QCD corrections to associated $t\bar{t}h$ production at hadron colliders

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We briefly present the status of QCD corrections to the inclusive total cross section for the production of a Higgs boson in association with a top-quark pair within the Standard Model at hadron colliders.

1. Introduction

The search for the Higgs boson of the Standard Model (SM) is one of the major tasks of the next generation of high-energy collider experiments. The direct limit on the SM Higgs boson mass, $M_h$, from LEP2 searches$^3$ and the indirect limit from electroweak precision data$^2$ strongly suggest the existence of a light Higgs boson, that may well be within the reach of a high-luminosity phase of the Fermilab Tevatron $p\bar{p}$ collider ($M_h \lesssim 180$ GeV)$^3$. However, since the dominant SM Higgs production channels are plagued with low event rates and large backgrounds, the Higgs boson search requires the highest possible luminosity, and all possible production channels should be considered. The production of a SM Higgs boson in association with a top-quark pair, $p\bar{p} \rightarrow t\bar{t}H$, can play a role for almost the entire Tevatron discovery range$^3$. Although the $t\bar{t}h$ event rate is small, the signature of such events is quite spectacular ($W^+W^-b\bar{b}b\bar{b}$). At the CERN LHC $pp$ collider, associated $t\bar{t}h$ production is one of the most promising processes for studying both the Higgs boson and the top quark. This process will provide a direct measurement of the top-Yukawa coupling$^2$. As for any other hadronic cross section, the next-to-leading-order (NLO) QCD corrections are expected to be numerically important and are crucial in reducing the (arbitrary) dependence of the cross sections on the factorization and renormalization scales. In the following we briefly describe the status of NLO QCD predictions for associated $t\bar{t}h$ production at the Tevatron and the LHC.

2. QCD corrections to $t\bar{t}h$ production

The inclusive total cross section for $p\bar{p} \rightarrow t\bar{t}h$ at $\mathcal{O}(\alpha_s^2)$ can be written as:

$$\sigma_{\text{NLO}}(p\bar{p} \rightarrow t\bar{t}h) = \sum_{ij} \int dx_1 dx_2 \sigma_i^{ij}(x_1, x_2, \mu) \hat{\sigma}_j^{ij}(x_1, x_2, \mu),$$

where $F_i^{p,\bar{p}}$ are the NLO parton distribution functions for parton $i$ in a proton/antiproton, defined at a generic factorization scale $\mu_f = \mu$, and $\hat{\sigma}_{NLO}$ is the $\mathcal{O}(\alpha_s^2)$ parton-level total cross section for incoming partons $i$ and $j$, renormalized at an arbitrary scale $\mu_r$, that we choose $\mu_r = \mu_f = \mu$. The NLO parton-level total cross section $\hat{\sigma}_{NLO}$ consists of the $\mathcal{O}(\alpha_s)$ Born cross section and the $\mathcal{O}(\alpha_s)$ corrections to the Born cross section, including the effects of mass factorization. It comprises virtual and real corrections to the parton-level $t\bar{t}h$ production processes, $qq \rightarrow t\bar{t}h$, and $gg \rightarrow t\bar{t}h$, and the tree-level $q\bar{q}$ initiated processes, $q\bar{q} \rightarrow t\bar{t}h$, which are of the same order in perturbation theory. The main challenges in the calculation of the $\mathcal{O}(\alpha_s)$ corrections come from the presence of pentagon diagrams in the virtual part with several massive external and internal particles, and from the computation of the real part in the presence of infrared (IR) singularities.

2.1. $t\bar{t}h$ production at the Tevatron

The NLO inclusive total cross section for $p\bar{p} \rightarrow t\bar{t}h$ at the Tevatron center-of-mass energy $\sqrt{s_{\text{Tev}}}$ = 2 TeV has been calculated independently by two groups$^3$. The numerical results of both calculations have been compared and they are found...
to be in very good agreement. For $p\bar{p}$ collisions at $\sqrt{s_H} = 2$ TeV, more than 95% of the tree-level cross section comes from the sub-process $q\bar{q} \to t\bar{t}h$ and the $gg$ initial state is numerically irrelevant. Therefore, in [8,9] when calculating $\sigma_{NLO}(p\bar{p} \to t\bar{t}h)$ of Eq. 1, we only included the $q\bar{q} \to t\bar{t}h$ channel, summed over all light quark flavors. In [9] the $O(\alpha_s)$ corrections to both $t\bar{t}h$ production channels have been considered.

In [8] we have calculated the pentagon scalar integrals as linear combinations of scalar box integrals using the method of [10]. The real corrections are computed using the phase space slicing method, in both the double [11] and single [12,13,14] cutoff approach. This is the first application of the single cutoff phase space slicing approach to a cross section involving more than one massive particle in the final state. As discussed in detail in [11], the numerical results of both methods agree within the statistical errors. In [11] the dipole subtraction formalism has been used to extract the IR singularities of the real part. To find agreement between calculations based on either of the three very different treatments of the real IR singularities represents a powerful check of the NLO calculations.

