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ABSTRACT: We present the analytic calculation of the planar master integrals which contribute to compute the two-loop light-fermion electroweak corrections to the production of a Higgs boson in association with a jet in gluon-gluon fusion. The complete dependence on the electroweak-boson mass is retained. The master integrals are evaluated by means of the differential equations method and the analytic results are expressed in terms of multiple polylogarithms up to weight four.

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[1]On leave from INFN, Laboratori Nazionali di Frascati, Italy.

Contents

1 Introduction

Since its discovery in 2012 [1, 2], the study of the Higgs boson has been one of the dominant topics in the physics programme of the Large Hadron Collider (LHC). The Higgs signals provide a strong test of the Standard Model (SM) and can be a probe of New Physics (NP), in case a deviation from the SM behaviour of the Higgs properties will be revealed [3–6].

The major production channel of the Higgs boson at the LHC is gluon-gluon fusion. Since the Higgs boson does not couple directly to gluons, the coupling is mediated by a heavy-quark loop. Thus, the leading-order (LO) production requires the evaluation of one-loop amplitudes, the production at the next-to-leading order (NLO) accuracy requires the evaluation of two-loop amplitudes, and so forth. So far, in the full theory, i.e. with a complete dependence on the heavy-quark mass, Higgs production via gluon-gluon fusion is known at NLO [7, 8] (see also [9–12]). However, in the limit in which the heavy-quark mass is much heavier than the other scales in the process, the computations are made more tractable by using the Higgs Effective Field Theory (HEFT), i.e. by replacing the loop-mediated Higgs-gluon coupling by a tree-level effective coupling. That lowers by one loop the amplitudes to be computed. In the HEFT, Higgs production via gluon-gluon fusion is known at N³LO [13–17], whose accuracy has reached the 5% level [18].

In order to have access to a detailed study of the Higgs properties, precise theoretical predictions for more exclusive observables are needed. Of particular importance, for a detailed study of the SM structure of the loop-mediated Higgs-gluon coupling and of possible NP contributions to it, is the prediction of the transverse momentum distribution of a Higgs boson at high p_T [19–31].

The transverse momentum distribution of the Higgs boson in gluon-gluon fusion is known in the HEFT at NNLO [32–36]. While this approximation is satisfactory in the

region in which the Higgs p_T is smaller than the top-quark mass, in the high-p_T region it is known to give rise to predictions that can differ considerably from the ones in which the top-quark mass is treated exactly [37]. In the full theory, the production of a Higgs boson in association with a jet is known only at LO [38, 39]. Several approximations exist to Higgs plus one jet production at NLO in the full theory: (i) a numerical computation [40], which includes, though, only the dependence on the top-quark mass, while neglecting the bottom-quark mass; (ii) computations in the high p_T region [41, 42], based on the two-loop amplitudes for Higgs plus three partons, computed in the limit when the Higgs transverse momentum is larger than the top-quark mass, $p_T \gg m_t$ [43].; (iii) computations in the intermediate p_T region, where it is relevant to include also the top-bottom interference [44, 45], which is estimated by interfering a top-quark loop computed in the HEFT with a bottom-quark loop computed as an expansion in a small bottom-quark mass [46, 47].

The exact evaluation of the Higgs plus one jet production at NLO in the full theory, i.e. retaining the complete dependence on the mass of the heavy quark that runs into the loops, requires to compute the two-loop four-point amplitudes for Higgs plus three partons, where one of the loops is a heavy-quark loop, which involve elliptic iterated integrals. So far, only the planar contributions have been computed [48].

In addition, although the Higgs boson does not couple directly to massless fermions, its coupling to light fermions may be mediated by an electroweak-boson loop. In particular, the Higgs boson may also couple to gluons via a double loop, made by an electroweak-boson loop and a light-quark loop [49, 50]. This production mode makes up the bulk of the two-loop electroweak corrections to Higgs production via gluon-gluon fusion [51–53] and increases by about 5% the LO gluon-fusion cross section and by about 2% the N³LO cross section [18].

The NLO QCD corrections to the two-loop light-quark contribution to Higgs production via gluon-gluon fusion consist of the three-loop mixed QCD-electroweak corrections to Higgs production [54, 55], and of the two-loop four-point amplitudes for Higgs plus three partons, where one loop is an electroweak-boson loop and the other is a light-quark loop. These two-loop four-point amplitudes are presently unknown. Two approximated evaluations of the NLO QCD corrections have been computed: (a) the full corrections in the un-physical limit where the Higgs mass is much smaller than the electroweak-boson mass [56]; (b) a computation in which the virtual part is treated exactly [55], but the real radiation is included in the soft-gluon approximation [57].

In this paper, we present the analytic computation of the planar master integrals (MIs) relevant to the evaluation of the two-loop four-point amplitudes for Higgs plus three gluons, where one loop is an electroweak-boson loop and the other is a light-quark loop. They contribute to the mixed QCD-electroweak light-fermion corrections to the production of a Higgs boson with an additional jet, as well as to the real radiation of the NLO QCD corrections to the two-loop light-quark contribution to Higgs production via gluon-gluon fusion.

We performed the reduction to the MIs using the computer softwares FIRE5 [58] and LiteRed [59],[1] which implement Integration-by-parts identities (IBPs) [63–65] and Lorentz-invariance [66] identities, obtaining 48 MIs. Apart from the two-point functions, these MIs

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[1] Other public available softwares [60–62] for the IBPs reduction exist.

are new and presented in this paper for the first time. They are analitically computed using the differential equations method [67–71]. This method has proved to be very efficient for the computation of the MIs needed for higher-order corrections in the SM. In particular, we adopt the canonical basis approach [71–77] to the solution of the system of differential equations, which is expressed in terms of Chen-iterated integrals [78] represented as Goncharov multiple polylogarithms [79–81] (GPLs) up to weight four. The solutions are evaluated numerically using the software `GiNaC` [82, 83] and tested numerically against the software `FIESTA` [84] in the Euclidean and Minkowski regions of the phase space. We find agreement in both regions.

The analytic results presented in this paper are given as ancillary files uploaded with the arXiv submission.[2]

The paper is structured as follows. In the section 2 we give our notations and we describe the kinematic of the processes studied. In section 3 we describe briefly the method of differential equations and the canonical basis approach, moreover we give the alphabet associated to the solution. In section 4 we present the canonical basis and the transformation among the MIs in canonical form and the pre-canonical ones. Finally, in section 5 we present our conclusion.

2 Notations

In this paper we consider the partonic processes $gg \to Hg$, $gq \to qH$, $q\bar{q} \to gH$, and the crossed channels $H \to ggg$ and $H \to q\bar{q}g$. The external momenta corresponding either to gluons or to quarks are on their mass-shell $p_i^2 = 0$, while the external Higgs momentum p_4^2 is regarded as a variable. Therefore, we appoach the solution of the master integrals (MIs) of the topology as a three-scale problem, where, apart from the Higgs momentum p_4^2, the other two variables are the Mandelstam variables

$$s = (p_1 + p_2)^2, \quad t = (p_1 + p_3)^2. \tag{2.1}$$

For later convenience we define the dimensionless variabiles x, y, z such that

$$x = -\frac{s}{4m_B^2}, \quad y = -\frac{t}{4m_B^2}, \quad z = -\frac{p_4^2}{4m_B^2}, \tag{2.2}$$

where m_B^2 is the squared mass of the internal Electroweak boson (W or Z).

The physical phase-space region of the kinematic invariants (2.2) is

$$x < 0, \quad y < 0, \quad z < x + y, \tag{2.3}$$

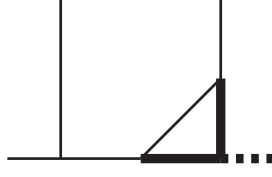for the decay channel, while for the production channel is

$$x < z < 0, \quad y > 0, \quad z > x + y. \tag{2.4}$$

The planar corrections can be computed considering the 7-denominator topology shown in figure 1. The MIs of the topology are defined by the two-loop dimensionally regularized

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[2]The ancillary files are in text format and the results, expressed as GPLs, are written in GiNac format.

Figure 1. Planar seven-denominator topology.

integrals

$$\int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{D_8^{a_8} \, D_9^{a_9}}{D_1^{a_1} D_2^{a_2} D_3^{a_3} D_4^{a_4} D_5^{a_5} D_6^{a_6} D_7^{a_7}} \,, \tag{2.5}$$

where $d = 4 - 2\epsilon$, a_i with $i = 1, \ldots, 7$ are integer numbers, while a_8 and a_9 are natural numbers and the normalization is such that

$$\mathcal{D}^d k_i = \frac{d^d k_i}{i\pi^{\frac{d}{2}}} e^{\epsilon \gamma_E} \left(\frac{m_B^2}{\mu^2} \right)^\epsilon. \tag{2.6}$$

The D_i, $i = 1, \ldots, 7$, are the denominators involved, while D_8, D_9 the numerators. They belong to the following set:

$$\left\{ -k_1^2, -(k_1 - k_2)^2, -(p_1 + k_1)^2, -(p_1 + p_2 + k_1)^2, -(p_3 - k_1)^2, \right.$$
$$\left. -(p_1 + p_2 + k_2)^2 + m_B^2, -(p_3 - k_2)^2 + m_B^2, -(p_3 + k_1 - k_2)^2, -(k_2 + p_2)^2 \right\}. \tag{2.7}$$

The number of MIs for this topology is 48, considering the different channels and crossings. Apart from two-point functions,[3] the MIs presented in this paper are new.

