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Top-Yukawa effects on the $\beta$-function of the strong coupling in the SM at four-loop level

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ABSTRACT: We present analytical results for the QCD $\beta$-function extended to the gaugeless limit of the unbroken phase of the Standard Model at four-loop level. Apart from the strong coupling itself we include the top-Yukawa contribution and the Higgs self-coupling. We observe a numerically small non-naive $\gamma_5$ contribution at order $y_t^4 g_s^4$, a feature not encountered in lower loop orders. We discuss the treatment of $\gamma_5$ which is more involved than in previous calculations at three-loop level.

KEYWORDS: Renormalization Group, Standard Model, QCD
1 Introduction

An important feature of the perturbative treatment of any quantum field theory is the evolution of couplings, fields and masses with the renormalization scale \( \mu \), which is usually set to a characteristic energy scale of the physical process under consideration. This evolution is described by the Renormalization Group (RG) functions, i.e. \( \beta \)-functions for the couplings and anomalous dimensions for fields and masses.

The \( \beta \)-function for any coupling \( X \) is defined as

\[
\beta_X (X, X_1, X_2, \ldots) = \mu^2 \frac{dX}{d\mu^2} = \sum_{n=1}^{\infty} \frac{1}{(16\pi^2)^n} \beta_X^{(n)}. \tag{1.1}
\]

It is a power series in all couplings \( X, X_1, X_2, \ldots \) of the theory and independent of all gauge parameters \( \xi \).

Recently the RG functions of the Standard Model (SM) were computed at three-loop accuracy. In the \( \overline{\text{MS}} \) scheme \( \beta \)-functions do not depend on masses [1], hence they can be computed in the unbroken phase of the SM. For the gauge couplings \( g_s, g_2 \) and \( g_1 \) of the SU\(_c\)(3), SU\(_L\)(2) and U\(_Y\)(1) subgroups of the SM the results were first published in [2, 3] and independently confirmed in [4]. For the top-Yukawa coupling \( y_t \), which is the numerically largest Yukawa coupling by far, and the parameters of the Higgs potential \( \lambda \) and \( m^2 \) the \( \beta \)-functions were first computed in the gaugeless limit, i.e. \( g_2, g_1 \to 0 \), along with the anomalous dimensions of the fields involved [5]. Later \( \beta_{\lambda} \) and \( \beta_{m^2} \) were extended to the full SM [6], confirmed by [7, 8], as well as \( \beta_{y_t} \) [9], where the \( \beta \)-functions for the smaller Yukawa couplings were also added. The one- and two-loop \( \beta \)-functions for the gauge couplings [10–21], Yukawa couplings [18, 20, 22, 23] and Higgs potential parameters [18, 20, 21, 24] have been known for a long time as well as partial three-loop results [25–31].
At four-loop level only the QCD β-function, i.e. \( \beta_{g_s}(g_s) \) or equivalently \( \beta_{\alpha_s}(\alpha_s) = \frac{2\alpha_s}{g_s^2} \beta_{g_s} \) with \( \alpha_s = \frac{g^2}{4\pi} \) is known \([32, 33]\).

Especially the evolution of the quartic Higgs self-coupling has received a lot of interest because of its close connection to the question of vacuum stability in the Standard Model. It has been shown that the stability of the SM vacuum up to some large energy scale \( \Lambda \sim M_{\text{Planck}} \) is approximately equivalent to the requirement that the running coupling \( \lambda(\mu) > 0 \) for \( \mu \leq \Lambda \) \([34–36]\). The function \( \beta_{\lambda} \) describing this evolution depends on all SM couplings an especially the large couplings \( y_t \) and \( g_s \) have a strong influence. As the evolution of all couplings is interdependent a precision calculation for the evolution of all - at least of the five largest \( (g_s, y_t, g_2, g_1 \text{ and } \lambda) \) - is well motivated. Many analyses of this question have been performed \([5, 37–49]\) during the last years.

In this paper we extend the QCD β-function to the gaugeless limit of the SM, i.e. we include the dependence on the top-Yukawa coupling \( y_t \) and the quartic Higgs self-coupling \( \lambda \). This can be seen as a first step to all three gauge coupling β-functions in the full SM. To start with the gaugeless limit seems reasonable, first because at the energy-scales of our experiments \( y_t \) is the second largest coupling in the SM after \( g_s \), followed by \( g_2, g_1 \) and \( \lambda \). In order to renormalize fermion loops with four scalar legs we should also add counterterm \( \propto \Phi^4 \) to the Lagrangian of our simplified model. This is exactly a contribution to the renormalization of \( \lambda \) which makes it natural to include \( \lambda \) as well.

Secondly, the gaugeless limit of the SM provides an excellent opportunity to study the proper treatment of \( \gamma_5 \), which is introduced in the Yukawa-part of the Lagrangian. This matrix is not well-defined in \( D = 4 - 2\varepsilon \) dimensions and hence constitutes a non-trivial challenge.

The paper is structured as follows: In the following section the technical details, especially the treatment of \( \gamma_5 \), as well as the automation of the calculation are discussed. Then the results are given and the relevance of the four-loop terms numerically determined at the scale of the top quark mass.

**Note:** During the finishing process of this paper a similar calculation was published by another group \([50]\). Their calculation was not performed with massive tadpole integrals but rather with massless propagator-like integrals and in the Background field gauge. Both results achieved with different methods agree if the same prescription for the treatment of \( \gamma_5 \) is used (see section 2.3).

## 2 Details of the calculation

### 2.1 Gaugeless limit of the SM

The Lagrangian of the SM in the unbroken phase can be decomposed into

\[
\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{SU(3)×SU(2)×U(1)}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\Phi},
\]  

(2.1)
where $\mathcal{L}_{SU(3) \times SU(2) \times U(1)}$ contains the kinetic terms of the fermions and gauge bosons, their interactions and the necessary gauge fixing and ghost terms. The Yukawa part $\mathcal{L}_{\text{Yukawa}}$ describes the coupling of the fermions to a scalar SU(2) doublet $\Phi = \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$ which results in fermion masses and the coupling of fermions to the Higgs boson after Spontaneous Symmetry Breaking as well as the mixing of the quark generations. The scalar part $\mathcal{L}_\Phi$ contains the kinetic term for the scalar field $\Phi$, its potential and its coupling to the electroweak gauge bosons through the covariant derivative. In the gaugeless limit we neglect two smaller gauge couplings $g_2$ and $g_1$ (electroweak sector). We also approximate the small Yukawa couplings, i.e. all but the top-Yukawa coupling $y_t$, by zero and arrive at a simplified model which includes QCD and top-Yukawa effects as well as the scalar potential:

$$\mathcal{L} = \mathcal{L}_{\text{QCD}} + \mathcal{L}_{y_t} + \mathcal{L}_\Phi$$

