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Heavy-quark mass effects in Higgs boson production at the LHC

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Abstract

We study the impact of heavy-quark masses in Higgs boson production through gluon fusion at the LHC. We extend previous computations of the fully differential cross section and of the transverse momentum spectrum of the Higgs boson by taking into account the finite top- and bottom-quark masses up to $\mathcal{O}(\alpha_s^3)$. We also discuss the issues arising when the heavy-quark mass is much smaller than the Higgs mass. Our results are implemented in updated versions of the `HNNLO` and `HRes` numerical programs.

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1 Introduction

The discovery of a new boson with mass $m_H \sim 125$ GeV by the ATLAS and CMS experiments at the LHC [1, 2] has lead, if at all possible, to a renewed interest in Higgs physics. Although the discovery is independent on the details of the theoretical modelling of the signal, to establish the extent to which the new resonance is consistent with the long sought Higgs boson requires accurate theoretical predictions for the Higgs production cross section and the associated distributions.

The main production mechanism of the Standard Model (SM) Higgs boson at hadron colliders is gluon fusion through a heavy-quark loop [3]. At the LHC the $gg \rightarrow H$ cross section is typically one order of magnitude larger than the cross section in the other channels for a wide range of the Higgs boson masses. It is thus essential to have the theoretical predictions for $gg \rightarrow H$ under very good control, and this implies an accurate evaluation of radiative corrections.

As the Higgs coupling to quarks is proportional to their masses, the main contributions arise from the top and bottom quarks. The calculation of radiative corrections is simplified in the so-called large- m_t approximation, in which the fermionic loop is replaced by an effective vertex and, thus, the number of loops is reduced by one. The QCD radiative corrections to this process at next-to-leading order (NLO) are known both in the large- m_t limit [4] and by keeping the exact dependence on the masses of the top and bottom quarks [5, 6, 7]. It turns out that the NLO corrections increase the cross section by 80-100% at the LHC [4, 5]. The next-to-next-to-leading (NNLO) corrections are known only in the large- m_t limit and increase the cross section by about 25 % [8, 9, 10]. The NNLO corrections have been successfully implemented in two independent fully-exclusive numerical programs **FehiPro** [11, 12, 13] and **HNNLO** [14, 15], which allow the user to compute the Higgs production cross section by applying arbitrary kinematical cuts on the Higgs decay products and the associated jet activity.

At hadron colliders the production of an (on shell) Higgs boson is characterized by its transverse momentum p_T and rapidity y . The rapidity distribution is essentially driven by the parton distribution functions of the partons in the colliding hadrons, and it is mildly sensitive to radiative corrections. By contrast, the p_T distribution is sensitive to multiple emissions from the initial state partons and its detailed knowledge is very important in the experimental analyses. A measurement of the Higgs p_T spectrum at the LHC is to be expected in the near future.

When $p_T \sim m_H$ the QCD radiative corrections to the transverse momentum cross section $d\sigma/dp_T$ can be evaluated through the standard fixed-order expansion. When $p_T \ll m_H$ the convergence of the perturbative expansion is spoiled by the presence of large logarithmic terms. To obtain reliable perturbative predictions over the whole range of transverse momenta, such terms must be resummed to all orders, and the result has to be consistently matched to the standard fixed-order result valid at $p_T \sim m_H$. A computation of the resummed p_T spectrum up to next-to-next-to-leading logarithmic accuracy [16, 17, 18], matched to the $\mathcal{O}(\alpha_s^4)$ result valid at large p_T [19, 20, 21] is implemented in the numerical program **HqT** [22, 23, 24]. An extension of this program, including the decay of the Higgs boson in the $\gamma\gamma$, WW and ZZ final states is implemented in the code **HRes** [25]. Both these calculations are performed by using the large- m_t approximation.

The purpose of the present paper is twofold. We first document the inclusion of heavy-quark mass effects up to NLO in the fully exclusive computation of Refs. [14, 15]. We then address

the implementation of mass effects in the resummed p_T spectrum. As far as top-mass effects are concerned, since $m_t \sim m_H$, the computation of the Higgs spectrum is still a *two scale* problem, and the implementation does not lead to substantial complications. The inclusion of bottom-mass effects is instead more difficult. Since $m_b \ll m_H$, the computation of the p_T spectrum becomes a *three scale* problem, whose solution beyond the fixed order is by far non trivial. We propose a simple treatment for this issue and we present new results for the resummed p_T spectrum and the ensuing uncertainties.

The paper is organized as follows. In Sec. 2 we discuss the implementation of the exact top- and bottom-mass dependence in the fully exclusive NNLO computation of Refs. [14, 15] and present some numerical results. In Sec. 3 we discuss the implementation of the mass effects in the resummed p_T spectrum. The issues arising when the heavy-quark mass is much smaller than the Higgs mass are discussed in Sec. 3.1, where we also present our treatment of the bottom quark in the resummed p_T spectrum. In Sec. 3.2 we present our numerical results. In Sec. 4 we draw our conclusions.

2 Mass effects at fixed order

In the following we briefly recall the subtraction formalism developed in Ref. [14] to deal with the soft and collinear divergences appearing in real and virtual QCD corrections at NLO and NNLO, and we discuss how the NNLO calculation of Refs. [14, 15] can be extended to include heavy-quark masses up to NLO.

We briefly introduce the theoretical framework and our notation. We consider the inclusive hard scattering process

$$h_1 + h_2 \rightarrow H + X, \quad (1)$$

where the collision of the two hadrons produces the Higgs boson H accompanied by an arbitrary and undetected final state X . The LO partonic subprocess is the gluon fusion mechanism $gg \rightarrow H$. We use the narrow-width approximation and we treat the Higgs boson as an on-shell particle with mass m_H . We use parton densities as defined in the $\overline{\text{MS}}$ factorization scheme, and we denote by $\alpha_s(\mu_R^2)$ the QCD running coupling at the renormalization scale μ_R in the $\overline{\text{MS}}$ renormalization scheme.

According to the formalism of Ref. [14] the *fully differential* cross section at (N)NLO can be schematically written as

$$d\sigma_{(N)NLO} = \mathcal{H}^{(N)NLO} \otimes d\sigma_{LO} + \left[d\sigma_{(N)LO}^{H+\text{jet}(s)} - d\sigma_{(N)LO}^{CT} \right]. \quad (2)$$

The first term on the right-hand side of Eq. (2) contains the LO cross section $d\sigma_{LO}$ suitably convoluted with a perturbatively computable hard-collinear function $\mathcal{H}^{(N)NLO}$. The second term of the right hand side of Eq. (2) contains the (N)LO cross section for the $H+\text{jet}(s)$ process, $d\sigma_{(N)LO}^{H+\text{jet}(s)}$. This cross section is finite as soon as the transverse momentum p_T of the Higgs boson is non vanishing, and can be obtained with any available method to perform NLO QCD computations. The first NLO calculation of $d\sigma^{H+\text{jet}(s)}$ was presented in Ref. [19], and was performed by using the FKS version of the subtraction formalism [26, 27]. In our numerical implementation we compute $d\sigma^{H+\text{jet}(s)}$ with the dipole subtraction method [28, 29] as implemented in the MCFM numerical

program [30]. The singularity at $p_T \rightarrow 0$ is subtracted by using the counterterm $d\sigma_{N(LO)}^{CT}$, which is computed as [14]

$$d\sigma_{N(LO)}^{CT} = d\sigma_{LO} \otimes \Sigma(p_T/m_H) d^2\mathbf{p}_T. \quad (3)$$

The function $\Sigma^H(p_T/m_H)$ depends only on the channel in which the process occurs at Born level (gluon fusion in the present case) and it embodies the singular behaviour of the Higgs p_T distribution as $p_T \rightarrow 0$ [23].

