Direct Higgs production and jet veto at hadron colliders

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Abstract

We consider Higgs boson production through gluon–gluon fusion in hadron collisions, when a veto is applied on the transverse momenta of the accompanying hard jets. We compute the QCD corrections to this process at NLO and NNLO, and present numerical results at the Tevatron and the LHC.

\textsuperscript{*}Talk given by M. Grazzini at the XXXVI\textdegree{} Rencontres de Moriond, QCD and Hadronic interactions, Les Arc1800, France
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\textsuperscript{‡}Partially supported by Fundación Antorchas and Conicet.
The search for the Higgs boson is one the main experimental challenges in high-energy physics. In the near future this search will be carried out at hadron colliders, the Tevatron and the LHC. LEP has established at 95% confidence-level that the mass \( M_H \) of the SM Higgs boson is larger than 114.1 GeV \(^1\), whereas precision electroweak measurements indicate that the Higgs boson should be light \( (M_H \approx 200 \text{ GeV}) \). At the Tevatron and the LHC, various channels \(^2\) \(^3\) can be exploited to search for the Higgs boson in this mass window.

Direct Higgs production followed by the decay \( H \to W^*W^*, Z^*Z^* \) is relevant for a Higgs boson with mass \( 140 \lesssim M_H \lesssim 190 \text{ GeV} \). In particular, the decay mode \( W^*W^* \to l^+l^-\nu\bar{\nu} \) is quite important \(^4\) \(^5\) \(^6\), since it is cleaner than \( W^*W^* \to l\nu jj \), and the decay rate \( H \to W^*W^* \) is higher than \( H \to Z^*Z^* \) by about one order of magnitude.

An important background for the direct Higgs signal \( H \to W^*W^* \to l^+l^-\nu\bar{\nu} \) is \( t\bar{t} \) production \( (tW \) production is also important at the LHC), where \( t \to \ell\bar{\nu}b \), thus leading to \( b \) jets with high \( p_T \) in the final state. If the \( b \) quarks are not identified, a veto cut on the transverse momenta of the jets accompanying the final-state leptons turns out to be essential, both at the Tevatron \(^2\) \(^5\) and at the LHC \(^3\) \(^4\), to cut the hard \( b \) jets arising from this background process.

Here we study the effect of a jet veto on the signal, or, more precisely, on the cross section for direct Higgs production. The events that pass the veto selection are those with \( p_T^{\text{jet}} < p_T^{\text{veto}} \), where \( p_T^{\text{jet}} \) is the transverse momentum of any final-state jets, defined by a cone algorithm. The cone size \( R \) of the jets will be fixed at the value \( R = 0.4 \). More details of our study are presented elsewhere \(^3\).

The vetoed cross section \( \sigma^{\text{veto}} \) at the c.m. energy \( \sqrt{s} \) can be computed through the following factorization formula:

\[
\sigma^{\text{veto}}(s, M_H^2; p_T^{\text{veto}}, R) = \sum_{a,b} \int_0^1 dx_1 \, dx_2 \, f_{a/h_1}(x_1, \mu_F^2) \, f_{b/h_2}(x_2, \mu_R^2) \int_0^1 dz \, \delta\left(z - \frac{\tau_H}{x_1 x_2}\right) \\
\cdot \sigma_0 z \, G_{ab}^{\text{veto}}(z; \alpha_S(\mu_R^2), M_H^2/\mu_R^2, M_H^2/\mu_F^2, p_T^{\text{veto}}, R),
\]

where \( \tau_H = M_H^2/s \), \( f_{a/h} \) is the parton density of the colliding hadron \( h \), and \( \mu_F \) and \( \mu_R \) are the factorization and renormalization scales, respectively. The vetoed cross section can also be written as

\[
\sigma^{\text{veto}}(s, M_H^2; p_T^{\text{veto}}, R) = \sigma(s, M_H^2) - \Delta \sigma(s, M_H^2; p_T^{\text{veto}}, R),
\]

where \( \sigma(s, M_H^2) \) is the inclusive cross section, and \( \Delta \sigma \) is the ‘loss’ in cross section due to the jet-veto procedure.

The partonic cross section \( \sigma_0 G_{ab}^{\text{veto}} \) in Eq. (1) is computable as a perturbative expansion in the QCD coupling \( \alpha_S \). Our calculation is performed by using the large-\( M_{tq\bar{q}} \) approximation, but the Born cross section \( \sigma_0 \) is evaluated exactly. At NLO the coefficient function \( G_{ab}^{\text{veto}} \) can be computed analytically \(^3\). At NNLO we subtract the NLO cross section for the production of Higgs plus jet(s) from the inclusive NNLO result. The NNLO inclusive cross section in Eq. (2) is evaluated by using the results of Refs. \(^7\) \(^8\) \(^9\) \(^10\) whereas the contribution \( \Delta \sigma \) is evaluated by using the numerical program of Ref. \(^10\).

