

Next-to-leading order mixed QCD-electroweak corrections to Higgs production at the LHC

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After ten years from its discovery, the Higgs boson is still under unprecedented scrutiny. A huge theoretical effort has been invested in modelling Higgs boson production through gluon fusion, reaching N³LO predictions in pure QCD. This incredible theoretical achievement makes the exact computation of sub-leading contributions, such as mixed QCD-Electroweak corrections, necessary. I will present the analytic calculation of the gluon- and quark-initiated two-loop four-point contributions to such class of corrections mediated by light quarks at order $v\alpha^2\alpha_S^{3/2}$.

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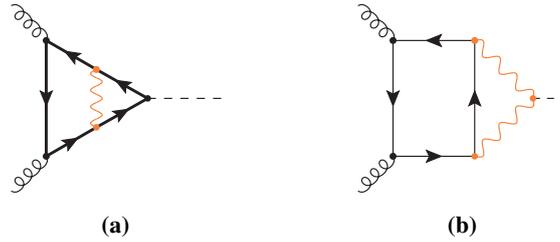


Figure 1: Different LO Electroweak corrections to Higgs boson production in gluon fusion.

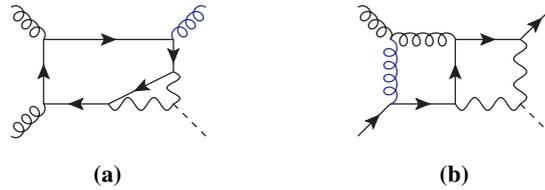


Figure 2: Prototypical diagrams for $ggHg$ (closed fermion loop, left) and $q\bar{q}Hg$ (open fermion line, right).

1. Motivations

Even after ten years from its joint discovery at ATLAS [1] and CMS [2], the Higgs boson remains under unprecedented scrutiny. Higgs production through gluon fusion, the main channel of production for the Higgs boson at the LHC, is expected to reach an experimental error of the order of the percent, or even lower. Such remarkable results must be met by equally reliable theoretical predictions.

At present, the small theoretical uncertainty associated to higher-order corrections made secondary effects and productions modes relevant. Except for the lack of N^3 LO PDFs, the other sources of theoretical uncertainties have all sizes of about 1%, and are given by the lack of full c - and b -quark mass inclusion, and the lack of an exact computation of NLO mixed QCD-Electroweak corrections.

In this contribution, based on [3, 4], we provide the last missing ingredients for the full evaluation of NLO mixed QCD-Electroweak corrections to Higgs plus one jet production from proton collisions at the LHC.

2. Processes analysis

Electroweak corrections to Higgs gluon fusion can be divided into two classes of diagrams, as depicted in Figure 1. On the one hand Electroweak bosons can occur inside the top-quark loop that connects the gluon and the Higgs (crf. Figure 1a), on the other hand, Electroweak bosons generated by the quark loop can merge to produce the Higgs boson (crf. Figure 1b). The first kind of contributions are only about 0.5% of the LO QCD cross section, while the second ones, the object of our studies, are dominated by light quarks and increase the total cross section of about 5% with respect to the LO QCD one.

Since we are interested in Higgs production starting from protons, both gluon-initiated and quark-initiated processes must be considered. In [5–9] the two- and three-loop corrections to ggH have been evaluated analytically with full dependence on the Electroweak and Higgs boson masses, and the same has been done at one-loop for the $q\bar{q}Hg$, $q\bar{q}Hgg$, and $q\bar{q}Hq\bar{q}$ in [10]. This leaves the two-loop contributions to ggH and to $q\bar{q}Hg$ to be evaluated (cfr. Figure 2).

The first difference with respect to the pure QCD case is given by chiral couplings stemming from vertices connecting quarks and Electroweak bosons. In case of closed fermion loops (as depicted in Figure 2a) terms containing a single γ_5 vanish summing over complete generations of massless quarks considering Standard Model couplings. The neat effect of such couplings is then reduced to an overall rescaling of the coupling constants, while the tensor structure of the amplitude is the same as for the pure QCD case

$$\mathcal{M} = f^{c_1 c_2 c_3} \epsilon_{\lambda_1}^\mu(\mathbf{p}_1) \epsilon_{\lambda_2}^\nu(\mathbf{p}_2) \epsilon_{\lambda_3}^\rho(\mathbf{p}_3) \left[\mathcal{F}_1 g_{\mu\nu} p_{2\rho} + \mathcal{F}_2 g_{\mu\rho} p_{1\nu} + \mathcal{F}_3 g_{\nu\rho} p_{3\mu} + \mathcal{F}_4 p_{3\mu} p_{1\nu} p_{2\rho} \right], \quad (1)$$

$$\mathcal{F}_{1\dots 4} = 4F_{1\dots 4, m_W} + \frac{2}{\cos^4 \theta_W} \left(\frac{5}{4} - \frac{7}{3} \sin^2 \theta_W + \frac{22}{9} \sin^4 \theta_W \right) F_{1\dots 4, m_Z}. \quad (2)$$

