PROCEEDINGS OF SCIENCE

Computational tools for scattering amplitudes at NLO QCD

Andreas van Hameren*
The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences
E-mail: hameren@ifj.edu.pl

The program HELAC-NLO is presented, which enables automated calculations for hard scattering processes at next-to-leading order QCD. In particular an update of ONELOOP, used for the evaluation of scalar master integrals, is addressed.

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*Speaker.

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1. Introduction

In order to achieve scientific successes in elementary particle physics, like the recent discovery of a boson with a mass of around 125GeV at the LHC, it is essential to have theoretical control over signals and backgrounds in a large variety of scattering processes. There are, for example, the processes involving the many production and decay channels of the Standard Model Higgs boson. They involve many particles in the final state, and the desired precision demands at least next-to-leading order accuracy for perturbative calculations in QCD. There has been a remarkable progress in recent years regarding such calculations for processes with four or more final-state particles and/or partons [1–12]. Also, there has been progress in combining NLO QCD calculations for three or more final-state particles with the all-order parton shower approach [13–18].

2. Helac-NLO

Several of the fixed-order calculations mentioned before [4,7,10] have been performed with the help of a collection of computer programs, published under the name HELAC-NLO, as a complete tool for such calculations [19]. It uses the implementation HELAC-DIPOLES [20] of the dipole-subtraction scheme in order to regularize the IR divergences in the real-radiation contribution of NLO QCD calculations. It also provides the integrated subtraction terms, the divergences of which are to be cancelled against those coming from the virtual contribution. HELAC-1LOOP [21] is used to provide the one-loop amplitudes for the latter. It applies OPP reduction with the help of CUTTOOLS [22], relying on the scalar master integrals provided by ONELOOP [23]. The necessary rational terms not provided by CUTTOOLS are also included [24, 25]. One of the basic ingredients in fixed-order calculations for processes with several final-state particles are tree-level off-shell currents, which are constructed using HELAC [26,27]. Phase space integration, finally, is performed with the help of KALEU [28], which employs dipole channels in order to deal with the real-radiation contribution.

3. OneLOop

There are many techniques constituting the art of calculating one-loop amplitudes with several external particles. The very fist bifurcation in the different approaches can be identified as the choice whether the amplitude is expressed in terms of universal one-loop functions, or not. In the latter case, numerical integration is applied to perform the one-loop integrals, in the former case the mentioned one-loop functions contain analytic expressions for one-loop integrals. In most approaches of this kind, the one-loop scalar integrals with up to four external legs (Figure 1) are necessary analytic building blocks. ONELOOP is a Fortran program to evaluates these, for all kinematical configurations relevant for collider-physics, and for any non-positive imaginary parts of the internal squared masses. Furthermore, it deals with all UV and IR divergences within dimensional regularization.

3.1 Numerical stability in one-loop calculations

In any numerical application aiming at the calculation of a quantity by expressing it in terms of a basis and finding the coefficients for this basis, numerical stability is an important issue. Such

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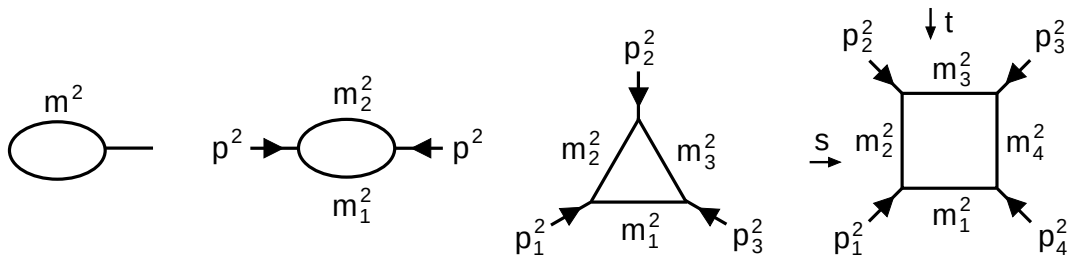

Figure 1: A graphical representation of the one-loop 1-point, 2-point, 3-point and 4-point scalar functions.

strategies involve the inversion of linear systems, and although these systems are rather small in the calculation of one-loop amplitudes, they can become near-singular, giving rise to small Gram determinants, and leading to numerical instabilities. In approaches that use tensor-integrals as an increased universal set of one-loop functions, as compared to the set of scalar functions, dedicated universal and process-independent techniques can be applied to cure the numerical instabilities as much as possible [29–33]. In approaches applying direct integrand-level reduction to the scalar integrals [34, 35] this has not been proven to be possible. In these, the strategy is to diagnose numerically unstable situations as such, and to redo the calculation at higher machine precision if necessary. This typically only happens in a small subset of all phase space points in a Monte Carlo calculation for which one has to evaluate the one-loop amplitude. One then has the possibility to differentiate, and redo only part of the computation at higher precision, *eg.* only the coefficients and not the basis functions. Still, it may be necessary to perform the full calculation at higher machine precision [36].