As far as the first term in Eq. (2) is concerned, the exact top and bottom mass dependence up to NLO can be implemented by replacing the Born cross section $d\sigma_{LO}$ evaluated in the large- m_t limit with the cross section with the exact dependence on the top and bottom masses [3], and by computing the exact expression of the coefficient \mathcal{H}^{NLO} .

The coefficient \mathcal{H}^{NLO} is

$$\mathcal{H}_{ab}^{NLO}(z_1, z_2, \alpha_S) = \delta_{ga}\delta_{gb}\delta(1-z_1)\delta(1-z_2) + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}_{ab}^{(1)}(z_1, z_2), \quad (4)$$

where $\mathcal{H}_{gg}^{(1)}$ contains the information on the virtual correction to the LO subprocess and is given by

$$\mathcal{H}_{gg}^{(1)}(z_1, z_2) = \delta(1-z_1)\delta(1-z_2) \left(C_A \frac{\pi^2}{6} + \frac{1}{2} \mathcal{A} \right), \quad (5)$$

whereas the off diagonal coefficients read

$$\mathcal{H}_{gq}^{(1)}(z_1, z_2) = \frac{1}{2} C_F z_2 \delta(1-z_1) \quad \mathcal{H}_{qg}^{(1)}(z_1, z_2) = \frac{1}{2} C_F z_1 \delta(1-z_2) \quad \mathcal{H}_{q\bar{q}}^{(1)}(z_1, z_2) = 0. \quad (6)$$

The function \mathcal{A} in Eq. (5) denotes the finite part of the virtual correction to $gg \rightarrow H$ defined according to the conventions of Ref. [16], and, in the large- m_t approximation it reads

$$\mathcal{A} = 5C_A + \frac{2}{3}C_A\pi^2 - 3C_F \equiv 11 + 2\pi^2. \quad (7)$$

To obtain the exact form of \mathcal{H}^{NLO} it is enough to replace the coefficient \mathcal{A} in Eq. (7) with the corresponding function with the exact dependence on the masses of the top and bottom quarks. The result can be found in Eq. (B.2) of Ref. [7] in terms of one-dimensional integrals, or as a fully analytic expression in Eq. (3.5) of Ref. [31] and Eq. (27) of Ref. [32], both in terms of harmonic polylogarithms. In our numerical implementation we use the result of Ref. [7], as implemented in the HIGLU numerical program.

We finally discuss the implementation of the heavy-quark masses in the second contribution on the right-hand side of Eq. (2). The cross section $d\sigma_{N(LO)}^{H+\text{jet}(s)}$ can be evaluated by replacing the $\mathcal{O}(\alpha_S^3)$ $H+3$ parton matrix element with its exact expression as a function of the heavy-quark masses [33]. Correspondingly, the $\mathcal{O}(\alpha_S^3)$ contribution to the subtraction counterterm $d\sigma_{(N)LO}^{CT}$ must be evaluated by using the exact expression for the Born cross section $d\sigma_{LO}$ in Eq. (3), so as to cancel the singular behaviour at small p_T .

The procedure defined above allows us to compute the fully differential Higgs production cross section up to NLO according to Eq. (2). The NNLO matrix elements [34, 35, 36] are known only in the large- m_t approximation[†]. As a consequence, at $\mathcal{O}(\alpha_S^4)$ we include only the top-quark

[†]Corrections to the large- m_t approximation at NNLO have been considered in Refs. [37, 38, 39, 40, 41, 42, 43].

contribution, evaluated in the large- m_t approximation, and we normalize it with the exact m_t -dependent Born cross section, $\sigma_{LO}(m_t)$. More precisely, we multiply the $\mathcal{O}(\alpha_S^4)$ contributions by the ratio $\sigma_{LO}(m_t)/\sigma_{LO}(m_t \rightarrow \infty)$.

2.1 Numerical results

We have implemented the exact heavy-quark mass dependence in a new version of the numerical code HNNLO. The program HNNLO is a parton level event generator that allows the user to compute the Higgs production cross section and the associated distributions up to NNLO in QCD perturbation theory, and to apply arbitrary infrared-safe cuts on the Higgs decay products and the recoiling QCD radiation. The program includes the $H \rightarrow \gamma\gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$ and $H \rightarrow ZZ \rightarrow 4l$ decay modes.

In the following, we present only a limited sample of the numerical results that can be obtained with our program. We consider Higgs boson production in pp collisions at $\sqrt{s} = 8$ TeV and we use the MSTW2008 sets of parton distributions [44], with densities and α_S evaluated at each corresponding order (i.e., we use $(n + 1)$ -loop α_S at N^n LO). Unless stated otherwise, we set the renormalization and factorization scales to the Higgs boson mass, $\mu_R = \mu_F = m_H$, and we set $m_t = 172.5$ GeV and $m_b = 4.75$ GeV.

The first quantity that is important to test with the modified program is the inclusive cross section. In Table 1 we study the impact of heavy-quark masses at NLO. We report the NLO cross sections evaluated with the exact top and bottom mass dependence, normalized to the NLO result in the large- m_t limit.

m_H (GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t \rightarrow \infty)}$	$\frac{\sigma_{NLO}(m_t, m_b)}{\sigma_{NLO}(m_t \rightarrow \infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

Table 1: Impact of the heavy-quark masses on the inclusive NLO cross sections. All results are normalized to the $m_t \rightarrow \infty$ result.

From Table 1 we see that the mass effects change the cross section at the few percent level, and that the bottom contribution decreases the cross section by a few percent. This effect is well known, and it is due to the negative interference with the top-quark contribution. We have compared our results with those obtained with the numerical program HIGLU [5, 7] and found very good agreement.

We now move to consider the impact of mass effects on the p_T cross section. Such effects have been studied at NLO in earlier works [45, 46, 47, 13, 48, 49].

In Fig. 1 (left panel) we plot the p_T spectrum of the Higgs boson at NLO with full dependence on the masses of the top and bottom quarks and we compare it with the corresponding result in which only the top-quark contribution is considered. Both results are normalized to the result obtained in the large- m_t limit. To better emphasize the impact of the bottom quark, in the right

panel of Fig. 1 we show the full NLO result normalized to the result obtained neglecting the bottom quark.

We see that, when only the top contribution is considered, the cross section at low p_T is larger than the corresponding cross section in the large- m_t limit. In this region the recoiling parton is soft and/or collinear, and the differential cross section factorizes into a universal factor times the Born level contribution. The limit of the solid and dashed histograms in the left panel of Fig. 1 thus correspond to the ratios $\sigma_{LO}(m_t, m_b)/\sigma_{LO}(m_t \rightarrow \infty) = 0.949$ and $\sigma_{LO}(m_t)/\sigma_{LO}(m_t \rightarrow \infty) = 1.066$, respectively.

The results in Fig. 1 show that the impact of the bottom quark is important, especially in the low- p_T region, since it substantially deforms the shape of the spectrum. At large p_T values, the impact of the bottom quark becomes small and the differential cross section quickly departs from its value in the large- m_t limit. This is a well known feature of the large- m_t approximation: at large p_T the parton recoiling against the Higgs boson is sensitive to the heavy-quark loop, and the large- m_t approximation breaks down.

Another feature that is evident from Fig. 1 is that the qualitative behaviour of the results is rather different. When considering the NLO result with only the top quark included, in a wide region of transverse momenta the shape of the spectrum is rather stable and in rough agreement with what is obtained in the large- m_t approximation. This is not the case when the bottom contribution is included: the shape of the spectrum quickly changes in the small- and intermediate- p_T region and the spectrum becomes harder. We will come back to this point in Sec. 3.1.

