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The 3-loop anomalous dimensions from off-shell operator matrix elements*

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We report on the calculation of the three-loop flavor polarized and unpolarized non-singlet and the polarized singlet anomalous dimensions using massless off-shell operator matrix elements in a gauge-variant framework. We also reconsider the unpolarized two-loop singlet anomalous dimensions and correct errors in the foregoing literature.

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1. Introduction

In these proceedings we report on recent results of the calculation of unpolarized and polarized three-loop anomalous dimensions based on massless off-shell operator matrix elements (OMEs) [1, 2] and the unpolarized two-loop case [3] correcting previous results in Refs. [4, 5].

The unpolarized and polarized non-singlet and singlet anomalous dimensions have been calculated at one- [6], two- [3, 7], and three-loop order [1, 2, 8–14]. Here different techniques as off-shell massless OMEs, the forward Compton amplitude, in part also with scalar and gravitational currents, and massive on-shell OMEs have been used. In the latter case one obtains the contributions $\propto T_F$, which are the complete anomalous dimensions in the cases $(\Delta)\gamma_{qq}^{(2),PS}$ and $(\Delta)\gamma_{qg}^{(2)}$.

The method of massless off-shell OMEs is the traditional method to calculate the anomalous dimensions, cf. [1a-c]. However, it is a gauge-dependent environment implying in the unpolarized singlet case new operator mixings [15]. It is our goal to set up a program chain allowing for a fully automated calculation of the three-loop anomalous dimensions without making structural assumptions motivated by QCD or the expected representation of the final results in terms of harmonic sums [16, 17]. The paper is organized as follows. We discuss first the basic formalism and describe then the calculation method, before we present some examples for the three-loop anomalous dimensions.

2. Basic Formalism and Details of the Calculation

We form the expectation values of the local twist-2 operators in the unpolarized and polarized case, cf. e.g. [18], between off-shell quark and gluon states and consider the physical projections, which are calculated to three-loop order. There are also other contributions due to the violation of the equation of motion (EOM), which, however, are not related to the anomalous dimensions. From the physical projection we extract the three-loop anomalous dimensions from the $O(1/\varepsilon)$ terms, where $\varepsilon = D - 4$ denotes the dimensional parameter. The corresponding amplitudes are gauge-variant, i.e. they depend on the gauge parameter ξ in the R_ξ gauges. The structure of the pole terms are fully predicted by the renormalization group and do depend on lower order expansion coefficients to higher orders in ε . In the unpolarized case, the mixing of more local operators has to be considered [3–5, 15], which we considered up to two-loop orders in [3].

In the polarized singlet case the anomalous dimensions are first calculated in the Larin scheme [19], which is a consistent scheme. Finally we transform the anomalous dimensions to the M-scheme [5, 10].

3. Details of the calculation

The calculation of the unrenormalized massless off-shell OMEs is performed in the following way. Diagram generation, the performance of Lorentz/Dirac and color algebra are performed by using the packages QGRAF, FORM and color [20–23]. The local operators are resummed into propagators

by observing the current crossing relations, cf. [24, 25], as has been described in Ref. [26],

$$\sum_{N=0}^{\infty} (\Delta.k)^N \left(t^N \pm (-t)^N \right) \rightarrow \left[\frac{1}{1 - \Delta.k t} \pm \frac{1}{1 + \Delta.k t} \right]. \quad (1)$$

The three-loop anomalous dimensions are obtained from the contributions of $O(1/\varepsilon)$, determining the N th moment analytically.

The number of diagrams are of $O(700)$. They are reduced to $O(250)$ master integrals using the code `Crusher` [27] by applying the integration-by-parts relations [28, 29]. Coupling constant and wave function renormalization are performed [30, 31] and results from lower order factorizing diagrams are used [3], implemented in the package `SolveCoupledSystem` [33]. The necessary initial values for the difference equations can be obtained from [29, 34]. Based on 3000 Mellin moments we use the method of guessing [35, 36] and its implementation in Sage [37, 38] to obtain the recurrences for the different color and multiple zeta value factors [39]. It turned out that $O(1600)$ moments suffice and the largest difference equations was of $o = 16$ and degree $d = 304$. These difference equations are solved using methods from difference field theory [40] implemented in the package `Sigma` [41, 42]. Functions of the package `HarmonicSums` [16, 17, 43–49] are used to compactify the final results. The automated calculation at Intel(R) Xeon(R) CPU E5-2643 v4 processors amounted to about 40 days of CPU time for the projects [1, 2].

All anomalous dimensions can be expressed in terms of harmonic sums [16, 17]

$$S_{b,\vec{a}}(N) = \sum_{k=1}^N \frac{(\text{sign}(b))^k}{k^{|\vec{a}|}} S_{\vec{a}}(k), \quad S_{\emptyset} = 1, \quad b, a_i \in \mathbb{Z} \setminus \{0\}, N \in \mathbb{N} \setminus \{0\}. \quad (2)$$

Accordingly, the corresponding z -space expressions are given by harmonic polylogarithms [47].

