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Analytic two-loop electroweak corrections at high energies

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The high-energy behaviour of electroweak scattering amplitudes is of theoretical and phenomenological interest. In these proceedings, we summarize recent progress in analytic high-energy calculations for two-loop four-point electroweak amplitudes in the full Standard Model. As a representative application, we discuss the electroweak corrections to Higgs boson pair production, where rich structures of logarithmic and power corrections appear and sizeable effects are found in the high-energy region.

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1. Introduction

There has been a long history of studying the high-energy behaviour of scattering amplitudes in quantum field theory, starting from the classic works of Sudakov and Weinberg [1, 2]. In recent years, electroweak scattering amplitudes in this limit have drawn renewed attention [3–5], motivated by the need for high-precision predictions at the Large Hadron Collider (LHC) and by the development of new analytic methods for multi-loop calculations.

The state of the art has advanced in several directions. In QCD and QED, high-energy expansions of massive two-loop amplitudes have been studied for a number of phenomenologically important processes [6–22]. Electroweak two-loop amplitudes in the full Standard Model (SM) are more involved because several mass scales appear simultaneously in the Feynman diagrams. In the literature, logarithmic electroweak corrections at the leading power have been intensively studied [23–32], and have been recently implemented in `OpenLoops` [33, 34]. Beyond logarithmic and leading-power approximations, the complete high-energy expansion of two-loop four-point electroweak amplitudes in the full SM has only been obtained recently in Ref. [5] for Higgs boson pair production $gg \to HH$.

In these proceedings, we summarize the analytic roadmap for two-loop electroweak amplitudes at high energies. We first discuss the high-energy expansion strategy for electroweak amplitudes and the `AsyInt` [35, 36] approach to master integrals. We then describe its application to the top-quark-induced next-to-leading order electroweak (NLO EW) corrections to $gg \to HH$, and show their sizable impacts in the high-energy region.

2. High-energy expansion of electroweak amplitudes

The high-energy limit of four-point electroweak amplitudes considered in the Feynman gauge is characterized by

$$s, |t| \gg m_t^2, m_W^2, m_Z^2, m_H^2. \tag{1}$$

In this limit, the SM masses are treated as small parameters compared with the Mandelstam variables. The dependence on the masses is explicitly kept in the asymptotic high-energy expansion. These masses appearing in the loop diagrams are further expanded around an electroweak central scale, which can be conveniently chosen as the top-quark mass

$$\delta_X = 1 - \frac{m_X}{m_{\rm EW}}, \quad X = H, W, Z \ \text{ and } \ m_{\rm EW} = m_t. \tag{2}$$

Since the limiting behaviour of Eq. (1) is characterized by the power-log series in small masses, the mass-difference δ_X expansion becomes a Taylor expansion. For $gg \to HH$, the calculation can be further simplified through a small external-Higgs-mass expansion, which is again a Taylor expansion. Note that this small external-mass expansion is in principle not a necessary step, but can reduce the complexity of both amplitudes and integral calculations. After these expansions and subsequent IBP reductions, the resulting master integrals $\vec{I}$ depend on the variables s, t and $m_{\rm EW}$.

In the high-energy limit, a convenient way to proceed is to use differential equations with respect to the mass parameter

$$\frac{\partial}{\partial m_{\rm EW}^2} \vec{I} = M(s, t, m_{\rm EW}^2, \epsilon) \vec{I}, \tag{3}$$

