Direct Higgs production at hadron colliders

Massimiliano Grazzini\textsuperscript{(a,b)}

\textsuperscript{(a)}Dipartimento di Fisica, Università di Firenze, I-50019 Sesto Fiorentino, Florence, Italy
\textsuperscript{(b)}INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Florence, Italy

Abstract

We consider QCD corrections to Higgs boson production through gluon-gluon fusion in hadron collisions. We compute the effects of soft-gluon emission to all orders. We present numerical results at the Tevatron and the LHC.
The most important mechanism for SM Higgs boson production at hadron colliders is gluon–gluon fusion through a heavy (top) quark loop. NLO QCD corrections to this process are known to be large \[1, 2, 3\]: their effect increases the LO inclusive cross section by about 80-100%. Recently, the calculation of the NNLO corrections has been completed in the large-\(M_t\) approximation \[4, 5, 6, 7, 8\]. This approximation has been shown to work well at NLO provided the exact dependence on the mass \(M_t\) of the top quark is retained in the LO result.

In Fig. 1 we show the NNLO effect with respect to NLO at the Tevatron and the LHC, as a function of the mass \(M_{H}\) of the SM Higgs boson. We use the MRST2001 set \[9\], which includes approximated NNLO parton distributions, with \(\alpha_s\) consistently evaluated at one-loop, two-loop, three-loop order for the LO, NLO, NNLO results, respectively. The factorization and renormalization scales \(\mu_F\) and \(\mu_R\) are fixed to \(M_H\). The solid line is the full NNLO result \[8\] while the dashed line is the result including only soft and virtual plus leading collinear contributions (SVC) \[4\]. We see that the NNLO effect is moderate at the LHC: in the case of a light Higgs, the \(K\)-factor is about 2.1–2.2, corresponding to an increase of about 20% with respect to NLO. The NNLO effect is more sizeable at the Tevatron where \(K \sim 3\), the increase being of about 40% with respect to NLO. Fig. 1 shows that the SVC approximation works remarkably well, the differences with respect to the full result being only about 2% at the LHC and 4% at the Tevatron. Thus the bulk of the NNLO contributions is due to soft and collinear radiation \[4, 5, 6\], which factorizes from the heavy-quark loop, whereas the hard radiation \[7\] gives only a very small effect. The dominance of soft and collinear radiation has two important consequences. First, it can be considered as a justification of the use of the large \(M_t\)-approximation at NNLO. Second, it suggests that multiple soft-gluon emission beyond NNLO can give a relevant effect. Here we discuss the effects of resummation of soft (Sudakov) emission to all orders \[10\].

The cross section \(\hat{\sigma}_{gg}\) for the partonic subprocess \(gg \to H + X\) at the centre-of-mass energy \(\hat{s} = M_{H}^2/z\) can be written as

\[
\hat{\sigma}_{gg}(\hat{s}, M_{H}^2) = \sigma_0 z G_{gg}(z) ,
\]
where $M_H$ is the Higgs mass, $\sigma_0$ is the Born-level cross section and $G_{gg}$ is the perturbatively computable coefficient function. Soft-gluon resummation is performed \[11\] in Mellin (or $N$-moment) space ($N$ is the moment variable conjugate to $z$). The all-order resummation formula for the coefficient function $G_{gg}$ is \[4, 12\]:

$$
C_{gg,N}^{(\text{res})} = \alpha_S^2(\mu_R^2) C_{gg}(\alpha_S(\mu_R^2), \frac{M_h^2}{\mu_R^2}; \frac{M_H^2}{\mu_F^2}) \Delta_N^H(\alpha_S(\mu_R^2), \frac{M_h^2}{\mu_R^2}; \frac{M_H^2}{\mu_F^2}) .
$$

The function $C_{gg}(\alpha_S)$ contains all the terms that are constant in the large-$N$ limit, produced by hard virtual contributions and non-logarithmic soft corrections. It can be computed as a power series expansion in $\alpha_S$ as

$$
C_{gg}(\alpha_S(\mu_R^2), \frac{M_h^2}{\mu_R^2}; \frac{M_H^2}{\mu_F^2}) = 1 + \sum_{n=1}^{+\infty} \left( \frac{\alpha_S(\mu_R^2)}{\pi} \right)^n C_{gg}^{(n)}(\frac{M_h^2}{\mu_R^2}; \frac{M_H^2}{\mu_F^2}) ,
$$

where the perturbative coefficients $C_{gg}^{(n)}$ are closely related to those of the $\delta(1-z)$ contribution to $G_{gg}(z)$. The radiative factor $\Delta_N^H$ embodies the large logarithmic terms due to soft-gluon radiation. To implement resummation, the radiative factor is expanded to a given logarithmic accuracy as

