

Automated one-loop calculations with GoSam 2.0

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We present the version 2.0 of the program GOSAM, which is a public program package to compute one-loop corrections to multi-particle processes. The extended version of the “Binoth-Les-Houches-Accord” interface to Monte Carlo programs is also implemented. This allows a large flexibility regarding the combination of the code with various Monte Carlo programs to produce fully differential NLO results, including the possibility of parton showering and hadronisation. We describe the new features of the code and illustrate the wide range of applicability for multi-particle processes at NLO, both within and beyond the Standard Model.

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1. Introduction

The development of automated NLO tools has seen much progress in the past years, leading to an almost industrial production of NLO QCD predictions for multi-particle processes. In fact, the pre-2013 “Les Houches wishlist” of Standard Model processes which are desired to be available at NLO is meanwhile fully ticked in what concerns fixed order QCD predictions, moving now towards parton shower matching, electroweak corrections, interferences, and NNLO corrections [1].

The standard at the LHC should be NLO corrections matched to a parton shower, ideally including the matching of different jet multiplicities. Flexible, automated NLO codes are a pre-requisite to achieve this goal. Here we will present the version 2.0 of the code GOSAM which is able to produce multi-particle one-loop predictions for user-defined processes, both within the Standard Model and beyond.

GOSAM [2,3] is a code which was designed to maximally exploit both the integrand reduction for dimensionally regulated one-loop amplitudes [4,5], as implemented in SAMURAI [6], as well as improved tensor reduction methods as developed in [7] and implemented in the code GOLEM95C [8–10]. An important new feature in version 2.0 is the fact that GOSAM can also be interfaced with a new library, called NINJA [11, 12], implementing an ameliorated integrand-reduction method, where the decomposition in terms of master integrals is achieved by Laurent expansion through semi-analytic polynomial divisions [13].

The new version of the program GOSAM [3] has been used already to produce a number of NLO predictions both within [14–23] and beyond [24, 25] the Standard Model. It contains important improvements in speed, numerical robustness, range of applicability and user-friendliness. GOSAM can be linked to different Monte Carlo programs via the Binoth-Les-Houches-Accord BLHA [26], where the extended version BLHA2 [27] is also implemented. The program can be downloaded from <http://gosam.hepforge.org>.

2. Workflow of the program

GOSAM can be used either as a standalone code producing one-loop (and colour/spin correlated tree level) amplitudes, or it can be used in combination with a modern Monte Carlo event generator program. The main workflow of GOSAM is shown in Fig. 1.

In the standalone version, the user will fill out a process run card `process.in` to define the process to be calculated, where also further options are available. Then the code for the virtual amplitudes is generated by invoking `gosam.py process.in`.

After running the above command with an appropriate run card, all the files which are relevant for code generation will be created. The command `make source` will invoke QGRAF [28] and FORM [29, 30] to generate the diagrams and algebraic expressions for the amplitudes, using also `spinney` [31] for the spinor algebra and `haggies` [32] for code generation. In version 2.0 of GOSAM, the production of optimized code largely relies on the new features of FORM version ≥ 4 . The command `make compile` will finally compile the produced code.

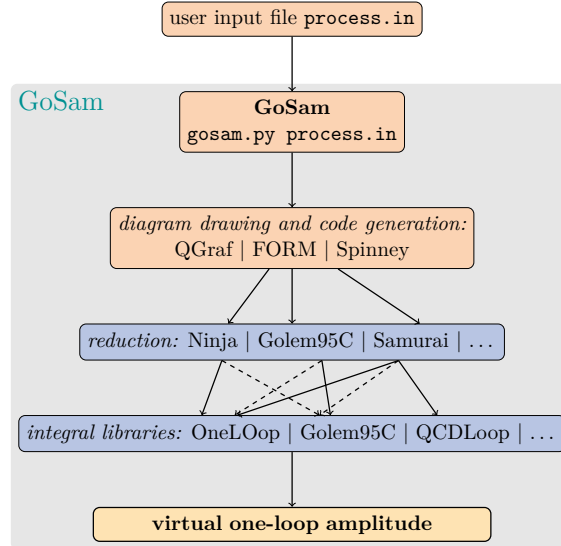


Figure 1: Basic flowchart of GOSAM.

We should point out that all the reduction- and integral libraries used in GOSAM-2.0 are included in the program package, and the installation script will take care of compilation and linking, such that the user does not have to worry about dependencies.

In the mode where GOSAM is used in combination with a Monte Carlo program providing the real radiation and infrared subtraction parts and performing the phase space integration, the whole amplitude generation process can be invoked automatically and steered by the Monte Carlo program setup, if the MC has the appropriate functionality. This is most conveniently done via the Bin θ -Les-Houches-Accord BLHA interface [26,27], which allows to link one-loop programs to Monte Carlo programs in a standardized way. This setup also allows to produce NLO results matched to a parton shower if provided by the Monte Carlo program.