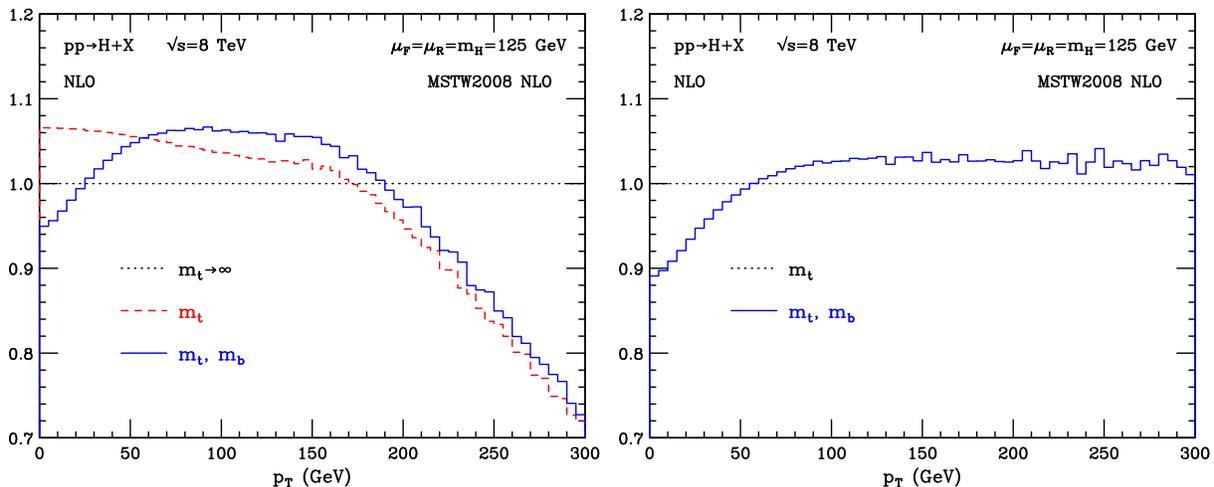


Figure 1: Transverse momentum distribution for a SM Higgs with $m_H = 125$ GeV computed at NLO. Left: result normalized to the large- m_t approximation. Right: normalized to the m_t -dependent result.

The mass effects in differential NLO distributions were previously discussed in Ref. [13]. We have compared our results with those of Ref. [13] and found agreement.

3 Mass effects in the resummed p_T spectrum

As we mentioned in the previous Section, the fixed order transverse momentum distribution diverges at small p_T . In order to obtain a reliable behaviour in this region the divergent contributions need to be resummed to all orders in perturbation theory. Once the resummation has been carried out, the result has to be properly matched to the standard fixed order result, so as to obtain a prediction which is valid in the entire range of transverse momenta. In this Section we briefly recall the resummation procedure of Refs. [23, 50] and we comment on the inclusion of mass effects.

The QCD expression of the Higgs boson doubly differential cross section is

$$\begin{aligned} \frac{d\sigma}{dy dp_T^2}(y, p_T, m_H, s) &= \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) \\ &\times \frac{d\hat{\sigma}_{ab}}{d\hat{y} dp_T^2}(\hat{y}, p_T, m_H, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2), \end{aligned} \quad (8)$$

where $f_{a/h_i}(x, \mu_F^2)$ ($a = q_f, \bar{q}_f, g$) are the parton densities of the colliding hadrons (h_1 and h_2) at the factorization scale μ_F , and $d\hat{\sigma}_{ab}$ are the partonic cross sections. The centre-of-mass energy of the two colliding hadrons is denoted by s , and \hat{s} is the partonic centre-of-mass energy. The rapidity, \hat{y} , and the centre-of-mass energy, \hat{s} , of the partonic subprocess are related to the corresponding hadronic variables y and s as:

$$\hat{y} = y - \frac{1}{2} \ln \frac{x_1}{x_2}, \quad \hat{s} = x_1 x_2 s. \quad (9)$$

The partonic cross section $d\hat{\sigma}_{ab}$ is computable in QCD perturbation theory but its series expansion in α_S contains the logarithmically-enhanced terms, $(\alpha_S^n/p_T^2) \ln^m(m_H^2/p_T^2)$, that we want to resum.

To this purpose, the partonic cross section is rewritten as the sum of two terms,

$$\frac{d\hat{\sigma}_{a_1 a_2}}{d\hat{y} dp_T^2} = \frac{d\hat{\sigma}_{a_1 a_2}^{(\text{res.})}}{d\hat{y} dp_T^2} + \frac{d\hat{\sigma}_{a_1 a_2}^{(\text{fin.})}}{d\hat{y} dp_T^2}. \quad (10)$$

The logarithmically-enhanced contributions are embodied in the ‘resummed’ component $d\hat{\sigma}_{a_1 a_2}^{(\text{res.})}$. The ‘finite’ component $d\hat{\sigma}_{a_1 a_2}^{(\text{fin.})}$ is free of such contributions, and it can be computed by a truncation of the perturbative series at a given fixed order. In particular we compute $d\hat{\sigma}_{a_1 a_2}^{(\text{fin.})}$ starting from $[d\hat{\sigma}_{a_1 a_2}]_{\text{f.o.}}$, the usual perturbative series truncated at a given fixed order in α_S , and we subtract the perturbative truncation of the resummed component at the same order:

$$\left[\frac{d\hat{\sigma}_{a_1 a_2}^{(\text{fin.})}}{d\hat{y} dp_T^2} \right]_{\text{f.o.}} = \left[\frac{d\hat{\sigma}_{a_1 a_2}}{d\hat{y} dp_T^2} \right]_{\text{f.o.}} - \left[\frac{d\hat{\sigma}_{a_1 a_2}^{(\text{res.})}}{d\hat{y} dp_T^2} \right]_{\text{f.o.}}. \quad (11)$$

The resummed component of the partonic cross section is obtained by working in impact parameter b space

$$\frac{d\hat{\sigma}_{a_1 a_2}^{(\text{res.})}}{d\hat{y} dp_T^2}(\hat{y}, p_T, m_H, \hat{s}; \alpha_S) = \frac{m_H^2}{\hat{s}} \int_0^\infty db \frac{b}{2} J_0(bp_T) \mathcal{W}_{a_1 a_2}(\hat{y}, b, m_H, \hat{s}; \alpha_S), \quad (12)$$

where $J_0(x)$ is the 0th-order Bessel function, and the factor \mathcal{W} embodies the all-order dependence on the large logarithms $\ln(m_H^2 b^2)$ at large b , which correspond to $\ln(m_H^2/p_T^2)$ terms in p_T space.

In the case of the p_T cross section integrated over the rapidity, it is convenient to define [51, 23] the N -moments \mathcal{W}_N of \mathcal{W} with respect to $z = m_H^2/\hat{s}$ at fixed m_H . In the case in which the dependence on the rapidity is taken into account, it is useful to consider ‘double’ (N_1, N_2) -moments with respect to the two variables $z_1 = e^{+\hat{y}} m_H/\sqrt{\hat{s}}$ and $z_2 = e^{-\hat{y}} m_H/\sqrt{\hat{s}}$ at fixed m_H (note that $0 < z_i < 1$). We thus introduce $\mathcal{W}^{(N_1, N_2)}$ as follows [50]:

$$\mathcal{W}_{a_1 a_2}^{(N_1, N_2)}(b, m_H; \alpha_S) = \int_0^1 dz_1 z_1^{N_1-1} \int_0^1 dz_2 z_2^{N_2-1} \mathcal{W}_{a_1 a_2}(\hat{y}, b, m_H, \hat{s}; \alpha_S). \quad (13)$$

More generally, for any function $h(y; z)$ with $|y| < -\ln \sqrt{z}$ and $0 < z < 1$ we define (N_1, N_2) Mellin moments as

$$h^{(N_1, N_2)} \equiv \int_0^1 dz_1 z_1^{N_1-1} \int_0^1 dz_2 z_2^{N_2-1} h(y; z), \quad \text{where } : y = \frac{1}{2} \ln \frac{z_1}{z_2}, \quad z = z_1 z_2. \quad (14)$$

By taking (N_1, N_2) moments the QCD factorization formula (8) becomes

$$d\sigma^{(N_1, N_2)} = \sum_{a_1, a_2} f_{a_1/h_1, N_1+1} f_{a_2/h_2, N_2+1} d\hat{\sigma}_{a_1 a_2}^{(N_1, N_2)}, \quad (15)$$

where $f_{a/h, N} = \int_0^1 dx x^{N-1} f_{a/h}(x)$ are the standard Mellin moments of the parton distributions.

