged Higgs boson with mass 200 GeV for LHC energies of 7, 8, 13, and 14 TeV. The inset plot shows the aNNLO/LO K factors. The corrections are large, around 50%, for much of the p_T range shown. The distributions peak at a p_T value of around 65 GeV for this mass choice.

In Fig. 4 I plot the corresponding aNNLO p_T distributions of the charged Higgs boson with mass 500 GeV. The inset plot shows the aNNLO/LO K factors, and, again, the corrections are large. The distributions now peak at a higher p_T value of around 110 GeV.

It is useful to also study normalized distributions since normalization removes the dependence on $\tan\beta$, and it minimizes the dependence on the choice of pdf. Such normalized distributions are also often favored in experimental studies and comparisons with theory.

In Fig. 5 I plot the aNNLO normalized p_T distributions, $(1/\sigma)d\sigma/dp_T$, of the charged Higgs boson with mass 200 GeV (left plot) and 500 GeV (right plot) for LHC energies of 7, 8, 13, and 14 TeV. The shape of the normalized p_T distributions depends on the energy, as

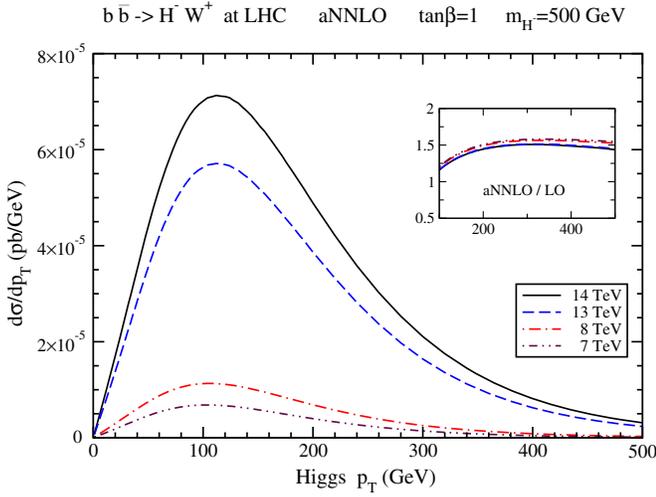


FIG. 4. The aNNLO charged Higgs p_T distributions for $b\bar{b} \rightarrow H^- W^+$ at the LHC with $\sqrt{S} = 7, 8, 13,$ and 14 TeV, and $m_H = 500$ GeV.

expected, with higher peaks at lower energies. I also observe that the peaks are lower for a 500 GeV mass than for 200 GeV.

The charged Higgs rapidity, Y , distribution is given by

$$\frac{d\sigma}{dY} = \int_0^{p_T^{\max}} 2p_T dp_T \int_{x_2^{\min}}^1 dx_2 \times \int_0^{s_4^{\max}} ds_4 \frac{x_1 x_2 S}{x_2 S + T_1} \phi(x_1) \phi(x_2) \frac{d^2 \hat{\sigma}}{dt du}, \quad (4.2)$$

where $p_T^{\max} = ((S + m_H^2 - m_W^2)^2 / (4S \cosh^2 Y) - m_H^2)^{1/2}$, and the rest of the quantities are defined as before. I again note that the total cross section can also be obtained by integrating the rapidity distribution, $d\sigma/dY$, over rapidity

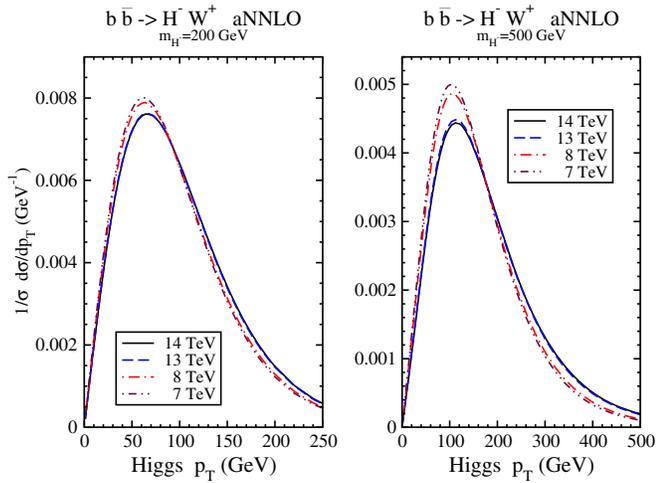


FIG. 5. The aNNLO charged Higgs normalized p_T distributions for $b\bar{b} \rightarrow H^- W^+$ at the LHC with $\sqrt{S} = 7, 8, 13,$ and 14 TeV, and $m_H = 200$ GeV (left) and 500 GeV (right).

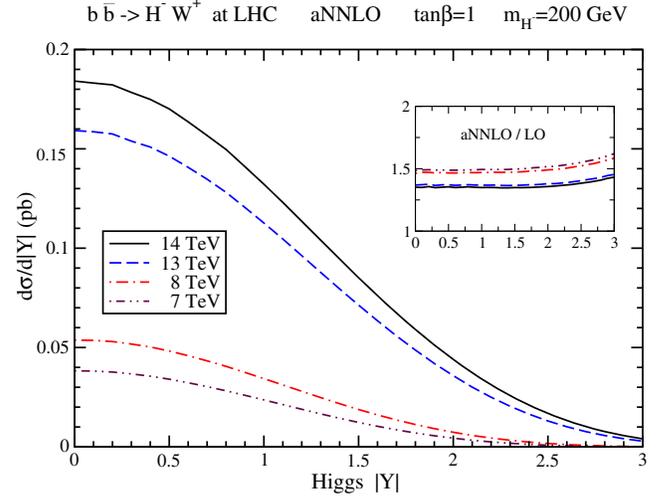


FIG. 6. The aNNLO charged Higgs rapidity distributions for $b\bar{b} \rightarrow H^- W^+$ at the LHC with $\sqrt{S} = 7, 8, 13,$ and 14 TeV, and $m_H = 200$ GeV.

with limits $Y_{\min}^{\max} = \pm(1/2) \ln[(1 + \beta)/(1 - \beta)]$ where $\beta = (1 - 4m_H^2/S)^{1/2}$, and again I have checked for consistency that I get the same numerical results as in Sec. III.