(2.2)

with

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} g_{\mu\nu} G_{\mu\nu}^a + \frac{1}{2(1 - \xi)} (\partial_{\mu} A_{\nu}^a)^2 + \partial_{\mu} c^a \partial^\mu c^a + g_s f^{abc} \partial_{\mu} c^a A_\mu^b c^c$$

$$+ \sum_q \left\{ \frac{i}{2} \bar{q} \gamma^\mu q + g_s \bar{q} A_\mu^a T^a q \right\},$$

(2.3)

$$\mathcal{L}_{y_t} = -y_t \left\{ (\bar{t} P_{\nu} t) \Phi_2^2 + (\bar{t} P_{\nu} t) \Phi_2 - (\bar{b} P_{\nu} t) \Phi_1^2 - (\bar{P}_{\nu} b) \Phi_1 \right\},$$

(2.4)

$$\mathcal{L}_\Phi = \partial_{\mu} \Phi^d \partial^\mu \Phi - m^2 \Phi^d \Phi - \lambda \left( \Phi^d \Phi \right)^2.$$  

(2.5)

Here $q$ runs over all quark flavours, the gluon field strength tensor is given by

$$C_{\mu\nu}^a = \partial_{\mu} A_{\nu}^a - \partial_{\nu} A_{\mu}^a + g_s f^{abc} A_{\mu}^b A_{\nu}^c$$

(2.6)

and $f^{abc}$ are the structure constants of the colour gauge group with the generators $T^a$ which satisfy

$$[T^a, T^b] = i f^{abc} T^c.$$  

(2.7)

The Yukawa sector mixes left-handed (L) and right-handed (R) Weyl spinors which can be projected out from Dirac spinors used in our Feynman rules by the application of the projectors

$$P_L = \frac{1}{2} (1 - \gamma_5) \quad P_R = \frac{1}{2} (1 + \gamma_5).$$

(2.8)

The left- and right-handed parts of the quark fields and vertices participating in the Yukawa interaction are renormalized differently.

The Lagrangian (2.2) is renormalized with the counterterms

$$\delta \mathcal{L}_{\text{QCD}} = -\frac{1}{4} \delta Z_3^{(2g)} (\partial_{\mu} A_{\nu}^a - \partial_{\nu} A_{\mu}^a)^2 - \frac{1}{2} \delta Z_1^{(3g)} g_s f^{abc} (\partial_{\mu} A_{\nu}^a - \partial_{\nu} A_{\mu}^a) A_\mu^b A_\nu^c$$

$$- \frac{1}{4} \delta Z_1^{(4g)} \left\{ \left( f^{abc} A_{\mu}^b A_\mu^c \right)^2 + \delta Z_3^{(2g)} g_s \partial_{\mu} c^a \partial^\mu c^a + \delta Z_1^{(cgg)} g_s f^{abc} \partial_{\mu} c^a A_{\mu}^b c^c \right\}$$

$$+ \sum_q \left\{ \frac{i}{2} \bar{q} \gamma^\mu q \left[ \delta Z_{2,\mu}^{(2g)} P_L + \delta Z_{2,R}^{(2g)} P_R \right] q + g_s \bar{q} A_\mu^a T^a \left[ \delta Z_{1,L}^{(qgg)} P_L + \delta Z_{1,R}^{(qgg)} P_R \right] q \right\},$$

(2.9)
\[ \delta L_{\text{Yukawa}} = -\delta Z_1^{(4\Phi)} y_t \left\{ (\bar{t} P_R t) \Phi_2^2 + (\bar{t} P_L t) \Phi_2 - (\bar{b} P_R t) \Phi_1^* - (\bar{t} P_L b) \Phi_1 \right\}, \]
\[ \delta L_\Phi = \delta Z_2^{(2\Phi)} \partial_\mu \Phi^\dagger \partial^\mu \Phi - m^2 \delta Z_4 \Phi^4 + \delta Z_1^{(4\Phi)} (\Phi^\dagger \Phi)^2. \]

All these renormalization constants were computed at three-loop level in the course of the calculations in [5]. The simplest way to derive the renormalization constant for the strong gauge coupling \( g_s \) is via
\[ Z_{g_s} = \frac{Z_1^{(ccg)}}{Z_3^{(2c)} \sqrt{Z_3^{(2g)}}}. \]
where we use the renormalization constants \( Z = 1 + \delta Z \) in the \( \overline{\text{MS}} \)-scheme. All divergent integrals are regularized in \( D = 4 - 2\varepsilon \) space time dimensions.

2.2 Automation and calculation with massive tadpoles

The calculation begins with the generation of all necessary 1PI Feynman diagrams with two external ghost or gluon legs for \( Z_3^{(2c)} \) or \( Z_3^{(2g)} \) and with two external ghost and one external gluon leg for \( Z_1^{(ccg)} \). This was done with the program QGRAF [51].

The C++ programs Q2E and EXP [52, 53] are then used to identify the topology of the diagram. Later we will Taylor expand in the external momenta and use projectors on the integrals in order to make them scalar. For example the ghost-gluon vertex corrections are proportional to the outgoing ghost momentum \( q^\mu \), where \( \mu \) is the Lorentz index of the gluon leg. Hence we expand to first order in \( q \), use the projector \( \frac{q^\mu q^\mu}{q^2} \) on the integral and set \( q \to 0 \) after that. This is allowed as \( \overline{\text{MS}} \) renormalization constants do not depend on external momenta. After having set all external momenta to zero we are left with tadpole integrals. The fermion traces, the expansion in the external momenta and the insertion of counterterms in one-loop, two-loop and three-loop diagrams was performed using FORM [54, 55]. The colour factors were computed with the FORM package COLOR [56]. The tadpole integrals up to three-loop order were computed with the FORM-based package MATAD[57].