By using double Mellin moments the resummation structure of the logarithmic terms in $\mathcal{W}_{a_1 a_2}^{(N_1, N_2)}$ can be organized in exponential form as follows:

$$\mathcal{W}^{(N_1, N_2)}(b, m_H; \alpha_S) = \sigma_{LO}(\alpha_S, m_H) \mathcal{H}^{(N_1, N_2)}(m_H, \alpha_S; m_H^2/Q^2) \exp\{\mathcal{G}^{(N_1, N_2)}(\alpha_S, \tilde{L}_Q; m_H^2/Q^2)\}, \quad (16)$$

where

$$\tilde{L}_Q = \ln \left(\frac{Q^2 b^2}{b_0^2} + 1 \right), \quad (17)$$

$b_0 = 2e^{-\gamma_E}$ ($\gamma_E = 0.5772\dots$ is the Euler number) and, to simplify the notation, the dependence on the flavour indices has been understood. The scale Q in Eq. (17), named resummation scale, parametrizes the arbitrariness in the resummation procedure. Its role is analogous to the role played by the renormalization (factorization) scale in the context of the renormalization (factorization) procedure. The resummed cross section does not depend on Q when evaluated at all perturbative orders, but its dependence on Q appears after truncation of the resummed expression at a given logarithmic accuracy.

The function $\mathcal{H}^{(N_1, N_2)}$ corresponds to the double Mellin transform of the function \mathcal{H} introduced in Sect. 2. More precisely, the coefficients $\mathcal{H}(z_1, z_2, \alpha_S)$ correspond to the Mellin inversion of $\mathcal{H}^{(N_1, N_2)}$ evaluated at $Q = m_H$.

The form factor $\exp\{\mathcal{G}\}$ includes the complete dependence on b and, in particular, it contains all the terms that order-by-order in α_S are logarithmically divergent when $b \rightarrow \infty$. The functional dependence on b is expressed through the large logarithmic terms $\alpha_S^n \tilde{L}_Q^m$ with $1 \leq m \leq 2n$.

Note that we use the logarithmic variable \tilde{L}_Q (see Eq. (17)) to organize the resummation of the large logarithms $\ln(Q^2 b^2)$. In the region in which $Qb \gg 1$ we have $\tilde{L}_Q \sim \ln(Q^2 b^2)$ and the use

of the variable \tilde{L}_Q is fully legitimate to arbitrary logarithmic accuracy. When $Qb \ll 1$, we have $\tilde{L}_Q \rightarrow 0$ and $\exp\{\mathcal{G}(\alpha_S, \tilde{L}_Q)\} \rightarrow 1$. Therefore, the use of \tilde{L}_Q reduces the effect produced by the resummed contributions in the small- b region (i.e., at large and intermediate values of p_T), where the large- b resummation approach is not justified. In particular, setting $b = 0$ (which corresponds to integrate over the entire p_T range) we have $\exp\{\mathcal{G}(\alpha_S, \tilde{L}_Q)\} = 1$: this property implies [23] a unitarity constraint on the total cross section; transverse-momentum resummation acts on the shape of the p_T distribution of the Higgs boson without affecting its total production rate.

The formalism briefly recalled above defines a systematic expansion [23] of Eq. (10) whose orders are denoted as NLL+NLO, NNLL+NNLO and so forth. In this notation the first label (NLL, NNLL, ...) refers to the logarithmic accuracy at small p_T and the second label (NLO, NNLO, ...) refers to the customary perturbative order for the inclusive cross section. More precisely, at NLL+NLO accuracy we use the NLL expression for the form factor $\exp\{\mathcal{G}\}$, include the coefficient $\mathcal{H}^{(1)}$, and expand the finite component to $\mathcal{O}(\alpha_S^3)$. At NNLL+NNLO accuracy we use the NNLL expression for the form factor $\exp\{\mathcal{G}\}$, include the coefficient $\mathcal{H}^{(2)}$ [18], and truncate the finite component to $\mathcal{O}(\alpha_S^4)$.

We point out that the NNLL+NNLO (NLL+NLO) result includes the *full* NNLO (NLO) perturbative contribution, supplemented with the resummation of the logarithmically enhanced terms in the small- p_T region at (N)NLL.

Having recalled the resummation formalism, we can now briefly comment on the implementation of the exact top- and bottom-mass dependence in the resummed spectrum. We note that the resummed cross section is proportional to the Born term (see Eq. (16)), whose heavy-quark mass dependence can be implemented in a straightforward manner. At NLL+NLO accuracy the additional mass dependence is embodied in the coefficient $\mathcal{H}_{gg}^{(1)}$ in Eq. (5) whose mass dependence enters through the finite part of the virtual corrections \mathcal{A} (see Eq. (7)). It is thus straightforward to replace the approximated expression of the function \mathcal{A} with its exact expression, as was done at fixed order. All the remaining mass effects enter through the matching procedure in Eq. (10) and are treated at fixed order. They can be thus dealt with analogously to what is done in the fixed order calculation and described in Sec. 2.

3.1 Bottom quark loop

The implementation of mass effects outlined in the previous section is straightforward and is certainly appropriate when the heavy-quark mass is of the order of the Higgs mass, as in the case of the top quark. When the heavy-quark mass is much smaller than the Higgs mass, as in the case of the bottom quark, the computation of the p_T spectrum becomes a *three scale* problem, whose solution beyond fixed order is by far non trivial.

The impact of the heavy-quark masses in the p_T spectrum at NLO was shown in Fig. 1. When only the top quark effect is considered, the behaviour of the p_T spectrum in the small- p_T region is very similar to the corresponding behaviour in the large- m_t limit. In this region in fact the p_T spectrum is divergent, and the singularity is driven by the well known soft and collinear singularities of the relevant $H + 3$ parton matrix element. Since such singular behaviour is universal, the shape of the spectrum in this p_T region does not depend on the inclusion of the

top-quark mass.

When the bottom-quark mass is included, the behaviour of the spectrum is rather different. When $p_T \lesssim m_b$ the behaviour is still driven by the singularities of the $H + 3$ parton matrix element, but in the region $m_b \lesssim p_T < m_H$ the shape of the spectrum is distorted.

In order to better understand what happens, in the following we examine the analytic behaviour of the QCD matrix elements [33]. To make the discussion simpler let us consider the amplitude of the Higgs production in the $qg \rightarrow Hq$ channel. In this channel only one Feynman diagram contributes, which is shown in Fig. 2: it consists in a triangular loop in which one of the gluons is off shell and radiated from the incoming quark line. In the small- p_T region the singular behaviour is due to the collinear region, in which the gluon with momentum $p_1 - p_3$ goes on shell.

In Fig. 3 we plot the p_T spectrum in this channel normalized to the corresponding result in the large- m_t limit. We see that the qualitative behaviour is the same observed in Fig. 1: the behaviour of the spectrum is distorted in the small and intermediate p_T region by the presence of the bottom mass.