3 The system of differential equations

The analytic computation of the master integrals is performed by using the differential equations method [67–70] applied to a canonical basis for the MIs [71, 72]. In order to find the canonical basis several approaches exist [71–75]. We adopt the semi-algorithmic approach described in [76, 77]. The canonical basis $\vec{f}(\vec{x}, \epsilon)$ satisfies a system of first order partial linear differential equations with respect to the kinematic invariants $\vec{x}$,

$$\frac{\partial \vec{f}(\vec{x}, \epsilon)}{\partial x_i} = \epsilon \, A_i(\vec{x}) \vec{f}(\vec{x}, \epsilon) \tag{3.1}$$

where $i \in \{1, \ldots, n\}$, n is the number kinematic invariants and $A_i(\vec{x})$ is the set of matrices defining the differential equations. The linear system of partial differential equations, eq. (3.1), is equivalent to the following differential form,

$$d\vec{f}(\vec{x}, \epsilon) = \epsilon \, d\tilde{A}(\vec{x}) \vec{f}(\vec{x}, \epsilon) \,, \tag{3.2}$$

where the matrix elements of $\tilde{A}(\vec{x})$ are $\mathbb{Q}$-linear combinations of logarithms, with

$$\frac{\partial \tilde{A}(\vec{x})}{\partial x_i} = A_i(\vec{x}) \,. \tag{3.3}$$

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[3]The two-point functions can be found for instance in [85, 86].

The set of linearly indipendent arguments of the logarithms is called the *alphabet* of the solution, and its elements are called *letters*. The matrices $A_i(\vec{x})$ satisfy the integrability condition

$$\frac{\partial A_j}{\partial x_i} - \frac{\partial A_i}{\partial x_j} = 0, \quad [A_i, A_j] = 0, \tag{3.4}$$

where $[A_i, A_j] = A_i A_j - A_j A_i$. The solution of the differential equations (3.2) can be formally written as a path ordered exponential:

$$\vec{f}(\vec{x}, \epsilon) = \mathbb{P} \exp\left(\epsilon \int_\gamma d\tilde{A}(\vec{x})\right) \vec{f}(\vec{x}_0, \epsilon), \tag{3.5}$$

where $\mathbb{P}$ stands for the path-ordering operator, γ is a path in the space of kinematic invariants and $\vec{f}(\vec{x}_0, \epsilon)$ is a vector of boundary conditions. In practice we are interested in a solution around $\epsilon = 0$. By series expanding $\vec{f}(\vec{x}, \epsilon)$,

$$\vec{f}(\vec{x}, \epsilon) = \sum_{k=0}^{\infty} \epsilon^k \vec{f}^{(k)}(\vec{x}), \tag{3.6}$$

and by parametrizing the integration contour with $t \in [0, 1]$, the solution, eq. (3.5), translates to iterated integrals [78]:

$$\vec{f}(x) = \vec{f}^{(0)}(\vec{x}_0) + \sum_{k=1}^{\infty} \epsilon^k \sum_{j=1}^{k} \int_0^1 dt_1 \frac{\partial \tilde{A}(t_1)}{\partial t_1} \int_0^{t_1} dt_2 \frac{\partial \tilde{A}(t_2)}{\partial t_2} \cdots \int_0^{t_{j-1}} dt_j \frac{\partial \tilde{A}(t_j)}{\partial t_j} \vec{f}^{(k-j)}(\vec{x}_0). \tag{3.7}$$

In general, the alphabet letters depend algebraically on the kinematic invariants x_i. However, for the problem under consideration, it is possible to perform a variable change such that the alphabet depends only rationally on the new variables. This implies that the solution eq. (3.7) can be directly expressed in terms of Goncharov multiple polylogarithms (GPLs) [79, 87], defined recursively as,

$$G(\alpha_1, \ldots, \alpha_n; z) = \int_0^z \frac{dt}{t - \alpha_1} G(\alpha_2, \ldots, \alpha_n; t). \tag{3.8}$$

The recursion ends when $n = 0$ where we conventionally set

$$G(; z) \equiv 1. \tag{3.9}$$

Moreover, in order to deal with the divergency at the basepoint 0 when $\alpha_n = 0$, one defines:

$$G\left(\vec{0}; z\right) \equiv \frac{1}{n!} \log(z)^n. \tag{3.10}$$

We remark that also when the alphabet letters are not rational functions it is often possible to find a representation of the solution in terms of polylogarithmic functions. One starts from the symbol [88] of the solution, which is obtained from the differential equations matrix $\tilde{A}(\vec{x})$ and the ϵ^0 order of the boundary conditions, by the following recursive formula,

$$\mathcal{S}\left(f_n^{(i)}(\vec{x})\right) = \sum_m \mathcal{S}\left(f_m^{(i-1)}(\vec{x})\right) \otimes \mathcal{S}\left(\tilde{A}_{nm}(\vec{x})\right). \tag{3.11}$$

The corresponding polylogarithmic expressions are found by using the algorithm of [88, 89], and its algebraic generalisation [48].

3.1 The alphabet

The system of differential equations depends originally on rational functions of x and y and on the following square root

$$\sqrt{z(1+z)}\,. \qquad (3.12)$$

Exploiting for instance the methods described in [77], it is possible to rationalize the square root (3.12) by means of the change of variables

$$z \to \frac{w^2}{1+2w}\,. \qquad (3.13)$$

It is then straightforward to define the differential equations with respect to x, y, w defined by the matrices $A_x(x,y,w), A_y(x,y,w), A_w(x,y,w)$ respectively and solve them by using the following iterative formula,

$$
\begin{aligned}
f_j^{(i)}(x,y,w) = \sum_k \Bigg[&\int_{x_0,y_0,w_0}^{x,y_0,w_0} A_{x,jk}(x,y,w) f_k^{(i-1)}(x,y,w) dx \\
&+ \int_{x,y_0,w_0}^{x,y,w_0} A_{y,jk}(x,y,w) f_k^{(i-1)}(x,y,w) dy \\
&+ \int_{x,y,w_0}^{x,y,w} A_{w,jk}(x,y,w) f_k^{(i-1)}(x,y,w) dw \Bigg] \\
&+ f_j^{(i)}(x_0,y_0,w_0),
\end{aligned} \qquad (3.14)
$$

where we denoted by, e.g., $A_{x,jk}(x,y,w)$ the matrix element of the matrix $A_x(x,y,w)$ and x_0, y_0, w_0 is a set of boundary points that in general depend on the master integral (see next section). The recursion above can be directly solved in terms of GPLs by factorizing the matrix elements with respect to the integration variable. By performing the factorization we obtain the (inverse) GPLs integration kernels, $(x - x_k), (y - y_k), (w - w_k)$, with

$$x_k \in \left\{0, -\frac{1}{4}, \frac{1}{4}\right\}, \qquad (3.15)$$

$$y_k \in \left\{0, -\frac{1}{4}, \frac{1}{4}, -x, -\frac{x}{4x+1}\right\}, \qquad (3.16)$$

$$
\begin{aligned}
w_k \in \Bigg\{ &0, -\frac{1}{2}, -1, \frac{1}{4}\left(-1 - i\sqrt{3}\right), \frac{1}{4}\left(-1 + i\sqrt{3}\right), 2x, -\frac{2x}{4x+1}, x - \sqrt{x^2 + x}, \\
&x + \sqrt{x^2 + x}, \frac{1}{4}\left(-1 + 4x - \sqrt{16x^2 + 8x - 3}\right), \frac{1}{4}\left(-1 + 4x + \sqrt{16x^2 + 8x - 3}\right), \\
&2y, -\frac{2y}{4y+1}, y - \sqrt{y^2 + y}, y + \sqrt{y^2 + y}, \frac{1}{4}\left(-1 + 4y - \sqrt{16y^2 + 8y - 3}\right), \\
&\frac{1}{4}\left(-1 + 4y + \sqrt{16y^2 + 8y - 3}\right), x + y - \sqrt{x^2 + 2xy + x + y^2 + y}, \\
&x + y + \sqrt{x^2 + 2xy + x + y^2 + y}, \frac{-x-y}{2y}, \frac{-x-y}{2x} \Bigg\}, \qquad (3.17)
\end{aligned}
$$

that correspond to the arguments of the GPLs of the solution.

4 The master integrals

The set of 48 MIs, which we refer as $\mathcal{T}_i$, $i \in \{1, \ldots, 48\}$, is shown in figure 2. The corresponding canonical basis elements $f_i(\vec{x})$ are defined as linear combinations of pre-canonical integrals with algebraic prefactors of the Mandelstam invariants and the space-time regulator. Their definition is provided in appendix B.

The boundary conditions for the canonical master integrals $f_3, \ldots, f_6, f_8, \ldots, f_{24}, f_{26}, \ldots, f_{36}, f_{38}, f_{40}, \ldots, f_{48}$ are fixed in the point $s = t = p_4^2 = 0$, which is a regular point for the previous canonical master integrals, instead, the master integrals f_1, f_2, f_7, f_{25} are divergent in $s = t = p_4^2 = 0$, but they are product of known one-loop master integrals. Finally, for the master integrals f_{37}, f_{39} we fix the boundary conditions, respectively, in the regular points $(s = 0, t = m_B^2, p_4^2 = 0)$ and $(s = m_B^2, t = 0, p_4^2 = 0)$.

The solution is obtained in the un-physical region defined by:

$$x \geq 0, \quad y \geq 0, \quad w \geq 0. \tag{4.1}$$

Since we are able to express all the canonical integrals $f_1 \ldots f_{48}$ in terms of GPLs up to weight 4, the numerical check in all the regions of the phase space is straightforward. For the numerical evaluation of the masters we use the software `GiNaC` [82, 83]. The analytic continuation in the Minkowski region is perfomed (numerically) adding a small imaginary part to the squared c.m. energy, $s + i0^+$. The Minkowski physical regions are given, in terms of the variables x, y and w, by:

$$\text{H decay:} \qquad x < 0, \qquad\qquad y < 0, \qquad \frac{w^2}{1 + 2w} < x + y\,, \tag{4.2}$$

$$\text{H + jet:} \qquad x < \frac{w^2}{1 + 2w} < 0, \qquad y > 0, \qquad \frac{w^2}{1 + 2w} > x + y\,. \tag{4.3}$$

where no branch cuts are present. We checked different points of the phase space against `FIESTA` [84], finding complete agreement.

