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Automated Computation of Scattering Amplitudes from Integrand Reduction to Monte Carlo tools

Hans van Deurzen[a], Gionata Luisoni[a], Pierpaolo Mastrolia[a,b], Giovanni Ossola[c,d,*], Zhibai Zhang[c,d]

[a]*Max-Planck Insitut für Physik, Föhringer Ring 6, 80805 München, Germany*
[b]*Dipartimento di Fisica e Astronomia, Università di Padova, and INFN Sezione di Padova, via Marzolo 8, 35131 Padova, Italy*
[c]*Physics Department, New York City College of Technology, The City University of New York, 300 Jay Street Brooklyn, NY 11201, USA*
[d]*The Graduate School and University Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, USA*

Abstract

After a general introduction about the calculation of one-loop scattering amplitudes via integrand-level techniques, which led to the construction of efficient and automated computational tools for NLO predictions, we briefly describe an approach to the reduction of scattering amplitudes based on integrand-level reduction via multivariate polynomial division also applicable beyond one-loop amplitudes. We also review the main features of the GoSam 2.0 automated framework for NLO calculations and show some of its application to Standard Model processes involving the production massive particles, such as the Higgs boson or top-quark pairs, obtained embedding of the virtual amplitudes produced by GoSam within existing Monte Carlo tools.

Keywords: Scattering Amplitudes, Integrand Reduction, Automation

1. Introduction

The evaluation of scattering amplitudes allows us to test the phenomenological prediction of particle theory with the measurement at collider experiments. By a more abstract point of view, scattering amplitudes can be studied in terms of their symmetries and analytic properties. The understanding of their mathematical structure naturally provides the theoretical framework to develop new techniques for their evaluation, and ultimately to design more efficient computational algorithms for the production of physical cross sections and differential distributions.

Theory predictions play a fundamental role in the particle physics experiments at current hadron colliders. The high luminosity accumulated by the experimental collaborations during the Run-I of the Large Hadron Collider (LHC), allowed for a very detailed investigation of the Standard Model of particle physics. In these analyses, for example to study the properties of the recently discovered Higgs boson [1–4], theoretical predictions are indispensable both for the signal and for the modeling of the relevant background processes, which share similar experimental signatures. Beyond Higgs studies, precise theory predictions allow one to constrain model parameters in the event that a signal of New Physics is detected during the Run-II at the LHC with improved energy.

In this interplay between theoretical prediction and experimental data, it is crucial that the level of productivity of the theory matches the precision of the measurements. Since leading-order (LO) results are affected by large uncertainties, theory predictions are not reliable without accounting for higher orders. Therefore, it is of primary interest to provide theoretical tools which are able to perform the comparison of LHC data to theory at next-to-leading-order (NLO) accuracy.

One of the scopes of this talk is to summarize the recent progress in the evaluation of scattering amplitudes and provide a brief description of integrand-level tech-

*Speaker and Corresponding Author

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niques, in particular the OPP reduction algorithm, the $d-$dimensional decomposition of scattering amplitudes, and the integrand reduction via multivariate polynomial division.

We will also review the main features of the GoSam framework [5, 6] for the automated computation of one-loop amplitudes and some of the recent results obtained using it. Since the main purpose of GoSam is the computation of the virtual NLO part, in order to produce integrated cross sections and differential distributions it should be interfaced with Monte Carlo (MC) tools. We will focus on this important point in the last part of the talk, where we show some examples of applications.

For a wider outlook on the field, we refer the reader to the plenary presentation of Pierpaolo Mastrolia at this conference [7]. Detailed reports and comprehensive reviews on the different topics described here can be also found in [8–12].

2. Scattering Amplitudes at NLO

The computation of NLO matrix elements requires, in addition to the tree-level LO result, the evaluation of one-loop virtual corrections and contributions from real emission. Both terms are separately infrared (IR) divergent and only their combination leads to a physical result. Moreover, the virtual part is also ultraviolet (UV) divergent, and the UV poles are removed by the renormalization procedure.

