Top-Bottom Interference Effects in Higgs Plus Jet Production at the LHC

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We compute next-to-leading order QCD corrections to the top-bottom interference contribution to $H + j$ production at the LHC. To achieve this, we combine the recent computation of the two-loop amplitudes for $gg \rightarrow Hg$ and $gg \rightarrow Hq$, performed in the approximation of a small $b$-quark mass, and the numerical calculation of the squared one-loop amplitudes for $gg \rightarrow Hgg$ and $gg \rightarrow Hqg$, performed within OpenLOOPS. We find that QCD corrections to the interference are large and similar to the QCD corrections to the top-mediated Higgs production cross section. We also observe a significant reduction in the mass-renormalization scheme uncertainty once the next-to-leading order QCD prediction for the interference is employed.

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Detailed exploration of the Higgs boson properties is a major part of the physics program at the Large Hadron Collider (LHC). It is hoped that studies of the Higgs couplings will reveal possible physics beyond the standard model (BSM), especially if it mostly manifests itself through interactions with the Higgs bosons. The goal, therefore, is to precisely measure Higgs boson couplings to various particles in the standard model and to search for small deviations. For example, assuming that the energy scale of particles in the standard model and to search for small to precisely measure Higgs boson couplings to various interactions with the Higgs bosons. The goal, therefore, is to precisely measure Higgs boson couplings to various particles in the standard model and to search for small deviations. For example, assuming that the energy scale of particles in the standard model and to search for small deviations. For example, assuming that the energy scale of particles in the standard model and to search for small deviations. For example, assuming that the energy scale of particles in the standard model and to search for small deviations. For example, assuming that the energy scale of particles in the standard model and to search for small deviations. For example, assuming that the energy scale of particles in the standard model and to search for small deviations. For example, assuming that the energy scale of particles in the standard model and to search for small deviations. For example, assuming that the energy scale of particles in the standard model and to search for small deviations.
efficient numerical methods that can be used in physical planar and nonplanar box diagrams with internal masses. Corrections require two-loop computations that include leading-order processes only occurs at one loop, the virtual contributions from real and virtual corrections. Since the kinematic variables and the quark masses [9], loop amplitudes are known exactly as functions of external order, these processes are mediated by top or bottom loops [23], and the charm Yukawa coupling; for example, it is expected that at high-luminosity LHC, the charm Yukawa coupling can be constrained to lie in the interval $y_c/y_c^{SM} \in [-2.9, 4.2]$ at the 95% confidence level.

This discussion suggests that the shape of the Higgs boson transverse momentum distribution, from moderate to high $p_{\perp}$ values, is important for a proper description of the kinematic features of Higgs bosons produced at the LHC and also may provide important information about physics beyond the standard model. Accurate standard model predictions for this observable are key for achieving these goals. As we already mentioned, the pQCD description of the Higgs boson transverse momentum distribution, in the approximation of the pointlike $ggH$ coupling, is rather advanced, see Refs. [5,17], but there is very little understanding of how its not-pointlike component is affected by QCD radiative corrections. To clarify this issue, we report on the computation of QCD radiative corrections to top-bottom interference contribution to Higgs boson production at the LHC in this Letter.

The calculation of the NLO QCD corrections to the top-bottom interference is nontrivial. The leading-order production of the Higgs boson with nonvanishing transverse momentum occurs in different partonic channels, namely $gg \to Hg, qg \to Hq, \bar{q}g \to H\bar{q},$ and $q\bar{q} \to Hg.$ At leading order, these processes are mediated by top or bottom loops (the charm contribution in the SM is negligible). The one-loop amplitudes are known exactly as functions of external kinematic variables and the quark masses [9].

At NLO, the production cross section receives contributions from real and virtual corrections. Since the leading-order process only occurs at one loop, the virtual corrections require two-loop computations that include planar and nonplanar box diagrams with internal masses. The computation of such Feynman diagrams is a matter of active current research that includes attempts to develop efficient numerical methods that can be used in physical kinematics [18] and to extend existing analytic methods to make them applicable to two-loop Feynman diagrams with internal masses [19].