\(^1\)We include all the soft and virtual contributions and the hard terms of the form \( (1 - z)^n \) up to \( n = 1 \). Higher powers of \( (1 - z) \) give very small effects \(^3\).
In the following we present numerical results both at NLO and at NNLO. These are obtained by using the parton distributions of the MRST2001 set \cite{11}, with densities and QCD coupling evaluated at each corresponding order. The MRST2001 set includes (approximate) NNLO parton densities. We fix $\mu_F = \mu_R = M_H$ (the scale dependence is studied in Ref. \cite{6}).

Figure 1: Vetoed cross section and K-factors: NLO results at the Tevatron Run II.

Figure 2: Vetoed cross section and K-factors: NNLO results at the Tevatron Run II.

We first present results at the Tevatron Run II. In Fig. 1 (Fig. 2) we show the dependence of the NLO (NNLO) calculation on the Higgs mass for different values of $p_T^{veto}$ (15, 20, 30 and 50 GeV). The vetoed cross sections $\sigma^{veto}(s, M^2_H; p_T^{veto}, R)$ and the inclusive cross section $\sigma(s, M^2_H)$ are given in the plots on the left-hand side. The inset plots gives an idea of the ‘loss’ in cross section once the veto is applied, by showing the ratio between the cross section difference $\Delta \sigma$ in Eq. (2) and the inclusive cross section at the same perturbative order. As can be observed, for large values of the cut, say $p_T^{veto} = 50$ GeV, less than $\sim 10\%$ of the inclusive cross section is vetoed.
The veto effect increases by decreasing $p_T^{\text{veto}}$, but at NLO (NNLO) it is still smaller than $\sim 30\%$ ($\sim 40\%$) when $p_T^{\text{veto}} = 15$ GeV. On the right-hand side of Figs. 1 and 2 we show the corresponding K-factors, i.e. the vetoed cross sections normalized to the LO result, which is independent of the value of the cut.

Figure 3: Vetoed cross sections and K-factors at NLO at the LHC.

Figure 4: Vetoed cross sections and K-factors at NNLO at the LHC.

The LHC results for $p_T^{\text{veto}} = 20$, 30, 50 and 70 GeV are presented in Figs. 3 and 4. At fixed value of the cut, the impact of the jet veto, both in the ‘loss’ of cross section and in the reduction of the K-factors, is larger at the LHC than at the Tevatron. For example, when $p_T^{\text{veto}} = 50$ GeV at the LHC we have $\Delta \sigma / \sigma \sim 18\% (25\%)$ at NLO (NNLO).

The results presented above have a simple physical interpretation [6]. The dominant part of QCD corrections is due to soft and collinear radiation [7] (incidentally, this justifies the use of
the large-$M_{\text{top}}$ approximation), and leads to enhancement of the cross section. The characteristic scale of the highest transverse momentum $p_{T}^{\text{max}}$ of the accompanying jets is $p_{T}^{\text{max}} \sim \langle 1 - z \rangle M_{H}$, where the average value $\langle 1 - z \rangle = \langle 1 - M_{H}^{2} / \hat{s} \rangle$ of the distance from the partonic threshold is small. As a consequence the jet veto procedure is weakly effective unless the value of $p_{T}^{\text{veto}}$ is substantially smaller than $p_{T}^{\text{max}}$. Decreasing $p_{T}^{\text{veto}}$, the enhancement of the inclusive cross section due to soft radiation at higher orders is reduced, and the jet veto procedure tends to improve the convergence of the perturbative series. At the LHC Higgs production is less close to threshold than at the Tevatron and, therefore, the accompanying jets are harder. Thus, at fixed $p_{T}^{\text{veto}}$, the effect of the jet veto is stronger at the LHC than at the Tevatron.

Note that the numerical results presented here (slightly) differ from those in Ref. [6], because of the following three reasons. i) Here we include the exact $M_{\text{top}}$-dependence of the Born cross section $\sigma_{0}$, while in Ref. [6] $\sigma_{0}$ was approximated by its large-$M_{\text{top}}$ limit. This affects the absolute value of the cross sections, but not the ratios $\Delta \sigma / \sigma$ and the K-factors. ii) In Ref. [6] we used the parton densities of the MRST2000 set [12]. The differences between the parton densities of Refs. [11] and [12] lead to effects of $\sim 10\%$. iii) The contribution of the NNLO hard terms [9], not included in Ref. [6], decreases the NNLO inclusive cross section by $\sim 7\%$ at the Tevatron and $\sim 5\%$ at the LHC. Owing to the subtraction in Eq. (2), this NNLO decrease becomes relatively more important when $p_{T}^{\text{veto}}$ becomes small (i.e. when $\Delta \sigma$ increases).

Acknowledgments. This work was supported in part by the EU Fourth Framework Programme “Training and Mobility of Researchers”, Network “Quantum Chromodynamics and the Deep Structure of Elementary Particles”, contract FMRX–CT98–0194 (DG 12 – MIHT).

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