3.2 Usage

In light of the foregoing, ONELOOP has been upgraded to be used at higher machine precision. This may be any intrinsic floating point type provided by the Fortran compiler, or any of the multi precision types provided by the programs `mpfun90`, `arprec`, `qd` or `ddfun90` [37]. After downloading the latest version of ONELOOP from

`http://helac-phegas.web.cern.ch/helac-phegas/OneLOop.html`

and unpacking it, the user should enter the ONELOOP directory and fill out the file `Config`. Then, the scripts

```
./configure.py
./create.py
```

should be executed in order to create the source file and to build the library. As the extensions of the scripts indicate, the user is required to have `python` available on their system. If the user only desires to create the source file, they may execute

```
./create.py source
```

instead of `./create.py`. If the user wishes to incorporate the creation of the source file into the build of a larger program or library, they can use the script `avh_olo.py` which can be found in the `src` directory. Instead of specifying the parameters in the file `Config`, they can be given as arguments to this script, *eg.*

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```
./src/avh_olo.py dpkind="kind(1d0)" mptype="mpfun90"
```

The routines provided by OneLOop are accessed via a module

```
use avh_olo
```

It supplies a single generic subroutine for all scalar functions for all intrinsic kinds, types (real or complex) and multi precision types of arguments

```
call olo( rslt ,m ,rmu )                                  !A0
call olo( rslt ,p,m1,m2 ,rmu )                            !B0
call olo( rslt ,p1,p2,p3 ,m1,m2,m3 ,rmu )                 !C0
call olo( rslt ,p1,p2,p3,p4,s,t ,m1,m2,m3,m4 ,rmu )       !D0
```

The output `rslt` shall be an array of shape `(0:2)` and of the same complex kind/type as the input. Its entries contain the ε^0, ε^{-1} and ε^{-2} contribution respectively, where ε is defined within dimensional regularization following $D = 4-2\varepsilon$. The input may be real or complex with the following restrictions: all squared momenta and masses must real, or all squared momenta must be real and all squared masses complex, or all squared momenta and masses must be complex. The imaginary part of complex momenta is ignored. The renormalization scale `rmu` is optional real input. If not provided, the default value is used, which can be set with

```
call olo_scale( rmu )
```

If this routine is not called, the default value is 1. The type and kind of the input for this routine shall be `real(kind(1d0))`.

The subroutines for the scalar functions infer from the input whether an IR singlular case is encountered. This means that the input must reflect the exact kinematics for such a case, *i.e.* exact zeros and/or exact identities between input values. This can be unpractical, and a routine is provided to set a finite resolution threshold

```
call olo_onshell( thrs )
```

The input `thrs` has the dimension of a squared mass, and sets the value below which input is considered to be zero, or absolute values of differences between input arguments are considered to be zero. The type and kind of the input for this routine shall be `real(kind(1d0))`.

In case one of the multi precision packages `mpfun90` or `arprec` is used, the precision can be set during runtime with

```
call olo_precision( ndigits )
```

The program will check whether the particular number of digits has been requested before. If not, the necessary tables of expansion terms and thresholds will be filled and stored, and this will happen only once.

By default, all messages issued by OneLOop are sent to standard output. This can be changed with

```
call olo_unit( iunit ,message )
```

The integer `iunit` shall be the unit the user wants the messages to be sent to, and the character `message` shall be one of `'error'`, `'warning`, `'message'`, `'printall'`. If the last option is set, all input and output of all scalar functions is sent to a logfile specified by `iunit`.

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Besides the scalar functions, ONELOOP also provides the 2-point Passarino-Veltman coefficient functions B_{11}, B_{00} and B_1 via

```
call olo( b11,b00,b1,b0 ,p,m1,m2, rmu )
```

The first four arguments represent the respective functions including the scalar function, and are arrays of shape `(0:2)` again.

4. Summary

The package HELAC-NLO for the calculation of hard scattering processes at NLO QCD was presented. In particular, an update of the component ONELOOP for the evaluation of one-loop scalar functions was presented, with the feature that it can now evaluate them at arbitrary precision.

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