In Fig. 6 I plot the aNNLO rapidity distributions, $d\sigma/d|Y|$, of the charged Higgs boson with mass 200 GeV for LHC energies of 7, 8, 13, and 14 TeV. The inset plot shows the aNNLO/LO K factors. The corrections are quite large, especially at lower LHC energies, and they grow at larger values of charged Higgs rapidity.

In Fig. 7 I plot the corresponding aNNLO rapidity distributions of the charged Higgs boson with mass 500 GeV. The aNNLO/LO K factors are again shown in the inset plot. I observe that the 7 and 8 TeV K factors increase rapidly at larger values of rapidity.

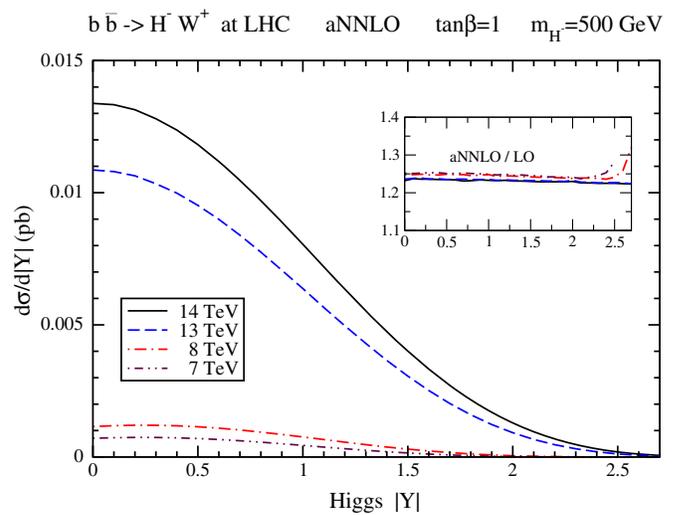


FIG. 7. The aNNLO charged Higgs rapidity distributions for $b\bar{b} \rightarrow H^- W^+$ at the LHC with $\sqrt{S} = 7, 8, 13,$ and 14 TeV, and $m_H = 500$ GeV.

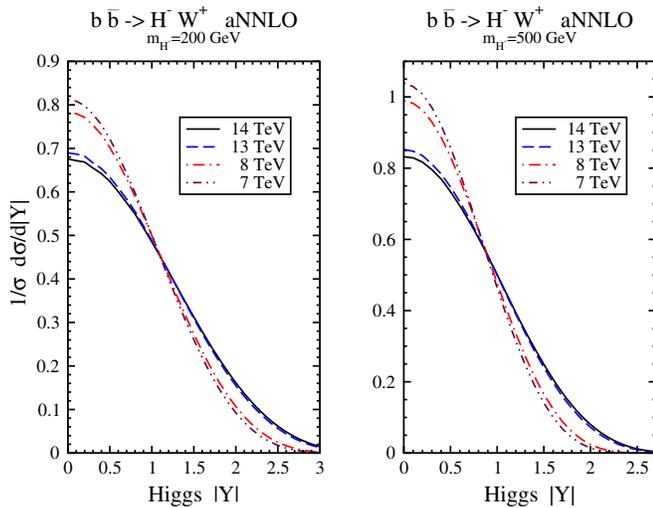


FIG. 8. The aNNLO charged Higgs normalized rapidity distributions for $b\bar{b} \rightarrow H^-W^+$ at the LHC with $\sqrt{S} = 7, 8, 13,$ and 14 TeV, and $m_H = 200$ GeV (left) and 500 GeV (right).

Finally, in Fig. 8 I plot the aNNLO normalized rapidity distributions, $(1/\sigma)d\sigma/d|Y|$, of the charged Higgs boson with mass 200 GeV (left plot) and 500 GeV (right plot) for LHC energies of $7, 8, 13,$ and 14 TeV. For a given charged Higgs mass the normalized rapidity distributions at lower

energies have higher peaks at central rapidity with corresponding smaller values at large $|Y|$, as expected. The fall of the distributions with increasing $|Y|$ is sharper for $m = 500$ GeV than for 200 GeV at all LHC energies.

V. CONCLUSIONS

The cross sections for the associated production of a charged Higgs boson with a W boson, via $b\bar{b} \rightarrow H^-W^+$, receive sizable contributions from collinear and soft-gluon corrections. These radiative contributions have been resummed, and approximate double-differential cross sections have been derived at NLO, NNLO, and N^3 LO. Numerical predictions have been provided for the total cross section for H^-W^+ production at LHC energies as well as for the p_T and rapidity distributions of the charged Higgs boson. The higher-order corrections are significant, and they enhance the total cross section and differential distributions for H^-W^+ production at the LHC.

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