5 Conclusions

In this paper we have computed analytically the planar master integrals relevant to the evaluation of the two-loop four-point amplitudes for Higgs plus three gluons, where one loop is an electroweak-boson loop and the other is a light-quark loop. Those amplitudes contribute to the mixed QCD-electroweak light-fermion corrections to the production of a Higgs boson with an additional jet, as well as to the real radiation of the NLO QCD corrections to the two-loop light-quark contribution to Higgs production via gluon-gluon fusion.

The master integrals are evaluated with the differential equations method applied to a canonical set of basis integrals. Since the alphabet of the solution depends on a single square root, it is possible to find a variable change such that the matrices associated to the system of differential equations can be expressed in terms of rational functions. This allows a direct integration of the differential equations in terms of generalized polylogarithms up to weight 4. The expression of the master integrals in terms of generalized polylogarithms is quite flexible and can be evaluated numerically in a fast and precise way.
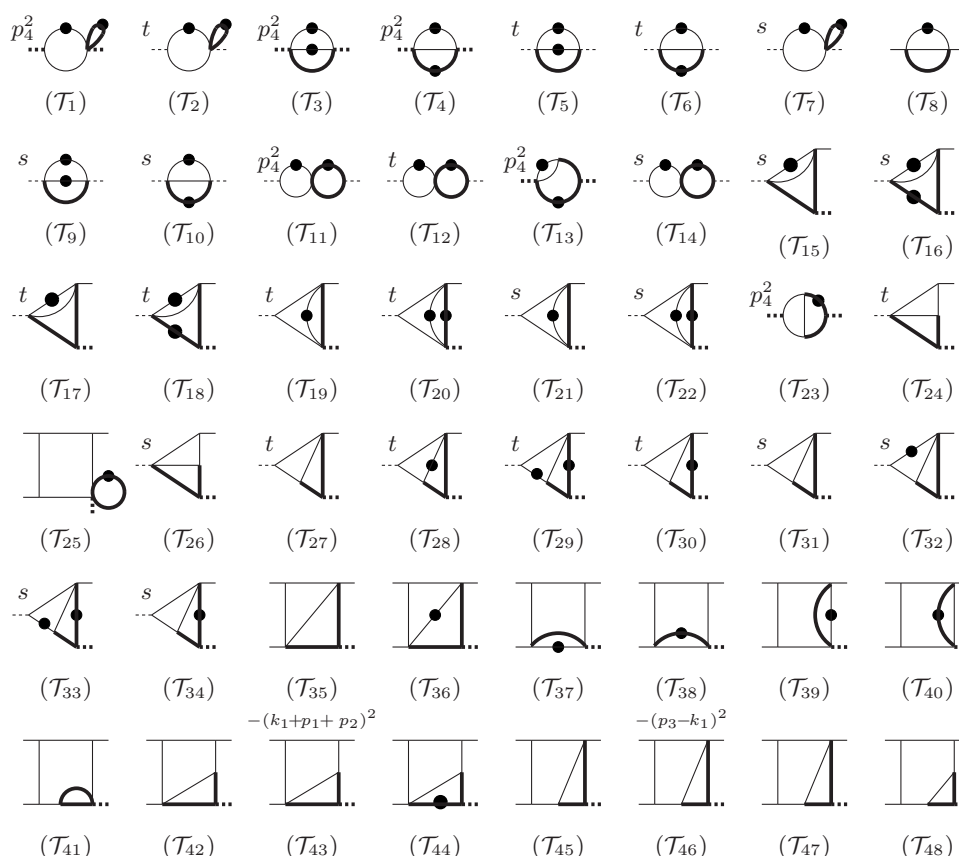
Figure 2. Master integrals in pre-canonical form. Internal plain thin lines represent massless propagators, while thick lines represent the vector-boson propagator. External plain thin lines represent massless particles on their mass-shell. External dashed thin lines represent the dependence on s, t, or m_H^2. The external dashed thick line represents the Higgs on its mass-shell.

Acknowledgments

A Routing for the pre-canonical master integrals

In this appendix we give the expression for the pre-canonical master integrals in the form of eq. (2.5).

$$\mathcal{T}_1 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \, \frac{1}{D_4^2 D_5 D_7^2}, \qquad\qquad \mathcal{T}_2 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \, \frac{1}{D_3^2 D_5 D_7^2},$$

$$\mathcal{T}_3 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \, \frac{1}{D_2^2 D_5^2 D_6}, \qquad\qquad \mathcal{T}_4 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \, \frac{1}{D_2^2 D_5 D_6^2},$$

$$\mathcal{T}_5 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \, \frac{1}{D_2^2 D_3^2 D_7}, \qquad\qquad \mathcal{T}_6 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \, \frac{1}{D_2^2 D_3 D_7^2},$$

$$\mathcal{T}_7 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1^2 D_4 D_7^2}, \qquad \mathcal{T}_8 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1^2 D_2 D_7},$$

$$\mathcal{T}_9 = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1^2 D_2^2 D_6}, \qquad \mathcal{T}_{10} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1^2 D_2 D_6^2},$$

$$\mathcal{T}_{11} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_4^2 D_5 D_6 D_7^2}, \qquad \mathcal{T}_{12} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_3^2 D_5 D_6^2 D_7},$$

$$\mathcal{T}_{13} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2^2 D_5 D_6^2 D_7}, \qquad \mathcal{T}_{14} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1^2 D_4 D_6 D_7^2},$$

$$\mathcal{T}_{15} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1^2 D_2 D_6 D_7}, \qquad \mathcal{T}_{16} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1^2 D_2 D_6^2 D_7},$$

$$\mathcal{T}_{17} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2^2 D_3 D_6 D_7}, \qquad \mathcal{T}_{18} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2^2 D_3 D_6 D_7^2},$$

$$\mathcal{T}_{19} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2^2 D_3 D_5 D_6}, \qquad \mathcal{T}_{20} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2^2 D_3 D_5 D_6^2},$$

$$\mathcal{T}_{21} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2^2 D_4 D_7}, \qquad \mathcal{T}_{22} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2^2 D_4 D_7^2},$$

$$\mathcal{T}_{23} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2 D_4 D_5 D_6 D_7^2}, \qquad \mathcal{T}_{24} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2 D_3 D_4 D_6 D_7},$$

$$\mathcal{T}_{25} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_3 D_4 D_5 D_7^2}, \qquad \mathcal{T}_{26} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_5 D_6 D_7},$$

$$\mathcal{T}_{27} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2 D_3 D_5 D_6 D_7}, \qquad \mathcal{T}_{28} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2^2 D_3 D_5 D_6 D_7},$$

$$\mathcal{T}_{29} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2 D_3 D_5^2 D_6^2 D_7}, \qquad \mathcal{T}_{30} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_2 D_3 D_5 D_6^2 D_7},$$

$$\mathcal{T}_{31} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_4 D_6 D_7}, \qquad \mathcal{T}_{32} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1^2 D_2 D_4 D_6 D_7},$$

$$\mathcal{T}_{33} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_4^2 D_6 D_7^2}, \qquad \mathcal{T}_{34} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_4 D_6 D_7^2},$$

$$\mathcal{T}_{35} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_3 D_6 D_7}, \qquad \mathcal{T}_{36} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2^2 D_3 D_6 D_7},$$

$$\mathcal{T}_{37} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2^2 D_3 D_5 D_6}, \qquad \mathcal{T}_{38} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_3 D_5 D_6^2},$$

$$\mathcal{T}_{39} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2^2 D_3 D_4 D_7}, \qquad \mathcal{T}_{40} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_3 D_4 D_7^2},$$

$$\mathcal{T}_{41} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_3 D_4 D_5 D_6 D_7^2}, \qquad \mathcal{T}_{42} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_3 D_5 D_6 D_7},$$

$$\mathcal{T}_{43} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{D_4}{D_1 D_2 D_3 D_5 D_6 D_7}, \qquad \mathcal{T}_{44} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_3 D_5 D_6^2 D_7},$$

$$\mathcal{T}_{45} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_3 D_4 D_6 D_7}, \qquad \mathcal{T}_{46} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{D_5}{D_1 D_2 D_3 D_4 D_6 D_7},$$

$$\mathcal{T}_{47} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_3 D_4 D_6 D_7^2}, \qquad \mathcal{T}_{48} = \int \mathcal{D}^d k_1 \mathcal{D}^d k_2 \frac{1}{D_1 D_2 D_3 D_4 D_5 D_6 D_7}.$$

$$(A.1)$$

B   The canonical basis

$$f_1 = \epsilon^2 p_4^2 \, \mathcal{T}_1 \,,$$

$$f_2 = \epsilon^2 t \, \mathcal{T}_2 \,,$$

$$f_3 = \epsilon^2 \left(m_B^2 - p_4^2\right) \mathcal{T}_3 + 2 m_B^2 \epsilon^2 \, \mathcal{T}_4 \,,$$

$$f_4 = \epsilon^2 p_4^2 \, \mathcal{T}_4 \,,$$

$$f_5 = -2 m_B^2 \epsilon^2 \mathcal{T}_6 + \epsilon^2 \left(t - m_B^2\right) \mathcal{T}_5 \,,$$

$$f_6 = \epsilon^2 t \, \mathcal{T}_6 \,,$$

$$f_7 = \epsilon^2 s \, \mathcal{T}_7 \,,$$

$$f_8 = \epsilon^2 (\epsilon - 1) \, \mathcal{T}_8 \,,$$

$$f_9 = \epsilon^2 \left(s - m_B^2\right) \mathcal{T}_9 + \epsilon^2 \left(s - 2 m_B^2\right) \mathcal{T}_{10} \,,$$