A similar result is valid for open quark lines (cfr. Figure 2b), although in this case a scheme conserving the anticommutativity of γ_5 is employed to move γ_5 to touch an external polarized spinor so that it converts into ± 1 . In this way we still obtain the same tensor structure as in QCD, but with a rescaling of the coupling depending on the chirality of the quark line

$$\mathcal{M}_L^{\text{open}} = T_{i_1 i_2}^{c_3} \left(\frac{2}{\cos^4 \theta_W} Q_q^2 \sin^4 \theta_W \right) \bar{v}_{s_1}(\mathbf{p}_1) \mathbb{P}_L \left[\tau_{1,\mu} A_{1,m_Z}^{\text{open}} + \tau_{2,\mu} A_{2,m_Z}^{\text{open}} \right] u_{s_2}(\mathbf{p}_2) \epsilon_\mu^{\lambda_3}(\mathbf{p}_3), \quad (3)$$

$$\begin{aligned} \mathcal{M}_R^{\text{open}} &= T_{i_1 i_2}^{c_3} \bar{v}_{s_1}(\mathbf{p}_1) \left\{ \mathbb{P}_R \left[\tau_{1,\mu} A_{1,m_W}^{\text{open}} + \tau_{2,\mu} A_{2,m_W}^{\text{open}} \right] + \right. \\ &\quad \left. + \frac{2}{\cos^4 \theta_W} \left(T_q - Q_q \sin^2 \theta_W \right)^2 \mathbb{P}_R \left[\tau_{1,\mu} A_{1,m_Z}^{\text{open}} + \tau_{2,\mu} A_{2,m_Z}^{\text{open}} \right] \right\} u_{s_2}(\mathbf{p}_2) \epsilon_\mu^{\lambda_3}(\mathbf{p}_3), \end{aligned} \quad (4)$$

$$\begin{aligned} \mathcal{M}^{\text{closed}} &= T_{i_1 i_2}^{c_3} \frac{1}{2} \bar{v}_{s_1}(\mathbf{p}_1) \left\{ 4 \left[\tau_{1,\mu} F_{1,m_W}^{\text{closed}} + \tau_{2,\mu} F_{2,m_W}^{\text{closed}} \right] + \frac{2}{\cos^4 \theta_W} \times \right. \\ &\quad \left. \times \left(\frac{5}{4} - \frac{7}{3} \sin^2 \theta_W + \frac{22}{9} \sin^4 \theta_W \right) \left[\tau_{1,\mu} F_{1,m_Z}^{\text{closed}} + \tau_{2,\mu} F_{2,m_Z}^{\text{closed}} \right] \right\} u_{s_2}(\mathbf{p}_2) \epsilon_\mu^{\lambda_3}(\mathbf{p}_3), \end{aligned} \quad (5)$$

$$\tau_{1,\mu} = \not{p}_3 p_{2\mu} - p_2 \cdot p_3 \gamma_\mu, \quad \tau_{2,\mu} = \not{p}_3 p_{1\mu} - p_1 \cdot p_3 \gamma_\mu. \quad (6)$$

3. Evaluation of the form factors

We construct and apply projectors in order to extract the single form factors F of Eqs. (1) to (5) in terms of two-loop Feynman integrals. Such integrals are (sub-)graphs of the six top sectors depicted in Figure 3 (T2 and T6 are enough to describe the integrals appearing in the $ggHg$ amplitude, while the other four sectors are necessary to cover the integrals coming from the $q\bar{q}Hg$

