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Higher-order QCD corrections to associated VH production with $H \to b\bar{b}$ decay at the LHC

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We consider QCD radiative corrections to the production of a Standard Model Higgs boson H in association with a vector boson V ($V = W/Z$) at hadron colliders. We present a fully exclusive perturbative QCD calculation at next-to-next-to-leading order (NNLO) for the production of the VH pair, including the Higgs boson decay into a bottom-antibottom quark ($b\bar{b}$) pair up to next-to-leading order in QCD. We consider the selection cuts that are typically applied in the LHC experimental analysis, and we compare perturbative fixed-order results with NLO parton shower predictions.

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1. Introduction

The investigation of the origin of the electroweak symmetry breaking is one of the main goal for physics study at the Large Hadron Collider (LHC). For the above reason it is of primary importance to compare the theoretical predictions for the production of the Standard Model (SM) Higgs boson [1] with the experimental data collected by the ATLAS and CMS Collaborations [2].

One of the most important Higgs boson H production mechanism is in association with a vector gauge boson V ($V = W^{\pm}, Z$), with the Higgs boson decaying into a bottom-antibottom pair ($H \to b\bar{b}$) and the vector boson decaying leptonically ($V \to l_1 l_2$).

Due to the complicated experimental selection cuts required by this process, it is essential to have accurate theoretical prediction at the level of differential distributions. High precision demands in particular the computation of the higher-order QCD radiative corrections. The next-to-leading order (NLO) QCD corrections to *VH* production are the same as those of the Drell–Yan process while at next-to-next-to-leading order (NNLO) the QCD corrections differ from those to the Drell–Yan process by contributions where the Higgs boson couples to quarks (and in the case of *ZH* production also to gluons) through a heavy-quark loop.

We present the calculation of the NNLO QCD radiative correction for *VH* production [3, 4, 5] performed using the q_T subtraction method [6]. We include the DY like contributions up to NNLO and the gluon induced heavy-quark loops contributions to *ZH* production which are substantial at the LHC due to the large gluon luminosity. The quark induced heavy-quark loops contributions have been shown to give a marginal impact on the *ZH* total cross section (around 1% for $m_H \simeq 125\,\mathrm{GeV}$ at the LHC) [7] and are therefore neglected in the present paper. The $H \to b\bar{b}$ decay is computed at NLO by using the dipole subtraction method [8] and it is included at fully differential level. Our fully-differential computation includes finite-width effects and the leptonic decay of the V boson with its spin correlations.

2. Computation

We now introduce the theoretical framework adopted in our calculation. We consider the hard scattering process

$$pp \to VH + X \to V b\bar{b} + X\,, \tag{2.1}$$

where the Higgs boson H, which subsequently decays into a $b\bar{b}$ pair, is produced together with a vector boson V[1].

The fully differential cross section for the production process (2.1) can be written as:

$$d\sigma_{pp\to VH+X} = d\sigma^{(0)}_{pp\to VH+X} + d\sigma^{(1)}_{pp\to VH+X} + d\sigma^{(2)}_{pp\to VH+X} + \mathscr{O}(\alpha_S^3)\,, \tag{2.2}$$

where $d\sigma^{(0)}$ is the LO contribution, and $d\sigma^{(1)}$ and $d\sigma^{(2)}$ the NLO and NNLO correction, respectively. Analogously, the $H \to b\bar{b}$ differential decay rate has the following perturbative expansion

$$d\Gamma_{H\to b\bar{b}} = d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}} + d\Gamma^{(2)}_{H\to b\bar{b}} + \mathscr{O}(\alpha_S^3)\,. \tag{2.3}$$

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[1] The leptonic decay of the vector boson (including spin correlations) has no effect from the point of view of QCD corrections and therefore it has been understood to simplify the notation.