4. Anomalous Dimensions

We have calculated all the non-singlet anomalous dimensions $\gamma_{qq}^{\pm, \text{NS}}, \gamma_{qq}^{s, \text{NS}}, \Delta\gamma_{qq}^{s, \text{NS}}$ for unpolarized and polarized deep-inelastic scattering and also for transversity $\gamma_{qq}^{\pm, \text{tr}, \text{NS}}$ as well as the singlet polarized anomalous dimensions in Ref. [1, 2]. They can all be expressed in terms of harmonic sums, for which we apply the algebraic relations [48]. If also the structural relations are applied [49] only 10 harmonic sums contribute.

$$\{S_1, S_{2,1}, S_{-2,1}, S_{-3,1}, S_{-4,1}, S_{2,1,1}, S_{-2,1,1}, S_{2,1,-2}, S_{-3,1,1}, S_{-2,1,1,1}\}. \quad (3)$$

As examples we show one of the transversity anomalous dimensions

$$\begin{aligned} \gamma_{\text{NS}}^{(2), \text{tr}, +} &= \frac{1}{2} \left[1 + (-1)^N \right] \\ &\times \left\{ C_F \left\{ T_F^2 N_F^2 \left[\frac{8(-8 + 17N + 17N^2)}{9N(1+N)} - \frac{128}{27} S_1 - \frac{640}{27} S_2 + \frac{128}{9} S_3 \right] \right. \right. \\ &\left. \left. + C_{ATF} N_F \left[-\frac{16(-22 + 45N + 45N^2)}{9N(1+N)} + \left(-\frac{16(9 + 209N + 209N^2)}{27N(1+N)} + 64S_3 \right) \right] \right\} \right. \end{aligned}$$

$$\begin{aligned}
& + \frac{256}{3} S_{-2,1} - 128 \zeta_3 \Big) S_1 + \frac{5344}{27} S_2 - \frac{448}{3} S_3 + \frac{320}{3} S_4 + \left(-\frac{1280}{9} S_1 + \frac{128}{3} S_2 \right) S_{-2} \\
& + \left(-\frac{640}{9} + \frac{128}{3} S_1 \right) S_{-3} + \frac{128}{3} S_{-4} - \frac{256}{3} S_{3,1} + \frac{1280}{9} S_{-2,1} + \frac{128}{3} S_{-2,2} - \frac{512}{3} S_{-2,1,1} \\
& + 96 \zeta_3 \Big] + C_A^2 \left[\frac{-968 + 1657N + 1657N^2}{18N(1+N)} + \left(\frac{4P_{14}}{3(-1+N)N(1+N)(2+N)} - 176S_3 \right. \right. \\
& \left. \left. - 256S_4 + 512S_{3,1} - \frac{704}{3} S_{-2,1} - 1024S_{-2,2} - 1024S_{-3,1} + 2048S_{-2,1,1} \right) S_1 + \left(-128S_3 \right. \right. \\
& \left. \left. - 512S_{-2,1} \right) S_1^2 + \left(-\frac{8344}{27} + 384S_3 + 1536S_{-2,1} \right) S_2 + \frac{3112}{9} S_3 - \frac{880}{3} S_4 + 64S_5 \right. \\
& + \left(\frac{16P_2}{(-1+N)N(1+N)(2+N)} + \frac{32(-241 + 134N + 134N^2)S_1}{9(-1+N)(2+N)} - \frac{352}{3} S_2 - 64S_3 \right. \\
& \left. - 1536S_{2,1} + 128S_{-2,1} - 192\zeta_3 \right) S_{-2} + \left(48 - 192S_1 \right) S_{-2}^2 + \left(256S_1^2 - 768S_2 - 320S_{-2} \right. \\
& \left. + \frac{32(-107 + 67N + 67N^2)}{9(-1+N)(2+N)} - \frac{352}{3} S_1 \right) S_{-3} + \left(-\frac{208}{3} + 320S_1 \right) S_{-4} - 704S_{-5} - 384S_{2,3} \\
& - 768S_{2,-3} + \frac{704}{3} S_{3,1} + 384S_{4,1} - \frac{64(-107 + 67N + 67N^2)S_{-2,1}}{9(-1+N)(2+N)} - \frac{352}{3} S_{-2,2} \\
& + 1088S_{-2,3} - 448S_{-4,1} + 1536[S_{2,1,-2} + S_{-2,2,1} + S_{-3,1,1}] - 768S_{3,1,1} \\
& \left. + \frac{1408}{3} S_{-2,1,1} + 512S_{-2,1,-2} - 3072S_{-2,1,1,1} - \frac{24(-6 + 5N + 5N^2)\zeta_3}{(-1+N)(2+N)} \right] \Big\} \\
& + C_F^2 \left\{ T_F N_F \left[92 + \left(-\frac{8(-8 + 55N + 55N^2)}{3N(1+N)} + \frac{1280}{9} S_2 - \frac{512}{3} S_3 - \frac{512}{3} S_{-2,1} + 128\zeta_3 \right) \right. \right. \\
& \times S_1 - \frac{80}{3} S_2 - \frac{128}{3} S_2^2 + \frac{1856}{9} S_3 - \frac{512}{3} S_4 + \left(\frac{2560}{9} S_1 - \frac{256}{3} S_2 \right) S_{-2} + \left(\frac{1280}{9} \right. \\
& \left. \left. - \frac{256}{3} S_1 \right) S_{-3} - \frac{256}{3} S_{-4} + \frac{256}{3} S_{3,1} - \frac{2560}{9} S_{-2,1} - \frac{256}{3} S_{-2,2} + \frac{1024}{3} S_{-2,1,1} - 96\zeta_3 \right] \\
& + C_A \left[-\frac{151}{2} + \left(-\frac{8(-206 + 211N + 211N^2)}{3(-1+N)N(1+N)(2+N)} - \frac{4288}{9} S_2 + \frac{1984}{3} S_3 + 320S_4 - 1024S_{3,1} \right. \right. \\
& \left. \left. + \frac{1984}{3} S_{-2,1} + 3712S_{-2,2} + 3840S_{-3,1} - 7168S_{-2,1,1} \right) S_1 + \left(256S_3 + 1792S_{-2,1} \right) S_1^2 \right. \\
& \left. + \left(\frac{604}{3} - 832S_3 - 5248S_{-2,1} \right) S_2 + \frac{352}{3} S_2^2 - \frac{6160}{9} S_3 + \frac{2416}{3} S_4 \right. \\
& \left. + \left(-\frac{48P_2}{(-1+N)N(1+N)(2+N)} + \left(-\frac{64P_7}{9(-1+N)N(1+N)(2+N)} - 256S_2 \right) S_1 \right. \right.
\end{aligned}$$

