Vol. 38 (2007) *ACTA PHYSICA POLONICA B* No 11

NNLO VIRTUAL CORRECTIONS TO $W^+ W^-$ PRODUCTION AT THE LHC*

Grigorios Chachamis

Institut für Theoretische Physik und Astrophysik, Universität Würzburg
Am Hubland, 97074 Würzburg, Germany

(Received October 16, 2007)

We report on a recent calculation of the two-loop virtual QCD corrections to the W boson pair production in the quark–anti-quark-annihilation channel in the limit where all kinematical invariants are large compared to the mass of the W boson. Our result is exact up to terms suppressed by powers of the W boson mass. The infrared pole structure is in agreement with the prediction of Catani's general formalism for the singularities of two-loop QCD amplitudes.

PACS numbers: 12.38.Bx, 13.85.–t, 14.70.Fm

1. Introduction

W pair production via quark–anti-quark-annihilation is a very important process at the Large Hadron Collider (LHC) for two main reasons. Firstly, it can serve as a signal process in the search for new Physics since it can be used to measure the vector boson trilinear couplings as predicted by the Standard Model (SM). Deviations from these predictions may come from decays of new heavy particles into SM vector boson pairs or anomalous couplings and would signal new Physics [1]. Secondly, $q\bar{q} \to W^+W^-$ is the dominant irreducible background to the promising Higgs discovery channel $pp \to H \to W^*W^* \to l\bar{\nu}\bar{l}'\nu'$ in the mass range $\mathrm{M_{Higgs}}$ between 140 and 180 GeV [2]. In this paper, we describe the computation of the two-loop virtual QCD corrections to the W boson pair production in the quark–anti-quark-annihilation channel. The full result will appear in Ref. [3].

Due to its importance, the study of W pair production in hadronic collisions has attracted a lot of attention in the literature. The Born cross section was computed almost 30 year ago [4], whereas the next-to-leading

* Presented at the XXXI International Conference of Theoretical Physics, "Matter to the Deepest", Ustroń, Poland, September 5–11, 2007.

order (NLO) QCD corrections to the tree-level were computed in Refs. [5–9] and were proven to be large. They enhance the tree-level by almost 70% which falls to a (still) large 30% after imposing a jet veto. Another process that adds to the $pp \to W^+W^-$ background is the W pair production in the loop induced gluon fusion channel, $gg \to W^+W^-$. This contributes at $\mathcal{O}(\alpha_s^2)$ relative to the quark–anti-quark-annihilation channel but is nevertheless enhanced due to the large gluon flux at the LHC. The corrections from gluon fusion increase the W pair background estimate by almost 30% after certain experimental Higgs search cuts are imposed [10, 11].

Given that the NLO QCD corrections to the background are large and also that the cross section for the process $H \to WW \to l\bar{\nu}\,\bar{l}'\nu'$ (signal process for the Higgs discovery) is known at NNLO [12], the NNLO corrections to $q\bar{q} \to W^+W^-$ need to be computed. This will allow a theoretical estimate for W production from $q\bar{q}$-annihilation with accuracy better than 10%, as well as having both the signal and the background process calculated at the same order of the perturbative expansion (NNLO). In this paper, we address the task of computing the NNLO two-loop virtual part, more precisely the interference of the two-loop with the Born amplitude. We work in the limit of fixed scattering angle and high energy, where all kinematical invariants are large compared to the mass m of the W.

2. The calculation

Our methodology for obtaining the massive amplitude (massless fermion–boson scattering was studied in Ref. [13]) is very similar to the one followed in Refs. [14–16], an evolution actually, of the methods employed in Refs. [17, 18]. The amplitude is reduced to a form that contains only a small number of integrals (master integrals) with the help of the Laporta algorithm [19]. In our calculation there are 71 master integrals. Next comes the construction, in a fully automatic way, of the Mellin–Barnes (MB) representations [20, 21] of all the master integrals using the `MBrepresentation` package [22]. The representations are then analytically continued in the dimension of space-time with the help of the `MB` package [23] revealing the full singularity structure. An asymptotic expansion in the mass parameter is performed by closing contours and the integrals are finally resumed, either with the help of `XSummer` [24], or the `PSLQ` algorithm [25].