$$f_{10} = \epsilon^2 s \, \mathcal{T}_{10} \,,$$

$$f_{11} = \epsilon^2 \sqrt{\left(p_4^2\right)^3} \sqrt{4 m_B^2 - p_4^2} \, \mathcal{T}_{11} \,,$$

$$f_{12} = \epsilon^2 \sqrt{p_4^2} \sqrt{4 m_B^2 - p_4^2} \, t \, \mathcal{T}_{12} \,,$$

$$f_{13} = \epsilon^2 \sqrt{p_4^2} \sqrt{4 m_B^2 - p_4^2} \, m_B^2 \, \mathcal{T}_{13} + \epsilon^2 \left(m_B^2 - p_4^2\right) \frac{\sqrt{4 m_B^2 - p_4^2}}{4 \sqrt{p_4^2}} \mathcal{T}_3$$

$$+ \epsilon^2 \left(m_B^2 - p_4^2\right) \frac{4 m_B^2 - p_4^2}{4 \sqrt{p_4^2}} \mathcal{T}_4 - \epsilon^2 (\epsilon - 1) \frac{\sqrt{4 m_B^2 - p_4^2}}{2 \sqrt{p_4^2}} \mathcal{T}_8 \,,$$

$$f_{14} = \epsilon^2 \sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2} \, s \, \mathcal{T}_{14} \,,$$

$$f_{15} = \epsilon^3 \left(s - p_4^2\right) \mathcal{T}_{15} \,,$$

$$f_{16} = \epsilon^2 \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2} \left(m_B^2 p_4^2 - p_4^2 s + s^2\right)}{2 s - p_4^2} \mathcal{T}_{16} + \epsilon^2 (\epsilon - 1) \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2}}{2 p_4^2 - 4 s} \mathcal{T}_8$$

$$+ \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2} \left(s - m_B^2\right)}{2 \left(2 p_4^2 - 4 s\right)} \mathcal{T}_9 - 3 \epsilon^3 \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2} \left(s - p_4^2\right)}{2 p_4^2 - 4 s} \mathcal{T}_{15} \,,$$

$$f_{17} = \epsilon^3 (t - p_4^2) \, \mathcal{T}_{17} \,,$$

$$f_{18} = \epsilon^2 \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2} \left(m_B^2 p_4^2 - p_4^2 t + t^2\right)}{-p_4^2 + 2 t} \mathcal{T}_{18} - 3 \epsilon^3 \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2} \left(t - p_4^2\right)}{2 p_4^2 - 4 t} \mathcal{T}_{17}$$

$$+ \epsilon^2 (\epsilon - 1) \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2}}{2 p_4^2 - 4 t} \mathcal{T}_8 + \epsilon^2 \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2} \left(t - m_B^2\right)}{2 \left(2 p_4^2 - 4 t\right)} \mathcal{T}_5$$

$$+ \epsilon^2 \frac{\sqrt{4 m_B^2 - p_4^2} \sqrt{p_4^2} \, t \left(t - m_B^2\right)}{2 \left(p_4^2 t - t^2\right)} \mathcal{T}_6 \,,$$

$$f_{19} = \epsilon^3 \left(t - p_4^2\right) \mathcal{T}_{19} \,,$$

$$f_{20} = \epsilon^2 \frac{m_B^2 \left(t - p_4^2\right) \left(m_B^2 - p_4^2 + t\right)}{-2m_B^2 - p_4^2 + t} \mathcal{T}_{20} + \epsilon^3 \frac{\left(p_4^2 - t\right) \left(-4m_B^2 + p_4^2 - t\right)}{2m_B^2 + p_4^2 - t} \mathcal{T}_{19}$$
$$+ \epsilon^2 \frac{\left(p_4^2 - t\right) t}{2m_B^2 + p_4^2 - t} \mathcal{T}_2 - \epsilon^2 \frac{2m_B^2 \left(m_B^2 - p_4^2\right)}{-2m_B^2 - p_4^2 + t} \mathcal{T}_3 - \epsilon^2 \frac{2m_B^2 \left(2m_B^2 + p_4^2\right)}{-2m_B^2 - p_4^2 + t} \mathcal{T}_4,$$

$$f_{21} = \epsilon^3 (s - p_4^2) \mathcal{T}_{21},$$

$$f_{22} = \frac{\epsilon^2 m_B^2 \left(s - p_4^2\right) \left(m_B^2 - p_4^2 + s\right)}{-2m_B^2 - p_4^2 + s} \mathcal{T}_{22} + \frac{\epsilon^3 \left(p_4^2 - s\right) \left(-4m_B^2 + p_4^2 - s\right)}{2m_B^2 + p_4^2 - s} \mathcal{T}_{21}$$
$$- \frac{2\epsilon^2 m_B^2 \left(m_B^2 - p_4^2\right)}{-2m_B^2 - p_4^2 + s} \mathcal{T}_3 - \frac{2\epsilon^2 m_B^2 \left(2m_B^2 + p_4^2\right)}{-2m_B^2 - p_4^2 + s} \mathcal{T}_4 + \frac{2\epsilon^2 m_B^2 s}{-2m_B^2 - p_4^2 + s} \mathcal{T}_7,$$

$$f_{23} = \epsilon^2 (-1 + 2\epsilon) m_B^2 p_4^2 \mathcal{T}_{23} + \epsilon^2 p_4^4 \mathcal{T}_{11} - \epsilon^2 m_B^2 p_4^2 \mathcal{T}_{13},$$

$$f_{24} = \epsilon^4 \left(t - p_4^2\right) \mathcal{T}_{24},$$

$$f_{25} = \epsilon^3 s t \mathcal{T}_{25},$$

$$f_{26} = \epsilon^4 \left(s - p_4^2\right) \mathcal{T}_{26},$$

$$f_{27} = \epsilon^4 \left(t - p_4^2\right) \mathcal{T}_{27},$$

$$f_{28} = \epsilon^3 m_B^2 \left(t - p_4^2\right) \mathcal{T}_{28},$$

$$f_{29} = \epsilon^2 m_B^2 p_4^2 t \mathcal{T}_{29} + 2\epsilon^4 t \mathcal{T}_{27} + \frac{1}{2} m_B^2 \epsilon^3 \left(p_4^2 - t\right) \mathcal{T}_{28} + \frac{1}{2} p_4^2 \epsilon^3 \left(p_4^2 + t\right) \mathcal{T}_{30}$$
$$+ \frac{\epsilon^2 \left(-4m_B^2 + p_4^2\right) t}{2m_B^2 + p_4^2 - t} \mathcal{T}_2 - \frac{\epsilon^2 \left(4m_B^4 - 5m_B^2 p_4^2 + p_4^4\right)}{-2m_B^2 - p_4^2 + t} \mathcal{T}_3 - \frac{\epsilon^2 \left(8m_B^4 + 2m_B^2 p_4^2 - p_4^4\right)}{-2m_B^2 - p_4^2 + t} \mathcal{T}_4$$
$$+ \frac{\epsilon^2 \left(m_B^2 - t\right) t}{2 \left(p_4^2 - 2t\right)} \mathcal{T}_5 + \frac{\epsilon^2 t \left(m_B^2 - p_4^2 + t\right)}{p_4^2 - 2t} \mathcal{T}_6 - \frac{(\epsilon - 1)\epsilon^2 \left(p_4^2 - t\right)}{p_4^2 - 2t} \mathcal{T}_8 + p_4^2 t \epsilon^2 \mathcal{T}_{12}$$
$$+ m_B^2 p_4^2 \epsilon^2 \mathcal{T}_{13} - \frac{\epsilon^3 \left(3p_4^4 - 5p_4^2 t + t^2\right)}{p_4^2 - 2t} \mathcal{T}_{17} + \frac{p_4^2 \epsilon^2 \left(m_B^2 p_4^2 + t(t - p_4^2)\right)}{p_4^2 - 2t} \mathcal{T}_{18}$$
$$- \frac{2\epsilon^3 \left(3p_4^2 - 2t\right) \left(m_B^2 - p_4^2 + t\right)}{2m_B^2 + p_4^2 - t} \mathcal{T}_{19} + \frac{\epsilon^2 m_B^2 \left(3p_4^2 - 2t\right) \left(m_B^2 - p_4^2 + t\right)}{2m_B^2 + p_4^2 - t} \mathcal{T}_{20},$$

$$f_{30} = \epsilon^3 \sqrt{p_4^2} \sqrt{4m_B^2 - p_4^2} \left(t - p_4^2\right) \mathcal{T}_{30},$$

$$f_{31} = \epsilon^4 \left(s - p_4^2\right) \mathcal{T}_{31},$$

$$f_{32} = \epsilon^3 s \left(s - p_4^2\right) T_{32},$$

$$f_{33} = \epsilon^2 m_B^2 p_4^2 s \mathcal{T}_{33} + 2\epsilon^4 \left(p_4^2 + s\right) \mathcal{T}_{31} + \epsilon^3 s \left(s - p_4^2\right) \mathcal{T}_{32} + \epsilon^3 p_4^2 \left(p_4^2 + s\right) \mathcal{T}_{34}$$
$$+ \frac{2\epsilon^2 p_4^2 \left(p_4^2 - m_B^2\right)}{2m_B^2 + p_4^2 - s} \mathcal{T}_3 - \frac{2\epsilon^2 p_4^2 s}{2m_B^2 + p_4^2 - s} \mathcal{T}_4 + \frac{2\epsilon^2 s \left(4m_B^2 + 3p_4^2 - 2s\right)}{2m_B^2 + p_4^2 - s} \mathcal{T}_7$$
$$- \frac{p_4^2 (\epsilon - 1)\epsilon^2}{p_4^2 - 2s} \mathcal{T}_8 + \frac{\epsilon^2 p_4^2 \left(m_B^2 - s\right)}{2 \left(p_4^2 - 2s\right)} \mathcal{T}_9 + \frac{\epsilon^2 p_4^2 \left(m_B^2 - s\right)}{p_4^2 - 2s} \mathcal{T}_{10} + 2\epsilon^2 m_B^2 p_4^2 \mathcal{T}_{13}$$
$$+ 2\epsilon^2 p_4^2 s \mathcal{T}_{14} + \frac{\epsilon^3 p_4^2 \left(7s - 5p_4^2\right)}{p_4^2 - 2s} \mathcal{T}_{15} + \frac{2\epsilon^2 p_4^2 \left(m_B^2 p_4^2 + s(s - p_4^2)\right)}{p_4^2 - 2s} \mathcal{T}_{16}$$
$$- \frac{4\epsilon^3 p_4^2 \left(m_B^2 - p_4^2 + s\right)}{2m_B^2 + p_4^2 - s} \mathcal{T}_{21} + \frac{2m_B^2 p_4^2 \epsilon^2 \left(m_B^2 - p_4^2 + s\right)}{2m_B^2 + p_4^2 - s} \mathcal{T}_{22},$$