$$\begin{aligned}
& + \frac{992}{3} S_2 + 64 S_3 + 5376 S_{2,1} - 384 S_{-2,1} + 576 \zeta_3 \Big) S_{-2} + \left(-96 + 512 S_1 \right) S_{-2}^2 \\
& + \left(-\frac{32(-187 + 134N + 134N^2)}{9(-1+N)(2+N)} + \frac{992}{3} S_1 - 1152 S_1^2 + 2624 S_2 + 960 S_{-2} \right) S_{-3} \\
& + \left(\frac{560}{3} - 1472 S_1 \right) S_{-4} + 2304 S_{-5} + 768 S_{2,3} + 2688 S_{2,-3} - \frac{1856}{3} S_{3,1} - 768 S_{4,1} \\
& + \frac{64(-187 + 134N + 134N^2) S_{-2,1}}{9(-1+N)(2+N)} + \frac{992}{3} S_{-2,2} - 3648 S_{-2,3} + 1728 S_{-4,1} \\
& - 5376 [S_{2,1,-2} + S_{-2,2,1} + S_{-3,1,1}] + 1536 [S_{3,1,1} - S_{-2,1,-2}] - \frac{3968}{3} S_{-2,1,1} \\
& + 10752 S_{-2,1,1,1} + \frac{72(-6 + 5N + 5N^2) \zeta_3}{(-1+N)(2+N)} \Big] \Big\} \\
& + C_F^3 \left\{ -29 + \left(\frac{384(-1 + N + N^2)}{(-1+N)N(1+N)(2+N)} + 128 S_2^2 - 384 S_3 + 128 S_4 + 512 S_{3,1} \right. \right. \\
& - 384 S_{-2,1} - 3328 S_{-2,2} - 3584 S_{-3,1} + 6144 S_{-2,1,1} \Big) S_1 - 256 S_{-2}^2 S_1 + \left(12 + 512 S_3 \right. \\
& + 4352 S_{-2,1} \Big) S_2 - 96 S_2^2 + 104 S_3 - 480 S_4 + \left(\frac{32 P_2}{(-1+N)N(1+N)(2+N)} \right. \\
& + \left. \left(\frac{384}{(-1+N)N(1+N)(2+N)} + 512 S_2 \right) S_1 - 192 S_2 + 128 S_3 - 4608 S_{2,1} + 256 S_{-2,1} \right. \\
& - 384 \zeta_3 \Big) S_{-2} + \left(\frac{192}{(-1+N)(2+N)} - 192 S_1 + 1280 S_1^2 - 2176 S_2 - 640 S_{-2} \right) S_{-3} \\
& + \left(-96 + 1664 S_1 \right) S_{-4} - 1792 S_{-5} + 384 [-S_{2,3} + S_{3,1} + S_{4,1}] - 2304 S_{2,-3} \\
& - \frac{384 S_{-2,1}}{(-1+N)(2+N)} - 1536 S_1^2 S_{-2,1} - 192 S_{-2,2} + 2944 S_{-2,3} - 1664 S_{-4,1} + 4608 S_{2,1,-2} \\
& - 768 S_{3,1,1} + 768 S_{-2,1,1} + 1024 S_{-2,1,-2} + 4608 [S_{-2,2,1} + S_{-3,1,1}] - 9216 S_{-2,1,1,1} \\
& \left. - \frac{48(-6 + 5N + 5N^2) \zeta_3}{(-1+N)(2+N)} \right\} \Big\}. \tag{4}
\end{aligned}$$