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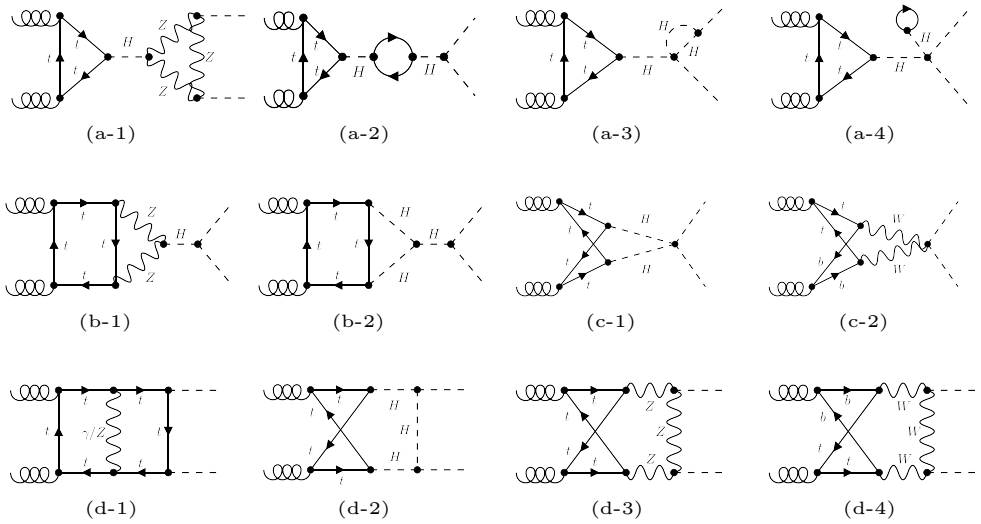

Figure 1: Sample Feynman diagrams contributing to the NLO EW corrections to $gg \to HH$.

and plug in the power-logarithmic series ansatz for each master integral

$$I_n = \sum_{i,j,k} C_{ijk}^{(n)}(s,t)\, \epsilon^i\, m_{\mathrm{EW}}^j\, \log^k(m_{\mathrm{EW}}^2). \tag{4}$$

The resulting linear system of equations from the differential equations can be solved in terms of unknown boundary functions $C_{ijk}^{(n)}(s,t)$. These functions can be extracted from the boundary master integrals, which are calculated with `AsyInt` [35] in a direct parametric integration approach incorporating the method of regions [37] . The most complicated fully massive EW non-planar master integrals are computed in Ref. [4], for which we also employed the t-differential equations approach for the expanded master integrals as in Eq. (4), in order to compute the boundary functions at higher orders in ϵ and m_{EW}. The final analytic results of the master integrals are expressed in terms of Harmonic Polylogarithms and special transcendental constants. For technical details regarding master integral calculations, we refer to Refs. [4, 35].

3. Application to Higgs boson pair production

We now discuss the application to the top-quark-induced electroweak corrections to $gg \to HH$. The process is loop-induced at LO and the NLO EW corrections require two-loop amplitudes, whose sample diagrams are shown in Fig. 1. In recent years, substantial efforts have been devoted to the computation of these contributions using different methods [3–5, 38–45].

The amplitude is decomposed into two Lorentz structures with scalar form factors. Following the conventions of Ref. [5], one writes

$$\mathcal{M}^{\mu\nu} = F_1\, T_1^{\mu\nu} + F_2\, T_2^{\mu\nu}, \tag{5}$$

and the form factors are expanded perturbatively as

$$F = F^{(0)} + \frac{\alpha_s}{\pi} F^{(1,0)} + \frac{\alpha}{\pi} F^{(0,1)} + \cdots . \tag{6}$$

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The term $F^{(0,1)}$ denotes the electroweak form factors considered here.

The calculation is performed in several expansion steps, as described above. First, the masses of the internally propagating particles are expanded around $m_{\rm EW} = m_t$ in the parameters δ_X defined in Eq. (2). Second, the final-state Higgs boson mass is expanded at the integrand level. The resulting scalar integrals are then reduced to master integrals and computed in the high-energy limit with `AsyInt` and differential equations (see Refs. [4, 10, 11, 35]).

The renormalization is performed in the on-shell scheme for the input parameters e, m_W, m_Z, m_t and m_H. The result is then transformed to the G_μ scheme. Tadpole contributions are included consistently, following the *Fleischer–Jegerlehner* tadpole scheme. For details of the renormalization procedure including the treatment of gauge-fixing parameters in the general R_ξ gauge, we refer to Refs. [39, 41].