We will present here the result for a non-planar two-loop box master integral with two massive legs (Fig. 1). The Mellin–Barnes representation of this integral is 7-fold and reads:

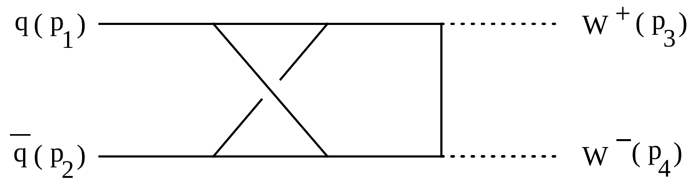

Fig. 1. A non-planar two-loop box master integral with two massive legs. p_j are the external momenta, with $p_1{}^2 = p_2{}^2 = 0$ and $p_3{}^2 = p_4{}^2 = m^2$, m the mass of W.

$$
\begin{aligned}
I_{\mathrm{NP}} &= -(-s)^{-3-2\varepsilon} \int\limits_{-i\infty}^{i\infty} \prod_{j=1}^{7} dz_j \left(\frac{s}{m^2}\right)^{-z1} \left(\frac{t}{m^2}\right)^{-z2} \left(\frac{u}{m^2}\right)^{-z3} \\
&\quad \times \Gamma(-\varepsilon)^2 \Gamma(1+z_1)\Gamma(z_2)\Gamma(z_3)\Gamma(-z_4)\Gamma(-z_5) \\
&\quad \times \Gamma(-z_1-z_2-z_3+z_4+z_5)\Gamma(-1-\varepsilon-z_4-z_6)\Gamma(-z_6) \\
&\quad \times \Gamma(-2-2\varepsilon-z_1-z_7)\Gamma(-z_5-z_7)\Gamma(-z_6-z_7) \\
&\quad \times \Gamma(-2-2\varepsilon+z_2-z_4-z_5-z_6-z_7)\Gamma(1-z_2+z_5+z_7) \\
&\quad \times \Gamma(-2-2\varepsilon+z_3-z_4-z_5-z_6-z_7)\Gamma(1-z_3+z_5+z_7) \\
&\quad \times \Gamma(3+2\varepsilon+z_1+z_6+z_7)\Gamma(1+z_4+z_6+z_7) \\
&\quad \times \big(\Gamma(-1-3\varepsilon)\Gamma(-2\varepsilon)\Gamma(-1-2\varepsilon-z_4-z_6)^2 \\
&\quad \times \Gamma(-z_5-z_6-z_7)\big)^{-1} \,. \qquad (1)
\end{aligned}
$$

This specific master integral is needed up to order $\mathcal{O}((m^2/s)^{-1})$. After the analytical continuation in the spacetime dimension and the expansion in the mass one is able to perform the resumation which yields:

$$
\begin{aligned}
I_{\mathrm{NP}} &= +\frac{1}{2m_s\varepsilon^4} + \frac{1}{m_s\varepsilon^3}\left\{-2\mathrm{L}_m + \mathrm{L}_x + \mathrm{L}_y\right\} \\
&\quad + \frac{1}{m_s\varepsilon^2}\left\{4\mathrm{L}_m^2 - 4\mathrm{L}_x\mathrm{L}_m - 4\mathrm{L}_y\mathrm{L}_m + \mathrm{L}_x^2 + \mathrm{L}_y^2 + 2\mathrm{L}_x\mathrm{L}_y - \frac{89\pi^2}{12}\right\} \\
&\quad + \frac{1}{m_s\varepsilon}\left\{-\frac{16\mathrm{L}_m^3}{3} + 8\mathrm{L}_x\mathrm{L}_m^2 + 8\mathrm{L}_y\mathrm{L}_m^2 - 4\mathrm{L}_x^2\mathrm{L}_m - 4\mathrm{L}_y^2\mathrm{L}_m - 8\mathrm{L}_x\mathrm{L}_y\mathrm{L}_m \right. \\
&\quad \left. + \frac{89\pi^2\mathrm{L}_m}{3} + \frac{2\mathrm{L}_x^3}{3} + \frac{2\mathrm{L}_y^3}{3} + 2\mathrm{L}_x\mathrm{L}_y^2 + 2\mathrm{L}_x^2\mathrm{L}_y - \frac{40\zeta_3}{3} - \frac{89\mathrm{L}_x\pi^2}{6} - \frac{89\mathrm{L}_y\pi^2}{6}\right\}
\end{aligned}
$$

