Associated Higgs Boson Production with Heavy Quarks at Hadron Colliders: Impact of NLO Results

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We emphasize the role that the associated production of a Higgs boson with a pair of top-antitop quarks can play at present and future hadron colliders. Results of recent calculations of the NLO total cross section for the associated production of a Standard Model like Higgs boson with a pair of top-antitop quarks at the Tevatron ($\sqrt{s}$ = 2 TeV) are presented.

1. Introduction

The possibility of discovering a Higgs boson in the range between $115 - 130$ GeV is becoming increasingly likely. The Standard Model (SM) precision fits are consistent with a light Higgs boson [1]. At the same time, the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) requires the existence of a scalar Higgs boson lighter than about 130 GeV [2]. Both the Fermilab Tevatron and the CERN Large Hadron Collider (LHC) will focus on the search for a light Higgs boson. Since in the low mass range, below the W-pair threshold, a Higgs boson mainly decays hadronically into $b\bar{b}$ pairs, both the Tevatron and the LHC will have to optimize their search strategies in order to overcome the overwhelming hadronic background. This implies that all available Higgs boson production and decay channels have to be considered.

In this context, the associated production of a Higgs boson with a pair of top-antitop quarks has drawn increasing attention. In spite of the very small cross section, this production mode has an extremely distinctive signature, and recent analyses have shown that it can be within the reach not only of the LHC, but also of the Tevatron, if integrated luminosities of 15-30 fb^{-1} become available [3]. From ongoing studies [4] we learn that including $p\bar{p} \to t\bar{t}H$ among the Higgs search channels could lower the luminosity required for discovery of a SM like Higgs at the Tevatron by as much as 15-20%, given the high significance of the corresponding signature [5]. If not at the Tevatron, this mode will surely be used at the LHC, where it is instrumental in the discovery of a light SM like Higgs [6, 7]. The higher statistics available at the LHC will also allow a first precision measurement of the top quark Yukawa coupling at the 20% level.

In view of the relevance that this production mode can have in particular for the Tevatron, we have recently completed the calculation of the inclusive total cross section for $p\bar{p} \to t\bar{t}h$, for a SM Higgs ($h = h_{SM}$), at the Tevatron center of mass energy $\sqrt{s} = 2$ TeV, including first order QCD corrections [8, 9]. The main impact of next-to-leading order (NLO) QCD corrections is in reducing the dependence on the renormalization and factorization scales of the Born level cross section enormously, giving us increased confidence in our theoretical predictions. We will briefly discuss the characteristics of our calculation in Sec. 2, and present our results in Sec. 3. This calculation has also been performed by the authors of Ref. [10], and results of our two groups are in very good agreement.

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2. General Framework

The $\mathcal{O}(\alpha_s^3)$ total cross section for $p\bar{p}\to t\bar{t}h$ is defined as:

$$\sigma_{NLO}(p\bar{p}\to t\bar{t}h)=\sum_{ij}\int dx_1dx_2\mathcal{F}_i^p(x_1,\mu)\mathcal{F}_j^{\bar{p}}(x_2,\mu)\hat{\sigma}_{NLO}^{ij}(x_1,x_2,\mu)\ ,\tag{1}$$

where we denote by $\mathcal{F}_i^{p,\bar{p}}$ the NLO parton distribution functions for parton i in a proton/antiproton, defined at a generic factorization scale $\mu_f=\mu$. $\hat{\sigma}_{NLO}^{ij}$ is the $\mathcal{O}(\alpha_s^3)$ parton level total cross section for incoming partons i and j, made of the two channels $q\bar{q}$, $gg\to t\bar{t}h$, and renormalized at an arbitrary scale μ_r which we also take to be $\mu_r=\mu$. We note that because of the large mass of the produced $t\bar{t}h$ final state, this process is very close to threshold at the Tevatron, for $p\bar{p}$ collision at center of mass energy $\sqrt{s}=2$ TeV. As a consequence, at the Tevatron more than 95% of the tree level total cross section comes from $q\bar{q}\to t\bar{t}h$, summed over all light quark flavors, and the gg contribution is completely negligible. Therefore we compute $\sigma_{NLO}(p\bar{p}\to t\bar{t}h)$ by including in $\hat{\sigma}_{NLO}^{ij}$ only the $\mathcal{O}(\alpha_s)$ corrections to $q\bar{q}\to t\bar{t}h$. The calculation of $gg\to t\bar{t}h$ at $\mathcal{O}(\alpha_s^3)$ is, however, crucial to determine $\sigma_{NLO}(pp\to t\bar{t}h)$ for the LHC, since in pp collisions at $\sqrt{s}=14$ TeV a large fraction of the total cross section comes from the $gg\to t\bar{t}h$ channel. The $\mathcal{O}(\alpha_s^3)$ total cross section for the LHC has been estimated within the Effective Higgs Approximation in Ref. [11]. Full results are presented in Ref. [10] and will also appear in Ref. [12].