By treating the Higgs boson within the narrow width approximation, the differential cross section for the process in (2.1) can be written as

$$d\sigma_{pp\to VH+X\to Vb\bar{b}+X} = \left[\sum_{k=0}^{\infty} d\sigma^{(k)}_{pp\to VH+X}\right] \times \left[\frac{\sum_{k=0}^{\infty} d\Gamma^{(k)}_{H\to b\bar{b}}}{\sum_{k=0}^{\infty}\Gamma^{(k)}_{H\to b\bar{b}}}\right] \times Br(H\to b\bar{b})\,. \tag{2.4}$$

Through Eq. (2.4) we can exploit the precise prediction of the Higgs boson branching ratio into b quarks $Br(H\to b\bar{b})$, reported in Ref. [9], by which we normalize the contributions to the differential decay rate of the Higgs boson. We first consider NLO corrections to the production process in Eq. (2.4) and ignore QCD corrections to the decay, we thus have

$$d\sigma^{\mathrm{NLO(prod)+LO(dec)}}_{pp\to VH+X\to Vb\bar{b}+X} = \left[d\sigma^{(0)}_{pp\to VH+X} + d\sigma^{(1)}_{pp\to VH+X}\right] \times d\Gamma^{(0)}_{H\to b\bar{b}}/\Gamma^{(0)}_{H\to b\bar{b}} \times Br(H\to b\bar{b})\,. \tag{2.5}$$

By including NLO corrections to the $H\to b\bar{b}$ decay we obtain

$$\begin{aligned} d\sigma^{\mathrm{NLO(prod)+NLO(dec)}}_{pp\to VH+X\to Vb\bar{b}+X} \; = \; & \left[d\sigma^{(0)}_{pp\to VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} \right. \\ & \left. + \; d\sigma^{(1)}_{pp\to VH+X} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}} \right] \times Br(H\to b\bar{b})\,, \end{aligned} \tag{2.6}$$

which represents the complete NLO calculation considered in Ref. [10]. We point out here that at the first order in α_{S} the factorization between production and decay is indeed exact because of colour conservation. In other words the interference of QCD radiation in Higgs boson production and decay vanishes at this order. This property does not hold beyond $\mathscr{O}(\alpha_{\mathrm{S}})$.

As a first step towards a complete NNLO calculation we consider the following approximation of Eq. (2.4)

$$\begin{aligned} d\sigma^{\mathrm{NNLO(prod)+NLO(dec)}}_{pp\to VH+X\to l\nu b\bar{b}+X} \; = \; & \left[d\sigma^{(0)}_{pp\to VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} \right. \\ & \left. + \; \left(d\sigma^{(1)}_{pp\to VH+X} + d\sigma^{(2)}_{pp\to VH+X}\right) \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}} \right] \times Br(H\to b\bar{b})\,. \end{aligned} \tag{2.7}$$

In Eq. (2.7) we include QCD corrections to the production stage up to NNLO, and the Higgs decay is treated up to NLO. Although this is not a fully consistent approximation, since it neglects some $\mathscr{O}(\alpha_{\mathrm{S}}^2)$ contributions in Eq. (2.4), we believe it captures the relevant radiative effects (see discussion in the next Section).

The NNLO computation for the production process is performed in [3] by using the q_T subtraction method proposed in Ref. [6]. This method allows us to compute the QCD radiative corrections up to NNLO for the whole class of hadronic collisions producing a colourless final state at LO and it has been successfully applied to the computation of NNLO corrections to several other hadronic processes [6, 11, 12, 13, 14]. We include the DY like contributions to *WH* and *ZH* production up to NNLO through an extension of the numerical program `DYNNLO` [11]. In order to take into account the gluon induced heavy-quark loops contributions to *ZH* production, we extended the analytical formulae in Refs. [15] including the decay of the gauge bosons and we checked them numerically with `GoSam` [16].

The $H \to b\bar{b}$ decay at NLO is computed by using the dipole subtraction method [8] and is included in a fully differential numerical code both for massless and massive b quarks [4]. After absorbing the large logarithmic terms of the type $\log(m_H/m_b)$ into the running $Hb\bar{b}$ Yukawa coupling, the effect of the non-vanishing b mass is completely negligible.

3. Phenomenological results

In the following we present an illustrative selection of numerical results for WH production at the LHC at $\sqrt{s} = 8$ and 14 TeV [2]. We consider the selection cuts that are typically applied in the LHC experimental analysis for the WH case and we compare the perturbative fixed-order results with the NLO parton shower predictions of the MC@NLO generator [17].