$$f_{34} = \epsilon^3 \sqrt{p_4^2} \sqrt{4m_B^2 - p_4^2} \left(s - p_4^2\right) \mathcal{T}_{34},$$

$$f_{35} = \epsilon^4 \left(s+t\right) \mathcal{T}_{35} \,,$$

$$f_{36} = \epsilon^3 \left(-\left(m_B^2(s+t)-st\right)\right) \mathcal{T}_{36} + 2\epsilon^4 (s+t) \mathcal{T}_{35} \,,$$

$$f_{37} = \epsilon^3 t \left(s-m_B^2\right) \mathcal{T}_{37} + \epsilon^3 \left(s-m_B^2\right) t \mathcal{T}_{38} \,,$$

$$f_{38} = \epsilon^3 s t \mathcal{T}_{38} \,,$$

$$f_{39} = \epsilon^3 s \left(t-m_B^2\right) \mathcal{T}_{39} + \epsilon^3 s \left(t-m_B^2\right) \mathcal{T}_{40} \,,$$

$$f_{40} = \epsilon^3 s t \mathcal{T}_{40} \,,$$

$$f_{41} = \epsilon^3 \sqrt{p_4^2} \sqrt{4m_B^2-p_4^2}\, s t \mathcal{T}_{41} \,,$$

$$f_{42} = \epsilon^4 t \left(s-p_4^2\right) \mathcal{T}_{42} \,,$$

$$f_{43} = \epsilon^4 t \mathcal{T}_{43} + \epsilon^4 p_4^2 t \mathcal{T}_{42} - \epsilon^4 t \mathcal{T}_{35} \,,$$

$$
\begin{aligned}
f_{44} = {} & -\frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,t\left(m_B^2 p_4^2 + s\left(s-p_4^2\right)\right)}{p_4^2-2s}\mathcal{T}_{44} + \frac{\epsilon^4 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,t}{p_4^2-2s}\mathcal{T}_{43} \\
& +\frac{\epsilon^4 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,(2p_4^2-s)\,t}{p_4^2-2s}\mathcal{T}_{42} + \frac{\epsilon^2\left(m_B^2-3p_4^2\right)\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,t}{3\left(p_4^2-2s\right)\left(2m_B^2+p_4^2-t\right)}\mathcal{T}_{2} \\
& -\frac{\epsilon^2\left(m_B^2-p_4^2\right)\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(10m_B^2-3\left(3p_4^2+t\right)\right)}{12\left(p_4^2-2s\right)\left(2m_B^2+p_4^2-t\right)}\mathcal{T}_{3} \\
& +\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(-10m_B^4+m_B^2\left(p_4^2+3t\right)+3p_4^2\left(p_4^2+t\right)\right)}{6\left(p_4^2-2s\right)\left(2m_B^2+p_4^2-t\right)}\mathcal{T}_{4} \\
& +\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(t-m_B^2\right)\left(3p_4^2-2t\right)}{8\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{5} \\
& +\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2t(m_B^2+p_4^2)-3m_B^2 p_4^2\right)}{4\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{6} \\
& +\frac{(\epsilon-1)\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(11p_4^2-16t\right)}{6\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{8} + \frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(s-m_B^2\right)}{8\left(p_4^2-2s\right)}\mathcal{T}_{9} \\
& -\frac{\epsilon^2 m_B^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}}{4p_4^2-8s}\mathcal{T}_{10} - \frac{\epsilon^2\sqrt{\left(p_4^2\right)^3}\sqrt{4m_B^2-p_4^2}\,t}{p_4^2-2s}\mathcal{T}_{12} \\
& -\frac{\epsilon^2 m_B^2\sqrt{\left(p_4^2\right)^3}\sqrt{4m_B^2-p_4^2}}{p_4^2-2s}\mathcal{T}_{13} + \frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(s-p_4^2\right)}{2p_4^2-4s}\mathcal{T}_{15} \\
& +\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2p_4^4-2p_4^2 t-t^2\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{17} \\
& -\frac{\epsilon^2\sqrt{\left(p_4^2\right)^3}\sqrt{4m_B^2-p_4^2}\left(m_B^2 p_4^2+t\left(t-p_4^2\right)\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{18}
\end{aligned}
$$

$$+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2\left(3p_4^2-t\right)+2p_4^2\left(t-p_4^2\right)\right)}{\left(p_4^2-2s\right)\left(2m_B^2+p_4^2-t\right)}\mathcal{T}_{19}$$

$$-\frac{\epsilon^2 m_B^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(7p_4^2-t\right)\left(m_B^2-p_4^2+t\right)}{6\left(p_4^2-2s\right)\left(2m_B^2+p_4^2-t\right)}\mathcal{T}_{20}$$

$$+\frac{\epsilon^4\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(p_4^2-s\right)}{p_4^2-2s}\mathcal{T}_{26}$$

$$-\frac{\epsilon^4\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(p_4^2+t\right)}{p_4^2-2s}\mathcal{T}_{27}-\frac{\epsilon^2 m_B^2\sqrt{\left(p_4^2\right)^3}\sqrt{4m_B^2-p_4^2}\,t}{p_4^2-2s}\mathcal{T}_{29}$$

$$-\frac{\epsilon^3\sqrt{\left(p_4^2\right)^3}\sqrt{4m_B^2-p_4^2}\left(p_4^2+t\right)}{2\left(p_4^2-2s\right)}\mathcal{T}_{30}+\frac{\epsilon^4\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(3s+t\right)}{2\left(p_4^2-2s\right)}\mathcal{T}_{35}$$

$$+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2(s+t)-st\right)}{4(p_4^2-2s)}\mathcal{T}_{36}$$

$$+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,t\left(s-m_B^2\right)}{6\left(p_4^2-2s\right)}\mathcal{T}_{37}-\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2-3s\right)t}{6\left(p_4^2-2s\right)}\mathcal{T}_{38}\,,$$

$$f_{45}=\epsilon^4 s\left(t-p_4^2\right)\mathcal{T}_{45}\,,$$

$$f_{46}=\epsilon^4 s\,\mathcal{T}_{46}+\epsilon^4 p_4^2 s\,\mathcal{T}_{45}-\epsilon^4 s\,\mathcal{T}_{35}\,,$$

$$f_{47}=-\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,s\left(m_B^2 p_4^2+t\left(t-p_4^2\right)\right)}{p_4^2-2t}\mathcal{T}_{47}+\frac{\epsilon^4\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,s}{p_4^2-2t}\mathcal{T}_{46}$$

$$+\frac{\epsilon^4\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2p_4^2-t\right)s}{p_4^2-2t}\mathcal{T}_{45}$$

$$-\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2-p_4^2\right)\left(10m_B^2-3\left(3p_4^2+s\right)\right)}{12\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)}\mathcal{T}_3$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(-10m_B^4+m_B^2\left(p_4^2+3s\right)+3p_4^2\left(p_4^2+s\right)\right)}{6\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)}\mathcal{T}_4$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(t-m_B^2\right)}{8\left(p_4^2-2t\right)}\mathcal{T}_5-\frac{\epsilon^2 m_B^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}}{4p_4^2-8t}\mathcal{T}_6$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,s\left(m_B^2-3p_4^2\right)}{3\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)}\mathcal{T}_7+\frac{(\epsilon-1)\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(11p_4^2-16s\right)}{6\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_8$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(s-m_B^2\right)\left(3p_4^2-2s\right)}{8\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_9$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2s\left(m_B^2+p_4^2\right)-3m_B^2 p_4^2\right)}{4\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{10}-\frac{\epsilon^2 m_B^2\sqrt{p_4^2}^3\sqrt{4m_B^2-p_4^2}}{p_4^2-2t}\mathcal{T}_{13}$$

$$-\frac{\epsilon^2 \sqrt{p_4^2}^3 \sqrt{4m_B^2-p_4^2}\, s}{p_4^2-2t}\mathcal{T}_{14}+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2p_4^4-2p_4^2 s-s^2\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{15}$$

$$-\frac{\epsilon^2\sqrt{p_4^2}^3\sqrt{4m_B^2-p_4^2}\left(m_B^2 p_4^2+s\left(s-p_4^2\right)\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{16}+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(t-p_4^2\right)}{2p_4^2-4t}\mathcal{T}_{17}$$

$$+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2\left(3p_4^2-s\right)+2p_4^2\left(s-p_4^2\right)\right)}{\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)}\mathcal{T}_{21}$$

$$-\frac{\epsilon^2 m_B^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(7p_4^2-s\right)\left(m_B^2-p_4^2+s\right)}{6\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)}\mathcal{T}_{22}$$