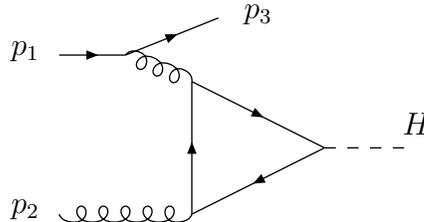


Figure 2: Typical Feynman diagrams for the $qg \rightarrow Hq$ process.

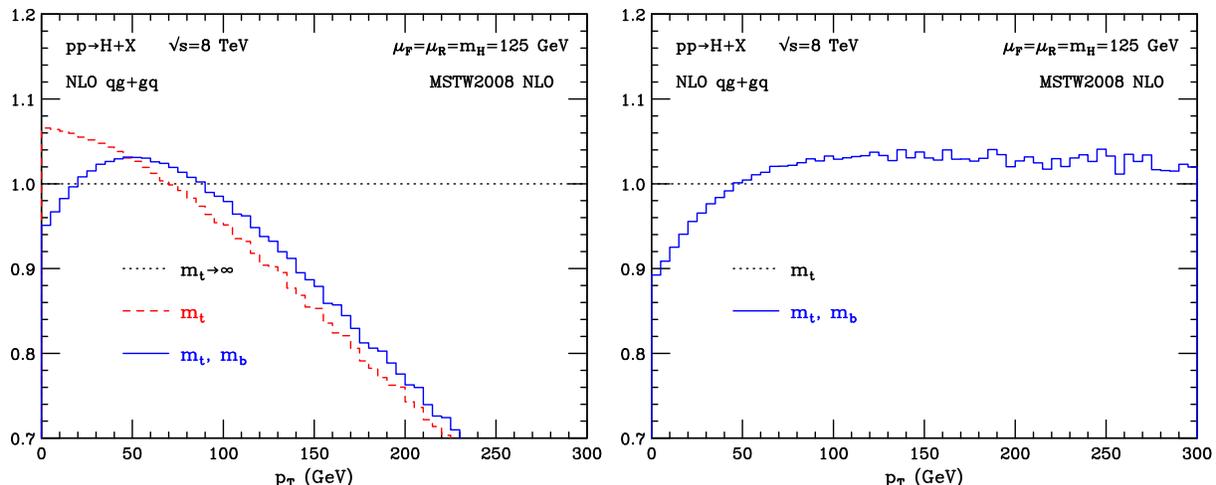


Figure 3: Transverse momentum distribution for a SM Higgs with $m_H = 125$ GeV computed at NLO in the $qg + gq$ channel. Left: result normalized to the large- m_t approximation. Right: normalized to the m_t -dependent result.

This behaviour is somewhat against intuition: in the region $p_T \ll m_H$ we could expect the

cross section to factorize naively as in the large- m_t limit, and the structure of the triangular loop to affect only the overall normalization. This would lead to a similar behaviour of the exact and approximated p_T spectra, and thus to a relatively flat behaviour of the histogram in Fig. 3. As we will see below, such behaviour is disrupted by the effect of the bottom mass.

The matrix element squared for the process $q(p_1) + g(p_2) \rightarrow q(p_3) + H$ is given by [33]

$$|\mathcal{M}_{qg \rightarrow qH}(s, t, u)|^2 = \alpha_W \alpha_S^3 C_F C_A \frac{u^2 + s^2}{(-t) m_W^2} \frac{m_H^4}{(u + s)^2} |A_5(t, s, u)|^2, \quad (18)$$

where α_W is the EW coupling, m_W is the W mass, and s, t and u are the Mandelstam invariants

$$s = (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_2 - p_3)^2, \quad (19)$$

satisfying

$$s + u + t = m_H^2, \quad ut = sp_T^2. \quad (20)$$

The physical region of these invariants is $u \leq 0$, $t \leq 0$ and $s \geq m_H^2$. The function $A_5(t, s, u)$ is given by

$$A_5(t, s, u) = \sum_f \frac{m_f^2}{m_H^2} \left[4 + \frac{4t}{u + s} \left[W_1^f(t) - W_1^f(m_H^2) \right] \right] \quad (21)$$

$$+ \left[1 - \frac{4m_f^2}{u + s} \right] \left[W_2^f(t) - W_2^f(m_H^2) \right], \quad (22)$$

where the summation is over the heavy-quark running in the triangular loop. The explicit expressions for the functions W_1^f and W_2^f are given in Ref. [33]. In the physical region ($t \leq 0$) they read

$$W_1^f(t) = 2(1 + 4m_f^2/(-t))^{1/2} \operatorname{arcsinh}(\sqrt{-t}/(2m_f)) \quad W_2^f(t) = 4 \operatorname{arcsinh}^2(\sqrt{-t}/(2m_f)). \quad (23)$$

In the limit $|t| \ll 4m_f^2$ we have

$$W_1^f(t) \rightarrow 2 \quad W_2^f(t) \rightarrow 0 \quad (24)$$

and the amplitude $A_5(t, s, u)$ reduces to

$$A_5(t, s, u) \rightarrow A_1(m_H^2) = \sum_f \frac{m_f^2}{m_H^2} \left[4 - W_2^f(m_H^2) \left(1 - \frac{4m_f^2}{m_H^2} \right) \right], \quad (25)$$

where $A_1(m_H^2)$ is the Born $gg \rightarrow H$ amplitude [3]. In this limit the matrix element squared $|\mathcal{M}_{qg \rightarrow qH}(s, t, u)|^2$ can thus be written as

$$|\mathcal{M}_{qg \rightarrow qH}(s, t, u)|^2 \rightarrow \alpha_W \alpha_S^3 C_A \frac{m_H^4}{(-t) m_W^2} \hat{P}_{gq}(z) |A_1(m_H^2)|^2, \quad (26)$$

where

$$\hat{P}_{gq}(z) = C_F \frac{1 + (1 - z)^2}{z} \quad (27)$$

and $z = m_H^2/s$.

As it is mentioned above, we are interested in the $p_T \sim m_b$ region. In this case one still can use the $|t| \rightarrow 0$ limit for the terms coming from the top quark contribution, while for the terms involving the bottom quark this approximation is not justified. The bottom quark contribution to $A_5(t, s, u)$ in the region of interest can be written as

$$A_{5b}(t, s, u) = \frac{m_b^2}{m_H^2} \left[4 - (W_2^b(m_H^2) - W_2^b(t)) \left(1 - \frac{4m_b^2}{m_H^2} \right) \right], \quad (28)$$

which differs from Eq. (25) by the presence of the $W_2^b(t)$ contribution. In the region in which $|t| \sim 4m_b^2$ the term proportional to $W_2(t)$ in Eq. (28) cannot be neglected. This means that naive collinear factorization, which would lead us to recover the Born result in Eq. (25), and thus Eq. (26), is not a good approximation here. Furthermore, $W_2(t)$ is an increasing function of $-t$, and hence, of p_T , thus explaining the steep behaviour in Fig. 3.

The analytic behaviour in the gg channel is more complicated but the physical picture remains the same: when the transverse momentum of the Higgs boson is much smaller than its mass, but of the order of the bottom quark mass, the naive factorization valid in the large- m_t limit does not apply. This implies that the resummed calculation of the Higgs p_T spectrum, which is based on the assumption that only the two scales p_T and m_H are relevant, cannot be straightforwardly extended to include the bottom quark. The resummation formalism is in fact based on the possibility to factorize and resum the emission of multiple soft and collinear partons from the underlying Born subprocess. In other words, the presence of non factorizable contributions at p_T of order m_b and larger not only spoils soft and collinear factorization beyond this region, but introduces an effective scale of the order of m_b which acts as a cut off in the integration of the soft and collinear spectrum, effectively replacing the natural scale m_H in the logarithmically enhanced terms.

