Analytical Calculations for $\mathrm{Wt\bar{t}}$ Production

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The Standard Model of particle physics, describing the interactions of the fundamental particles of our universe, can without doubt be considered one of the biggest success stories of modern physics. It has been tested up to high precision in collider experiments such as those performed at the Large Hadron Collider (LHC) at CERN, culminating in the discovery of the Higgs boson in 2012. Although no prediction of the Standard Model could be falsified so far, there are still many phenomena that cannot be explained by it. In order to find possible physics beyond the Standard Model in absence of direct detection, we need to probe it at even higher precision. The LHC is expected to provide more precise experimental data after the full evaluation of the Run 3 data set and the upgrade to the High-Luminosity phase (HL-LHC), which is why precise theory predictions at the order of $\mathcal{O}(1\%)$ level are needed to get statistically significant results.

Theoretical predictions for cross sections are obtained from the absolute squares of scattering amplitudes, computed perturbatively as a power series in the relevant coupling constant. The scattering of high energetic hadrons, as performed at the LHC, can be treated perturbatively using parton distribution functions to connect the hard scattering cross section, providing the scattering probability for quarks and gluons in QCD, with the non-perturbative nature of the hadrons. At each order in perturbation theory, the respective amplitude is computed as a sum of Feynman diagrams. Starting at next-to-leading order (NLO), the diagrams involve loops, requiring the integration over the free momentum running in the loop, leading to Feynman integrals. Evaluating the Feynman integrals poses one of the main challenges when pushing the computation of the perturbative series to higher orders and thereby increasing the precision of predictions for the scattering amplitude.

The associated production of a W boson with a top-antitop quark pair ($\mathrm{Wt\bar{t}}$ production) is one of the heaviest Standard Model signatures currently probed at the LHC. It plays a crucial role in the search for physics beyond the Standard Model and is an important background for other processes of interest, such as Higgs boson production in association with a top-antitop quark pair ($\mathrm{Ht\bar{t}}$) and four-top production ($\mathrm{t\bar{t}t\bar{t}}$). The rates measured in experiments for $\mathrm{Wt\bar{t}}$ production are systematically above the theoretical predictions but within the given error bars, demanding preciser theoretical prediction.

A more theoretical motivation to study $\mathrm{Wt\bar{t}}$ production is given by the current interest in five-point processes, as the complexity of Feynman integrals does not only grow with the order in perturbation theory but also with the number of kinematic variables, i.e. external particles and masses, involved. While one-loop five-point processes have successfully been dealt with, two-loop five-point amplitudes involving masses are still an active field of research.

We compute the next-to-leading order contribution to the scattering amplitude of $\mathrm{Wt\bar{t}}$

production, e.g., $\overline{d} + u \to \bar{t} + t + W^+$, analytically, providing a starting ground for the computation at two-loop order. We present the amplitude as a form factor decomposition, $A = \sum_i F_i T_i$, writing it as a linear combination of scalar form factors F_i, containing the kinematic dependence of the amplitude and a basis of tensors T_i, governing the tensorial structure of the process. A convenient method to deal with the tensor structure at all loop orders is the 't Hooft Veltman scheme (tHV). It allows for a form factor decomposition of the scattering amplitude, keeping the set of basis tensors fixed, independent of the loop order. While the form factor decomposition is a convenient way to provide the analytic result for the amplitude, the complexity of the representation depends on the choice of tensor basis. Generally, form factors have a non-trivial dependence on the gram determinant in the denominator, that cancels in the amplitude at tree-level and leading poles at higher order. For an optimal choice of basis tensors, the spurious pole in the gram determinant would cancel already at the level of the form factors. We explore various methods to improve the tensor basis and argue, that fixing the helicities of the massless quarks is natural, while trying to cancel the gram determinant by fixing linear combinations of the chiralities of the massive quarks or the polarization vector of the W boson is not expedient. The question if there exists a better tensor basis is left open for further investigation.

While the form factors at tree level are rational functions in the kinematic variables, at NLO they contain scalar integrals in the loop momentum. The scalar Feynman integrals can be grouped into integral families based on their denominator structure, forming vector spaces with a finite number of basis integrals, the master integrals. Therefore, all scalar integrals can be reduced to a linear combination of master integrals using integration-by-parts (IBP) relations. We compute the master integrals of each family by deriving closed first order differential equations in the kinematic variables for them, that can be solved after numerically computing boundary values for the master integrals. One particularly useful way to do so, is to chose canonical master integrals, leading to a differential equation in the canonical form. This allows for a solution in terms of iterated integrals order by order in the dimensional regulator.

We insert the reduction into the form factors and simplify the rational coefficients in front of independent integrals at each order in the ε-expansion. Finally, we discuss the next steps and main challenges towards computing the two-loop amplitude.