While the LO matrix elements and the NLO real parts have been available for a long time, until recently the evaluation of the virtual part of one-loop contributions represented the bottleneck towards the automation of NLO computation. The standard method for the computation of NLO virtual corrections relies on the evaluation of all NLO Feynman diagrams associated with the process. The general task of the calculation is to compute, for each diagram contributing to the amplitude and for each phase space point, the following integral:

$$\mathcal{M} = \int d^d\bar{q}\ \mathcal{A}(\bar{q}) = \int d^d\bar{q} \frac{\mathcal{N}(\bar{q})}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}}\,, \qquad (1)$$

where the $\bar{q}$ denotes integration momenta in $d = 4 - 2\epsilon$ dimensions following the prescription $\bar{q}^2 = q^2 - \mu^2$ and $\bar{D}_i = (\bar{q} + p_i)^2 - m_i^2 = (q + p_i)^2 - \mu^2 - m_i^2$, are accordingly the $d-$dimensional denominators generated by the propagators of the particles inside the loop.

It is well known [13, 14] that the evaluation of the one-loop diagrams can be performed by decomposing each integral $\mathcal{M}$ in terms of a finite set of scalar master integrals (MIs), plus an additional rational function of the masses and momenta appearing in the original amplitude, known in the literature as *rational part* $\mathcal{R}$. The one-loop "master formula" allows to rewrite the integral in Eq. (1) as

$$\begin{aligned}\mathcal{M} \ =\ & \sum_{i_0<i_1<i_2<i_3}^{m-1} \mathbf{d}(\mathbf{i_0 i_1 i_2 i_3}) \int d^d\bar{q}\, \frac{1}{\bar{D}_{i_0}\bar{D}_{i_1}\bar{D}_{i_2}\bar{D}_{i_3}} + \\ + & \sum_{i_0<i_1<i_2}^{m-1} \mathbf{c}(\mathbf{i_0 i_1 i_2}) \int d^d\bar{q}\, \frac{1}{\bar{D}_{i_0}\bar{D}_{i_1}\bar{D}_{i_2}} + \\ + & \sum_{i_0<i_1}^{m-1} \mathbf{b}(\mathbf{i_0 i_1}) \int d^d\bar{q}\, \frac{1}{\bar{D}_{i_0}\bar{D}_{i_1}} + \\ + & \sum_{i_0}^{m-1} \mathbf{a}(\mathbf{i_0}) \int d^d\bar{q}\, \frac{1}{\bar{D}_{i_0}} \ +\ \mathcal{R}\,. \end{aligned} \qquad (2)$$

The calculation of virtual amplitudes can be visualized in terms of three tasks: i) the *generation* of the unintegrated amplitudes $\mathcal{A}$, namely their numerator functions $\mathcal{N}(q)$ and the list of denominators $\bar{D}_i$; ii) the *reduction* of the amplitude to determine all coefficients multiplying each of the MIs in Eq. (2) and the rational term $\mathcal{R}$; iii) the *evaluation of the MIs* which, multiplied by the coefficients obtained in the reduction, provide the final result for the amplitudes. Since in the one-loop case, all scalar master integrals are known and available in public codes [15–19], and amplitudes can be efficiently generated with algebraic or numerical techniques, people mostly focused on the intermediate step, namely the stable and efficient extraction of all the coefficients.

3. Integrand-Reduction Techniques

During the past decade, a powerful framework for one-loop calculation was developed by merging the idea of four-dimensional unitarity-cuts [20, 21], which allow to explore the (poly)logarithmic structure of the amplitudes, with the understanding of the universal algebraic form of any one-loop scattering amplitudes, contained in the OPP method [22–25].

The reduction at the integrand level is based on the decomposition of the numerator function of the amplitude in terms of the propagators that depend on the integration momentum, in order to identify before integration the structures that will generate the scalar integrals and their coefficients and those that will vanish upon integration of the loop momentum. In this approach, the coefficients in front of the MIs can be determined by solving a system of algebraic equations that are obtained by: i) the numerical evaluation of the numerator of the integrand at explicit values of the loop-variable; ii) and the knowledge of the most general polynomial structure of the integrand itself.