3. New features

3.1 Improvements in code generation

Using largely the features provided by FORM version ≥ 4.0 [30] to produce optimized expressions leads to more compact code and a speed-up in amplitude evaluation of about a factor of ten.

In addition, the new release contains an option called `diagsum` which combines diagrams differing only by a subdiagram into one “meta-diagram” to be processed as an entity. This further reduces the number of calls to the reduction program and therefore increases the computational speed. The `diagsum` mode is activated by default.

Another new feature in GOSAM-2.0 is the use of numerical polarisation vectors for massless gauge bosons. This means that the various helicity configurations for the massless bosons will be evaluated numerically, based on a unique code containing generic polarisation vectors, rather than producing separate code for each helicity configuration.

3.2 Improvements in the reduction

In GOSAM-2.0, the amplitude decomposition can be obtained by a new integrand-reduction

method [13], implemented in the C++ code NINJA [11, 12]. This novel D -dimensional unitarity-based algorithm is lighter than the original integrand reduction method, because less coefficients need to be determined, and it was found to be faster and numerically more accurate. The integrand-reduction library SAMURAI [6, 33], as well as the tensor reduction- and integral library GOLEM95C [8–10] are also available in GOSAM-2.0, and it is possible to switch between the different reduction methods “on the fly”. We would like to point out that the reduction library GOLEM95C also contains an interface to integrand-reduction methods via tensorial reconstruction [34], where the coefficients of tensor integrals rather than scalar integrals are reconstructed, and the tensor integrals are called from GOLEM95C. To rescue phase space points which do not pass the numerical precision test, we use GOLEM95C as the default.

3.3 Electroweak scheme choice

Renormalisation within the Standard Model can be performed using various schemes, which also may differ in the set of electroweak parameters considered as input parameters, while other electroweak parameters are derived ones. Within GOSAM-2.0, different schemes can be chosen by setting appropriately the flag `model.options`. If the flag is not set in the input card, GOSAM generates a code which uses M_W , M_Z and α as input parameters.

3.4 Stability tests and rescue system

For the precision analysis contained in GOSAM-2.0, and to set the trigger for the rescue system, we employ a hybrid method that combines the benefits in computational speed of testing the accuracy of the pole coefficients (called *pole test*) with the higher reliability of testing the finite part, where the latter is achieved by exploiting the invariance of the scattering amplitudes under an azimuthal rotation about the beam axis (called *rotation test*). In more detail, after computing the matrix elements, GOSAM-2.0 checks the precision δ_{pole} of the single pole with the *pole test*. Comparing the coefficient of the single pole \mathcal{S}_{IR} that can be obtained from the general structure of infrared singularities to the one provided by GOSAM-2.0, which we label \mathcal{S} , we define

$$\delta_{pole} = |(\mathcal{S}_{IR} - \mathcal{S})/\mathcal{S}_{IR}|. \quad (3.1)$$

The corresponding estimate of the number of correct digits in the result is provided by $P_{pole} = -\log_{10}(\delta_{pole})$. The value of P_{pole} is then compared with two thresholds P_{high} and P_{low} . If $P_{pole} > P_{high}$, the point is automatically accepted. If $P_{pole} < P_{low}$, the point is automatically discarded, or sent to the rescue system. If already the pole coefficient has a low precision, we can expect the finite part to be of the same level or worse. In the intermediate region where $P_{high} > P_{pole} > P_{low}$, it is more difficult to determine the quality of the result solely based on the pole coefficients. Only in this case the point is recalculated using a phase space point which is rotated around the beam axis to assess the numerical precision of the original point, i.e. the *rotation test* is performed.

3.5 New range of applicability

Higher rank integrals

The libraries NINJA, GOLEM95C and SAMURAI all support integrals with tensor ranks exceeding the number of propagators. These extensions are described in detail in Refs. [10, 13, 33]

and are contained in the distribution of GOSAM-2.0. The additional integrals will be called automatically by GOSAM if they occur in an amplitude, such that the user can calculate amplitudes involving higher rank integrals without additional effort.

Production of colour-/spin correlated tree amplitudes

GOSAM can also generate tree level amplitudes in a spin- and colour-correlated form. These matrix elements are particularly useful in combination with Monte Carlo programs which use these trees to build the dipole subtraction terms for the infrared divergent real radiation part. With these modified tree level matrix elements GOSAM is able to generate all necessary building blocks for a complete NLO calculation. Such a setup has been used successfully in combination with the framework of HERWIG++/MATCHBOX [1,48].

Support of complex masses

The integral libraries contained in the GOSAM package as well as the GOSAM code itself fully support complex masses. The latter are needed for the treatment of unstable particles via the introduction of the corresponding decay width. A consistent treatment of complex W - and Z -boson masses is given by the so-called complex mass scheme [35]. According to this scheme the boson masses and the weak mixing angle become

$$m_V^2 \rightarrow \mu_V^2 = m_V^2 - im_V \Gamma_V \quad (V = W, Z), \quad \cos^2 \theta_W = \frac{\mu_W^2}{\mu_Z^2}. \quad (3.2)$$

To use the complex mass scheme, the corresponding model files `sm_complex` or `smdiag_complex` should be called, where the latter contains a diagonal unity CKM matrix.