$$
+\frac{1}{m_s}\left\{\frac{16\mathrm{L}_m^4}{3}-\frac{32\mathrm{L}_x\mathrm{L}_m^3}{3}-\frac{32\mathrm{L}_y\mathrm{L}_m^3}{3}+8\mathrm{L}_x^2\mathrm{L}_m^2+8\mathrm{L}_y^2\mathrm{L}_m^2+16\mathrm{L}_x\mathrm{L}_y\mathrm{L}_m^2\right.
-\frac{178\pi^2\mathrm{L}_m^2}{3}-\frac{8\mathrm{L}_x^3\mathrm{L}_m}{3}-\frac{8\mathrm{L}_y^3\mathrm{L}_m}{3}-8\mathrm{L}_x\mathrm{L}_y^2\mathrm{L}_m-8\mathrm{L}_x^2\mathrm{L}_y\mathrm{L}_m+\frac{160\zeta_3\mathrm{L}_m}{3}
+\frac{178\mathrm{L}_x\pi^2\mathrm{L}_m}{3}+\frac{178\mathrm{L}_y\pi^2\mathrm{L}_m}{3}+\frac{\mathrm{L}_x^4}{3}+\frac{\mathrm{L}_y^4}{3}+\frac{4\mathrm{L}_x\mathrm{L}_y^3}{3}+2\mathrm{L}_x^2\mathrm{L}_y^2
+\frac{4\mathrm{L}_x^3\mathrm{L}_y}{3}-\frac{80\mathrm{L}_x\zeta_3}{3}-\frac{80\mathrm{L}_y\zeta_3}{3}+\frac{1111\pi^4}{720}-\frac{89\mathrm{L}_x^2\pi^2}{6}
\left.-\frac{89\mathrm{L}_y^2\pi^2}{6}-\frac{89\mathrm{L}_x\mathrm{L}_y\pi^2}{3}\right\}. \qquad (2)
$$

We have used above the compact notation $m_s = m^2/s$, $\mathrm{L}_m = \log(m^2/s)$, $\mathrm{L}_x = \log(x)$ and $\mathrm{L}_y = \log(1-x)$. $s = (p_1+p_2)^2$ and $t = (p_1-p_3)^2$ are the usual Mandelstam variables and $x = t/s$. One of the checks in our calculation was to verify numerically the analytic results for the masters.

The renormalization of the amplitude involves only the renormalization of the strong coupling constant α_{s} [26,27]. A non-trivial check for our computation is that the infrared pole structure of our renormalized result is in agreement with the prediction of Catani's general formalism for the singularities of the two-loop QCD amplitudes as described in Ref. [28].

3. Outlook

We have calculated the two-loop virtual QCD corrections to the W boson pair production in the quark–anti-quark-annihilation channel in the high energy limit. The two-loop result, along with the square of the one-loop $2\to2$ process have to be combined with the tree-level $2\to4$ and the one-loop $2\to3$ processes in order to obtain physical cross sections. Combining all these contributions will enable the analytic cancellation of the remaining infrared divergences. Initial state singularities will have to be absorbed into parton distribution functions of the hadrons (protons) in order to match with a precise parton evolution at NNLO [29,30].

This work was performed with support of the Sofja Kovalevskaja program of the Alexander von Humboldt Foundation.