We consider a SM Higgs boson with mass $m_H = 125$ GeV and width $\Gamma_H = 4.070$ MeV [9], we use the so called G_μ scheme for the electroweak couplings and the NNPDF2.3 parton distribution function set [18] with $\alpha_S(m_Z) = 0.118$. We compute the $H \to b\bar{b}$ decay in NLO QCD including the effects of the non-vanishing b mass and we normalize the $Hb\bar{b}$ Yukawa coupling such that $BR(H \to b\bar{b}) = 0.578$ [9]: this means that the prediction for the total cross-section of a *completely* inclusive quantity is insensitive to the higher-order corrections to the $H \to b\bar{b}$ decay. In the fixed order calculations the central values of the renormalization and factorization scales are fixed to the value $\mu_R = \mu_F = m_W + m_H$ while the central value of the renormalization scale for the $H \to b\bar{b}$ coupling is set to the value $\mu_r = m_H$. In the parton shower simulation the central scale is the default MC@NLO scale: the transverse mass of the WH system. The scale uncertainty band is obtained as follows: we vary $\mu_F = \mu_R$ and (in the fixed order case) independently μ_r by a factor of two around their central value.

We start the presentation of our results by considering WH production at the LHC at $\sqrt{s} = 8$ TeV. We implement the following kinematical cuts [19]: the charged lepton is required to have transverse momentum $p_T^l > 20$ GeV and pseudorapidity $|\eta_l| < 2.4$; the missing transverse momentum of the event is required to be $p_T^\nu > 35$ GeV. The W boson must have a transverse momentum $p_T^W > 160$ GeV and is required to be almost back-to-back with the Higgs boson candidate (the azimuthal separation of the W boson with the $b\bar{b}$ pair must fulfil $|\Delta\phi_{W,bb}| > 3$). Jets are reconstructed with the anti-k_T algorithm with $R = 0.4$ [20]. We also require events with exactly two (R) separated b-jets each with $p_T^b > 30$ GeV and $|\eta_b| < 2.5$. In the fixed-order calculation a jet is considered a b-jet if it contains at least one b-quark while in the MC@NLO simulation we require that, after hadronization, the jet contains at least one B-hadron.

In Fig. 1 (left panel) we show the predictions for the transverse-momentum distribution of the b-jet pair $p_T^{b\bar{b}}$ at various level of fixed-order perturbative accuracy and from MC@NLO. In the right panel of Fig. 1 we plot the p_T distributions normalized to the full NLO result (i.e. including NLO corrections to the $H \to b\bar{b}$ decay), with their scale uncertainty band. We observe from Fig. 1 that the hardest spectrum is the NLO one (with LO $H \to b\bar{b}$ decay) and that the inclusion of the NLO corrections to the $H \to b\bar{b}$ decay makes the spectrum softer and reduces the accepted cross

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[2] Phenomenological results for ZH production at the LHC will be presented in a forthcoming publication [5].