$$+\frac{\epsilon^4\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(p_4^2-t\right)}{p_4^2-2t}\mathcal{T}_{24}-\frac{\epsilon^4\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(p_4^2+s\right)}{p_4^2-2t}\mathcal{T}_{31}$$

$$-\frac{\epsilon^2 m_B^2 s\sqrt{p_4^2}^3\sqrt{4m_B^2-p_4^2}}{p_4^2-2t}\mathcal{T}_{33}-\frac{\epsilon^3\sqrt{p_4^2}^3\sqrt{4m_B^2-p_4^2}\left(p_4^2+s\right)}{2\left(p_4^2-2t\right)}\mathcal{T}_{34}$$

$$+\frac{\epsilon^4\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(s+3t\right)}{2\left(p_4^2-2t\right)}\mathcal{T}_{35}+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2(s+t)-st\right)}{4\left(p_4^2-2t\right)}\mathcal{T}_{36}$$

$$+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\, s\left(t-m_B^2\right)}{6\left(p_4^2-2t\right)}\mathcal{T}_{39}-\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\, s\left(m_B^2-3t\right)}{6\left(p_4^2-2t\right)}\mathcal{T}_{40}\,,$$

$$f_{48}=\epsilon^4 p_4^2\, s\, t\,\mathcal{T}_{48}+\frac{\epsilon^2\left(m_B^2-3p_4^2\right)\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,t}{3\left(p_4^2-2s\right)\left(2m_B^2+p_4^2-t\right)}\mathcal{T}_2+A\left(s,t,p_4^2\right)\mathcal{T}_3+B\left(s,t,p_4^2\right)\mathcal{T}_4$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2-t\right)\left(-2p_4^2+s+t\right)}{4\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_5$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2\left(-2p_4^2+s+t\right)+p_4^2 t\right)}{2\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_6$$

$$+\frac{(\epsilon-1)\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(11p_4^2-8(s+t)\right)}{3\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_8$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2-s\right)\left(-2p_4^2+s+t\right)}{4\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_9$$

$$+\frac{\epsilon^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2\left(-2p_4^2+s+t\right)+p_4^2 s\right)}{2\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{10}-\frac{\epsilon^2\sqrt{p_4^2}^3\sqrt{4m_B^2-p_4^2}\,t}{p_4^2-2s}\mathcal{T}_{12}$$

$$+\frac{2\epsilon^2 m_B^2{}^{3/2}\sqrt{4m_B^2-p_4^2}\left(-p_4^2+s+t\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{13}-\frac{\epsilon^2\sqrt{p_4^2}^3\sqrt{4m_B^2-p_4^2}\,s}{p_4^2-2t}\mathcal{T}_{14}$$

$$+\frac{\epsilon^3\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(3p_4^4+p_4^2(2t-3s)-2s(s+t)\right)}{2\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{15}$$

$$-\frac{\epsilon^2 \sqrt{p_4^2}^3 \sqrt{4m_B^2-p_4^2}\left(m_B^2 p_4^2 + s\left(s-p_4^2\right)\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{16}$$

$$+\frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(3p_4^4 + p_4^2(2s-3t) - 2t(s+t)\right)}{2\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{17}$$

$$-\frac{\epsilon^2 \sqrt{p_4^2}^3 \sqrt{4m_B^2-p_4^2}\left(m_B^2 p_4^2 + t\left(t-p_4^2\right)\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{18}$$

$$+\frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2\left(3p_4^2-t\right) + 2p_4^2\left(t-p_4^2\right)\right)}{\left(p_4^2-2s\right)\left(2m_B^2+p_4^2-t\right)}\mathcal{T}_{19}$$

$$-\frac{\epsilon^2 m_B^2 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(7p_4^2-t\right)\left(m_B^2-p_4^2+t\right)}{6\left(p_4^2-2s\right)\left(2m_B^2+p_4^2-t\right)}\mathcal{T}_{20}$$

$$+\frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2\left(3p_4^2-s\right) + 2p_4^2\left(s-p_4^2\right)\right)}{\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)}\mathcal{T}_{21}$$

$$-\frac{\epsilon^2 m_B^2 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(7p_4^2-s\right)\left(m_B^2-p_4^2+s\right)}{6\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)}\mathcal{T}_{22}$$

$$+\frac{\epsilon^4 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(p_4^2-t\right)}{p_4^2-2t}\mathcal{T}_{24} + \frac{\epsilon^4 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(p_4^2-s\right)}{p_4^2-2s}\mathcal{T}_{26}$$

$$-\frac{\epsilon^4 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(p_4^2+t\right)}{p_4^2-2s}\mathcal{T}_{27} + \epsilon^3 m_B^2\left(t-p_4^2\right)\mathcal{T}_{28}$$

$$-\frac{\epsilon^2 m_B^2 \sqrt{p_4^2}^3 \sqrt{4m_B^2-p_4^2}\,t}{p_4^2-2s}\mathcal{T}_{29} - \frac{\epsilon^3 \sqrt{p_4^2}^3 \sqrt{4m_B^2-p_4^2}\left(p_4^2+t\right)}{2\left(p_4^2-2s\right)}\mathcal{T}_{30}$$

$$-\frac{\epsilon^4 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(p_4^2+s\right)}{p_4^2-2t}\mathcal{T}_{31} + \epsilon^3 s\left(s-p_4^2\right)\mathcal{T}_{32}$$

$$-\frac{\epsilon^2 m_B^2 \sqrt{p_4^2}^3 \sqrt{4m_B^2-p_4^2}\,s}{p_4^2-2t}\mathcal{T}_{33} - \frac{\epsilon^3 \sqrt{p_4^2}^3 \sqrt{4m_B^2-p_4^2}\left(p_4^2+s\right)}{2\left(p_4^2-2t\right)}\mathcal{T}_{34}$$

$$+\frac{\epsilon^4 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2p_4^2(s+t) - s^2 - 6st - t^2\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{35}$$

$$+\frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2(s+t) - st\right)\left(p_4^2-s-t\right)}{2\left(p_4^2-2s\right)\left(p_4^2-2t\right)}\mathcal{T}_{36}$$

$$+\frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,t\left(s-m_B^2\right)}{6\left(p_4^2-2s\right)}\mathcal{T}_{37} - \frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2-3s\right)t}{6\left(p_4^2-2s\right)}\mathcal{T}_{38}$$

$$+\frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,s\left(t-m_B^2\right)}{6\left(p_4^2-2t\right)}\mathcal{T}_{39} - \frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,s\left(m_B^2-3t\right)}{6\left(p_4^2-2t\right)}\mathcal{T}_{40}$$

$$+\frac{\epsilon^4 \sqrt{p_4^2}\, t\left(-s\sqrt{4m_B^2-p_4^2}+2p_4^2\sqrt{4m_B^2-p_4^2}+\sqrt{p_4^2}\left(p_4^2-2s\right)\right)}{p_4^2-2s}\mathcal{T}_{42}$$

$$+\frac{\epsilon^4 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,t}{p_4^2-2s}\mathcal{T}_{43}-\frac{\epsilon^3 \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\,t\left(m_B^2 p_4^2+s\left(s-p_4^2\right)\right)}{p_4^2-2s}\mathcal{T}_{44}$$

$$+\frac{\epsilon^4 s \sqrt{p_4^2}\left(-t\sqrt{4m_B^2-p_4^2}+2p_4^2\sqrt{4m_B^2-p_4^2}+\sqrt{p_4^2}\left(p_4^2-2t\right)\right)}{p_4^2-2t}\mathcal{T}_{45}$$

$$+\frac{\epsilon^4 s \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}}{p_4^2-2t}\mathcal{T}_{46}-\frac{\epsilon^3 s \sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2 p_4^2+t\left(t-p_4^2\right)\right)}{p_4^2-2t}\mathcal{T}_{47}\,, \qquad \text{(B.1)}$$

where

$$A\left(s,t,p_4^2\right)=-\frac{\left(m_B^2-p_4^2\right)\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(20m_B^4\left(p_4^2-s-t\right)+m_B^2\left(2(3s+t)(s+3t)-8p_4^4\right)\right)}{6\left(p_4^2-2s\right)\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)\left(2m_B^2+p_4^2-t\right)}$$

$$+\frac{\left(m_B^2-p_4^2\right)\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(3p_4^6-4p_4^4(s+t)-p_4^2\left(s^2-5st+t^2\right)+st(s+t)\right)}{2\left(p_4^2-2s\right)\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)\left(2m_B^2+p_4^2-t\right)}$$

$$B\left(s,t,p_4^2\right)=-\frac{\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2m_B^2+p_4^2\right)s\left(-10m_B^4-3m_B^2 p_4^2+3p_4^4\right)}{3\left(p_4^2-2s\right)\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)\left(2m_B^2+p_4^2-t\right)}$$

$$-\frac{\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2m_B^2+p_4^2\right)\left(3s^2\left(m_B^2+p_4^2\right)-p_4^2\left(2m_B^2+p_4^2\right)\left(3p_4^2-5m_B^2\right)\right)}{3\left(p_4^2-2s\right)\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)\left(2m_B^2+p_4^2-t\right)}$$

$$-\frac{t^2\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(m_B^2+p_4^2\right)}{\left(p_4^2-2s\right)\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-t\right)}$$

$$+\frac{t\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(2m_B^2+p_4^2\right)\left(10m_B^4+3m_B^2 p_4^2-3p_4^4\right)}{3\left(p_4^2-2s\right)\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)\left(2m_B^2+p_4^2-t\right)}$$

$$-\frac{st\sqrt{p_4^2}\sqrt{4m_B^2-p_4^2}\left(20m_B^4+m_B^2\left(p_4^2-3s\right)-3p_4^2\left(p_4^2+s\right)\right)}{3\left(p_4^2-2s\right)\left(p_4^2-2t\right)\left(2m_B^2+p_4^2-s\right)\left(2m_B^2+p_4^2-t\right)}\,. \qquad \text{(B.2)}$$

References

[1] ATLAS collaboration, *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 [`arXiv:1207.7214`] [INSPIRE].

