Higgs production through gluon fusion: Updated cross sections at the Tevatron and the LHC

Daniel de Florian\textsuperscript{a,b,*,} Massimiliano Grazzini\textsuperscript{c}

\textsuperscript{a} Departamento de Física, FCEyN, Universidad de Buenos Aires, (1428) Pabellón 1, Ciudad Universitaria, Capital Federal, Argentina
\textsuperscript{b} Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
\textsuperscript{c} INFN, Sezione di Firenze and Dipartimento di Fisica, Università di Firenze, I-50019 Sesto Fiorentino, Florence, Italy

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\begin{abstract}
We present updated predictions for the total cross section for Higgs boson production by gluon–gluon fusion in hadron collisions. Our calculation includes the most advanced theoretical information available at present for this observable: soft-gluon resummation up to next-to-next-to-leading logarithmic accuracy, the exact treatment of the bottom-quark contribution up to next-to-leading order, and two-loop electroweak effects. We adopt the most recent parametrization of parton distribution functions at next-to-next-to-leading order, and we evaluate the corresponding uncertainties. In comparison with our previous central predictions, at the Tevatron the difference ranges from +9\% for \( m_H = 115 \text{ GeV} \) to −9\% for \( m_H = 200 \text{ GeV} \). At the LHC the cross section is instead significantly increased. The effect goes from +30\% for \( m_H = 115 \text{ GeV} \) to +9\% for \( m_H = 300 \text{ GeV} \), and is mostly due to the new parton distribution functions. We also provide new predictions for the LHC at \( \sqrt{s} = 10 \text{ TeV} \).
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a Higgs boson of $m_H \sim 120$ GeV at the LHC, the gluon distribution increases by about 6% with respect to the MRST2002 fit. The value of $\alpha_s(m_Z)$ also had a non-negligible change from 0.1154 to 0.1171. Considering that the total cross section is completely dominated by the gluon–gluon fusion channel, and that the lowest order contribution starts at $O(\alpha_s^2)$, with sizeable corrections at higher orders, it is not surprising that the mere change from MRST2002 to MSTW2008 partons can result in an increase of more than 10% in the production cross section, making an update mandatory. The change in the PDFs does not result in such a dramatic increase of the cross section at the Tevatron, since at $x \sim 0.06$, relevant for the production of a Higgs boson of $m_H \sim 120$ GeV, the gluon distribution is reduced by about 4%, but the decrease is partially compensated by the increase of the partonic cross section due to the larger coupling constant.

Besides the important effect of the PDFs, there are other theoretical reasons for revisiting the computation of the Higgs cross section at hadron colliders. In particular there has been an important effort to evaluate the electroweak (EW) corrections arising from $W$ and $Z$ boson coupling to the Higgs and to both light and heavy quarks in the loop [16]. The recent computation of Ref. [17] takes into account those contributions by avoiding the complications in the two-particle threshold using the complex-mass scheme. The EW corrections turn out to be of the order of a few percent, with a sign depending on the Higgs mass. The main uncertainty in the EW analysis comes from the fact that it is not completely clear how to take them into account in practice. In the partial factorization scheme of Ref. [17] the EW correction applies only to the LO result. In the complete factorization scheme instead, the EW correction multiplies the full QCD corrected cross section. Since QCD corrections are sizeable, the latter choice has a non-negligible effect on the actual impact of EW corrections in the computation. The recent analysis of higher-order QCD and EW corrections presented in Ref. [18], performed on the basis of an effective Lagrangian approach, supports the complete factorization hypothesis, suggesting that EW corrections become, to a good approximation, a multiplicative factor of the full QCD expansion.

The predictions we present below are obtained as follows. We first consider the top-quark contribution in the loop, and perform the calculation up NNLL + NNLO in the large-$m_t$ limit. The result is rescaled by the exact $m_t$ dependent Born cross section, since this is known to be an excellent approximation for the top-quark contribution. This resummed top-quark contribution provides the bulk of the Higgs cross section at hadron colliders. We then consider the bottom-quark contribution (more precisely, the bottom contribution and the top–bottom interference). Since in this case the effective theory approach is not applicable, we follow Ref. [18] and we include this contribution up to NLO only (but still computed with NNLO MSTW2008 partons), by using the program HIGLU [4]. Finally, we correct the result by including the EW effects evaluated in Ref. [17] in the complete factorization hypothesis. We set the heavy-quark masses to $m_t = 170.9$ GeV and $m_b = 4.75$ GeV, the latter consistently with the MSTW2008 set. Our central predictions ($\sigma_{\text{best}}$) are obtained by setting the factorization ($\mu_F$) and renormalization ($\mu_R$) scales equal to the Higgs boson mass.