$$
\Delta_N^H = \exp \left\{ \ln N \left[ g^{(1)}(\lambda) + g^{(2)}(\lambda, \frac{M_h^2}{\mu_R^2}; \frac{M_H^2}{\mu_F^2}) \right] + \alpha_S(\mu_R^2) g^{(3)}(\lambda, \frac{M_h^2}{\mu_R^2}; \frac{M_H^2}{\mu_F^2}) + \mathcal{O}(\alpha_S^2(\alpha_S \ln N)^4) \right\} ,
$$

such that the functions $g^{(1)}$, $g^{(2)}$ and $g^{(3)}$ respectively collect the leading logarithmic (LL), next-to-leading logarithmic (NLL) and next-to-next-to-leading logarithmic (NNLL) terms with respect to the expansion parameter $\lambda = \alpha_S(\mu_R^2) \ln N$.

NLL resummation \[4\] is controlled by three perturbative coefficients, $A_g^{(1)}$, $A_g^{(2)}$ and $C_{gg}^{(1)}$. The coefficients $A_g^{(1)}$ and $A_g^{(2)}$, which appear in the functions $g^{(1)}$ and $g^{(2)}$, are well known \[11\]. The coefficient $C_{gg}^{(1)}$ in Eq. (3) is extracted from the NLO result.

At NNLL accuracy three new coefficients are needed \[4\]: the coefficient $C_{gg}^{(2)}$ in Eq. (3) and two coefficients, $D^{(2)}$ and $A_g^{(3)}$, which appear in the NNLL function $g^{(3)}$. The functional form of $g^{(3)}$ was computed in Ref. \[13\]. The coefficients $D^{(2)}$ and $C_{gg}^{(2)}$ are obtained \[4\] from the NNLO result. The coefficient $A_g^{(3)}$ is not yet fully known: we use its exact $N_f^2$-dependence \[14\] and the approximate numerical estimate of Ref. \[13\].

Finally, the dominant collinear logarithmic terms can be accounted for by modifying the coefficient $C_{gg}^{(1)}$ in the resummation formula as \[4\]

$$
C_{gg}^{(1)} \rightarrow C_{gg}^{(1)} + 2A_g^{(1)} \frac{\ln N}{N} .
$$

In the following we present a preliminary study of the resummation effect at the Tevatron and the LHC. The hadron-level cross section is obtained by convoluting the partonic cross section in Eq. (1) with the parton distributions of the colliding hadrons. As in Fig. 1 we use the MRST2001 set. The resummed calculations are always matched to the corresponding fixed-order results, i.e. LL is matched to LO, NLL to NLO and NNLL to NNLO. We find that the effect of the inclusion
of the collinear term in Eq. (5) is very small, whereas the effect of the coefficient $A^{(3)}$ is completely negligible.

In Fig. 2 we present our results at the LHC, by plotting the $K$-factor, defined as the hadronic cross section as a function of $\mu_F$ and $\mu_R$, normalized to the LO result at $\mu_F = \mu_R = M_H$. In the left side of the figure the LO, NLO and NNLO bands are shown, defined varying $\mu_F = \mu_R$ between $0.5M_H$ and $2M_H$. In the right side of the figure the corresponding resummed results are plotted, the bands being now obtained setting $\mu_F = M_H$ and letting $\mu_R$ to range between $0.5M_H$ and $2M_H$. In both cases we have defined the bands in such a way to maximize them but avoiding completely independent scale variations such as $\mu_R = 0.5M_H$ and $\mu_F = 2M_H$, by which the ratio $\mu_F/\mu_R$ would be 4. Different definitions of the uncertainty bands are of course possible. We see that soft-gluon resummation gives a moderate effect, the NNLL effect being about $5-6\%$ with respect to NNLO for $M_H \approx 200$ GeV. In Fig. 3 we report the analogous results at the Tevatron Run II. The bands are defined as in Fig. 2. Here the resummation effects are larger: going from NLO to NLL accuracy, the cross section increases by 25-30%. NNLL resummation increases the NNLO cross section by $\sim 12-15\%$ when $M_H$ varies in the range 100-200 GeV. These results are not unexpected [6], since at the Tevatron the Higgs boson is produced closer to threshold and the effect of multiple soft-gluon emission is more important.

From these results we conclude that the theoretical predictions for Higgs boson production at hadron colliders are under control. A more detailed discussion of the present theoretical uncertainty will be given elsewhere [10].
Figure 3: Resummed K-factors at the Tevatron Run II.

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