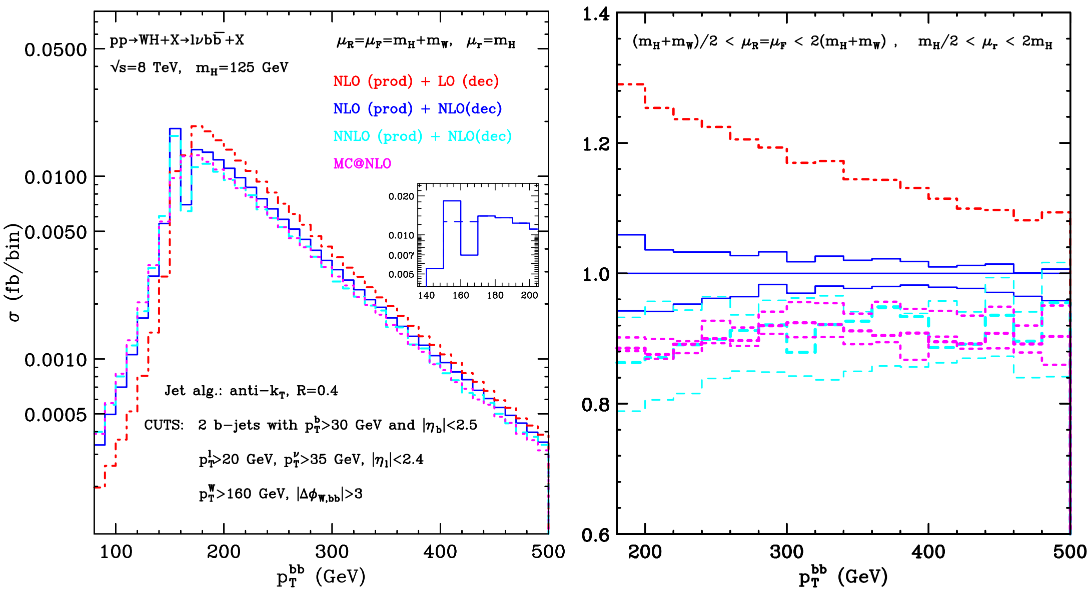

Figure 1: *Left panel: Transverse-momentum distribution of the b-jet pair computed at NLO with LO decay (red dot-dashes), NLO with NLO decay (blue solid), NNLO with NLO decay (cyan dashes) and with* MC@NLO *(magenta dots). The inset plot shows the region around $p_T^{bb} \sim 160$ GeV. Right panel: The same distributions normalized to the full NLO result.*

section by 12%. The inclusion of the NLO corrections produces instabilities of Sudakov type [21] around the LO kinematical boundary $p_T^{b\bar{b}} > 160$ GeV. To solve these perturbative instabilities an all-order resummation of the soft-gluon contributions is needed, however the effects of soft-gluon resummation can be mimicked by considering a more inclusive observable with a larger size of the bins around the critical point (see the dashed line in the inset plot of Fig. 1). The effect of the NNLO corrections for the production is not negligible: the spectrum becomes softer and the accepted cross section is further reduced by 9%.

Comparing the fixed order predictions to the MC@NLO result we observe that the effect of the shower is quantitative very similar to the effect of the NNLO corrections for the production plus NLO for the Higgs boson decay. As expected, the shower algorithm permits a more reliable description of the region around the LO kinematical boundary: the MC@NLO prediction has a smooth behaviour, without the instabilities of the fixed order case.

The NLO scale uncertainties are $\mathcal{O}(\pm 10\%)$ in the region $p_T \lesssim 200$ GeV and then decrease to $\mathcal{O}(\pm 5\%)$ or smaller for higher values of p_T. From Fig. 1 (right panel) we conclude that the inclusion of NLO corrections to the Higgs boson decay is important to obtain a reliable shape of the p_T spectrum. Nevertheless the MC@NLO prediction, even if it does not include the full NLO corrections to the decay, describes the shape of the spectrum rather well. The NNLO uncertainty band is larger than the NLO one, being at the $\pm 7-8\%$ level and marginally overlaps with the latter, while the NNLO and MC@NLO results are perfectly compatible within the uncertainties.

We now consider the case of *WH* production at the LHC with $\sqrt{s} = 14$ TeV. We follow the selection strategy of Ref. [22]: the Higgs boson is selected at large transverse momenta through its