At four-loop level there are two independent tadpole topologies, see Fig. 1. All scalar products \( p_i \cdot p_j (i, j = 1, \ldots, 10) \) can be written as linear combinations of the \( p_i^2 \) which can be expressed in terms of the scalar propagators \( D_i = \frac{1}{M^2 - p_i^2} \) and the auxiliary Mass \( M^2 \) (see below). Hence all four-loop integrals can be written in terms of functions
\[ \text{TAD}_{4l}(n_1, \ldots, n_{10}) := \int d^D p_1 \int d^D p_2 \int d^D p_3 \int d^D p_4 \prod_{i=1}^{10} D_i^{n_i}. \]

The integrals (2.13) can be reduced to Master Integrals (MI) using FIRE [59]. For the huge number of integrals in such a calculation the C++ version of FIRE 5 [60] is necessary. All MI needed for this computation can be found in [33]. The program FIESTA 3 [61] was

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1 All Feynman diagrams in this paper have been drawn with the Latex package Axodraw [58].
Figure 1: Four-loop tadpole topologies: $p_1, p_2, p_3, p_4$ are independent loop momenta, the others are linear combinations $p_5 = p_1 - p_1, p_6 = p_2 - p_1, p_7 = p_3 - p_2, p_8 = p_3 - p_4, p_9 = p_4 - p_2$ and $p_{10} = p_4 + p_2 - p_1 - p_3$.

used to numerically cross check these MI and some unreduced integrals as a check for our setup.

In order to compute the divergent part of the needed self-energies and vertex corrections we use the same method as in our previous calculations [5, 6]. This method was suggested in [62] and further developed in [63]. A step-by-step explanation of this method can be found in [46]. An auxiliary mass parameter $M^2$ is introduced in every propagator denominator. A naive Taylor expansion in the external momenta is performed before applying the projector to scalar integrals. After that all external momenta are set to zero which leaves us with scalar tadpole integrals. Subdivergences $\propto M^2$ are canceled by counterterms

$$\frac{M^2}{2} \delta Z^{(2g)}_{m^2} A^a_\mu A^a_\mu$$

$$\frac{M^2}{2} \delta Z^{(2\Phi)}_{m^2} \phi^4 \Phi.$$

which are computed order by order in perturbation theory and inserted in lower loop diagrams. Note that this method is only valid for computing UV divergent parts of Feynman diagrams, and hence Z-factors, not finite amplitudes.

2.3 Treatment of $\gamma_5$

The most important issue of this calculation is the proper treatment of $\gamma_5$ in dimensional regularization. In $D = 4$ dimensions it can be defined as

$$\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \frac{i}{4!} \varepsilon_{\mu\nu\rho\sigma} \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma$$

with $\varepsilon_{0123} = 1 = -\varepsilon^{0123}$. 

(2.15)

In most diagrams a naive treatment of $\gamma_5$ is sufficient, i.e. we use $\{\gamma_5, \gamma^\mu\} = 0$ and $\gamma_5^2 = 1$, valid in $D = 4$ dimensions, until only one or no $\gamma_5$ matrix remain on each fermion line, then discard diagrams with at least one $\gamma_5$. This is valid for fermion lines with less than four Lorentz indices and momenta flowing into the fermion line. Fig. 2 shows the schematic cases of $\gamma_5$ appearing on internal and external fermion lines. We start with the case of internal
As we set all momenta external to the whole Feynman diagram to zero for the computation of the UV divergent part of the diagram external momenta to a fermion line \((k_1, k_2, \ldots)\) are loop momenta from other loops. Taking the trace over the closed fermion loop in \(D = 4\) dimensions yields a result with terms proportional to \(\varepsilon_{\mu_1 \mu_2 \mu_3 \mu_4} k_1^\mu k_2^\beta\) and so on. In order for the \(\varepsilon\)-tensors not to vanish at least 4 free Lorentz structures are needed. Else the diagram is set to zero.

If we have only one internal fermion line with one \(\gamma_5\) on it and the final result is known to be scalar (not pseudoscalar), as are the counterterms we want to compute here, we can discard these terms as well. The only possibility for a non-naive contribution to the final result can appear in the case of two (or more) fermion lines. Here the two \(\varepsilon\)-tensors can be contracted and expressed in terms of the metric tensor

\[
\varepsilon^{\mu_1 \mu_2 \mu_3 \mu_4} \varepsilon_{\nu_1 \nu_2 \nu_3 \nu_4} = -\sum_{\pi} \text{sgn}(\pi) g^{\mu_{\pi(1)} \nu_1} g^{\mu_{\pi(2)} \nu_2} g^{\mu_{\pi(3)} \nu_3} g^{\mu_{\pi(4)} \nu_4},
\]

where the sum is taken over all permutations \(\pi\) of \((1,2,3,4)\) and

\[
\text{sgn}(\pi) = \begin{cases} +1 & \text{for } \pi \text{ even} \\ -1 & \text{for } \pi \text{ odd} \end{cases}
\]

The lhs of (2.16) is composed of intrinsically four-dimensional objects whereas the rhs can be used in \(D = 4 - 2\varepsilon\) dimensions, introducing an uncertainty of \(\mathcal{O}(\varepsilon)\). However, if the integrals appearing in the calculation of the Feynman diagram in question have only \(\frac{1}{\varepsilon}\) poles the divergent part, which we are interested in here, is unaffected.

For completeness we want to make a short remark about external fermion lines, such as the one shown in Fig. 2 (b), as well. Here we can anticommute the \(\gamma_5\) to the end of the fermion line and hence outside of all loops. But if we use a projector on the external fermion line in order to make the integral scalar and this involves taking a trace over the fermion line we have to treat it the same way as the internal ones. In the case of the three-loop \(\beta\)-function for the Yukawa couplings a non-naive \(\gamma_5\) effect from the contraction of the \(\varepsilon\)-tensors from an internal and an external fermion line was observed [5].
In the calculations needed for the renormalization constants in (2.12) only one type of diagram features two fermion lines with four external Lorentz indices or loop-momenta to them, namely in the gluon propagator, when each external leg is attached to a different fermion loop and the two fermion loops are connected by a gluon and two Φ-lines. A planar example is shown in Fig. 3.

There are 72 diagrams contributing to the non-naive part of the gluon propagator, which (like Fig. 3) are all obtained by connecting two fermion loops with an external gluon leg each by means of one gluon propagator and two scalar propagators in all possible ways. Using \( \{ \gamma_5, \gamma^\mu \} = 0 \) we move all \( \gamma_5 \) matrices on each fermion line to the same reading point, for which we choose the external vertex. We checked that the same result is obtained if we choose to place \( \gamma_5 \) to the left or to the right of the external \( \gamma^{\mu_{1,2}} \). We can also use the Larin prescription \([64]\)

\[
\gamma^\mu \gamma_5 = \frac{i}{3!} \varepsilon^{\mu\rho_1\rho_2\rho_3} \gamma_{\rho_1} \gamma_{\rho_2} \gamma_{\rho_3},
\]

which combines the two possibilities, with the same result. It is only important that the reading point is the same for all 72 diagrams. Due to \( \gamma_5^2 = 1 \) we are left with one or no \( \gamma_5 \) on each fermion line. If there is only one \( \gamma_5 \) on one fermion line the contribution is zero. Terms with no \( \gamma_5 \) contribute to the naive part of the gluon propagator. The remaining contribution from one \( \gamma_5 \) on each fermion line is what we call the non-naive contribution. The \( \gamma_5 \) prescription using the same external vertex in all diagrams was described in \([65]\) as a practical and consistent \( \gamma_5 \) scheme.