4. Installation and usage

4.1 Installation

The user can download the code either as a tar-ball or from a subversion repository at

`http://gosam.hepforge.org`

The installation of GOSAM-2.0 is very simple when using the installation script. The latter can be downloaded by

```
wget http://gosam.hepforge.org/gosam-installer/gosam_installer.py
```

To run the script the user should execute the following commands

```
chmod +x gosam_installer.py
./gosam_installer.py [-prefix=...]
```

Upon installation, the installer will ask some questions, which are described in more detail in the manual [36]. To use the default installation all the questions can be “answered” by pressing the ENTER key. The program GOSAM is designed to run in any modern Unix-like environment (Linux, Mac).

4.2 Using GOSAM

Here we only describe the usage of GOSAM in the standalone version. For the usage in combination with a Monte Carlo program, based on the BLHA interface, we refer to the manual [36]. In order to generate the matrix element for a given process the user should create a process specific setup file, `process.in`, which we call *process card*. A simple example process card for the QCD corrections to the process $e^+e^- \rightarrow t\bar{t}$, where all options take default values, looks as follows:

```
in = e+, e-
out = t, t~
order = gs, 0, 2
```

It is recommended to generate and modify a template file for the process card. This can be done by invoking the shell command `gosam.py --template process.in`, which generates the file `process.in` with some documentation for all defined options. The options are filled with the default values, and some paths are set by the installation script. In order to generate the Fortran code for the process specified in the input card the user simply needs to invoke `gosam.py process.in`.

5. Applications

Some examples of processes where the new version of GOSAM has already been used, in combination with various Monte Carlo programs, to produce phenomenological results are shown in Table 1. More details about the Higgs plus jets processes can also be found in the contribution of F. Tramontano [37].

5.1 Examples Beyond the Standard Model

Examples for the usage of GOSAM with a model file different from the Standard Model are the calculation of the SUSY QCD corrections to neutralino pair production in association with an extra jet, including full off-shell effects [24], or the QCD corrections to graviton plus jet production in models with large extra dimensions [25].

The corresponding model files in UFO [50] format were generated using `FeynRules` [51]. To import new model files within the GOSAM setup, the user only needs to specify the path to the model file in the *process card*. For more details about the setup and the phenomenological results we refer to [3, 24, 25].

6. Conclusions

GOSAM-2.0 is a flexible tool to calculate one-loop QCD corrections both within and beyond the Standard Model, as well as electroweak corrections. The new version of the program offers a wide range of applicability. In particular, integrals where the rank exceeds the number of propagators (needed e.g. in effective theories) are fully supported, and propagators for spin-2 particles are implemented. The complex mass scheme is supported, including the complexification of the couplings, and several electroweak schemes can be chosen. GOSAM-2.0 also contains a new integrand reduction method, the integrand decomposition via Laurent expansion, implemented in the

Table 1: NLO calculations done by interfacing GoSAM with different Monte Carlo programs.

GOSAM + MadDipole/MadGraph4/MadEvent [38–42]
$pp \rightarrow W^+W^- + 2 \text{ jets}$ [14]
$pp \rightarrow \gamma\gamma + 1,2 \text{ jets}$ [16, 21]
SUSY QCD corrections to $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + 1 \text{ jet}$ [24]
QCD corrections to $pp \rightarrow \text{graviton}(\rightarrow \gamma\gamma) + 1 \text{ jet}$ [25]
GOSAM + SHERPA [43, 44]
$pp \rightarrow W^+W^- b\bar{b}$ [23]
$pp \rightarrow t\bar{t} + 0,1 \text{ jet (merged+shower)}$ [18]
$pp \rightarrow H + 2 \text{ jets (gluon fusion)}$ [15]
$pp \rightarrow t\bar{t}H + 0,1 \text{ jet}$ [20]
$pp \rightarrow W^+W^+ + 2 \text{ jets}$ [45]
$pp \rightarrow W^\pm b\bar{b} (m_b \neq 0)$ [45]
GOSAM + MadDipole/MadGraph4/MadEvent+SHERPA
$pp \rightarrow H + 3 \text{ jets (gluon fusion)}$ [19]
GOSAM + POWHEG [46, 47]
$pp \rightarrow HW/HZ + 0,1 \text{ jet (merged+shower)}$ [17]
GOSAM + HERWIG++/MATCHBOX [48, 49]
$pp \rightarrow Z/\gamma^* + 1 \text{ jet (+shower)}$ [1]

library NINJA, which leads to a considerable gain in stability and speed. In addition, GoSAM-2.0 can provide spin-and colour correlated tree-level matrix elements. Monte Carlo programs can be interfaced easily using the Binoth-Les-Houches-Accord, where the new standards are also supported. The automated interface to Monte Carlo programs offers the possibility to produce parton showered events and to compare different Monte Carlo event generators at the NLO level.

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