and one of the polarized singlet anomalous dimensions,

$$\begin{aligned}
\Delta \gamma_{gg}^{(2)} &= C_A T_F^2 N_F^2 \left[-\frac{16 P_8}{27 N^2 (1+N)^2} S_1 - \frac{4 P_{48}}{27 N^3 (1+N)^3} \right] + C_F \left[T_F^2 N_F^2 \left[-\frac{8 P_{59}}{27 N^4 (1+N)^4} \right. \right. \\
& + \frac{64(N-1)(2+N)(-6-8N+N^2)}{9 N^3 (1+N)^3} S_1 + \frac{32(N-1)(2+N)}{3 N^2 (1+N)^2} S_1^2 \\
& \left. \left. - \frac{32(N-1)(2+N)}{N^2 (1+N)^2} S_2 \right] + C_A T_F N_F \left[\frac{8 P_6}{N^3 (1+N)^3} S_2 - \frac{8 P_9}{3 N^3 (1+N)^3} S_1^2 \right. \right.
\end{aligned}$$

$$\begin{aligned}
& + \frac{2P_{77}}{27(N-1)N^5(1+N)^5(2+N)} + \left(-\frac{8P_{67}}{9(-1+N)N^4(1+N)^4(2+N)} \right. \\
& \left. - \frac{32(N-1)(2+N)}{N^2(1+N)^2} S_2 + 128\zeta_3 \right) S_1 + \frac{32(N-1)(2+N)}{3N^2(1+N)^2} S_1^3 - \frac{32(34+N+N^2)}{3N^2(1+N)^2} \\
& \times S_3 + \left(\frac{128P_2}{(N-1)N^2(1+N)^2(2+N)} S_1 - \frac{32P_{23}}{(N-1)N^2(1+N)^3(2+N)} \right) S_{-2} \\
& - \frac{192(4-N-N^2)}{N^2(1+N)^2} S_{-3} + \frac{64(N-1)(2+N)}{N^2(1+N)^2} S_{2,1} - \frac{128(-8+N+N^2)}{N^2(1+N)^2} S_{-2,1} \\
& - \frac{64(-3+N)(4+N)}{N^2(1+N)^2} \zeta_3 \left. \right] + C_A^3 \left[\frac{64P_{16}}{9N^2(1+N)^2} S_{-2,1} - \frac{32P_{18}}{9N^2(1+N)^2} S_3 \right. \\
& + \frac{P_{74}}{27(N-1)N^5(1+N)^5(2+N)} + \left(\frac{4P_{69}}{9(N-1)N^4(1+N)^4(2+N)} \right. \\
& \left. - \frac{64P_{17}}{9N^2(1+N)^2} S_2 + 128S_2^2 + \frac{16(-96+11N+11N^2)}{3N(1+N)} S_3 + 192S_4 \right. \\
& \left. + \frac{1024}{N(1+N)} S_{-2,1} - 640S_{-2,2} - 768S_{-3,1} + 1024S_{-2,1,1} \right) S_1 \\
& + \left(-\frac{256(1+3N+3N^2)}{N^3(1+N)^3} + 128S_3 - 256S_{-2,1} \right) S_1^2 + \left(-\frac{16P_{41}}{9N^3(1+N)^3} \right. \\
& \left. + 64S_3 + 640S_{-2,1} \right) S_2 - \frac{256}{N(1+N)} S_2^2 - \frac{384}{N(1+N)} S_4 + 64S_5 \\
& + \left(\frac{32P_{52}}{9(N-1)N^3(1+N)^3(2+N)} + \left(-\frac{64P_{32}}{9(-1+N)N(1+N)^2(2+N)} + 256S_2 \right) \right. \\
& \left. \times S_1 - \frac{512}{N(1+N)} S_2 + 128S_3 - 768S_{2,1} \right) S_{-2} + \left(-\frac{16(24+11N+11N^2)}{3N(1+N)} \right. \\
& \left. + 64S_1 \right) S_{-2}^2 + \left(-\frac{32P_{15}}{9N^2(1+N)^2} - \frac{1536}{N(1+N)} S_1 + 384S_1^2 - 320S_2 \right) S_{-3} \\
& + \left(-\frac{1024}{N(1+N)} + 512S_1 \right) S_{-4} - 192S_{-5} - 384S_{2,-3} + \frac{1280}{N(1+N)} S_{-2,2} \\
& + 384S_{-2,3} + \frac{1536}{N(1+N)} S_{-3,1} - 384S_{-4,1} + 768S_{2,1,-2} - \frac{2048}{N(1+N)} S_{-2,1,1} \\
& \left. + 768[S_{-2,2,1} + S_{-3,1,1}] - 1536S_{-2,1,1,1} \right] \\
& + C_F^2 T_F N_F \left[-\frac{4P_{75}}{(N-1)N^5(1+N)^5(2+N)} + \left(\frac{32(N-1)(2+N)S_2}{N^2(1+N)^2} \right. \right. \\
& \left. \left. - \frac{16P_{42}}{N^4(1+N)^4} \right) S_1 + \frac{8(N-1)(2+N)(2+3N+3N^2)}{N^3(1+N)^3} S_1^2 - \frac{32(N-1)(2+N)}{3N^2(1+N)^2} \right.
\end{aligned}$$