We checked explicitly that only \( \varepsilon \) poles appear in the results for these diagrams. In fact, as an additional precaution we checked that at \( \mathcal{O}(\varepsilon) \) completely antisymmetric and completely symmetric structures composed of the metric and the eight indices appearing in the \( \varepsilon \) tensors do not give contributions to the divergent part. This was implemented as

\[
\varepsilon^\mu_1\nu_1\mu_2\nu_2\mu_3\nu_3\mu_4 = - \sum_\pi \text{sgn}(\pi) g_{\nu_1\nu_1}^\mu_1 g_{\nu_2\nu_2}^\mu_2 g_{\nu_3\nu_3}^\mu_3 g_{\nu_4\nu_4}^\mu_4 (1 + \varepsilon \cdot C^\text{as}) \\
+ \varepsilon \cdot C^\text{as} \sum_\pi g_{\nu_1\nu_1}^\mu_1 g_{\nu_2\nu_2}^\mu_2 g_{\nu_3\nu_3}^\mu_3 g_{\nu_4\nu_4}^\mu_4,
\]

(2.19)
where the labels $C_{as,s}$ parametrize the uncertainty introduced through (2.16) being applied in $D = 4 - 2\varepsilon$. As they drop out in the divergent term of our final result we are convinced that $\gamma_5$ can be treated in this way.

However, in contrast to the Yukawa coupling $\beta$-functions at three-loop level, we find here that the result is different if we do not choose the same reading point for $\gamma_5$ before taking the trace.

For instance, if we leave each $\gamma_5$ matrix at the point on the fermion line where it was introduced by the Feynman rules, i.e. we do not use $\{\gamma_5, \gamma^\mu\} = 0$ at all in terms with one $\gamma_5$ on each fermion line, the result for these terms is a factor 3 larger. This procedure is the opposite of moving all $\gamma_5$ to a common reading point, but note that we still use $\{\gamma_5, \gamma^\mu\} = 0$ and $\gamma_5^2 = 1$ in terms with two $\gamma_5$ on one fermion line. This shows, however, that anticommuting $\gamma_5$ along the fermion lines arbitrarily in each diagram spoils the result even though only $\frac{1}{\varepsilon}$ poles are visible in the final result. This becomes clear when we use $D = 4 - 2\tilde{\varepsilon}$ when evaluating the fermion traces and $D = 4 - 2\varepsilon$ in the integral reduction and the master integrals. Then we see terms $\propto \tilde{\varepsilon}^2$ independent of the labels $C_{as,s}$. This means that the ambiguity is introduced by anticommuting the $\gamma_5$ to different points in different terms. At present this issue is not fully understood. The approach described above using the external reading point seems intuitive. The result is also stable for choices of the reading point to the left or right of the external vertex. We check that the numerical impact of the non-naive terms is small. In fact, even a non-naive contribution of a factor 3 larger would be numerically small compared to the naive contribution.

Naturally, we checked that this treatment of $\gamma_5$ respects the Ward identity manifest in the transversal structure of the gluon self-energy.

### 3 Results

In this section we give the results for the four-loop $\beta$-function of the strong coupling $g_s$ in the gaugeless limit of the SM. For a generic $SU(N_c)$ gauge group the colour factors are expressed through the quadratic Casimir operators $C_F$ and $C_A$ of the fundamental and the adjoint representation of the corresponding Lie algebra. The dimension of the fundamental representation is called $N_c$. The adjoint representation has dimension $n_g$ and the trace $T_F$ defined by $T_F \delta^{ab} = \text{Tr} \left(T^a T^b\right)$ with the group generators $T^a$ of the fundamental representation. In addition we need a few higher order invariants constructed from the symmetric tensors

$$d_F^{abcd} = \frac{1}{6} \text{Tr} \left(T^a T^b T^c T^d + T^a T^b T^d T^c + T^a T^c T^b T^d + T^a T^d T^b T^c + T^a T^d T^c T^b\right),$$

from the generators of the fundamental representation and analogously $d_A^{abcd}$ constructed from the generators of the adjoint representation. The combinations needed and their

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\[\text{In the previous version of this paper a factor 6 was given due to a bug in this particular calculation. Thanks to the authors of [50] for pointing out the discrepancy with their calculation of the same quantity.}\]
SU($N_c$) values are

\[
\frac{d_F^{abcd} d_F^{abcd}}{n_g} = \frac{N_c^4 - 6N_c^2 + 18}{96N_c^2}, \quad \frac{d_F^{abcd} d_A^{abcd}}{n_g} = \frac{N_c(N_c^2 + 6)}{48},
\]

(3.2)

Furthermore for SU($N_c$) we have

\[
T_F = \frac{1}{2}, \quad C_F = \frac{N_c^2 - 1}{2N_c}, \quad C_A = N_c, \quad n_g = N_c^2 - 1.
\]

(3.3)

The number of active fermion flavours is denoted by $n_f$ (=6 in the SM).

\[
\frac{\beta^{(4)}_{\alpha}}{g_s} = g_s \left( \frac{40}{9} \frac{d_A^{abcd} d_A^{abcd}}{n_g} - \frac{150653}{972} C_A^4 - \frac{256}{9} \frac{d_F^{abcd} d_A^{abcd}}{n_g} - 23n_f T_F C_F^3 \right.
\]

\[+ \frac{2102}{27} n_f C_A T_F C_F^2 - \frac{7073}{486} n_f C_A^2 T_F C_F + \frac{39143}{162} n_f C_A^3 T_F + \frac{352}{9} n_f T_F C_F^4 \]

\[+ \frac{676}{27} n_f^2 T_F^2 C_F - \frac{8576}{243} n_f C_A T_F^2 C_F - \frac{3965}{81} n_f^2 C_A^2 T_F^2 - \frac{616}{243} n_f^3 T_F^2 C_F \]

\[+ \frac{212}{243} n_f^3 C_A T_F^3 - \frac{352}{3} \zeta_3 \frac{d_A^{abcd} d_A^{abcd}}{n_g} + \frac{22}{9} \zeta_3 C_A^4 + \frac{832}{3} \zeta_3 n_f T_F C_F^3 \]

\[\left. + \frac{176}{9} \zeta_3 n_f C_A T_F C_F^2 + \frac{328}{9} \zeta_3 n_f C_A^2 T_F C_F - \frac{68}{3} \zeta_3 n_f C_A^3 T_F - \frac{256}{3} \zeta_3 n_f^2 T_F C_F^4 \right)
\]