The generic structure of the high-energy expansion of the form factors is

$$F = \sum C_{ijn}^{k_W k_Z k_H}(s,t)\, m_t^i\, \log^j(m_t^2)\, \left(m_H^{\rm ext}\right)^{2n} \delta_W^{k_W}\, \delta_Z^{k_Z}\, \delta_H^{k_H}\,, \tag{7}$$

where the $m_H^{\rm ext}$ denotes the external Higgs mass. In practice, we compute deep high-energy expansions up to the orders m_t^{108}, $(m_H^{\rm ext})^4$ and δ_X^4 are obtained and used to construct Padé-improved approximations, in order to cover the phase space region down to fairly low values of Higgs transverse momentum p_T.

The analytic result also allows one to inspect the logarithmic structure of the form factors. For example, in the $m_t \to 0$ and $m_H^{\rm ext} = 0$ limit, the leading logarithmic terms of the box form factors take the form

$$F_{\rm box1}^{(0,1)} = \frac{m_W^4}{s^2 c_{\rm w}^6 s_{\rm w}^2}\left[l_{ms}^2\, \frac{36c_{\rm w}^6 + 32c_{\rm w}^4 - 40c_{\rm w}^2 + 17}{36}\left(l_{1ts}^2 + l_{ts}^2 - 2l_{1ts}l_{ts} + \pi^2 - 4\right)\right] + \cdots\,, \tag{8}$$

$$\begin{aligned} F_{\rm box2}^{(0,1)} = \frac{m_W^4}{s^2 c_{\rm w}^6 s_{\rm w}^2}\Bigg[& l_{ms}^3\, \frac{36c_{\rm w}^6 + 32c_{\rm w}^4 - 40c_{\rm w}^2 + 17}{27} + l_{ms}^2\left(-\frac{2}{9}\delta_Z\left(32c_{\rm w}^4 - 40c_{\rm w}^2 + 17\right)\right. \\ & - 8\,\delta_W\, c_{\rm w}^6 + \frac{36c_{\rm w}^6 + 32c_{\rm w}^4 - 40c_{\rm w}^2 + 17}{36t(s+t)}\left(l_{1ts}^2 (s+t)^2 - 2\,l_{1ts}\,t(s+t) - 2\,l_{ts}\,t(s+t)\right. \\ & \left.\left.\left. + l_{ts}^2\, t^2 + \pi^2\left(s^2 + 2st + 2t^2\right)\right)\right)\Bigg] + \cdots\,, \end{aligned} \tag{9}$$

where $c_{\rm w} \equiv \cos(\theta_{\rm w})$ is the cosine of the weak mixing angle and

$$l_{ms} = \log\left(\frac{m_t^2}{s}\right) + i\pi\,, \quad l_{ts} = \log\left(-\frac{t}{s}\right) + i\pi\,, \quad l_{1ts} = \log\left(1 + \frac{t}{s}\right) + i\pi\,. \tag{10}$$

Note that the counterterms do not contribute to the results shown in Eqs. (8) and (9); they come exclusively from the two-loop diagrams. We further note that $gg \to HH$ at NLO EW contains several coupling structures, resulting in rich structures of logarithmic and power corrections. For further analytic expressions we refer to the ancillary files of Ref. [5].

For numerical applications, the correction can be quantified through the ratio

$$r_{\rm EW} = \frac{\alpha}{\pi}\frac{\mathcal{U}^{(0,1)}}{\mathcal{U}^{(0)}}\,, \tag{11}$$

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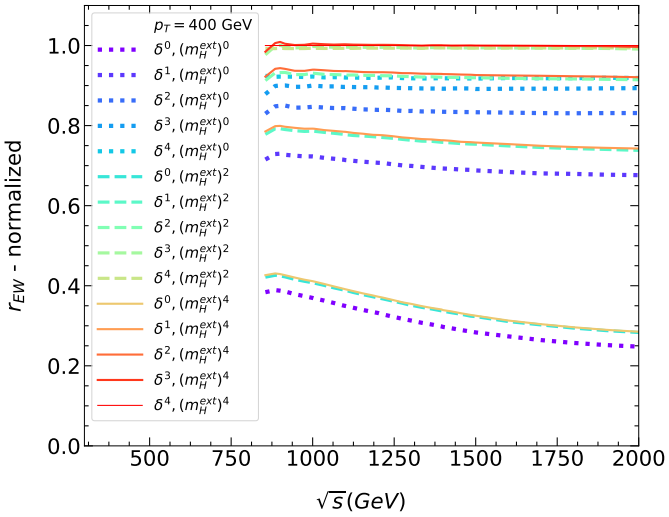