The $\mathcal{O}(\alpha_s^3)$ parton level total cross section can be written as:

$$\hat{\sigma}_{NLO}^{ij}(x_1,x_2,\mu)=\alpha_s^2(\mu)\left\{\hat{f}_{LO}^{ij}(x_1,x_2)+\frac{\alpha_s(\mu)}{4\pi}\hat{f}_{NLO}^{ij}(x_1,x_2,\mu)\right\}\equiv\hat{\sigma}_{LO}^{ij}(x_1,x_2,\mu)+\delta\hat{\sigma}_{NLO}^{ij}(x_1,x_2,\mu)\ ,\tag{2}$$

where $\delta\hat{\sigma}_{NLO}^{ij}(x_1,x_2,\mu)$ consists of both $\mathcal{O}(\alpha_s)$ virtual and real corrections to the Born cross section :

$$\delta\hat{\sigma}_{NLO}^{ij}(x_1,x_2,\mu)=\hat{\sigma}_{virt}^{ij}+\hat{\sigma}_{real}^{ij}\ .\tag{3}$$

The virtual part of the NLO cross section contains UV divergences that are renormalized by introducing a suitable set of counterterms. It also contains IR singularities that are cancelled by analogous singularities in the real part of the NLO cross section and in the renormalized parton distribution functions.

The calculation of the $\mathcal{O}(\alpha_s)$ virtual corrections has required us to evaluate pentagon scalar integrals with several massive external and internal particles. These integrals were not available in the literature, and we have calculated them by reducing them to a linear combination of box scalar integrals, by applying the method originally introduced in [13, 14].

The $\mathcal{O}(\alpha_s)$ real corrections, i.e. the cross section for $q\bar{q}\to t\bar{t}h+g$, have been calculated using two different implementations of the Phase Space Slicing (PSS) method, with the introduction of one [15, 16, 17] or two cutoffs [18] respectively. In both cases, the IR singularities due to the emission of either a soft or a collinear gluon can be isolated in specific regions of the phase space, and calculated analytically, while the integration over the remaining phase space is performed numerically using standard Monte Carlo techniques. In fact, this is the first application of the one cutoff PSS method to a case with more than one massive particle in the final state. A detailed description of our calculation can be found in Ref. [9].

3. Results

All the results presented in this section have been obtained using CTEQ4M parton distribution functions [19] and the 2-loop evolution of $\alpha_s(\mu)$ for the calculation of the NLO cross section, and CTEQ4L parton distribution functions and the 1-loop evolution of $\alpha_s(\mu)$ for the calculation of the lowest order cross section, σ_{LO}. The top-quark mass is taken to be $m_t=174$ GeV and $\alpha_s^{NLO}(M_Z)=0.116$.

The importance of having calculated the total cross section for $p\bar{p}\to t\bar{t}h$ at the NLO of QCD corrections is manifest in Fig. 1, where we show, for $M_h=120$ GeV, how at NLO the dependence on the arbitrary renormalization/factorization scale μ is significantly reduced. For $M_h=120$ GeV, the

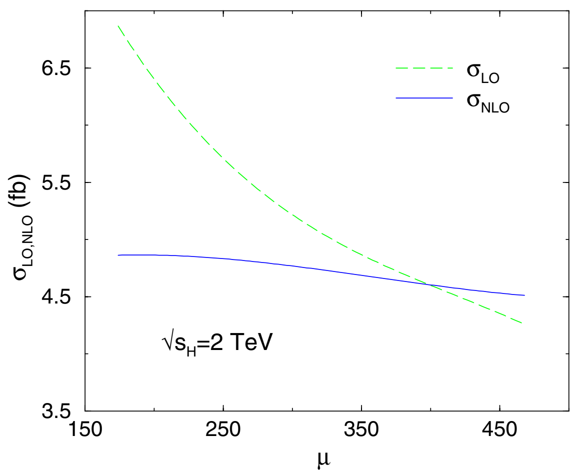

Figure 1: Dependence of $\sigma_{LO,NLO}(p\bar{p} \to t\bar{t}h)$ on the renormalization scale μ, at $\sqrt{s} = 2$ TeV, for $M_h = 120$ GeV.