In the following we propose a simple solution to this problem, which is based on the following observation. The dominant contribution to the transverse momentum cross section is given by the top quark, and, in this case, the resummation procedure is fully justified. The bottom-quark contribution, however, is important to obtain a reliable prediction for the transverse momentum spectrum. Since it introduces an additional scale that complicates the resummation of the large logarithmic terms, it would be better to treat it at fixed order. On the other hand, although small with respect to the top-quark contribution, the bottom contribution is still divergent as $p_T \rightarrow 0$. We thus would like the resummation to be effective only in the region $p_T \lesssim m_b$, where it is indeed needed. The resummation formalism of Ref. [23] does allow to achieve this goal, since it introduces an additional scale, the resummation scale (see Eq. (17)), which actually controls the transverse momentum region up to which resummation is effective.

We can thus proceed as follows. We split the calculation in two parts. The first part includes only the top-quark contribution, and can thus be treated up to NLL+NLO as discussed in Sec. 3, with a resummation scale $Q_1 \sim m_H$. The second part includes the bottom-quark contribution and the top-bottom interference, and we treat it separately, by choosing a resummation scale $Q_2 \sim m_b$. This procedure can be implemented through the following replacement in the resummed form factor of Eq. (16)

$$\mathcal{W}^{(N_1, N_2)} \longrightarrow \mathcal{W}_{\text{top}}^{(N_1, N_2)} + \mathcal{W}_{\text{bot}}^{(N_1, N_2)} \quad (29)$$

where

$$\mathcal{W}_{\text{top}}^{(N_1, N_2)}(b) = \sigma_{LO}(m_t) \mathcal{H}^{(N_1, N_2)}(m_H^2/Q_1^2; m_t) \exp\{\mathcal{G}^{(N_1, N_2)}(\tilde{L}_{Q_1}; m_H^2/Q_1^2)\} \quad (30)$$

$$\begin{aligned} \mathcal{W}_{\text{bot}}^{(N_1, N_2)}(b) = & \left[\sigma_{LO}(m_t, m_b) \mathcal{H}^{(N_1, N_2)}(m_H^2/Q_2^2; m_t, m_b) - \sigma_{LO}(m_t) \mathcal{H}^{(N_1, N_2)}(m_H^2/Q_2^2; m_t) \right] \\ & \times \exp\{\mathcal{G}^{(N_1, N_2)}(\tilde{L}_{Q_2}; m_H^2/Q_2^2)\}, \end{aligned} \quad (31)$$

and the dependence on α_S and m_H has been understood. We can finally add the NNLL+NNLO terms for the top quark contribution $\mathcal{W}_{\text{top}}^{(N_1, N_2)}(b)$ in the large- m_t limit by including the coefficients $\mathcal{H}^{(2)}$ [18] and the NNLL expression for the form factor $\exp\{\mathcal{G}\}$.

We note that by using this procedure the standard resummed result is automatically recovered by setting $Q_2 = Q_1$. We also note that, thanks to the unitarity constraint fulfilled by our formalism, the exact heavy-quark mass dependence up to NLO is recovered when integrating over p_T . Since the inclusive cross section is known to contain logarithmic terms of the form $\ln m_H/m_b$, such unitarity constraint implies that these logarithmic terms are correctly recovered (and not resummed) in the inclusive cross section.

3.2 Numerical results

We start the presentation of our results by considering the bottom quark contribution[‡]. Such contribution is dominated by the (negative) top-bottom interference. In the small- p_T region we resum the logarithmically enhanced terms up to NLL and do the matching to the bottom-quark contribution at NLO. Although these perturbative contributions are non physical, the way they are treated in the full calculation is essential. Since the scale up to which this resummation makes sense is lowered by the non factorizable contributions discussed in Sec. 3.1, we choose the corresponding resummation scale Q_2 of the order of the bottom mass. In Fig. 4 our NLL+NLO result for $Q_2 = m_b/2, m_b, 2m_b, 4m_b$ is compared to the fixed order NLO result. We see that the NLO result is divergent as $p_T \rightarrow 0$. We also notice that, as expected, increasing Q_2 makes the resummed p_T spectrum harder. We see that, for $Q_2 = m_b/2, m_b, 2m_b$ there is a rather good agreement of the resummed and fixed order results at $p_T \gtrsim 10$ GeV. On the contrary, the NLL+NLO result for $Q_2 = 4m_b$ does not agree with the fixed order result in this region. Since we want our resummation to be effective only in the very small p_T region, we choose $Q_2 = m_b$ as our central scale choice, and proceed by performing the full NLL+NLO calculation. Thanks to the unitarity constraint discussed in the previous section, the integral of our NLL+NLO result coincides with the inclusive NLO cross section. Since for $m_H = 125$ GeV $\sigma_{NLO}(m_t, m_b)/\sigma_{NLO}(m_t \rightarrow \infty) \sim 0.988$ (see Table 1), the inclusion of heavy quark masses affects the shape of the spectrum, by leaving the normalization of the transverse momentum cross section essentially unchanged.

In Fig. 5 we present our resummed spectrum computed with $Q_2 = m_b$ as discussed above, normalized to the corresponding result in the large- m_t limit, and we compare it with the corresponding result obtained ignoring the problem with the bottom quark contribution, and setting $Q_2 = Q_1 = m_H/2$. We see that the impact in the shape is significant. The choice $Q_2 = m_b$ makes the resummed p_T spectrum harder. This is not unexpected: since the resummed bottom-quark

[‡]Here and in the following, when we mention the “bottom quark contribution” we always refer to all the perturbative contributions involving a bottom-quark loop, i.e., purely bottom contributions and top-bottom interferences.

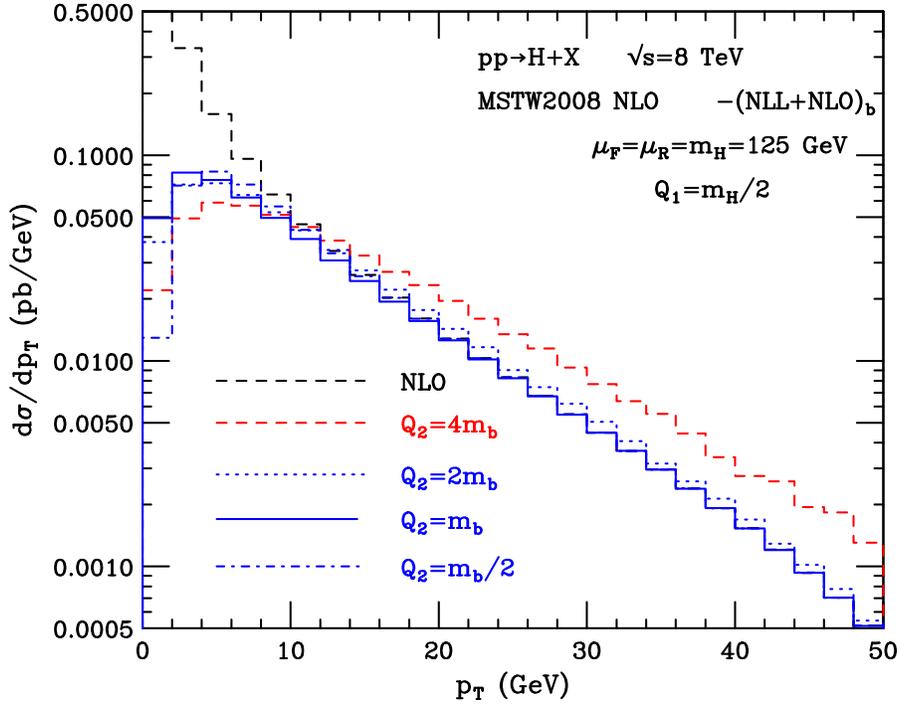


Figure 4: Bottom quark contributions to the transverse momentum spectrum of the Higgs boson at NLO and NLL+NLO for different choices of the scale Q_2 .

contribution is negative, choosing a smaller resummation scale for it reduces the cross section at small p_T and increases it at intermediate and large values of p_T . More precisely, the choice $Q_2 = m_b$ increases the cross section by about 1% (5%) at $p_T = 100$ GeV ($p_T = 40$ GeV), and decreases the cross section by about 25% in the first bin.