REFERENCES

[1] CDF Collaboration, *Phys. Rev. Lett.* **94**, 211801 (2005); D0 Collaboration, *Phys. Rev. Lett.* **94**, 151801 (2005).

[2] M. Dittmar, H.K. Dreiner, *Phys. Rev.* **D55**, 167 (1997) [hep-ph/9608317].

[3] G. Chachamis, M. Czakon, D. Eiras, to be published.
[4] R.W. Brown, K.O. Mikaelian, *Phys. Rev.* **D19**, 922 (1979).
[5] J. Ohnemus, *Phys. Rev.* **D44**, 1403 (1991).
[6] S. Frixione, *Nucl. Phys.* **B410**, 280 (1993).
[7] L.J. Dixon, Z. Kunszt, A. Signer, *Nucl. Phys.* **B531**, 3 (1998) [hep-ph/9803250].
[8] L.J. Dixon, Z. Kunszt, A. Signer, *Phys. Rev.* **D60**, 114037 (1999) [hep-ph/9907305].
[9] J.M. Campbell, R.K. Ellis, *Phys. Rev.* **D60**, (1999) 113006 [hep-ph/9905386].
[10] T. Binoth, M. Ciccolini, N. Kauer, M. Kramer, *J. High Energy Phys.* **0503**, 065 (2005) [hep-ph/0503094].
[11] T. Binoth, M. Ciccolini, N. Kauer, M. Kramer, *J. High Eenergy Phys.* **0612**, 046 (2006) [hep-ph/0611170].
[12] C. Anastasiou, G. Dissertori, F. Stockli, arXiv:0707.2373[hep-ph].
[13] C. Anastasiou, E.W.N. Glover, M.E. Tejeda-Yeomans, *Nucl. Phys.* **B629**, 255 (2002) [hep-ph/0201274].
[14] M. Czakon, A. Mitov, S. Moch, *Phys. Lett.* **B651**, 147 (2007) [arXiv:0705.1975[hep-ph]].
[15] M. Czakon, A. Mitov, S. Moch, arXiv:0707.4139[hep-ph].
[16] M. Czakon, J. Gluza, T. Riemann, *Phys. Rev.* **D71**, 073009 (2005) [hep-ph/0412164].
[17] M. Czakon, J. Gluza, T. Riemann, *Nucl. Phys.* **B751**, 1 (2006) [hep-ph/0604101].
[18] S. Actis *et al.*, arXiv:0704.2400[hep-ph].
[19] S. Laporta, *Int. J. Mod. Phys.* **A15**, 5087 (2000) [hep-ph/0102033].
[20] V.A. Smirnov, *Phys. Lett.* **B460**, 397 (1999) [hep-ph/9905323].
[21] J.B. Tausk, *Phys. Lett.* **B469**, 225 (1999) [hep-ph/9909506].
[22] G. Chachamis, M. Czakon, MBrepresentation.m, unpublished.
[23] M. Czakon, *Comput. Phys. Commun.* **175**, 559 (2006) [hep-ph/0511200].
[24] S. Moch, P. Uwer, *Comput. Phys. Commun.* **174**, 759 (2006) [math-ph/0508008].
[25] H.R.P. Ferguson, D.H. Bailey, see *e.g.* http://mathworld.wolfram.com/PSLQAlgorithm.html.
[26] T. van Ritbergen, J.A.M. Vermaseren, S.A. Larin, *Phys. Lett.* **B400**, 379 (1997) [hep-ph/9701390].
[27] M. Czakon, *Nucl. Phys.* **B710**, 485 (2005) [hep-ph/0411261].
[28] S. Catani, *Phys. Lett.* **B427**, 161 (1998) [hep-ph/9802439].
[29] S. Moch, J.A.M. Vermaseren, A. Vogt, *Nucl. Phys.* **B688**, 101 (2004) [hep-ph/0403192].
[30] A. Vogt, S. Moch, J.A.M. Vermaseren, *Nucl. Phys.* **B691**, 129 (2004) [hep-ph/0404111].