Figure 2: r_{EW} for various δ and m_H expansion terms normalized to highest available approximation for $p_T = 400$ GeV. The truncation uncertainty in δ_X and m_H^{ext} expansions is estimated conservatively to ±1%.

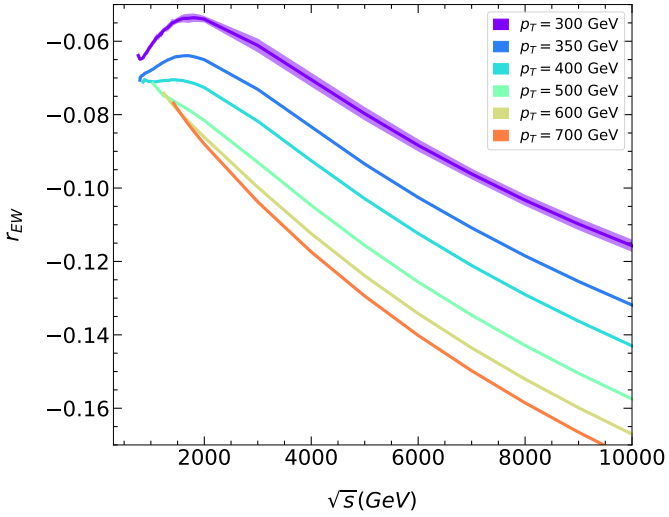

Figure 3: r_{EW} for various values of p_T as a function of $\sqrt{s}$. The plots show the same data for different ranges of $\sqrt{s}$ on the x axis. The uncertainty band (only visible for $p_T = 300$ GeV) is obtained from the Padé approximation.

where the squared matrix element is expanded as $|\mathcal{M}|^2 = \bar{X}_0\big(\mathcal{U}^{(0)} + \frac{\alpha_s}{\pi}\mathcal{U}^{(1,0)} + \frac{\alpha}{\pi}\mathcal{U}^{(0,1)}\big)$ with an overall prefactor $\bar{X}_0$. The high-energy expansion shows good convergence in a broad region of phase space, as illustrated in Fig. 2 for $p_T = 400$ GeV. The remaining uncertainty is dominated by the mass-difference expansions, and is conservatively estimated to be ±1% of the two-loop electroweak correction.

In Fig. 3, we show our results up to $\sqrt{s} = 10$ TeV. The resulting top-quark-induced electroweak correction is negative and reaches the order of −10% at high energies, supporting the observation

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from Ref. [40] for the hadronic invariant-mass or p_T distribution. The expansion remains reliable down to transverse momenta of about $p_T = 350\,\text{GeV}$, providing an analytic result for the boosted region of Higgs-boson pair production.

4. Summary

In these proceedings, we summarized recent progress towards analytic two-loop electroweak corrections at high energies. The central technical ingredient is the high-energy expansion of electroweak amplitudes and the calculation of massive two-loop four-point master integrals in this limit. This is achieved with the differential equation approach in combination with the `AsyInt` approach based on the direct parametric integrations and the method of regions.

As an application, we discussed the top-quark-induced electroweak corrections to $gg \to HH$. The result is obtained as a deep high-energy expansion, supplemented by mass-difference and external-Higgs-mass expansions. The analytic form factors exhibit rich structures of logarithmic and power corrections, and the corresponding electroweak correction is negative and of order -10% in the high-energy region. The expansion shows good convergence and remains reliable down to transverse momenta of about $p_T \geq 350\,\text{GeV}$. These results provide analytic input for boosted Higgs-pair production and illustrate the usefulness of high-energy expansions for electroweak two-loop amplitudes.

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