(3.4)

This is in agreement with [50] if the same $\gamma_5$ prescription is used. The term $\propto g_s^4 y_t^4 T_F^2$ is the only one affected by non-naive $\gamma_5$ contributions as explained above. The naive and non-naive (i. e. stemming from the contraction of two $\varepsilon$-tensors) contributions are

\[
g_s^4 y_t^4 T_F^2 \left( \frac{80}{3} - 32\zeta_3 \right) = g_s^4 y_t^4 T_F^2 \left( \frac{24}{(\text{naive})} + \frac{8}{(\text{non-naive})} - \frac{48\zeta_3}{(\text{naive})} + \frac{16\zeta_3}{(\text{non-naive})} \right).
\]

(3.5)
The lower loop results are

\[
\frac{\beta^{(3)}_{\alpha_s}}{g_s} = g_s^6 \left( -\frac{2857}{108} C_A^3 - n_f T_F C_F^2 + \frac{205}{18} n_f C_A T_F C_F \\
+ \frac{1415}{54} n_f C_A^2 T_F - \frac{22}{9} n_f^2 T_F^2 C_F - \frac{79}{27} n_f^2 C_A T_F^2 \right) \\
- g_s^4 y_t^2 \left( 3 T_F C_F + 12 C_A T_F \right) + g_s^2 y_t^4 \left( \frac{9}{2} T_F + \frac{7}{2} T_F N_c \right),
\]

(3.6)

\[
\frac{\beta^{(2)}_{\alpha_s}}{g_s} = g_s^4 \left( -\frac{17}{3} C_A^2 + 2 n_f T_F C_F + \frac{10}{3} n_f C_A T_F \right) - 2 g_s^2 y_t^2,
\]

(3.7)

\[
\frac{\beta^{(1)}_{\alpha_s}}{g_s} = g_s^2 \left( -\frac{11}{6} C_A + \frac{2}{3} n_f T_F \right).
\]

(3.8)

in agreement with [5]. The pure QCD part of (3.4) agrees with [32, 33].

For convenience we also give the \( \beta \)-function for \( \alpha_s \). We absorb the loop factor \( \frac{1}{16 \pi^2} \) into

\[
a_s = \frac{g_s^2}{(4\pi)^2} = \frac{\alpha_s}{4\pi}, \quad a_t = \frac{y_t^2}{(4\pi)^2}, \quad a_\lambda = \frac{\lambda}{(4\pi)^2}
\]

(3.9)

and define

\[
\beta_{\alpha_s}(a_s, a_t, a_\lambda) = \sum_{n=1}^{\infty} \beta^{(n)}_{\alpha_s}(a_s, a_t, a_\lambda).
\]

(3.10)
We find

\[
\frac{\beta^{(4)}}{\alpha_s} = a_s^4 \left( \frac{80}{9} \frac{\alpha_s^{abcd} \alpha_s^{abcd}}{n_f} - \frac{150653}{486} C_A^4 - \frac{512}{9} \frac{n_f \alpha_s^{abcd} \alpha_s^{abcd}}{n_f} - 46n_f T_F C_F^3 \right) \\
+ \frac{4204}{27} n_f C_A T_F C_F^2 - \frac{7073}{243} n_f C_A T_F C_F^3 + \frac{39143}{81} n_f C_A^3 T_F \\
+ \frac{704}{9} n_f^2 \frac{\alpha_s^{abcd} \alpha_s^{abcd}}{n_f} - \frac{1352}{27} n_f^2 T_F C_F^2 - 17152 \frac{n_f^2 C_A T_F C_F}{243} \\
- \frac{7930}{81} n_f^2 C_A^2 T_F^2 - \frac{1232}{243} n_f^3 T_F^3 C_F + \frac{424}{243} n_f^3 C_A T_F^3 - \frac{704}{3} \frac{n_f \alpha_s^{abcd} \alpha_s^{abcd}}{n_f} \\
+ \frac{44}{9} \xi_3 C_A + \frac{1664}{3} \frac{\alpha_s^{abcd} \alpha_s^{abcd}}{n_f} - \frac{352}{9} \xi_3 n_f C_A T_F C_F^2 C_F \\
+ \frac{656}{9} \xi_3 n_f^2 C_A^2 T_F - \frac{136}{3} \xi_3 n_f^2 C_A^2 T_F - \frac{512}{3} \xi_3 n_f^2 \frac{\alpha_s^{abcd} \alpha_s^{abcd}}{n_f} C_F \\
+ \frac{704}{9} \xi_3 n_f^2 T_F^2 C_F^2 - \frac{448}{9} \xi_3 n_f^2 C_A^2 T_F^2 - \frac{224}{9} \xi_3 n_f^2 \frac{\alpha_s^{abcd} \alpha_s^{abcd}}{n_f} T_F^2 \right) \\
+ a_s a_s^3 \left( -6n_f^2 T_F C_F^2 - \frac{523}{9} C_A T_F C_F^2 - \frac{1970}{9} C_A^2 T_F + \frac{644}{9} n_f T_F C_F C_F \right) \\
+ \frac{436}{9} n_f C_A T_F^2 + 144 \xi_3 T_F C_F^2 + 72 \xi_3 C_A T_F C_F \\
+ a_s^2 \xi_3 \xi_3 \left( -6n_f^2 T_F C_F + 41 n_f T_F C_F N_c + 72 n_f T_F + 50 C_A T_F N_c \right) \\
- \frac{48}{9} \xi_3 T_F C_F N_c + \left[ T_F^2 \left( \frac{160}{3} - 64 \xi_3 \right) \right] \\
+ a_s a_s^2 \left( -21 T_F^2 - 58 T_F N_c - 3 T_F N_c^2 - 12 \xi_3 T_F \right) \\
+ a_s^2 a_s a_s^2 \left( +72 T_F \right),
\]