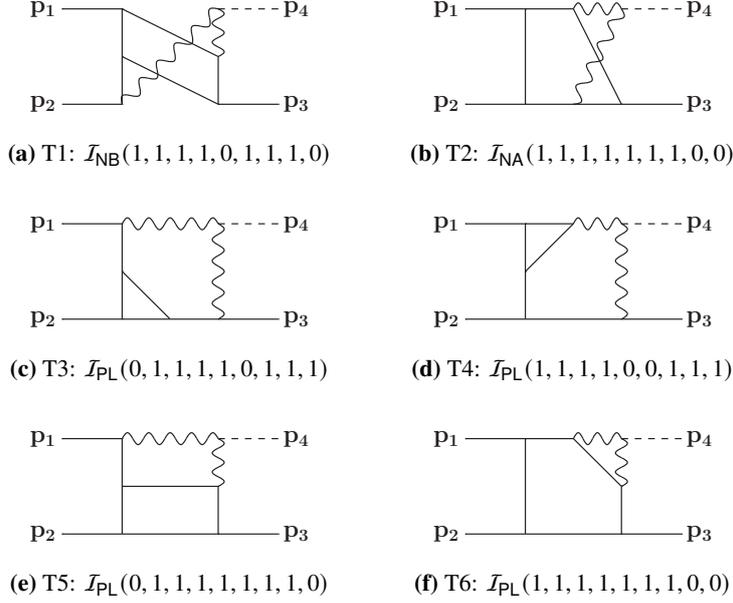


Figure 3: The six top sectors appearing in the amplitude. Straight (wavy) lines denote massless (massive) propagators. The dashed line indicates the Higgs boson.

process). We use the computer programs Reduze [11] and Kira [12] to reduce these Feynman integrals to a basis of Master Integrals (61 for the $ggHg$ case, 69 for the $q\bar{q}Hg$ case). The presence of the eight different square roots

$$\begin{aligned}
 r &= m_h^2 \sqrt{1 - 4m_V^2/m_h^2}, & r_{ust} &= \sqrt{s^2 u^2 + 2su(t-s)m_V^2 + (s+t)^2 m_V^4}, \\
 r_t &= \sqrt{r^2 - 4m_V^2 su/t}, & r_{sut} &= \sqrt{s^2 u^2 + 2su(t-u)m_V^2 + (t+u)^2 m_V^4}, \\
 r_u &= \sqrt{r^2 - 4m_V^2 st/u}, & r_{stu} &= \sqrt{s^2 t^2 + 2st(u-t)m_V^2 + (t+u)^2 m_V^4}, \\
 r_{tu} &= \sqrt{1 - 4m_V^2/(t+u)}, & r_{uts} &= \sqrt{u^2 t^2 + 2ut(s-t)m_V^2 + (s+t)^2 m_V^4},
 \end{aligned} \tag{7}$$

which, to our knowledge, are not simultaneously rationalizable, make the usage of differential equations ineffective to solve the master integrals. We then revert to direct integration over Feynman-Schwinger parameters. We find that all our master integrals are linearly reducible [13], i.e. there exists an order of integration such that each integral returns a hyperlogarithmic expression in terms of the next integration variable. This has the advantages that on the one hand we do not need to rationalize any square root (since they appear in the kinematics) and that on the other hand our result will still be written in terms of Goncharov polylogarithms (or GPLs).

It is important to notice that, despite the fact that two-loop integrals might contain poles up to ϵ^{-4} , we expect the $ggHg$ amplitude to be finite and the $q\bar{q}Hg$ one to have at most ϵ^{-2} singularities. To exploit this simpler pole structure we construct a (quasi-)finite basis of master integrals, removing UV- and IR-divergent terms. UV singularities are cured by raising the power of massive propagators until we reach a negative degree of divergence, while IR singularities are tackled by moving from

four to six dimensions [14, 15]

$$\mathcal{I}^{D+2}(a_1, \dots, a_7) = \frac{16}{stu(D-4)(D-3)} \int d^D k_1 d^D k_2 \frac{G(k_1, k_2, p_1, p_2, p_3)}{\mathcal{D}_1^{a_1} \dots \mathcal{D}_7^{a_7}} \quad (8)$$

where the Gram determinant G counters soft and collinear divergencies.

We compute the analytic ϵ -expansions of the master integrals using `HyperInt` [13] and insert them in the amplitudes, obtaining a linear combination of transcendental functions with algebraic coefficients. UV divergences and IR poles present in the $q\bar{q}Hg$ amplitude are removed by renormalization of α_S and subtraction of the Catani operator (see [16] for further details).