[2] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett.* **B 716** (2012) 30 [`arXiv:1207.7235`] [INSPIRE].

[3] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, S. Dittmaier et al., *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, arXiv:1101.0593 [INSPIRE].

[4] S. Dittmaier et al., *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*, arXiv:1201.3084 [INSPIRE].

[5] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, J.R. Andersen et al., *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, arXiv:1307.1347 [INSPIRE].

[6] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, arXiv:1610.07922 [INSPIRE].

[7] D. Graudenz, M. Spira and P.M. Zerwas, *QCD corrections to Higgs boson production at proton proton colliders*, *Phys. Rev. Lett.* **70** (1993) 1372 [INSPIRE].

[8] M. Spira, A. Djouadi, D. Graudenz and P.M. Zerwas, *Higgs boson production at the LHC*, *Nucl. Phys.* **B 453** (1995) 17 [hep-ph/9504378] [INSPIRE].

[9] R. Harlander and P. Kant, *Higgs production and decay: Analytic results at next-to-leading order QCD*, *JHEP* **12** (2005) 015 [hep-ph/0509189] [INSPIRE].

[10] C. Anastasiou, S. Beerli, S. Bucherer, A. Daleo and Z. Kunszt, *Two-loop amplitudes and master integrals for the production of a Higgs boson via a massive quark and a scalar-quark loop*, *JHEP* **01** (2007) 082 [hep-ph/0611236] [INSPIRE].

[11] U. Aglietti, R. Bonciani, G. Degrassi and A. Vicini, *Analytic Results for Virtual QCD Corrections to Higgs Production and Decay*, *JHEP* **01** (2007) 021 [hep-ph/0611266] [INSPIRE].

[12] R. Bonciani, G. Degrassi and A. Vicini, *Scalar particle contribution to Higgs production via gluon fusion at NLO*, *JHEP* **11** (2007) 095 [arXiv:0709.4227] [INSPIRE].

[13] C. Anastasiou, C. Duhr, F. Dulat and B. Mistlberger, *Soft triple-real radiation for Higgs production at N3LO*, *JHEP* **07** (2013) 003 [arXiv:1302.4379] [INSPIRE].

[14] C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B. Mistlberger, *Real-virtual contributions to the inclusive Higgs cross-section at N^3LO*, *JHEP* **12** (2013) 088 [arXiv:1311.1425] [INSPIRE].

[15] C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog et al., *Higgs Boson GluonFfusion Production Beyond Threshold in N^3LO QCD*, *JHEP* **03** (2015) 091 [arXiv:1411.3584] [INSPIRE].

[16] Y. Li, A. von Manteuffel, R.M. Schabinger and H.X. Zhu, *Soft-virtual corrections to Higgs production at N^3LO*, *Phys. Rev.* **D 91** (2015) 036008 [arXiv:1412.2771] [INSPIRE].

[17] C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B. Mistlberger, *Higgs Boson Gluon-Fusion Production in QCD at Three Loops*, *Phys. Rev. Lett.* **114** (2015) 212001 [arXiv:1503.06056] [INSPIRE].

[18] C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog et al., *High precision determination of the gluon fusion Higgs boson cross-section at the LHC*, *JHEP* **05** (2016) 058 [arXiv:1602.00695] [INSPIRE].

[19] R.V. Harlander and T. Neumann, *Probing the nature of the Higgs-gluon coupling*, *Phys. Rev.* **D 88** (2013) 074015 [arXiv:1308.2225] [INSPIRE].

[20] A. Banfi, A. Martin and V. Sanz, *Probing top-partners in Higgs+jets*, *JHEP* **08** (2014) 053 [arXiv:1308.4771] [InSPIRE].

[21] A. Azatov and A. Paul, *Probing Higgs couplings with high p_T Higgs production*, *JHEP* **01** (2014) 014 [arXiv:1309.5273] [InSPIRE].

[22] C. Grojean, E. Salvioni, M. Schlaffer and A. Weiler, *Very boosted Higgs in gluon fusion*, *JHEP* **05** (2014) 022 [arXiv:1312.3317] [InSPIRE].

[23] M. Schlaffer, M. Spannowsky, M. Takeuchi, A. Weiler and C. Wymant, *Boosted Higgs Shapes*, *Eur. Phys. J.* **C 74** (2014) 3120 [arXiv:1405.4295] [InSPIRE].

[24] M. Buschmann, C. Englert, D. Goncalves, T. Plehn and M. Spannowsky, *Resolving the Higgs-Gluon Coupling with Jets*, *Phys. Rev.* **D 90** (2014) 013010 [arXiv:1405.7651] [InSPIRE].

[25] S. Dawson, I.M. Lewis and M. Zeng, *Effective field theory for Higgs boson plus jet production*, *Phys. Rev.* **D 90** (2014) 093007 [arXiv:1409.6299] [InSPIRE].

[26] M. Buschmann, D. Goncalves, S. Kuttimalai, M. Schonherr, F. Krauss and T. Plehn, *Mass Effects in the Higgs-Gluon Coupling: Boosted vs Off-Shell Production*, *JHEP* **02** (2015) 038 [arXiv:1410.5806] [InSPIRE].

[27] D. Ghosh and M. Wiebusch, *Dimension-six triple gluon operator in Higgs+jet observables*, *Phys. Rev.* **D 91** (2015) 031701 [arXiv:1411.2029] [InSPIRE].

[28] S. Dawson, I.M. Lewis and M. Zeng, *Usefulness of effective field theory for boosted Higgs production*, *Phys. Rev.* **D 91** (2015) 074012 [arXiv:1501.04103] [InSPIRE].

[29] U. Langenegger, M. Spira and I. Strebel, *Testing the Higgs Boson Coupling to Gluons*, arXiv:1507.01373 [InSPIRE].

[30] A. Azatov, C. Grojean, A. Paul and E. Salvioni, *Resolving gluon fusion loops at current and future hadron colliders*, *JHEP* **09** (2016) 123 [arXiv:1608.00977] [InSPIRE].

[31] M. Grazzini, A. Ilnicka, M. Spira and M. Wiesemann, *Modeling BSM effects on the Higgs transverse-momentum spectrum in an EFT approach*, *JHEP* **03** (2017) 115 [arXiv:1612.00283] [InSPIRE].

[32] R. Boughezal, F. Caola, K. Melnikov, F. Petriello and M. Schulze, *Higgs boson production in association with a jet at next-to-next-to-leading order in perturbative QCD*, *JHEP* **06** (2013) 072 [arXiv:1302.6216] [InSPIRE].

[33] X. Chen, T. Gehrmann, E.W.N. Glover and M. Jaquier, *Precise QCD predictions for the production of Higgs + jet final states*, *Phys. Lett.* **B 740** (2015) 147 [arXiv:1408.5325] [InSPIRE].

[34] R. Boughezal, F. Caola, K. Melnikov, F. Petriello and M. Schulze, *Higgs boson production in association with a jet at next-to-next-to-leading order*, *Phys. Rev. Lett.* **115** (2015) 082003 [arXiv:1504.07922] [InSPIRE].

[35] R. Boughezal, C. Focke, W. Giele, X. Liu and F. Petriello, *Higgs boson production in association with a jet at NNLO using jettiness subtraction*, *Phys. Lett.* **B 748** (2015) 5 [arXiv:1505.03893] [InSPIRE].

[36] X. Chen, J. Cruz-Martinez, T. Gehrmann, E.W.N. Glover and M. Jaquier, *NNLO QCD corrections to Higgs boson production at large transverse momentum*, *JHEP* **10** (2016) 066 [arXiv:1607.08817] [InSPIRE].

[37] M. Grazzini and H. Sargsyan, *Heavy-quark mass effects in Higgs boson production at the LHC*, *JHEP* **09** (2013) 129 [arXiv:1306.4581] [INSPIRE].

[38] R.K. Ellis, I. Hinchliffe, M. Soldate and J.J. van der Bij, *Higgs Decay to tau+ tau-: A Possible Signature of Intermediate Mass Higgs Bosons at the SSC*, *Nucl. Phys.* **B 297** (1988) 221 [INSPIRE].

[39] R.P. Kauffman, *Higgs boson p_T in gluon fusion*, *Phys. Rev.* **D 44** (1991) 1415 [INSPIRE].

[40] S.P. Jones, M. Kerner and G. Luisoni, *Next-to-Leading-Order QCD Corrections to Higgs Boson Plus Jet Production with Full Top-Quark Mass Dependence*, *Phys. Rev. Lett.* **120** (2018) 162001 [arXiv:1802.00349] [INSPIRE].

[41] J.M. Lindert, K. Kudashkin, K. Melnikov and C. Wever, *Higgs bosons with large transverse momentum at the LHC*, *Phys. Lett.* **B 782** (2018) 210 [arXiv:1801.08226] [INSPIRE].

[42] T. Neumann, *NLO Higgs+jet at Large Transverse Momenta Including Top Quark Mass Effects*, *J. Phys. Comm.* **2** (2018) 095017 [arXiv:1802.02981] [INSPIRE].

[43] K. Kudashkin, K. Melnikov and C. Wever, *Two-loop amplitudes for processes $gg \to Hg, qg \to Hq$ and $q\bar{q} \to Hg$ at large Higgs transverse momentum*, *JHEP* **02** (2018) 135 [arXiv:1712.06549] [INSPIRE].

[44] J.M. Lindert, K. Melnikov, L. Tancredi and C. Wever, *Top-bottom interference effects in Higgs plus jet production at the LHC*, *Phys. Rev. Lett.* **118** (2017) 252002 [arXiv:1703.03886] [INSPIRE].