where

\[
a_s^2 a_s^2 T_F^2 \left( \frac{160}{3} T_F^2 - 64 \xi_3 T_F^2 \right) = a_s^2 a_s^2 T_F^2 \left( \frac{48}{(\text{naive})} + \frac{16}{(\text{non-naive})} - 96 \xi_3 + \frac{32 \xi_3}{(\text{naive})} + \frac{32 \xi_3}{(\text{non-naive})} \right). \tag{3.12}
\]

and

\[
\frac{\beta^{(3)}}{\alpha_s} = a_s^3 \left( -\frac{2857}{54} C_A^3 - 2n_f T_F C_F^2 + \frac{205}{9} n_f C_A T_F C_F \\
+ \frac{1415}{27} n_f C_A T_F^2 - \frac{44}{9} n_f^2 T_F C_F - \frac{158}{27} n_f^2 C_A T_F \right) \\
+ a_s a_s^2 \left( -6n_f^2 T_F C_F - 24 C_A T_F \right) + a_s^2 a_s \left( +9 T_F + 7 T_F N_c \right), \tag{3.13}
\]

\[
\frac{\beta^{(2)}}{\alpha_s} = a_s^2 \left( -\frac{34}{3} C_A^2 + 4n_f T_F C_F + \frac{20}{3} n_f C_A T_F \right) + a_s a_s \left( -4 T_F \right), \tag{3.14}
\]

\[
\frac{\beta^{(1)}}{\alpha_s} = a_s \left( -\frac{11}{3} C_A + \frac{4}{3} n_f T_F \right). \tag{3.15}
\]
Now we want to give a numerical evaluation of the \( \beta \)-functions at the scale of the top mass in order to get an idea of the size of the new terms. For \( M_t \approx 173.34 \pm 0.76 \text{ GeV} \) [66], \( M_H \approx 125.09 \pm 0.24 \text{ GeV} \) [67] and \( \alpha_s(M_Z) = 0.1184 \pm 0.0007 \) [68] we get the couplings in the \( \overline{\text{MS}} \)-scheme at this scale using two-loop matching relations [48]

\[
\begin{align*}
g_s(M_t) &= 1.1666 \pm 0.0035(\text{exp}), \\
y_t(M_t) &= 0.9369 \pm 0.0046(\text{exp}) \pm 0.0005(\text{theo}), \\
\lambda(M_t) &= 0.1259 \pm 0.0005(\text{exp}) \pm 0.0003(\text{theo})
\end{align*}
\] (3.16)

where the experimental uncertainty (exp) stems from \( M_t, M_H \) and \( \alpha_s(M_Z) \) and the theoretical one (theo) from the matching of on-shell to \( \overline{\text{MS}} \) parameters (these are taken from [48]). We find\(^3\)

\[
\beta_s^{(2)} \frac{1}{\beta_s^{(1)}(16\pi^2)^2} = 3.20 \times 10^{-2} \frac{1}{g_s^4} + 1.59 \times 10^{-3} \frac{1}{g_s^2 y_t^2}
\] (3.17)

\[
\beta_s^{(3)} \frac{1}{\beta_s^{(1)}(16\pi^2)^2} = -3.45 \times 10^{-4} \frac{1}{g_s^6} + 2.74 \times 10^{-4} \frac{1}{g_s^4 y_t^2} - 6.62 \times 10^{-5} \frac{1}{g_s^2 y_t^4}
\] (3.18)

\[
\beta_s^{(4)} \frac{1}{\beta_s^{(1)}(16\pi^2)^3} = 2.26 \times 10^{-4} \frac{1}{g_s^8} + 2.47 \times 10^{-5} \frac{1}{g_s^6 y_t^2} - 1.06 \times 10^{-5} \frac{1}{g_s^4 y_t^4} - 1.62 \times 10^{-7} \frac{1}{g_s^2 y_t^6} \]

\[
\quad + 2.77 \times 10^{-6} \frac{1}{g_s^8 y_t^2} + 1.06 \times 10^{-7} \frac{1}{g_s^6 y_t^4} - 1.82 \times 10^{-8} \frac{1}{g_s^4 y_t^6}
\] (3.19)

\[
\beta_s^{(4)} \frac{1}{\beta_s^{(1)}(16\pi^2)^3} = 2.26 \times 10^{-4} \frac{1}{g_s^8} + 2.47 \times 10^{-5} \frac{1}{g_s^6 y_t^2} - 1.06 \times 10^{-5} \frac{1}{g_s^4 y_t^4} - 1.62 \times 10^{-7} \frac{1}{g_s^2 y_t^6} \]

\[
\quad + 2.77 \times 10^{-6} \frac{1}{g_s^8 y_t^2} + 1.06 \times 10^{-7} \frac{1}{g_s^6 y_t^4} - 1.82 \times 10^{-8} \frac{1}{g_s^4 y_t^6}
\] (3.20)

We see that the top-Yukawa contributions have a sizable impact on the four-loop \( \beta \)-function for the strong coupling. The part \( \propto g_s^6 y_t^2 \) increases it by \( \sim 11\% \) and the part \( \propto g_s^4 y_t^4 \) decreases it by \( \sim 5\% \) at this scale compared to the pure QCD contribution \( \propto g_s^8 \). The non-naive term gives only a \( \sim 0.18\% \) contribution if we assume the \( \gamma_5 \) prescription with a readout point at the external gluon vertices. That is \( \sim 4\% \) of the total term \( \propto g_s^4 y_t^4 \). So even if we attached an uncertainty factor of 3 to the non-naive term the uncertainty is only \( \sim 0.6\% \) of the leading term \( \propto g_s^8 \) at this scale. We believe the result presented in this paper to be correct but we nevertheless note here that any deviation due to a different treatment of \( \gamma_5 \) would be phenomenologically irrelevant.

**Note added 29.08.2016:** In the second version of [50] the authors state that there are three possible results for the non-naive part of the four-loop \( \beta \)-function

\[
\frac{\beta_s^{(4)}}{\alpha_s} \bigg|_{(\text{non-naive})} = a_1^2 a_s^2 T_F^2 R \left( \frac{16}{3} + 32 \zeta_3 \right)
\] (3.21)

where \( R = 1, 2, 3 \) depending on the reading point prescription for \( \gamma_5 \). \( R = 1 \) corresponds to the external reading point prescription employed in this paper, \( R = 3 \) to the keeping \( \gamma_5 \) at there internal position where they are introduced by the Feynman rules. \( R = 2 \) corresponds

\(^3\)The labels under the braces indicate from which part of the \( \beta \)-function the contributions come.
to one internal and one external reading point. In [50] the self-energies are computed as massless propagators which allows access to the finite part in addition to the UV divergent part. Only for the internal reading point prescription corresponding to \( R = 3 \) the authors of [50] find a transversal finite part of the self-energy. This suggests that this is the correct result although a formal proof for this treatment of \( \gamma_5 \) is still not available.