$$\begin{aligned}
& \times S_1^3 - \frac{8(2+N)(2-11N-16N^2+9N^3)}{N^3(1+N)^3} S_2 + \frac{32(10+7N+7N^2)}{3N^2(1+N)^2} S_3 \\
& + \left(-\frac{64(10+N+N^2)}{(N-1)N(1+N)(2+N)} + \frac{512}{N^2(1+N)^2} S_1 \right) S_{-2} + \frac{256}{N^2(1+N)^2} S_{-3} \\
& - \left. \frac{64(N-1)(2+N)}{N^2(1+N)^2} S_{2,1} - \frac{512}{N^2(1+N)^2} S_{-2,1} + \frac{192(-2-N-N^2)}{N^2(1+N)^2} \zeta_3 \right] \\
& + C_A^2 T_F N_F \left[\frac{32P_4}{9N^2(1+N)^2} S_2 + \frac{32P_{11}}{9N^2(1+N)^2} S_{-3} - \frac{64P_{11}}{9N^2(1+N)^2} S_{-2,1} \right. \\
& + \frac{16P_{13}}{9N^2(1+N)^2} S_3 + \frac{2P_{76}}{27(N-1)N^5(1+N)^5(2+N)} + \left(\frac{1280}{9} S_2 - \frac{64}{3} S_3 \right. \\
& \left. - \frac{8P_{68}}{27(-1+N)N^4(1+N)^4(2+N)} - 128\zeta_3 \right) S_1 + \frac{64}{3} S_{-2}^2 \\
& + \left(\frac{64P_{45}}{9(N-1)N^2(1+N)^2(2+N)} S_1 - \frac{32P_{50}}{9(N-1)N^3(1+N)^3(2+N)} \right) S_{-2} \\
& \left. + \frac{128(-3+2N+2N^2)}{N^2(1+N)^2} \zeta_3 \right]. \tag{5}
\end{aligned}$$

The polynomials are given in Refs. [1, 2].

We have also recalculated the unpolarized two-loop anomalous dimensions using the method of massless off-shell OMEs. Here new local operators contribute [15] to cancel the gauge-variant contributions to obtain the anomalous dimensions. We corrected a series of errors contained in [4, 5] and provided all expansion coefficients emerging at two-loop order, which are relevant for upcoming four-loop calculations in Ref. [3].

5. Conclusions

We have calculated the three-loop polarized and unpolarized non-singlet anomalous dimensions, including transversity, and as well the polarized three-loop singlet anomalous dimensions applying the traditional method of massless off-shell operator matrix elements, a gauge-variant method, which requires special projections. The calculations have been performed without assuming special conditions concerning the structure of the final result. The method of arbitrary high Mellin moments plays a central role in these computations in establishing the corresponding difference equations through the method of guessing, after having exploited the equations for the master integrals. These equations are solved subsequently using algorithms of difference ring theory. We agree with all the results previously obtained in the literature. The polarized non-singlet anomalous dimension $\Delta\gamma_{qq}^{s,\text{NS}}$, related to the polarized structure function g_5^- , [24], has been calculated using the associated forward Compton amplitude. In the unpolarized singlet case also new OMEs contribute. Here we have calculated all contributions emerging at the two-loop level and corrected results in the literature. The present method is suited to be expanded to the four-loop level. The knowledge of the higher-loop anomalous dimensions form one important asset for the precise description of

the scaling violations of the deep inelastic structure functions, which provide an important way to measure the QCD coupling constant $\alpha_s(M_Z^2)$ [50] at highest precision possible.