However, if we focus on the top-bottom interference and its impact on Higgs production at the LHC, we can simplify the calculation by using the fact that the mass of the $b$ quark $m_b \sim 4.7$ GeV is numerically small. Indeed, since $m_b \ll m_H, p_{\perp}^{\rm typ},$ where $p_{\perp}^{\rm typ} \sim 30$ GeV is a typical Higgs boson transverse momentum, Feynman diagrams that describe Higgs production can be expanded in series in $m_b$ for the purposes of LHC phenomenology. We have checked at leading order that the use of scattering amplitudes either exact or expanded in $m_b$ leads to, at most, a few percent difference in the interference contribution to the Higgs $p_{\perp}$ distribution, down to $p_{\perp} \sim 10$ GeV. Since the interference contribution changes the Higgs boson transverse momentum spectrum by $O(5\%)$ at leading order, the percent difference between expanded and not expanded results is irrelevant for phenomenology.

Unfortunately, the expansion in $m_b$ is nontrivial since the Higgs boson production cross section depends logarithmically on the $b$-quark mass. Therefore, we need to devise a procedure to expand scattering amplitudes in $m_b$ and extract the nonanalytic terms. This can be done by deriving differential equations for master integrals that are needed to describe the two-loop corrections to $pp \to H + j$ and then solving them in the limit $m_b \to 0$ [20]. Indeed, since we can derive differential equations to describe the dependence of the master integrals on the mass parameter $m_b$ and on the Mandelstam kinematic variables, and since all the information about singular points of a particular Feynman integral is contained in the differential equations that this Feynman integral satisfies, we can systematically solve the differential equation in a series of $m_b$ and extract the nonanalytic behavior. We note that a similar method was used to compute the top-bottom interference contribution to the inclusive Higgs production cross section in Ref. [21].

We have used this method to calculate all the relevant two-loop scattering amplitudes to describe the production of a Higgs boson in association with a jet [20,22]. In our computation, all quarks in the initial and final states are massless, so that $b$-initiated processes are not included. The two-loop amplitudes mediated by top quark loops, required to describe the interference, are computed in the approximation of an infinitely heavy top quark [23].

To produce physical results for $H + j$ production, we need to combine the virtual corrections discussed above with the real corrections that describe inelastic processes, e.g., $gg \to H + gg, qg \to Hq + g$ etc. Computation of one-loop scattering amplitudes for these inelastic processes is nontrivial; it requires the evaluation of five-point Feynman integrals with massive internal particles. Nevertheless, such amplitudes are known analytically since long ago [24] and were recently reevaluated in Ref. [25].

In this Letter, we follow a different approach, based on the automated numerical computation of one-loop scattering
amplitudes developed in recent years. One such approach, known as OpenLoops [26], employs a hybrid tree-loop recursion. Its implementation is publicly available [27] and has been applied to compute one-loop QCD and electroweak corrections to multileg scattering amplitudes for a variety of complicated processes (see, e.g., Refs. [28,29]) and as an input for the real-virtual contributions in NNLO computations (see, e.g., Ref. [30]).

For applications in NNLO calculations, and similarly for the loop-induced process discussed in this Letter, the corresponding one-loop real contributions need to be computed in kinematic regions where one of the external partons becomes soft or collinear to other partons. A reliable computation in such kinematic regions is non-trivial, but OpenLoops appears to be perfectly capable of coping with this challenge thanks to the numerical stability of the employed algorithms. An important element of this stability is the employed tensor integral reduction library COLLIER [31].

We have implemented all virtual and real amplitudes in the POWHEG-BOX [32], where infrared singularities are regularized via Frixione-Kunszt-Signer (FKS) subtraction [33]. All OpenLoops amplitudes are accessible via a process-independent interface developed in Ref. [29]. The implementation within the POWHEG-BOX will allow for an easy matching of the fixed-order results presented here with parton showers at NLO. At leading order, this has been done in Ref. [34].

Using the methods described above, we calculated the NLO QCD corrections to the top-bottom interference contribution to $H + j$ production in hadron collisions. We identify the interference contribution through its dependence on top-bottom Yukawa couplings. For the Higgs production cross section, we write

$$da = d\sigma_t + d\sigma_{tb} + d\sigma_{bb},$$  

where individual contributions to the differential cross section scale as $d\sigma_t \sim O(y_t^2)$, $d\sigma_{tb} \sim O(y_t y_b)$, and $d\sigma_{bb} \sim O(y_b^2)$, given the hierarchy of the Yukawa couplings $y_t \approx y_b \ll 10^{-2}$, the last term in Eq. (3) can be safely neglected. Note, however, that if one focuses on Higgs-related observables that are inclusive with respect to the QCD radiation, $d\sigma_{bb}$ receives contributions from Higgs boson production in association with $b$ quarks, $gg \rightarrow Hbb$. These processes change inclusive Higgs boson observables at below a permille level, which makes them irrelevant unless $b$ jets in the final state are tagged. Our main focus is the top-bottom interference contribution $d\sigma_{tb}$. Considering the virtual corrections, we write

$$d\sigma_{tb}^{\text{virt}} \sim \text{Re} \left[ A_t^{\text{LO}} A_b^{\text{LO}*} + \frac{\alpha_s}{2\pi} \left( A_t^{\text{NLO}} A_b^{\text{LO}*} + A_t^{\text{LO}} A_b^{\text{NLO}*} \right) \right].$$  