4 Conclusions

We have presented an analytical result for the four-loop \( \beta \)-function of the strong coupling \( g_s \) in the gaugeless limit of the SM. This constitutes an important extension of the well-known QCD result as top-Yukawa coupling is numerically the next important coupling after \( g_s \), at least at the electroweak scale. Furthermore, this is an important step towards a complete calculation of the four-loop \( \beta \)-functions of the gauge couplings in the full SM.

An important feature of this result is the non-naive \( \gamma_5 \) contribution \( \propto g^4_s y^4_t \). In the pure gauge boson and fermion sector of the SM, given by \( \mathcal{L}_{\text{SU(3) \times SU(2) \times U(1)}} \), all non-naive contributions cancel in the sum of all diagrams, making this part of the SM anomaly free. This has been explicitly checked during the calculation of the three-loop \( \beta \)-functions for the gauge couplings in the SM [2, 3]. Here we see that with the inclusion of a scalar field non-naive contributions may appear in higher orders and special care will have to be taken when attempting a complete calculation of four-loop \( \beta \)-functions in the SM.

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References

[1] J. C. Collins, Normal Products in Dimensional Regularization, Nucl. Phys. B92 (1975) 477.

[2] L. N. Mihaila, J. Salomon, and M. Steinhauser, Gauge coupling beta functions in the standard model to three loops, Phys. Rev. Lett. 108 (2012) 151602.

[3] L. N. Mihaila, J. Salomon, and M. Steinhauser, Renormalization constants and beta functions for the gauge couplings of the Standard Model to three-loop order, Phys. Rev. D 86 (2012) 096008, [arXiv:1208.3357].
[4] A. Bednyakov, A. Pikelner, and V. Velizhanin, Anomalous dimensions of gauge fields and gauge coupling beta-functions in the Standard Model at three loops, JHEP 1301 (2013) 017, [arXiv:1210.6873].

[5] K. Chetyrkin and M. Zoller, Three-loop β-functions for top-Yukawa and the Higgs self-interaction in the Standard Model, JHEP 1206 (2012) 033, [arXiv:1205.2892].

[6] K. Chetyrkin and M. Zoller, β-function for the Higgs self-interaction in the Standard Model at three-loop level, JHEP 1304 (2013) 091, [arXiv:1303.2890].

[7] A. Bednyakov, A. Pikelner, and V. Velizhanin, Higgs self-coupling beta-function in the Standard Model at three loops, Nucl.Phys. B875 (2013) 552–565, [arXiv:1303.4364].

[8] A. Bednyakov, A. Pikelner, and V. Velizhanin, Three-loop Higgs self-coupling beta-function in the Standard Model with complex Yukawa matrices, arXiv:1310.3806.

[9] A. Bednyakov, A. Pikelner, and V. Velizhanin, Yukawa coupling beta-functions in the Standard Model at three loops, Phys.Lett. B722 (2013) 336–340, [arXiv:1212.6829].

[10] D. J. Gross and F. Wilczek, Ultraviolet Behavior of Non-Abelian Gauge Theories, Phys. Rev. Lett. 30 (1973) 1343–1346.

[11] H. D. Politzer, Reliable Perturbative Results for Strong Interactions?, Phys. Rev. Lett. 30 (1973) 1346–1349.

[12] D. Jones, Two-loop diagrams in yang-mills theory, Nuclear Physics B 75 (1974), no. 3 531–538.

[13] O. Tarasov and A. Vladimirov, Two Loop Renormalization of the Yang-Mills Theory in an Arbitrary Gauge, Sov.J.Nucl.Phys. 25 (1977) 585.

[14] W. E. Caswell, Asymptotic Behavior of Non-Abelian Gauge Theories to Two-Loop Order, Phys.Rev.Lett. 33 (1974) 244–246.

[15] E. Egorian and O. Tarasov, Two loop renormalization of the QCD in an arbitrary gauge, Teor.Mat.Fiz. 41 (1979) 26–32.

[16] D. R. T. Jones, Two-loop β function for a $G_1 \times G_2$ gauge theory, Phys. Rev. D 25 (1982) 581–582.

[17] M. S. Fischler and C. T. Hill, Effects of Large Mass Fermions on $M_X$ and $\sin^2 \theta_W$, Nucl.Phys. B193 (1981) 53.

[18] I. Jack and H. Osborn, General background field calculations with fermion fields, Nucl. Phys. B 249 (1985), no. 3 472–506.

[19] M. E. Machacek and M. T. Vaughn, Two-loop renormalization group equations in a general quantum field theory: (i). wave function renormalization, Nucl. Phys. B 222 (1983), no. 1 83–103.

[20] M.-x. Luo and Y. Xiao, Two loop renormalization group equations in the standard model, Phys. Rev. Lett. 90 (2003) 011601, [hep-ph/0207271].

[21] C. Ford, I. Jack, and D. Jones, The Standard model effective potential at two loops, Nucl.Phys. B387 (1992) 373–390, [hep-ph/0111190].

[22] M. Fischler and J. Oliensis, Two-loop corrections to the beta function for the higgs-yukawa coupling constant, Phys. Lett. B 119 (1982), no. 4 385–386.
[23] M. E. Machacek and M. T. Vaughn, Two-loop renormalization group equations in a general quantum field theory (ii). yukawa couplings, Nucl. Phys. B 236 (1984), no. 1 221–232.

[24] M. E. Machacek and M. T. Vaughn, Two-loop renormalization group equations in a general quantum field theory: (iii). scalar quartic couplings, Nucl. Phys. B 249 (1985), no. 1 70–92.

[25] T. Curtright, Three loop charge renormalization effects due to quartic scalar selfinteractions, Phys.Rev. D21 (1980) 1543.

[26] D. Jones, Comment on the charge renormalization effects of quartic scalar selfinteractions, Nucl. Phys. B 236 (1984), no. 1 221–232.

[27] O. Tarasov, A. Vladimirov, and A. Y. Zharkov, The Gell-Mann-Low Function of QCD in the Three Loop Approximation, Phys.Lett. B93 (1980) 429–432.

[28] O. Tarasov, A. Vladimirov, and A. Zharkov, The gell-mann-low function of qcd in the three-loop approximation, Physics Letters B 93 (1980), no. 4 429 – 432.