We proceed now by simplifying the finite remainders. We use the `Mathematica` package `MultivariateApart` [17] to partial-fraction our expressions without introducing spurious poles in the kinematics and reduce the set of algebraic prefactors to a basis of algebraic functions, collecting the new transcendental expressions and numerically checking for null terms and further relations. We further simplify the $ggHg$ amplitude by rewriting GPLs up to weight 3 in terms of Li_2 , $\text{Li}_{1,1}$, and logs, making analytic continuation explicit in the physical region of the process. At last, we combine the form factors to obtain the helicity amplitudes.

4. Conclusions

We evaluated the missing ingredients to the NLO mixed QCD-Electroweak corrections to Higgs production at the LHC in the form of analytic expressions for the helicity amplitudes with full dependence over the Electroweak and Higgs boson masses, written in terms of GPLs, Li , and log functions, paving the road for the evaluation of the cross section for Higgs plus jet production including both gluon- and quark-initiated channels, refining the results presented in [10]. Further steps include the evaluation of top-quark mass effects, which will require the explicit manipulation of γ_5 in D dimensions together with the reduction and evaluation of five-scale four-point Feynman integrals.

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References

- [1] ATLAS collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [1207.7214].
- [2] CMS collaboration, S. Chatrchyan et al., *Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [1207.7235].
- [3] M. Bonetti, E. Panzer, V. A. Smirnov and L. Tancredi, *Two-loop mixed QCD-EW corrections to $gg \rightarrow Hg$* , *JHEP* **11** (2020) 045 [2007.09813].

- [4] M. Bonetti, E. Panzer and L. Tancredi, *Two-loop mixed QCD-EW corrections to $q\bar{q} \rightarrow Hg$, $qg \rightarrow Hq$, and $\bar{q}g \rightarrow H\bar{q}$* , *JHEP* **06** (2022) 115 [2203.17202].
- [5] U. Aglietti, R. Bonciani, G. Degrossi and A. Vicini, *Two loop light fermion contribution to Higgs production and decays*, *Phys. Lett. B* **595** (2004) 432 [hep-ph/0404071].
- [6] G. Degrossi and F. Maltoni, *Two-loop electroweak corrections to Higgs production at hadron colliders*, *Phys. Lett. B* **600** (2004) 255 [hep-ph/0407249].
- [7] U. Aglietti, R. Bonciani, G. Degrossi and A. Vicini, *Two-loop electroweak corrections to Higgs production in proton-proton collisions*, in *TeV4LHC Workshop: 2nd Meeting*, 10, 2006, hep-ph/0610033.
- [8] M. Bonetti, K. Melnikov and L. Tancredi, *Two-loop electroweak corrections to Higgs–gluon couplings to higher orders in the dimensional regularization parameter*, *Nucl. Phys. B* **916** (2017) 709 [1610.05497].
- [9] M. Bonetti, K. Melnikov and L. Tancredi, *Three-loop mixed QCD-electroweak corrections to Higgs boson gluon fusion*, *Phys. Rev. D* **97** (2018) 034004 [1711.11113].
- [10] M. Becchetti, R. Bonciani, V. Del Duca, V. Hirschi, F. Moriello and A. Schweitzer, *Next-to-leading order corrections to light-quark mixed QCD-EW contributions to Higgs boson production*, *Phys. Rev. D* **103** (2021) 054037 [2010.09451].
- [11] A. von Manteuffel and C. Studerus, *Reduze 2 - Distributed Feynman Integral Reduction*, 1201.4330.
- [12] P. Maierhöfer, J. Usovitsch and P. Uwer, *Kira—A Feynman integral reduction program*, *Comput. Phys. Commun.* **230** (2018) 99 [1705.05610].
- [13] E. Panzer, *Algorithms for the symbolic integration of hyperlogarithms with applications to Feynman integrals*, *Comput.Phys.Commun.* **188** (2014) 148 [1403.3385].
- [14] O. V. Tarasov, *Connection between Feynman integrals having different values of the space-time dimension*, *Phys. Rev. D* **54** (1996) 6479 [hep-th/9606018].
- [15] R. Lee, *Space-time dimensionality D as complex variable: Calculating loop integrals using dimensional recurrence relation and analytical properties with respect to D* , *Nucl.Phys.* **B830** (2010) 474 [0911.0252].
- [16] S. Catani, *The Singular behavior of QCD amplitudes at two loop order*, *Phys.Lett.* **B427** (1998) 161 [hep-ph/9802439].
- [17] M. Heller and A. von Manteuffel, *MultivariateApart: Generalized partial fractions*, *Computer Physics Communications* **271** (2022) 108174 [2101.08283].