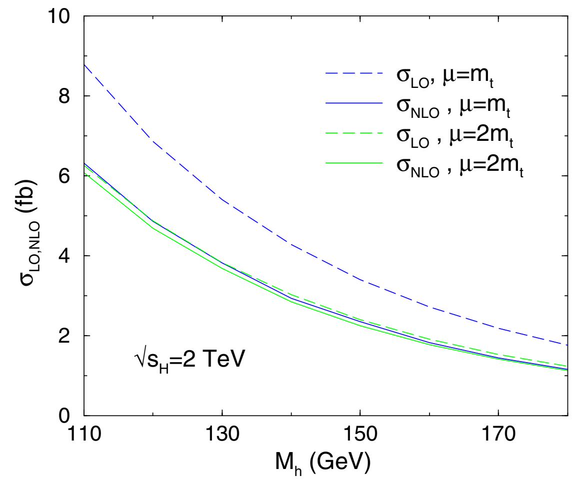

Figure 2: σ_{NLO} and σ_{LO} for $p\bar{p} \to t\bar{t}h$ as functions of M_h, at $\sqrt{s} = 2$ TeV, for $\mu = m_t$ and $\mu = 2m_t$.

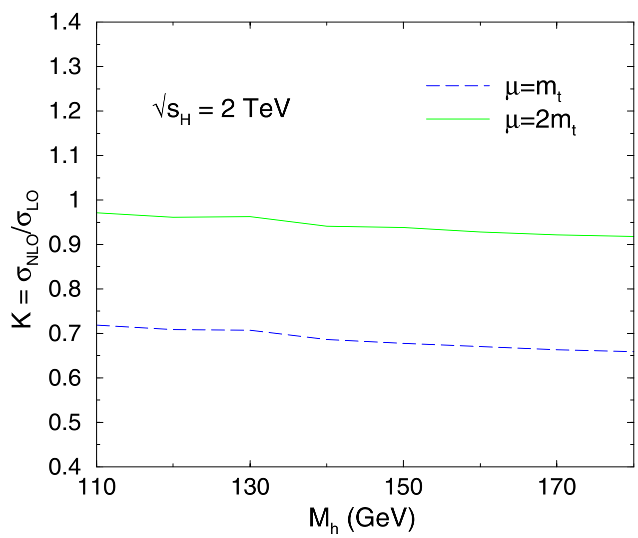

Figure 3: K factor for $p\overline{p} \to t\overline{t}h$ as a function of M_h, at $\sqrt{s} = 2$ TeV, for $\mu = m_t$ and $\mu = 2m_t$.

NLO cross section varies in the range $4.8 - 4.5$ fb with a residual renormalization and factorization scale dependence of the order of 8%. For larger Higgs masses the cross section becomes much smaller, with values of the order of 1 fb for $M_h = 180$ GeV, as illustrated in Fig. 2. Combining the residual scale dependence with the error from the parton distribution functions (6%) and from m_t (7%), we estimate the uncertainty on our theoretical prediction at about 12%.

In Fig. 1, we also notice that the LO and NLO cross section curves cross at a scale between $2m_t$ and $2m_t + M_h$. If we define as customary a K-factor as the ratio between the NLO and the LO cross sections, $K = \sigma_{NLO}/\sigma_{LO}$, the K factor for $p\bar{p} \to t\bar{t}h$ turns out to be smaller than one for scales roughly below $2m_t + M_h$ and bigger than one otherwise. The dependence of the K-factor on M_h is very mild, as shown in Fig. 3, where we plot the behavior of the K-factor for scales $\mu = m_t$ ($K \simeq 0.7$) and $\mu = 2m_t$ ($K \simeq 0.95$). It is worth noting, however, that, given the strong scale dependence of the LO cross section, the K-factor also shows a significant μ-dependence and therefore is an equally unreliable prediction. Therefore we would like to stress once more that we only discuss the K-factor as a qualitative indication of the impact of $\mathcal{O}(\alpha_s)$ QCD corrections. The physically meaningful quantity is the NLO cross section, not the K-factor.

4. Conclusions

The NLO inclusive total cross section for the Standard Model process $p\bar{p} \to t\bar{t}h$ at $\sqrt{s} = 2$ TeV shows a drastically reduced scale dependence as compared to the Born result and leads to increased confidence in predictions based on these results. The NLO QCD corrections slightly decrease or increase the Born level cross section depending on the renormalization and factorization scales used. The NLO inclusive total cross section for Higgs boson masses in the range accessible at the Tevatron, $120 < M_h < 180$ GeV, is of the order of $1 - 5$ fb.

Acknowledgments

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