The heavy-quark mass effects in the resummed p_T spectrum were first implemented up to NLL+NLO in Ref. [49]. In the latter paper the top and bottom quarks are treated on the same footing and the resummed calculation for the p_T spectrum corresponds to the case in which $Q_2 = Q_1 = m_H/2$. By comparing the dashed histogram in Fig. 5 with the corresponding curve in Fig. 6 of Ref. [49] we find relatively good agreement, despite the fact that Ref. [49] uses $\mu_F = \mu_R = m_H/2$. The good agreement is confirmed when we adopt the same scale choice. However, as discussed in Sect. 3.1, the choice $Q_2 = Q_1$ corresponds to ignore the factorization breaking in the bottom-quark contribution, and, in our opinion, it is not advisable.

The resummation of the logarithmically enhanced terms in the p_T spectrum is effectively performed by Monte Carlo event generators. The method of matching NLO computations to parton shower simulations, implemented in MC@NLO [52] and POWHEG [53], allows the user to achieve an accuracy which is roughly comparable to the accuracy of our resummed NLL+NLO calculation. Such Monte Carlo generators have traditionally used the large- m_t approximation in their implementations of Higgs production through gluon fusion. Recently, the exact top- and bottom-mass dependence has been implemented both in MC@NLO [54] and POWHEG [48]. A comparison of the relative effect of the exact top-mass dependence with respect to the result in the large- m_t limit shows a good agreement between the two generators. The inclusion of the bottom-quark mass leads instead to relatively large differences [54].

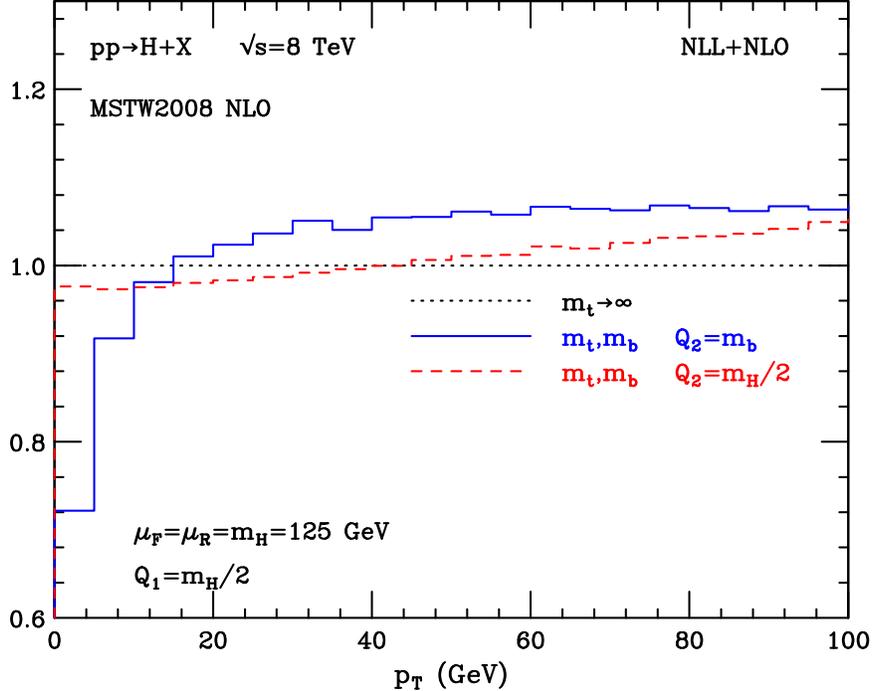


Figure 5: Transverse momentum spectra at NLL+NLO for $Q_2 = m_b$ and $Q_2 = m_H/2$ normalized to the result in the large- m_t limit.

Comparing our results with those of [54] we find that, in the case of $Q_1 = Q_2$ the quantitative impact of the bottom quark on the shape of the p_T spectrum is very similar to what found with MC@NLO, while POWHEG somewhat amplifies the effect of the bottom quark. This is not unexpected: the matching procedure implemented in MC@NLO carries many similarities to the one adopted in HRes, the difference being that, while in HRes the resummation is carried out analytically (see Sec. 3), in MC@NLO it is performed through the parton shower. On the contrary, POWHEG works rather differently: since it exponentiates the full real emission matrix element, the bottom-quark contribution is expected to affect the spectrum in a different way. Nonetheless, the arguments of Sect. 3.1 apply not only to analytical resummation, but also to Monte Carlo simulations. Since both MC@NLO and POWHEG treat the top and bottom contributions on the same footing, we do not regard the ensuing results as theoretically motivated. With our default choice of $Q_2 = m_b$ the shape of the spectrum is (accidentally) more similar to the POWHEG result, though in our case the effects of the bottom quark are confined to smaller values of p_T .

In order to assess the relevance of heavy-quark mass effects at NLL+NLO, it is important to compare their quantitative impact to the uncertainties affecting the resummed p_T spectrum computed in the large- m_t limit. At NLL+NLO, it is known that perturbative uncertainties are relatively large. While variations of the renormalization and factorization scales affect both the shape and the normalization of the p_T cross section, the choice of the resummation scale Q affects only the shape of the spectrum. In particular, as discussed above, increasing (decreasing) Q makes the spectrum harder (softer). In Fig. 6 (left) we present our resummed spectrum at NLL+NLO with inclusion of the heavy-quark masses as in Fig. 5, and compare it with the spectrum computed in the large- m_t limit for $Q = m_H/4, m_H$ with the numerical program HqT. We see that, as anticipated, the effect of resummation scale variations is large, well beyond the effect of heavy-

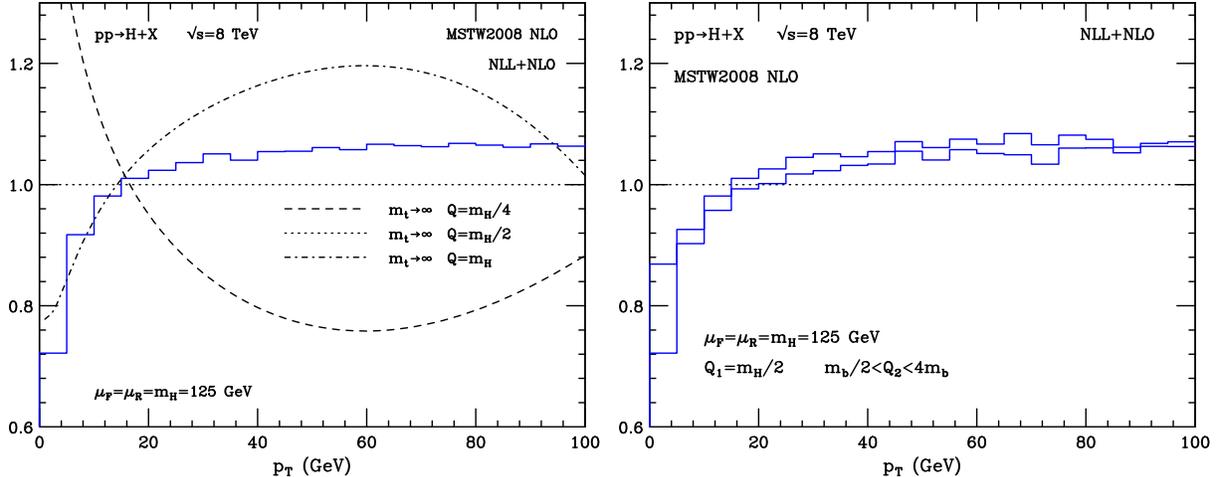


Figure 6: Left: transverse momentum spectrum at NLL+NLO with full dependence on heavy quark masses ($Q_2 = m_b$) normalized to the result in the large- m_t limit (solid histogram). The result is compared to the NLL+NLO results in the large- m_t limit obtained with $Q = m_H, m_H/4$. Right: transverse momentum spectra at NLL+NLO for $m_b/2 < Q_2 < 4m_b$ normalized to the result in the large- m_t limit.