Our results for the Tevatron at $\sqrt{s} = 1.96$ TeV and the LHC at $\sqrt{s} = 10$ TeV and $\sqrt{s} = 14$ TeV are presented in Tables 1, 2 and 3, respectively. Comparing to our previous predictions (see Tables 1 and 2 of Ref. [7]), the cross sections change significantly. At the Tevatron the effect ranges from $+9\%$ for $m_H = 115$ GeV to $-9\%$ for $m_H = 200$ GeV. At the LHC the effect goes from $+30\%$ for $m_H = 115$ GeV to $-9\%$ for $m_H = 300$ GeV. It is worth noticing that at the LHC more than half of the increase arises from the modification in the gluon distribution and the coupling constant.

The bottom contribution, dominated by bottom–top interference, is small and negative. The different treatment of this contribution with respect to the previous analysis [7] results in an increase of the cross section from about 7% ($m_H = 115$ GeV) to 4% ($m_H = 200$ GeV) at the Tevatron and from 5% ($m_H = 110$ GeV) to 2% ($m_H = 300$ GeV) at the LHC. The inclusion of the EW corrections results in an increase of the cross section by about 5% for $m_H \leq 160$ GeV, and a decrease by about 2% for 200 GeV $< m_H \leq 300$ GeV.

Our results for the Tevatron can be compared to those recently presented in Ref. [18], obtained using the same set of PDFs. Besides the different choice for the bottom–quark mass and the implementation of an effective Lagrangian calculation for the EW corrections,
the main difference with our work arises in the calculation of the top-quark contribution to the cross section. In Ref. [18] the latter contribution is computed up to NNLO but choosing $\mu_F = \mu_R = m_H/2$, as an attempt to mimic the effects of soft-gluon resummation beyond NNLO. The final numerical differences at the Tevatron turn out to be small and of the order of a few per mille at the lowest masses, increasing to 2.5% at $m_H = 200$ GeV.

We now discuss the various sources of uncertainty affecting the cross sections presented in Tables 1, 2 and 3. The uncertainty basically has two origins: the one coming from the partonic cross sections, and the one arising from our limited knowledge of the PDFs.

Uncalculated higher-order QCD radiative corrections are the most important source of uncertainty on the partonic cross section. A method, which is customarily used in perturbative QCD calculations, to estimate their size is to vary the renormalization and factorization scales around the hard scale $m_H$, as an attempt to mimic the effects of soft-gluon resummation beyond NNLO. The numerical differences at the Tevatron turn out to be small and of the order of a few per mille at the lowest masses, increasing to 2.5% at $m_H = 200$ GeV.

We finally point out that a related and important uncertainty is the one coming from the value of the QCD coupling. In modern PDF sets $\alpha_S(m_Z)$ is obtained together with the parton densities through a global fit to the available data, and thus there will be a correlation between the error on $\alpha_S(m_Z)$ and on the gluon density. Since the gluon fusion process starts at $O(\alpha_s^2)$, it is easy to foresee that the uncertainty on $\alpha_S(m_Z)$ may have an important impact on the cross section. Neglecting correlations with the gluon density, a 3% uncertainty on $\alpha_S(m_Z)$ would lead to an effect of about ±9–10% on the production cross section at both the Tevatron and the LHC.

To summarize, we have presented updated predictions for the cross section for Higgs boson production at the Tevatron and the LHC. The results are based on the most advanced theoretical information available at present for this observable, including soft-gluon resummation up to NNLL accuracy and two-loop EW corrections. In comparison with the central predictions of Ref. [7], at the Tevatron the difference ranges from +9% to −9% for 115 GeV $\leq m_H \leq 200$ GeV. At the LHC the effect goes from +30% to +9% for 115 GeV $\leq m_H \leq 300$ GeV, and is mostly due to the new PDFs. We have then reviewed [7] the uncertainties that affect the Higgs production cross section, and we have shown that they are still relatively large, especially at the Tevatron. The above uncertainties should be taken into account in Higgs boson searches and studies at both the Tevatron and the LHC.