The leading-order (one-loop) term in this formula is known, including full mass dependence. The NLO (two-loop) amplitudes with the top quark $A_t^{\text{NLO}}$ are only known in the limit $m_t \rightarrow \infty$. Since as an input for the NLO calculation we only require the finite reminder of the virtual amplitude $A_t^{\text{NLO}}$, we can safely use the corresponding finite reminder of $A_t^{\text{NLO}}(m_t \rightarrow \infty)$ as its approximation. In principle, one can improve on this by computing $1/m_t$ corrections to $A_t^{\text{NLO}}(m_t \rightarrow \infty)$, see Ref. [35], but it is not expected that they will have significant impact on the interference at moderate values of the Higgs transverse momentum $p_\perp < m_t$. The real emission contributions are computed with exact top- and bottom-mass dependence throughout the Letter.

In what follows, we present the QCD corrections to the top-bottom interference contribution to the Higgs boson transverse momentum distribution and to the Higgs rapidity distribution in $H + j$ production. We consider proton collisions at the 13 TeV LHC and take the mass of the Higgs boson to be $m_H = 125$ GeV.

We work within a fixed flavor-number scheme and do not consider bottom quarks as partons in the proton. We use the NNPDF3.0 set of parton distribution functions (PDFs) [36]. We also use the strong coupling constant $\alpha_s(m_Z)$ that is provided with this PDF set. We renormalize the $b$-quark mass in the on-shell scheme and use $m_b = 4.75$ GeV as its numerical value. We choose renormalization and factorization scales to be equal and take, as the central value $\mu = H_T/2$, $H_T = \sqrt{m_H^2 + p_\perp^2 + \sum_j p_{\perp,j}}$, where the sum runs over all partons in the final state.

To quantify the impact of the top-bottom interference on an observable $O$, it is convenient to define the following quantity

$$R_{\text{int}}[O] = \frac{\int d\sigma_{bb}\delta(O - O(\bar{x}))}{\int d\sigma_{tb}\delta(O - O(\bar{x}))},$$  

where $\bar{x}$ is a set of phase-space variables. Note that we do not expand the $\sigma_{bb}$ cross section in the denominator in Eq. (3) in powers of $\alpha_s$. Therefore, any change in $R_{\text{int}}$ in consecutive orders in perturbation theory would reflect differences in QCD corrections to the $tb$ interference and the pointlike contribution to $H + j$ production. In what follows, we present $R_{\text{int}}$ as a function of the Higgs boson transverse momentum $p_\perp$ and the (pseudo)rapidity $\eta_H$.

The impact of the top-bottom interference on the Higgs boson transverse momentum distribution is shown in Fig. 1. We observe that the leading-order interference changes the Higgs boson transverse momentum distribution by $-8\%$ at $p_\perp \sim 20$ GeV and $+2\%$ at $p_\perp \sim 100$ GeV. Since the QCD corrections to color-singlet production in gluon annihilation are large, and since it is not clear a priori if the QCD corrections to the interference are similar to the QCD corrections to the pointlike cross section, large modifications of these LO results cannot be excluded. The NLO computation, illustrated in Fig. 1, clarifies this point. There, filled bands in blue for the leading and red for
the pointlike cross section however, appear to be very similar to NLO QCD corrections. For example, between leading and next-to-leading order are very small. The scale variation bands are very narrow (at leading order, hardly visible) due to a cancellation of large scale variation changes between the numerator and denominator. The hashed bands indicate the uncertainty due to mass-renormalization scheme variation. See text for details.