[29] S. Larin and J. Vermaseren, The Three loop QCD Beta function and anomalous dimensions, Phys. Lett. B303 (1993) 334–336, [hep-ph/9302208].

[30] M. Steinhauser, Higgs decay into gluons up to $O(\alpha^3 G(F)m^2)$, Phys.Rev. D59 (1999) 054005, [hep-ph/9809507].

[31] A. Pickering, J. Gracey, and D. Jones, Three loop gauge beta function for the most general single gauge coupling theory, Phys.Lett. B510 (2001) 347–354, [hep-ph/0104247].

[32] T. van Ritbergen, J. Vermaseren, and S. Larin, The Four loop beta function in quantum chromodynamics, Phys. Lett. B400 (1997) 379–384, [hep-ph/9701390].

[33] M. Czakon, The Four-loop QCD beta-function and anomalous dimensions, Nucl.Phys. B710 (2005) 485–498, [hep-ph/0411261].

[34] N. Cabibbo, L. Maiani, G. Parisi, and R. Petronzio, Bounds on the Fermions and Higgs Boson Masses in Grand Unified Theories, Nucl. Phys. B158 (1979) 295–305.

[35] C. Ford, D. Jones, P. Stephenson, and M. Einhorn, The Effective potential and the renormalization group, Nucl. Phys. B395 (1993) 17–34, [hep-lat/9210033].

[36] G. Altarelli and G. Isidori, Lower limit on the higgs mass in the standard model: An update, Phys. Lett. B 337 (1994), no. 1-2 141–144.

[37] F. Bezrukov and M. Shaposhnikov, Standard Model Higgs boson mass from inflation: two loop analysis, JHEP 07 (2009) 089, [arXiv:0904.1537].

[38] M. Holthausen, K. S. Lim, and M. Lindner, Planck scale Boundary Conditions and the Higgs Mass, JHEP 1202 (2012) 037, [arXiv:1112.2415].

[39] J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto, et al., Higgs mass implications on the stability of the electroweak vacuum, Phys. Lett. B709 (2012) 222–228, [arXiv:1112.3022].

[40] Z.-z. Xing, H. Zhang, and S. Zhou, Impacts of the Higgs mass on vacuum stability, running fermion masses and two-body Higgs decays, arXiv:1112.3112.

[41] F. Bezrukov, M. Y. Kalmykov, B. A. Kniehl, and M. Shaposhnikov, Higgs Boson Mass and New Physics, JHEP 1210 (2012) 140, [arXiv:1205.2893].

[42] G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, et al., Higgs mass and
vacuum stability in the Standard Model at NNLO, JHEP 1208 (2012) 098, [arXiv:1205.6497].

[43] M. Zoller, Vacuum stability in the SM and the three-loop β-function for the Higgs self-interaction, arXiv:1209.5609.

[44] I. Masina, Higgs boson and top quark masses as tests of electroweak vacuum stability, Phys.Rev. D87 (2013), no. 5 053001, [arXiv:1209.0393].

[45] M. F. Zoller, Standard Model beta-functions to three-loop order and vacuum stability, arXiv:1411.2843.

[46] M. Zoller, Three-loop beta function for the Higgs self-coupling, PoS LL2014 (2014) 014, [arXiv:1407.6608].

[47] M. Zoller, Beta-function for the Higgs self-interaction in the Standard Model at three-loop level, PoS (EPS-HEP 2013) (2013) 322, [arXiv:1311.5085].

[48] D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, et al., Investigating the near-criticality of the Higgs boson, arXiv:1307.3536.

[49] A. V. Bednyakov, B. A. Kniehl, A. F. Pikelner, and O. L. Veretin, Fate of the Universe: Gauge Independence and Advanced Precision, arXiv:1507.0883.

[50] A. V. Bednyakov and A. F. Pikelner, Four-loop strong coupling beta-function in the Standard Model, arXiv:1508.0268.

[51] P. Nogueira, Automatic Feynman graph generation, J. Comput. Phys. 105 (1993) 279–289.

[52] T. Seidensticker, Automatic application of successive asymptotic expansions of Feynman diagrams, hep-ph/9905298.

[53] R. Harlander, T. Seidensticker, and M. Steinhauser, Complete corrections of Order αs to the decay of the Z boson into bottom quarks, Phys.Lett. B426 (1998) 125–132, [hep-ph/9712228].

[54] J. A. M. Vermaseren, New features of FORM, math-ph/0010025.

[55] M. Tentyukov and J. A. M. Vermaseren, The multithreaded version of FORM, hep-ph/0702279.

[56] T. Van Ritbergen, A. Schellekens, and J. Vermaseren, Group theory factors for Feynman diagrams, International Journal of Modern Physics A 14 (1999), no. 1 41–96.

[57] M. Steinhauser, MATAD: A program package for the computation of massive tadpoles, Comput. Phys. Commun. 134 (2001) 335–364, [hep-ph/0009029].

[58] R. Harlander, T. Seidensticker, and M. Steinhauser, Complete corrections of Order αs to the decay of the Z boson into bottom quarks, Phys.Lett. B426 (1998) 125–132, [hep-ph/9712228].

[59] J. A. M. Vermaseren, Azodraw, Comput. Phys. Commun. 83 (1994) 45–58.

[60] M. Misiak and M. Münz, Two loop mixing of dimension five flavor changing operators, Phys. Lett. B344 (1995) 308–318, [hep-ph/9409454].
K. G. Chetyrkin, M. Misiak, and M. Münz, *Beta functions and anomalous dimensions up to three loops*, Nucl. Phys. **B518** (1998) 473–494, [hep-ph/9711266].

S. Larin, *The Renormalization of the axial anomaly in dimensional regularization*, Phys.Lett. **B303** (1993) 113–118, [hep-ph/9302240].

J. G. Korner, D. Kreimer, and K. Schilcher, *A Practicable gamma(5) scheme in dimensional regularization*, Z. Phys. **C54** (1992) 503–512.

ATLAS, CDF, CMS, and D0, *First combination of Tevatron and LHC measurements of the top-quark mass*, arXiv:1403.4427.

ATLAS, CMS Collaboration, G. Aad et al., *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments*, Phys. Rev. Lett. **114** (2015) 191803, [arXiv:1503.0758].

S. Bethke, *World Summary of $\alpha_s$ (2012)*, Nucl.Phys.Proc.Suppl. **234** (2013) 229–234, [arXiv:1210.0325].