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References

[1] R. Barate, et al., LEP Working Group for Higgs boson searches, ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, Phys. Lett. B 565 (2003) 61.
[2] J. Qian, CDF Collaboration, DØ Collaboration, arXiv:0812.3979 [hep-ex], Proc. Phys. Lett. B 264 (2001) 640.
[3] W.L. van Neerven, A. Vogt, Phys. Lett. B 490 (2000) 111.
[4] A. Djouadi, M. Spira, P.M. Zerwas, Phys. Lett. B 264 (1991) 440.
[5] R.V. Harlander, W.B. Kilgore, Phys. Rev. D 64 (2001) 013015.
[6] S. Dawson, Nucl. Phys. B 539 (1999) 283.
[7] A. Djouadi, M. Spira, P.M. Zerwas, Phys. Lett. B 264 (2001) 640.
[8] R.V. Harlander, W.B. Kilgore, Phys. Rev. Lett. 88 (2002) 201801.
[9] S. Anastasiou, K. Melnikov, Nucl. Phys. B 646 (2002) 220.
[10] R. Barate, et al., LEP Working Group for Higgs boson searches, ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, Phys. Lett. B 565 (2003) 61.
[11] J. Qian, CDF Collaboration, DØ Collaboration, arXiv:0812.3979 [hep-ex], Proc. Phys. Lett. B 264 (2001) 640.
[12] W.L. van Neerven, A. Vogt, Phys. Lett. B 490 (2000) 111.
[13] A. Djouadi, M. Spira, P.M. Zerwas, Phys. Lett. B 264 (1991) 440.
[14] R.V. Harlander, W.B. Kilgore, Phys. Rev. D 64 (2001) 013015.
[15] S. Catani, D. de Florian, M. Grazzini, JHEP 0105 (2001) 025.
[16] R.V. Harlander, W.B. Kilgore, Phys. Rev. D 64 (2001) 013015.
[17] S. Catani, D. de Florian, M. Grazzini, JHEP 0307 (2003) 028.
[18] S. Moch, A. Vogt, Phys. Lett. B 631 (2005) 48.
[19] E. Laenen, L. Magnea, Phys. Lett. B 632 (2006) 270.
[20] A. Djouadi, M. Spira, P. M. Zerwas, Phys. Lett. B 511 (1999) 379.
[21] S. Moch, A. Vogt, Phys. Lett. B 631 (2005) 48.
[22] E. Laenen, L. Magnea, Phys. Lett. B 632 (2006) 270.
[23] A. Djouadi, M. Spira, P. M. Zerwas, Phys. Lett. B 511 (1999) 379.
[24] S. Moch, A. Vogt, Phys. Lett. B 631 (2005) 48.
[25] E. Laenen, L. Magnea, Phys. Lett. B 632 (2006) 270.
[26] A. Djouadi, M. Spira, P. M. Zerwas, Phys. Lett. B 511 (1999) 379.
[27] S. Moch, A. Vogt, Phys. Lett. B 631 (2005) 48.
[28] E. Laenen, L. Magnea, Phys. Lett. B 632 (2006) 270.
[29] A. Djouadi, M. Spira, P. M. Zerwas, Phys. Lett. B 511 (1999) 379.
[30] S. Moch, A. Vogt, Phys. Lett. B 631 (2005) 48.
[15] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, arXiv:0901.0002 [hep-ph].
[16] U. Aglietti, R. Bonciani, G. Degrassi, A. Vicini, Phys. Lett. B 595 (2004) 432;
    G. Degrassi, F. Maltoni, Phys. Lett. B 600 (2004) 255;
    U. Aglietti, R. Bonciani, G. Degrassi, A. Vicini, Contributed to the TeV4LHC Workshop, Brookhaven, Upton, New York, February 2005, arXiv:hep-ph/0610033.
[17] S. Actis, G. Passarino, C. Sturm, S. Uccirati, Phys. Lett. B 670 (2008) 12;
    S. Actis, G. Passarino, C. Sturm, S. Uccirati, Nucl. Phys. B 811 (2009) 182.
[18] C. Anastasiou, R. Boughezal, F. Petriello, arXiv:0811.3458v2 [hep-ph].
[19] M. Schreck, M. Steinhauser, Phys. Lett. B 655 (2007) 148.
[20] S. Marzani, R.D. Ball, V. Del Duca, S. Forte, A. Vicini, Nucl. Phys. B 800 (2008) 127;
    S. Marzani, R.D. Ball, V. Del Duca, S. Forte, A. Vicini, Nucl. Phys. B (Proc. Suppl.) 186 (2009) 98.