[45] F. Caola, J.M. Lindert, K. Melnikov, P.F. Monni, L. Tancredi and C. Wever, *Bottom-quark effects in Higgs production at intermediate transverse momentum*, *JHEP* **09** (2018) 035 [arXiv:1804.07632] [INSPIRE].

[46] K. Melnikov, L. Tancredi and C. Wever, *Two-loop $gg \to Hg$ amplitude mediated by a nearly massless quark*, *JHEP* **11** (2016) 104 [arXiv:1610.03747] [INSPIRE].

[47] K. Melnikov, L. Tancredi and C. Wever, *Two-loop amplitudes for $qg \to Hq$ and $q\bar{q} \to Hg$ mediated by a nearly massless quark*, *Phys. Rev.* **D 95** (2017) 054012 [arXiv:1702.00426] [INSPIRE].

[48] R. Bonciani, V. Del Duca, H. Frellesvig, J.M. Henn, F. Moriello and V.A. Smirnov, *Two-loop planar master integrals for Higgs$\to$ 3 partons with full heavy-quark mass dependence*, *JHEP* **12** (2016) 096 [arXiv:1609.06685] [INSPIRE].

[49] U. Aglietti, R. Bonciani, G. Degrassi and A. Vicini, *Two loop light fermion contribution to Higgs production and decays*, *Phys. Lett.* **B 595** (2004) 432 [hep-ph/0404071] [INSPIRE].

[50] U. Aglietti, R. Bonciani, G. Degrassi and A. Vicini, *Master integrals for the two-loop light fermion contributions to $gg \to H$ and $H \to \gamma\gamma$*, *Phys. Lett.* **B 600** (2004) 57 [hep-ph/0407162] [INSPIRE].

[51] G. Degrassi and F. Maltoni, *Two-loop electroweak corrections to Higgs production at hadron colliders*, *Phys. Lett.* **B 600** (2004) 255 [hep-ph/0407249] [INSPIRE].

[52] G. Degrassi and F. Maltoni, *Two-loop electroweak corrections to the Higgs-boson decay $H \to \gamma\gamma$*, *Nucl. Phys.* **B 724** (2005) 183 [hep-ph/0504137] [INSPIRE].

[53] S. Actis, G. Passarino, C. Sturm and S. Uccirati, *NLO Electroweak Corrections to Higgs Boson Production at Hadron Colliders*, *Phys. Lett.* **B 670** (2008) 12 [arXiv:0809.1301] [INSPIRE].

[54] 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 [arXiv:1610.05497] [INSPIRE].

[55] M. Bonetti, K. Melnikov and L. Tancredi, *Three-loop mixed QCD-electroweak corrections to Higgs boson gluon fusion*, *Phys. Rev.* **D 97** (2018) 034004 [arXiv:1711.11113] [INSPIRE].

[56] C. Anastasiou, R. Boughezal and F. Petriello, *Mixed QCD-electroweak corrections to Higgs boson production in gluon fusion*, *JHEP* **04** (2009) 003 [arXiv:0811.3458] [INSPIRE].

[57] M. Bonetti, K. Melnikov and L. Tancredi, *Higher order corrections to mixed QCD-EW contributions to Higgs boson production in gluon fusion*, *Phys. Rev.* **D 97** (2018) 056017 [*Erratum ibid.* **D 97** (2018) 099906] [arXiv:1801.10403] [INSPIRE].

[58] A.V. Smirnov, *FIRE5: a C++ implementation of Feynman Integral REduction*, *Comput. Phys. Commun.* **189** (2015) 182 [arXiv:1408.2372] [INSPIRE].

[59] R.N. Lee, *LiteRed 1.4: a powerful tool for reduction of multiloop integrals*, *J. Phys. Conf. Ser.* **523** (2014) 012059 [arXiv:1310.1145] [INSPIRE].

[60] C. Anastasiou and A. Lazopoulos, *Automatic integral reduction for higher order perturbative calculations*, *JHEP* **07** (2004) 046 [hep-ph/0404258] [INSPIRE].

[61] A. von Manteuffel and C. Studerus, *Reduze 2 - Distributed Feynman Integral Reduction*, arXiv:1201.4330 [INSPIRE].

[62] P. Maierhöfer, J. Usovitsch and P. Uwer, *Kira — A Feynman integral reduction program*, *Comput. Phys. Commun.* **230** (2018) 99 [arXiv:1705.05610] [INSPIRE].

[63] K.G. Chetyrkin and F.V. Tkachov, *Integration by Parts: The Algorithm to Calculate β-functions in 4 Loops*, *Nucl. Phys.* **B 192** (1981) 159 [INSPIRE].

[64] F.V. Tkachov, *A Theorem on Analytical Calculability of Four Loop Renormalization Group Functions*, *Phys. Lett.* **100B** (1981) 65 [INSPIRE].

[65] S. Laporta, *High precision calculation of multiloop Feynman integrals by difference equations*, *Int. J. Mod. Phys.* **A 15** (2000) 5087 [hep-ph/0102033] [INSPIRE].

[66] T. Gehrmann and E. Remiddi, *Differential equations for two loop four point functions*, *Nucl. Phys.* **B 580** (2000) 485 [hep-ph/9912329] [INSPIRE].

[67] A.V. Kotikov, *Differential equations method: New technique for massive Feynman diagrams calculation*, *Phys. Lett.* **B 254** (1991) 158 [INSPIRE].

[68] E. Remiddi, *Differential equations for Feynman graph amplitudes*, *Nuovo Cim.* **A 110** (1997) 1435 [hep-th/9711188] [INSPIRE].

[69] T. Gehrmann and E. Remiddi, *Analytic continuation of massless two loop four point functions*, *Nucl. Phys.* **B 640** (2002) 379 [hep-ph/0207020] [INSPIRE].

[70] M. Argeri and P. Mastrolia, *Feynman Diagrams and Differential Equations*, *Int. J. Mod. Phys.* **A 22** (2007) 4375 [arXiv:0707.4037] [INSPIRE].

[71] J.M. Henn, *Lectures on differential equations for Feynman integrals*, *J. Phys.* **A 48** (2015) 153001 [arXiv:1412.2296] [INSPIRE].

[72] J.M. Henn, *Multiloop integrals in dimensional regularization made simple*, *Phys. Rev. Lett.* **110** (2013) 251601 [arXiv:1304.1806] [INSPIRE].

[73] M. Argeri, S. Di Vita, P. Mastrolia, E. Mirabella, J. Schlenk, U. Schubert et al., *Magnus and Dyson Series for Master Integrals*, *JHEP* **03** (2014) 082 [arXiv:1401.2979] [INSPIRE].

[74] R.N. Lee, *Reducing differential equations for multiloop master integrals*, *JHEP* **04** (2015) 108 [arXiv:1411.0911] [INSPIRE].

[75] A. Georgoudis, K.J. Larsen and Y. Zhang, *Azurite: An algebraic geometry based package for finding bases of loop integrals*, *Comput. Phys. Commun.* **221** (2017) 203 [arXiv:1612.04252] [INSPIRE].

[76] T. Gehrmann, A. von Manteuffel, L. Tancredi and E. Weihs, *The two-loop master integrals for $q\bar{q} \to VV$*, *JHEP* **06** (2014) 032 [arXiv:1404.4853] [INSPIRE].

[77] M. Becchetti and R. Bonciani, *Two-Loop Master Integrals for the Planar QCD Massive Corrections to Di-photon and Di-jet Hadro-production*, *JHEP* **01** (2018) 048 [arXiv:1712.02537] [INSPIRE].

[78] K.-T. Chen, *Iterated path integrals*, *Bull. Am. Math. Soc.* **83** (1977) 831.

[79] A. Goncharov, *Polylogarithms in arithmetic and geometry*, *Proceedings of the International Congress of Mathematicians* **1,2** (1995) 374.

[80] A.B. Goncharov, *Multiple polylogarithms and mixed Tate motives*, math/0103059 [INSPIRE].

[81] E. Remiddi and J.A.M. Vermaseren, *Harmonic polylogarithms*, *Int. J. Mod. Phys.* **A 15** (2000) 725 [hep-ph/9905237] [INSPIRE].

[82] C.W. Bauer, A. Frink and R. Kreckel, *Introduction to the GiNaC framework for symbolic computation within the C++ programming language*, *J. Symb. Comput.* **33** (2000) 1 [cs/0004015].

[83] J. Vollinga and S. Weinzierl, *Numerical evaluation of multiple polylogarithms*, *Comput. Phys. Commun.* **167** (2005) 177 [hep-ph/0410259] [INSPIRE].

[84] A.V. Smirnov, *FIESTA4: Optimized Feynman integral calculations with GPU support*, *Comput. Phys. Commun.* **204** (2016) 189 [arXiv:1511.03614] [INSPIRE].

[85] U. Aglietti and R. Bonciani, *Master integrals with one massive propagator for the two loop electroweak form-factor*, *Nucl. Phys.* **B 668** (2003) 3 [hep-ph/0304028] [INSPIRE].

[86] U. Aglietti and R. Bonciani, *Master integrals with 2 and 3 massive propagators for the 2 loop electroweak form-factor — planar case*, *Nucl. Phys.* **B 698** (2004) 277 [hep-ph/0401193] [INSPIRE].

[87] A.B. Goncharov, *Multiple polylogarithms and mixed Tate motives*, math/0103059 [INSPIRE].

[88] A.B. Goncharov, M. Spradlin, C. Vergu and A. Volovich, *Classical Polylogarithms for Amplitudes and Wilson Loops*, *Phys. Rev. Lett.* **105** (2010) 151605 [arXiv:1006.5703] [INSPIRE].

[89] C. Duhr, H. Gangl and J.R. Rhodes, *From polygons and symbols to polylogarithmic functions*, *JHEP* **10** (2012) 075 [arXiv:1110.0458] [INSPIRE].