References

- [1] J. Blümlein, P. Marquard, C. Schneider and K. Schönwald, Nucl. Phys. B **971** (2021) 115542 [arXiv: 2107.06267 [hep-ph]].
- [2] J. Blümlein, P. Marquard, C. Schneider and K. Schönwald, JHEP **01** (2022) 193 [arXiv:2111.12401 [hep-ph]].
- [3] J. Blümlein, P. Marquard, C. Schneider and K. Schönwald, Nucl. Phys. B **980** (2022), 115794 [arXiv:2202.03216 [hep-ph]].
- [4] Y. Matiounine, J. Smith and W.L. van Neerven, Phys. Rev. D **57** (1998) 6701–6722 [arXiv:hep-ph/9801224 [hep-ph]];
- [5] Y. Matiounine, J. Smith and W.L. van Neerven, Phys. Rev. D **58** (1998) 076002 [hep-ph/9803439].
- [6] D.J. Gross and F. Wilczek, Phys. Rev. D **8** (1973) 3633–3652; Phys. Rev. D **9** (1974) 980–993; H. Georgi and H.D. Politzer, Phys. Rev. D **9** (1974) 416–420; K. Sasaki, Prog. Theor. Phys. **54** (1975) 1816–1827; M.A. Ahmed and G.G. Ross, Phys. Lett. B **56** (1975) 385–390.
- [7] E.G. Floratos, D. A.Ross and C.T. Sachrajda, Nucl. Phys. B **129** (1977) 66–88 Erratum: [Nucl. Phys. B **139** (1978) 545–546]; **152** (1979) 493–520; A. Gonzalez-Arroyo and C. Lopez, Nucl. Phys. B **166** (1980) 429–459; A. Gonzalez-Arroyo, C. Lopez and F. J. Yndurain, Nucl. Phys. B **159** (1979) 512–527; Nucl. Phys. B **153** (1979) 161–186; G. Curci, W. Furmanski and R. Petronzio, Nucl. Phys. B **175** (1980) 27–92; W. Furmanski and R. Petronzio, Phys. Lett. B **97** (1980) 437–442; E.G. Floratos, C. Kounnas and R. Lacaze, Nucl. Phys. B **192** (1981) 417–462; R. Hamberg and W.L. van Neerven, Nucl. Phys. B **379** (1992) 143–171; R. Mertig and W.L. van Neerven, Z. Phys. C **70** (1996) 637–654 [hep-ph/9506451v2]; W. Vogelsang, Phys. Rev. D **54** (1996) 2023–2029 [hep-ph/9512218]; Nucl. Phys. B **475** (1996) 47–72 [hep-ph/9603366]; R.K. Ellis and W. Vogelsang, *The Evolution of parton distributions beyond leading order: The Singlet case*, arXiv:hep-ph/9602356 [hep-ph]; S. Moch and J.A.M. Vermaseren, Nucl. Phys. B **573** (2000) 853–907 [hep-ph/9912355].
- [8] S. Moch, J.A.M. Vermaseren and A. Vogt, Nucl. Phys. B **688** (2004) 101–134 [hep-ph/0403192].
- [9] A. Vogt, S. Moch and J.A.M. Vermaseren, Nucl. Phys. B **691** (2004) 129–181 [hep-ph/0404111].

- [10] S. Moch, J.A.M. Vermaseren and A. Vogt, Nucl. Phys. B **889** (2014) 351–400 [arXiv:1409.5131 [hep-ph]].
- [11] J. Ablinger, A. Behring, J. Blümlein, A. De Freitas, A. von Manteuffel and C. Schneider, Nucl. Phys. B **890** (2014) 48–151 [arXiv:1409.1135 [hep-ph]].
- [12] J. Ablinger, A. Behring, J. Blümlein, A. De Freitas, A. von Manteuffel and C. Schneider, Nucl. Phys. B **922** (2017) 1–40 [arXiv:1705.01508 [hep-ph]].
- [13] A. Behring, J. Blümlein, A. De Freitas, A. Goedicke, S. Klein, A. von Manteuffel, C. Schneider and K. Schönwald, Nucl. Phys. B **948** (2019) 114753 [arXiv:1908.03779 [hep-ph]].
- [14] T. Gehrmann et al., these Proceedings and in preparation.
- [15] J.A. Dixon and J.C. Taylor, Nucl. Phys. B **78** (1974) 552–560;
H. Kluberg-Stern and J. B. Zuber, Phys. Rev. D **12** (1975) 482–488; 3159–3180;
S. Sarkar, Nucl. Phys. B **82** (1974) 447–460;
S. Sarkar and H. Strubbe, Nucl. Phys. B **90** (1975) 45–51;
S.D. Joglekar and B.W. Lee, Annals Phys. **97** (1976) 160–215;
S.D. Joglekar, Annals Phys. **108** (1977) 233–241; **109** (1977) 210–287;
J.C. Collins and R.J. Scalise, Phys. Rev. D **50** (1994) 4117–4136 [arXiv:hep-ph/9403231 [hep-ph]];
B.W. Harris and J. Smith, Phys. Rev. D **51** (1995) 4550–4560 [arXiv:hep-ph/9409405 [hep-ph]];
G. Falcioni and F. Herzog, JHEP **05** (2022) 177 [arXiv:2203.11181 [hep-ph]].
- [16] J.A.M. Vermaseren, Int. J. Mod. Phys. A **14** (1999) 2037–2076 [hep-ph/9806280].
- [17] J. Blümlein and S. Kurth, Phys. Rev. D **60** (1999) 014018 [hep-ph/9810241].
- [18] J. Blümlein, Prog. Part. Nucl. Phys. **69** (2013) 28–84 [arXiv:1208.6087 [hep-ph]].
- [19] S.A. Larin, Phys. Lett. B **303** (1993) 113–118 [hep-ph/9302240].
- [20] P. Nogueira, J. Comput. Phys. **105** (1993) 279–289.
- [21] I. Bierenbaum, J. Blümlein and S. Klein, Nucl. Phys. B **820** (2009) 417–482 [arXiv:0904.3563 [hep-ph]].
- [22] J.A.M. Vermaseren, *New features of FORM*, math-ph/0010025;
M. Tentyukov and J. A. M. Vermaseren, Comput. Phys. Commun. **181** (2010) 1419–1427 [hep-ph/0702279].
- [23] T. van Ritbergen, A.N. Schellekens and J.A.M. Vermaseren, Int. J. Mod. Phys. A **14** (1999) 41–96 [arXiv:hep-ph/9802376 [hep-ph]].
- [24] J. Blümlein and N. Kochelev, Nucl. Phys. B **498** (1997) 285–309 [arXiv:hep-ph/9612318 [hep-ph]].