As illustrated in Fig. 1 for $M_h = 120$ GeV, $\sigma_{NLO}(p\bar{p} \to t\bar{t}h)$ at $\sqrt{s_H} = 2$ TeV shows a significantly reduced scale dependence as compared to the leading-order (LO) result and leads to increased confidence in predictions based on these results. Over the entire range of $M_h$ accessible at the Tevatron, the NLO corrections decrease the LO rate for $\mu < 2m_t + M_h$.

To determine the potential of the Tevatron to search for the SM Higgs boson, the predictions for all Higgs production processes have to be under good theoretical control. In Fig. 2 we show the scale dependence of the inclusive total cross sections at NLO (next-to-NLO in case of $gg \to h$) for the main SM Higgs production processes, including associated $t\bar{t}h$ production, in the $M_h$ range accessible at the Tevatron. The $p\bar{p} \to b\bar{b}h$ cross section is only known at LO and thus not shown in Fig. 2. It is comparable in size to the $t\bar{t}h$ cross section for $\mu = m_t$ and $M_h = 120$ GeV. As illustrated in Fig. 2, the QCD NLO calculations for the $q\bar{q} \to Wh, Zh$ [15], $qq \to qqh$ [16] and $q\bar{q} \to t\bar{t}h$ [8,9] processes provide reliable predictions for the inclusive total cross sections at the Tevatron. However, the NLO corrections to the $gg \to h$ cross section [7,8] are large (up to $\sim 100\%$), and $\sigma_{NLO}$ still strongly depends on the factorization/renormalization scale. The QCD next-to-NLO (NNLO) $gg \to h$ cross section became available recently [19,20]. As illustrated in Fig. 2 [21], the NNLO corrections are crucial to obtain reliable predictions.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Dependence of $\sigma_{LO,NLO}(\mu \rightarrow t\bar{t}h)$ on the renormalization/factorization scale $\mu$, at the Tevatron ($\sqrt{s_H} = 2$ TeV), for $M_h = 120$ GeV [8].}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure2.png}
\caption{$\sigma_{NLO,NNLO}$ for SM Higgs production processes at the Tevatron ($\sqrt{s_H} = 2$ TeV) as a function of $M_h$. For $p\bar{p} \to t\bar{t}h$ the renormalization/factorization scale is varied between $m_t + M_h/2 < \mu < 2m_t + M_h$.}
\end{figure}

2.2. $t\bar{t}h$ production at the LHC

While the observation of the $t\bar{t}h$ process at the Tevatron will be quite challenging, at the LHC the $t\bar{t}h$ mode will play a crucial role in the 110 GeV $\leq M_h \leq 130$ GeV mass region both for discovery and for precision measurements of the Higgs boson couplings. For determining $\sigma_{NLO}(p\bar{p} \to t\bar{t}h)$ at the LHC, the $O(\alpha_s)$ corrections to the sub-
process $gg \rightarrow t\bar{t}h$ are crucial, since $pp$ collisions at $\sqrt{s_H}=14$ TeV are dominated by the $gg$ initial state. Results for $\sigma_{NLO}(pp \rightarrow t\bar{t}h)$ at $\sqrt{s_H}=14$ TeV have been provided in [7] and results of an independent calculation will be presented in [22]. A detailed comparison of the numerical results of the two groups is presently under way.

Although the calculation of the $O(\alpha_s)$ corrections to $gg \rightarrow t\bar{t}h$ is technically similar to the one for the $q\bar{q}$ initiated process, new challenges arise, e.g., the occurrence of spurious singularities in the calculation of the pentagon diagrams due to a vanishing Gram determinant at the phase space boundaries. The resulting numerical instabilities can be controlled by applying an extrapolation procedure from the numerically safe to the unsafe region [7]. However, we found that, also in the case of the $gg$ initiated subprocess, the occurrence of these singularities can be avoided by cancelling terms in the numerator against the propagators wherever possible, after interfering the pentagon amplitude with the Born-matrix element. We compared the numerical results of both treatments of these spurious singularities and found agreement within the statistical error. Details of the calculation will be presented elsewhere [22].

As is the case at the Tevatron, the scale dependence of $\sigma_{NLO}(pp \rightarrow t\bar{t}h)$ at $\sqrt{s_H}=14$ TeV is strongly reduced compared to the LO result. At the LHC, the NLO QCD corrections enhance the LO cross section over the entire range of values for the renormalization/factorization scale shown in Fig. 1, unlike at the Tevatron where they mostly decrease the Born-level cross section.

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