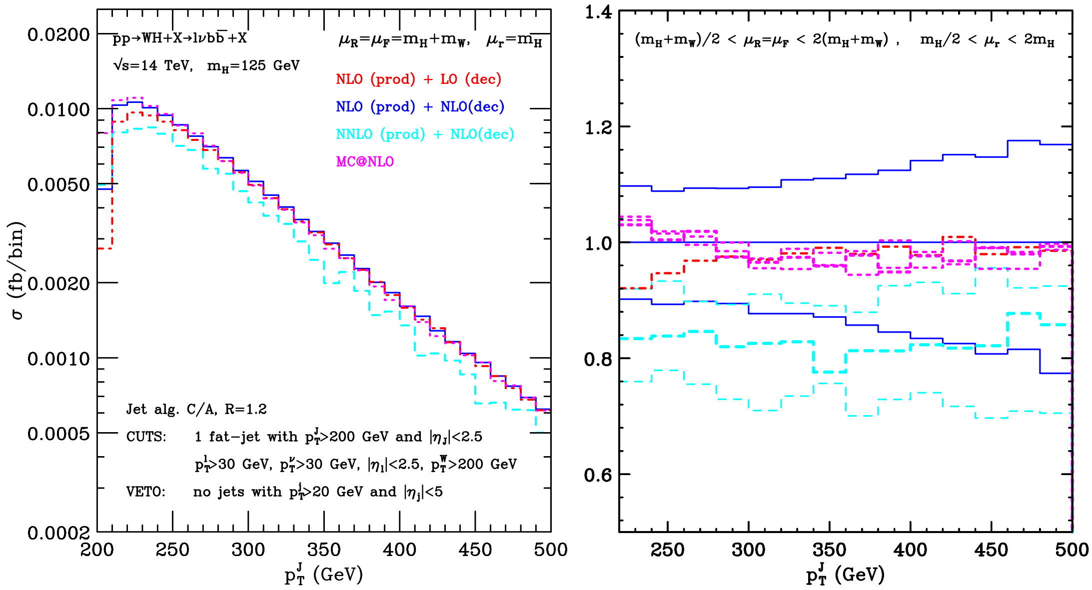

Figure 2: *Left panel: Transverse-momentum distribution of the fat jet computed at NLO with LO decay (red dot-dashes), NLO with NLO decay (blue solid), NNLO with NLO decay (cyan dashes) and with* MC@NLO *(magenta dots). Right panel: The same distribution normalized to the full NLO result.*

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 $p_T^{\text{miss}} > 30$ GeV. We also require the W boson to have $p_T^W > 200$ GeV. Jets are reconstructed with the Cambridge/Aachen algorithm [23], 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. In the MC@NLO simulation, the fat jet is required to contain two B hadrons. We also apply a veto on further light jets with $p_T^j > 20$ GeV and $|\eta_j| < 5$.

Our results for the p_T distribution of the Higgs boson candidate in this *boosted* scenario are reported in Fig. 2. First of all we observe that the effect of NLO corrections for the decay is much smaller compared with the results of the $\sqrt{s} = 8$ TeV analysis, and essentially it is negligible for $p_T \gtrsim 300$ GeV. This is not unexpected: the (boosted) fat jet is essentially *inclusive* over QCD radiation and the impact of the QCD corrections to the decay is well accounted for by the inclusive QCD corrected $H \to b\bar{b}$ branching ratio. The NLO scale uncertainty is about $\pm 10\%$ at $p_T \gtrsim 200$ GeV, and it increases to about $\pm 20\%$ at $p_T \sim 500$ GeV. We also note that the MC@NLO prediction is in good agreement as well with the complete NLO result. The NNLO result is smaller than NLO by about 16%, and it is at the border of the band from scale variations. The NNLO scale uncertainty band overlaps with the NLO band, and is smaller in size. In summary, our results on the boosted scenario at $\sqrt{s} = 14$ TeV show that the shape of the H p_T spectrum is rather stable, with uncertainties at the few percent level. The normalization of the accepted cross section has instead larger uncertainties with respect to the analysis at $\sqrt{s} = 8$ TeV. From Fig. 2 we estimate that these uncertainties are at the $10 - 15\%$ level.

4. Conclusions

We have studied the effect of QCD radiative corrections on the associated production of the Higgs boson with a vector boson V in hadronic collisions, followed by the $V \to l_1 l_2$ and the $H \to b\bar{b}$ decays. We performed a QCD calculation that includes the contributions up to NNLO for the *VH* production and up to NLO for the $H \to b\bar{b}$ decay. Our computation is implemented in a parton level Monte Carlo numerical program that allows us to apply arbitrary kinematical cuts on the V and H decay products and on the accompanying QCD radiation.

We have compared the effects of the QCD radiative corrections at various level of accuracy for the *WH* case with the results obtained with the MC@NLO event generator. We find that, in the analysis at $\sqrt{s} = 8$ TeV, the NLO corrections to the $H \to b\bar{b}$ decay can be important to obtain a reliable p_T spectrum of the Higgs boson, but that the final state radiation is well accounted for by the Monte Carlo parton shower.

In the boosted analysis at $\sqrt{s} = 14$ TeV with a jet veto the perturbative uncertainties are more sizeable. NNLO corrections to the production process decrease the cross section by an amount which depend on the detail of the applied cuts while they have a mild effect on the shape of the Higgs boson p_T spectrum.

In summary, even if the effect of higher orders QCD corrections at the level of inclusive cross sections is modest, the impact on the accepted cross section and on the kinematical distributions can be quite important, in particular when severe selection cuts are applied, as it typically happens in Higgs boson analysis at the LHC.

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