- [25] H.D. Politzer, Phys. Rept. **14** (1974) 129–180
- [26] J. Ablinger, J. Blümlein, C. Raab, C. Schneider and F. Wißbrock, Nucl. Phys. B **885** (2014) 409–447 [arXiv:1403.1137 [hep-ph]].
- [27] P. Marquard and D. Seidel, *The Crusher algorithm*, unpublished.
- [28] J. Lagrange, Nouvelles recherches sur la nature et la propagation du son, Miscellanea Taurinensis, t. II, 1760-61; Oeuvres t. I, p. 263;
C.F. Gauß, Theoria attractionis corporum sphaeroidicorum ellipticorum homogeneorum methodo novo tractate, Commentationes societatis scientiarum Gottingensis recentiores, Vol III, 1813, Werke Bd. V pp. 5-7;
G. Green, Essay on the Mathematical Theory of Electricity and Magnetism, Nottingham, 1828 [Green Papers, pp. 1-115];
M. Ostrogradski, Mem. Ac. Sci. St. Peters., **6** (1831) 39–53;
S. Laporta, Int. J. Mod. Phys. A **15** (2000) 5087–5159 [hep-ph/0102033].
- [29] K.G. Chetyrkin and F.V. Tkachov, Nucl. Phys. B **192** (1981) 159–204.
- [30] D.J. Gross and F. Wilczek, Phys. Rev. Lett. **30** (1973) 1343–1346;
H.D. Politzer, Phys. Rev. Lett. **30** (1973) 1346–1349;
W.E. Caswell, Phys. Rev. Lett. **33** (1974) 244–246;
D.R.T. Jones, Nucl. Phys. B **75** (1974) 531–538;
O.V. Tarasov, A.A. Vladimirov and A.Y. Zharkov, Phys. Lett. B **93** (1980) 429–432;
S.A. Larin and J.A.M. Vermaseren, Phys. Lett. B **303** (1993) 334–336 [hep-ph/9302208];
T. van Ritbergen, J.A.M. Vermaseren and S.A. Larin, Phys. Lett. B **400** (1997) 379–384 [hep-ph/9701390];
M. Czakon, Nucl. Phys. B **710** (2005) 485–498 [hep-ph/0411261];
P.A. Baikov, K.G. Chetyrkin and J.H. Kühn, Phys. Rev. Lett. **118** (2017) no.8, 082002 [arXiv:1606.08659 [hep-ph]];
P.A. Baikov, K.G. Chetyrkin and J.H. Kühn, Phys. Rev. Lett. **118** (2017) no.8, 082002 [arXiv:1606.08659 [hep-ph]];
F. Herzog, B. Ruijl, T. Ueda, J.A.M. Vermaseren and A. Vogt, JHEP **02** (2017) 090 [arXiv:1701.01404 [hep-ph]];
T. Luthe, A. Maier, P. Marquard and Y. Schröder, JHEP **10** (2017) 166 [arXiv:1709.07718 [hep-ph]].
- [31] K.G. Chetyrkin, G. Falcioni, F. Herzog and J.A.M. Vermaseren, JHEP **1710** (2017) 179 Addendum: [JHEP **1712** (2017) 006] [arXiv:1709.08541 [hep-ph]];
K.G. Chetyrkin, Nucl. Phys. B **710** (2005) 499–510 [arXiv:hep-ph/0405193 [hep-ph]]. E. Egorian and O.V. Tarasov, Teor. Mat. Fiz. **41** (1979) 26–32 [Theor. Math. Phys. **41** (1979) 863–867];
T. Luthe, A. Maier, P. Marquard and Y. Schröder, JHEP **1701** (2017) 081 [arXiv:1612.05512 [hep-ph]].
- [32] J. Blümlein and C. Schneider, Phys. Lett. B **771** (2017) 31–36 [arXiv:1701.04614 [hep-ph]].