The next-to-leading order predictions show the result for \( R_{\text{int}}(p_\perp) \), computed in the pole mass renormalization scheme. The widths of the bands indicate changes in the predictions caused by variations of renormalization and factorization scales by a factor of two around the central value \( \mu = H_T/2 \). In fact, we observe that differences between leading and next-to-leading order are very small. For example, \( R_{\text{int}}^{\text{NLO}}(p_\perp) \) appears to be smaller than \( R_{\text{int}}^{\text{LO}}(p_\perp) \) by less than a percent at \( p_\perp < 60 \) GeV and practically coincides with it at higher values of \( p_\perp \). We emphasize that these small changes in \( R_{\text{int}} \) imply sizable \( O(40\text{--}50\%) \) corrections to the \( t\bar{b} \) interference proper that, however, appear to be very similar to NLO QCD corrections to the pointlike cross section \( \sigma_{t\bar{b}} \). The scale variation bands are very narrow (at leading order, hardly visible) due to a cancellation of large scale variation changes between the numerator and denominator in Eq. (3). Similar results for the Higgs boson rapidity distribution for events, with \( p_\perp > 30 \) GeV, are shown in Fig. 2.

The above result for the scale variation suggests that the uncertainties in predicting the size of top-bottom interference effects in \( H + j \) production are small since both the size of corrections and the scale variation bands are similar to the corrections to the pointlike \( pp \rightarrow H + j \) cross section. Such a conclusion, nevertheless, misses an important source of uncertainties related to a possible choice of a different mass-renormalization scheme. Indeed, since the leading-order interference contribution is proportional to the square of the bottom mass \( R_{\text{int}} \sim m_b^2 \), and since at leading order a change in the mass renormalization scheme simply amounts to the use of different numerical values for \( m_b \) in calculating \( R_{\text{int}} \), it is easy to see that this ambiguity is very significant. Indeed, suppose that we choose to renormalize the bottom mass in the \( \overline{\text{MS}} \) scheme and we take \( m_b = m_b^{\overline{\text{MS}}}(100 \) GeV\( ) = 3.07 \) GeV as an input parameter [37]. Since \( [m_b^{\overline{\text{MS}}}(100 \) GeV\( )/m_b^{\text{pole}}]^2 \approx 0.4 \), this implies that \( R_{\text{int}}^{\text{LO}} \) is reduced by more than a factor of two, practically independent of the \( p_\perp \) value. This large leading-order variation is shown as a hashed blue band in Figs. 1 and 2, where we have taken \( m_b = m_b^{\text{pole}} \) and \( m_b = m_b^{\overline{\text{MS}}}(100 \) GeV\( ) \) as the two boundary values.

This large ambiguity in the leading-order value of \( R_{\text{int}} \) is somewhat reduced at next-to-leading order, where the effect of the mass renormalization scheme change is less dramatic but, nevertheless, significant. The scheme dependence at NLO for the setup explained in the previous paragraph is shown as a hashed red band. For \( p_\perp < 60 \) GeV, the mass renormalization scheme uncertainty is reduced by almost a factor of two, whereas the reduction of uncertainty is only marginal at higher \( p_\perp \). This happens because at high transverse momenta, there is a significant cancellation between \( A_{t\bar{b}}^{\text{NLO}}A_{t\bar{b}}^{\text{LO}^*} \) and \( A_{t\bar{b}}^{\text{LO}}A_{t\bar{b}}^{\text{NLO}} \), cf. Eq. (2). Since the first term involves leading order \( b \)-quark contributions, it experiences large variations when the \( b \)-quark mass renormalization scheme is changed, and this causes large variations in \( R_{\text{int}} \) at high \( p_\perp \). The interference contribution to the Higgs rapidity distribution in Fig. 2 shows similar features. The mass variation band at NLO is smaller than the LO variation band at large absolute values of the pseudorapidity (small \( p_\perp \)) and practically indistinguishable from it at the central rapidity values (large \( p_\perp \)).
interference are large, yet they appear to track very well corrections to the pointlike component of the cross section. The strong dependence of the LO interference on the mass-renormalization scheme is reduced at NLO, but at high values of the Higgs transverse momentum or at central rapidity, the remaining ambiguities are significant. It is not clear how the situation at high $p_\perp$ and/or small absolute $\eta_H$ can be further improved. However, we want to emphasize that in these kinematic regions, the interference is numerically small compared to the $O(y_t^2)$ contribution. Nevertheless, with this result at hand, one can try to provide the best possible theoretical predictions for the Higgs transverse momentum distribution that combine the known results for the $p_\perp$ resummation NNLO corrections to $H + j$ in the pointlike approximation with the top-bottom interference. All the ingredients are now available. We plan to return to this problem before long.

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