quark masses for $p_T \gtrsim 20$ GeV. In the region $p_T \lesssim 20$ GeV instead, the effect of the bottom-quark mass and of resummation scale variation are comparable. In Fig. 6 (right) we study the impact of Q_2 variations on the p_T spectrum. Since we have chosen $Q_2 = m_b$ as central value of the scale, the standard practice would suggest to vary Q_2 between $m_b/2$ and $2m_b$ to estimate the theoretical uncertainty. However, we should not forget that in the region $m_b \lesssim p_T \lesssim m_H$ there are potentially large logarithmic contributions beyond $\mathcal{O}(\alpha_s^3)$ that in our approach are treated essentially at fixed order. To be conservative, we thus extend the upper limit of Q_2 to $4m_b$. We see that the impact of Q_2 variations is moderate, at the level of $\pm 1 - 2\%$, except in the first bin, where it reaches about $\pm 10\%$. This is also the region of transverse momenta where the effect of the bottom quark is more significant.

We now move to consider the NNLL+NNLO results. Since for $m_H = 125$ GeV we have[§] $\sigma_{NNLO}(m_t, m_b)/\sigma_{NNLO}(m_t \rightarrow \infty) \sim 1.007$, the inclusion of heavy quark masses, as happens at NLL+NLO, affects the shape of the spectrum, but leaves the normalization of the transverse momentum cross section essentially unchanged. In Fig. 7 (left) the NNLL+NNLO spectrum normalized to the NNLL+NNLO result in the large- m_t limit is presented, and compared to the large- m_t limit results for $Q = m_H/4$ and $Q = m_H$. Comparing with Fig. 6 (left) we see that the impact of heavy-quark mass effects in the NNLL+NNLO result is similar to what observed at NLL+NLO. This should somewhat be expected, since the NNLL+NNLO terms we are adding are evaluated in the large- m_t limit. We notice that, as is known [23], the effect of resummation scale variations at this order is much smaller and we conclude that mass effects in the low- p_T region are even more important. In Fig. 7 (right) we study the impact of Q_2 variations at this order. As in Fig. 6, we vary Q_2 in the range $m_b/2 < Q_2 < 4m_b$. We see that the effects is moderate and similar to what found at NLL+NLO.

[§]We remind the reader (see Sec. 2) that the $\mathcal{O}(\alpha_s^4)$ terms in our calculation are rescaled with the exact m_t dependent Born cross section.

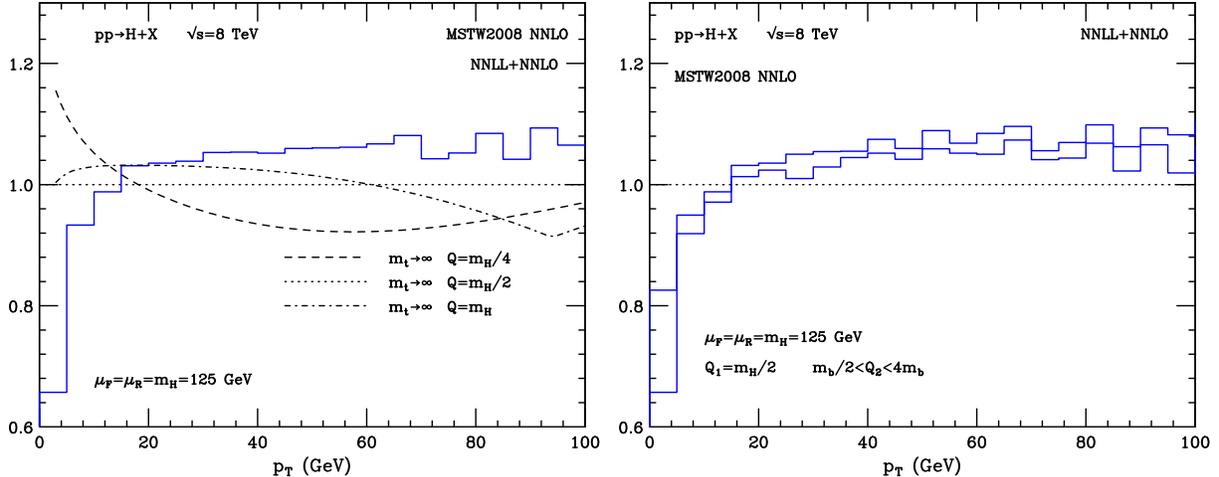


Figure 7: The same as in Fig. 6 but at NNLL+NNLO.

We finally add few comments on the uncertainties affecting the *shape* of the resummed p_T spectrum at NNLL+NNLO. Such uncertainties were previously studied in Ref. [24], within the large- m_t approximation, by using the HqT numerical program. It was shown (see Fig. 4 of Ref. [24]) that the combined variation of resummation, renormalization and factorization scale leads to effects up to $\mathcal{O}(\pm 5\%)$ on the normalized spectrum $1/\sigma \times d\sigma/dp_T$. Non-perturbative effects (see Ref. [23] and references therein) are expected to significantly affect the p_T distribution only in the region $p_T \lesssim 10$ GeV, and, in particular, to make the spectrum (slightly) harder. Compared to the above effects, the impact of heavy quark-masses discussed in this paper is certainly relevant, since it leads to a distortion of the spectrum at least of the same order, and definitely larger at small p_T . From the previous discussion we conclude that the estimated uncertainty from the treatment of the bottom quark on the shape of the spectrum is typically small, at the $\pm 1 - 2\%$ level, but it increases to the $\pm 10\%$ level at very small p_T ($p_T \lesssim m_b$).

4 Conclusions

In this paper we have considered heavy-quark mass effects in Higgs boson production through gluon fusion at the LHC. We have extended previous computations of the fully exclusive $gg \rightarrow H$ cross section and of the resummed p_T spectrum by implementing the exact top- and bottom-mass dependence up to $\mathcal{O}(\alpha_S^3)$.

The implementation of the top-mass dependence does not lead to substantial complications. By contrast, since $m_b \ll m_H$, the inclusion of the exact bottom-mass dependence in the resummed p_T spectrum implies the solution of a non-trivial three-scale problem. We have studied the analytical behaviour of the relevant QCD matrix elements, showing that, when the bottom-quark contribution is considered, naive factorization is valid only in a limited region of the phase space, i.e. when $p_T \lesssim 2m_b$. We have provided a simple solution to this issue by controlling the resummed bottom-quark contribution through an additional resummation scale Q_2 , which was chosen of the order of the bottom mass m_b . We have shown that this solution has a clear advantage: it limits

the impact of the resummation to the region where it is really needed, i.e. $p_T \lesssim 2m_b$, and our resummed result for the bottom quark contributions smoothly merges with the fixed order NLO result at $p_T \gtrsim 2m_b$, where the resummation is not anymore justified (see Fig. 4).

We have studied the impact of mass effects on the NLL+NLO calculation, by showing that the effect of heavy-quark masses is significant, although at this order large uncertainties affect the resummed p_T spectrum. When going to NNLL+NNLO, where the perturbative uncertainties are much smaller, the impact of heavy-quark masses is even more relevant, since it significantly distorts the spectrum in the low- p_T region. Our calculations are implemented in updated versions of the HNNLO and HRes numerical programs.

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