- [33] J. Blümlein, P. Marquard and C. Schneider, PoS (RADCOR2019) 078 [arXiv:1912.04390 [cs.SC]].
- [34] F.V. Tkachov, Phys. Lett. B **100** (1981) 65–68; Theor. Math. Phys. **56** (1983) 866–870; Teor. Mat. Fiz. **56** (1983) 350–356;
See also: T. Gehrmann, E.W.N. Glover, T. Huber, N. Ikizlerli and C. Studerus, JHEP **06** (2010) 094 [arXiv:1004.3653 [hep-ph]];
R.N. Lee, A.V. Smirnov and V.A. Smirnov, Nucl. Phys. B Proc. Suppl. **205-206** (2010) 308–313 [arXiv:1005.0362 [hep-ph]];
R.N. Lee and V.A. Smirnov, JHEP **02** (2011) 102 [arXiv:1010.1334 [hep-ph]].
- [35] M. Kauers, *Guessing Handbook*, JKU Linz, Technical Report RISC 09-07.
- [36] J. Blümlein, M. Kauers, S. Klein and C. Schneider, Comput. Phys. Commun. **180** (2009) 2143–2165 [arXiv:0902.4091 [hep-ph]].
- [37] Sage, <http://www.sagemath.org/>
- [38] M. Kauers, M. Jaroschek, and F. Johansson, in: Computer Algebra and Polynomials, Editors: J. Gutierrez, J. Schicho, Josef, M. Weimann, Eds.. Lecture Notes in Computer Science **8942** (Springer, Berlin, 2015) 105–125 [arXiv:1306.4263 [cs.SC]].
- [39] J. Blümlein, D.J. Broadhurst and J.A.M. Vermaseren, Comput. Phys. Commun. **181** (2010), 582–625 [arXiv:0907.2557 [math-ph]].
- [40] M. Karr, J. ACM **28** (1981) 305–350;
M. Bronstein, J. Symbolic Comput. **29** (2000) no. 6 841–877;
C. Schneider, *Symbolic Summation in Difference Fields*, Ph.D. Thesis RISC, Johannes Kepler University, Linz technical report 01–17 (2001);
C. Schneider, An. Univ. Timisoara Ser. Mat.-Inform. **42** (2004) 163–179;
C. Schneider, J. Differ. Equations Appl. **11** (2005) 799–821;
C. Schneider, Appl. Algebra Engrg. Comm. Comput. **16** (2005) 1–32;
C. Schneider, J. Algebra Appl. **6** (2007) 415–441;
C. Schneider, Clay Math. Proc. **12** (2010) 285–308 [arXiv:0904.2323 [cs.SC]];
C. Schneider, Ann. Comb. **14** (2010) 533–552 [arXiv:0808.2596];
C. Schneider, in: Computer Algebra and Polynomials, Applications of Algebra and Number Theory, J. Gutierrez, J. Schicho, M. Weimann (ed.), Lecture Notes in Computer Science (LNCS) 8942 (2015) 157–191 [arXiv:1307.7887 [cs.SC]];
C. Schneider, J. Symb. Comput. **72** (2016) 82–127 [arXiv:1408.2776 [cs.SC]]. C. Schneider, J. Symb. Comput. **80** (2017) 616–664 [arXiv:1603.04285 [cs.SC]]. S.A. Abramov, M. Bronstein, M. Petkovšek, Carsten Schneider, J. Symb. Comput. **107** (2021) 23–66 [arXiv:2005.04944 [cs.SC]].
- [41] C. Schneider, Sémin. Lothar. Combin. **56** (2007) 1–36 article B56b.
- [42] C. Schneider, Simplifying Multiple Sums in Difference Fields, in: Computer Algebra in Quantum Field Theory: Integration, Summation and Special Functions Texts and Monographs in

- Symbolic Computation eds. C. Schneider and J. Blümlein (Springer, Wien, 2013) 325–360 [arXiv:1304.4134 [cs.SC]].
- [43] J. Ablinger, J. Blümlein and C. Schneider, J. Phys. Conf. Ser. **523** (2014) 012060 [arXiv:1310.5645 [math-ph]];
J. Ablinger, PoS (LL2014) 019 [arXiv:1407.6180[cs.SC]]; *A Computer Algebra Toolbox for Harmonic Sums Related to Particle Physics*, Diploma Thesis, JKU Linz, 2009, arXiv:1011.1176[math-ph]; *Computer Algebra Algorithms for Special Functions in Particle Physics*, Ph.D. Thesis, Linz U. (2012) arXiv:1305.0687[math-ph]; PoS (LL2016) 067; Experimental Mathematics 26 (2017) [arXiv:1507.01703 [math.CO]]; PoS (RADCOR2017) 001 [arXiv:1801.01039 [cs.SC]]; arXiv:1902.11001 [math.CO]; PoS (LL2018) 063. [40]
- [44] J. Ablinger, J. Blümlein and C. Schneider, J. Math. Phys. **54** (2013) 082301 [arXiv:1302.0378 [math-ph]]. [41]
- [45] J. Ablinger, J. Blümlein, C.G. Raab and C. Schneider, J. Math. Phys. **55** (2014) 112301 [arXiv:1407.1822 [hep-th]].
- [46] J. Ablinger, J. Blümlein and C. Schneider, J. Math. Phys. **52** (2011) 102301 [arXiv:1105.6063 [math-ph]].
- [47] E. Remiddi and J.A.M. Vermaseren, Int. J. Mod. Phys. A **15** (2000) 725–754 [hep-ph/9905237].
- [48] J. Blümlein, Comput. Phys. Commun. **159** (2004) 19–54 [arXiv:hep-ph/0311046 [hep-ph]].
- [49] J. Blümlein, Comput. Phys. Commun. **180** (2009) 2218–2249 [arXiv:0901.3106 [hep-ph]].
- [50] S. Bethke *et al.*, *Workshop on Precision Measurements of α_s* , arXiv:1110.0016 [hep-ph];
S. Moch *et al.*, *High precision fundamental constants at the TeV scale*, arXiv:1405.4781 [hep-ph];
S. Alekhin, J. Blümlein and S.O. Moch, Mod. Phys. Lett. A **31** (2016) no.25, 1630023.