

# GoSam applications for automated NLO calculations

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**Abstract.** We present applications of the program GOSAM for the automated calculation of one-loop amplitudes. Results for NLO QCD corrections to beyond the Standard Model processes as well as Higgs plus up to three-jet production in gluon fusion are shown. We also discuss some new features of the program.

## 1. Introduction

With the LHC data confirming the Standard Model to an almost incredible extent, precision measurements will be of enormous importance in order to scrutinize the Higgs properties and be sensitive to deviations from the Standard Model, and such measurements should come in hand with precision predictions. Therefore, it is of primary interest to provide tools which allow one to perform the comparison of LHC data to theory at NLO accuracy.

The automation of NLO calculations for multi-particle final states has seen an enormous level of progress in the past years, as can be seen from examples for recent achievements in terms of codes [1–10] providing one-loop amplitudes.

In this talk, we explain the usage and present applications of the program GOSAM [4], which can generate and evaluate one-loop amplitudes for multi-particle processes in a fully automated way. GOSAM also offers the possibility to be interfaced – via the Binoth Les Houches interface [11, 12] – to different Monte Carlo programs providing the real radiation and the infrared subtraction terms. Further, an interface to model files in Universal FeynRules Output (UFO) [13] or LanHEP [14] format allows to extend the application range of the code to Beyond the Standard Model physics.

## 2. The GoSam program

### 2.1. Generation of the virtual amplitudes

Amplitudes are expressed in terms of Feynman diagrams, where the integrand is generated analytically using QGRAF [15], FORM [16], spinney [17] and haggies [18].

The information about the model is either read from the built-in Standard Model file or is generated from a Universal FeynRules Output (UFO) [13, 19] or LanHEP [14] file. Precompiled MSSM\_UFO and MSSM\_LHEP files and examples for their import can also be found in the subdirectory `examples/model`.

The program offers the option to use different reduction techniques: either the unitarity-based integrand reduction [20, 21] as implemented in SAMURAI [22] or traditional tensor reduction as implemented in `golem95C` [23, 24] interfaced through tensorial reconstruction at the integrand level [25], or a combination of both.

## 2.2. Installation and Usage

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

<http://projects.hepforge.org/gosam/>

To install GOSAM, the user needs to run

```
python setup.py install --prefix MYPATH
```

If MYPATH is not among the system default paths, the environment variables `PATH`, `LD_LIBRARY_PATH` and `PYTHONPATH` might have to be set accordingly. For more details we direct the user to [4] and the reference manual coming with the code.

Prerequisites are a Linux/Unix environment, Python ( $\geq 2.6$ ), JAVA ( $\geq 1.5$ ), Make, and a Fortran95 compiler. On top of a standard Linux environment, the programs FORM [16, 26] version  $\geq 3.3$ , and QGRAF [15] need to be installed on the system. Further, at least one of the libraries SAMURAI [22] or `golem95C` [24] needs to be present at compile time of the generated code. For the user's convenience we have prepared a package `gosam-contrib-1.0.tar.gz` containing SAMURAI and `golem95C` together with the integral libraries OneLoop [27], QCD-Loop [28] and FF [29]. The package is available from <http://projects.hepforge.org/gosam/>.

In order to generate the code for a process, the user needs to prepare an input file which we will call *process.in*, containing

- process specific information, such as a list of initial and final state particles, their helicities (optional), the order of the coupling constants, and the underlying model;
- scheme specific information, such as the regularisation and renormalisation schemes;
- system specific information, such as paths to programs and libraries or compiler options;
- optional information for optimisations which control the code generation.

The code can also generate a template input file. In order to import settings with system specific information in an automated way, the user can prepare a file *gosam.rc* which will be imported into *process.in* by `gosam.py -m gosam.rc -t process.in`. The virtual amplitude can then be generated and compiled by invoking

```
gosam.py process.in
make compile
```

## 2.3. Interfacing with Monte Carlo programs for the real radiation

The so-called ‘‘Binoth Les Houches Accord’’ (BLHA) [11, 12] defines an interface for a standardised communication between one-loop programs (OLP) and Monte Carlo (MC) tools, where the latter provide the Born amplitude, as well as the matrix elements for the NLO real radiation and the infrared subtraction terms. GOSAM can act as an OLP in the framework of the BLHA, such that the calculation of complete cross sections is straightforward.

In the BLHA setup, the MC writes an order file containing the process specifications, called for example `olp_order.lh`, which can be used by `gosam.py` to generate the virtual amplitude as follows:

**Table 1.** NLO calculations done by interfacing GOSAM with different Monte Carlo programs.

GOSAM + MadDipole/MadGraph4/MadEvent [30–35]
$pp \rightarrow b\bar{b}b\bar{b}$ [36, 37] $pp \rightarrow W^+W^- + 2 \text{ jets}$ [38] $pp \rightarrow \gamma\gamma + 1, 2 \text{ jets}$ [39, 40] SUSY QCD corrections to $pp \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 + \text{jet}$ [41] QCD corrections to $pp \rightarrow \text{graviton}(\rightarrow \gamma\gamma) + \text{jet}$ [42]
GOSAM + SHERPA [43, 44]
$pp \rightarrow W^+W^+ + 2 \text{ jets}$ $pp \rightarrow W^\pm b\bar{b}$ $pp \rightarrow W^+W^- b\bar{b}$ [45] $pp \rightarrow W^+W^-$ $pp \rightarrow W^\pm + 0, 1, 2, 3 \text{ jets}$ $pp \rightarrow Z/\gamma + 0, 1, 2 \text{ jets}$ $pp \rightarrow t\bar{t} + 0, 1 \text{ jets}$ [46] $pp \rightarrow H + 2 \text{ jets (gluon fusion)}$ [47] $pp \rightarrow t\bar{t}H + 0, 1 \text{ jet}$ [48]
GOSAM + MadDipole/MadGraph4/MadEvent+SHERPA
$pp \rightarrow H + 3 \text{ jets (gluon fusion)}$ [49]
GOSAM + POWHEG [50, 51]
$pp \rightarrow HW/HZ + 0 \text{ and } 1 \text{ jet}$ [52]

```
gosam.py --olp --mc=MCname --config=YourPathTo/gosam.rc olp_order.lh
```

The sequence `--mc=MCname` is optional, but can facilitate to adapt to MC specific settings. Supported names at the moment are `sherpa` and `powhegbox`. If `gosam.rc` is in the current working directory or in the GOSAM installation directory, its specification in the command line can be omitted. The following sequence of commands will generate and compile the files for the virtual matrix element:

```
sh ./autogen.sh --prefix = 'pwd'
make install
```

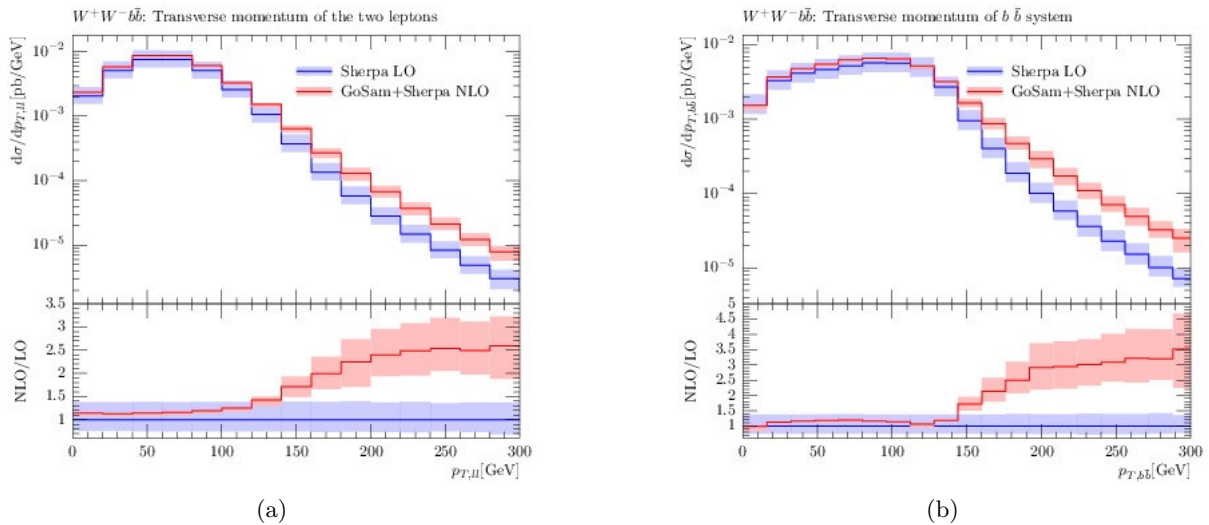
For more detailed information we refer to the BLHA `HowTo` on the GOSAM webpage. Examples for full NLO calculations with GOSAM interfaced to different MC programs are shown in Table 1. Further, pre-generated code to be used within SHERPA for a large number of processes can be downloaded from <http://projects.hepforge.org/gosam/proc>. To produce results for these processes, no GOSAM installation is needed. Automated scripts coming with the process packages will ensure smooth running within the SHERPA framework.

### 3. Phenomenological results

In the following we show a selection of results obtained with GOSAM interfaced to different Monte Carlo programs.

### 3.1. $W^+W^-b\bar{b}$

We calculated the NLO QCD corrections to the process  $pp(p\bar{p}) \rightarrow W^+W^-b\bar{b} + X \rightarrow (e^+\nu_e)(\mu^-\bar{\nu}_\mu)b\bar{b} + X$ , leading to a final state which is a signature of the decay of a  $t\bar{t}$  pair with leptonic  $W$  boson decays, including singly-resonant and non-resonant contributions. Results are shown for the LHC at 7 TeV. All final state partons are clustered into jets with a separation  $R > 0.5$  using the anti- $k_T$  jet algorithm [53, 54] implemented in `Fastjet` [55]. Each event has to contain at least two  $b$ -jets with  $p_{T,b} > 30$  GeV and  $\eta_b < 2.5$ . Further cuts are  $p_{T,l} > 20$  GeV,  $\eta_l < 2.5$ ,  $p_{T,\text{miss}} > 20$  GeV.



**Figure 1.** Results for (a) the transverse momentum distribution of the lepton pair stemming from  $W^+W^-$  boson decay and (b) transverse momentum distribution of the sum of the two tagged  $b$ -jet momenta.

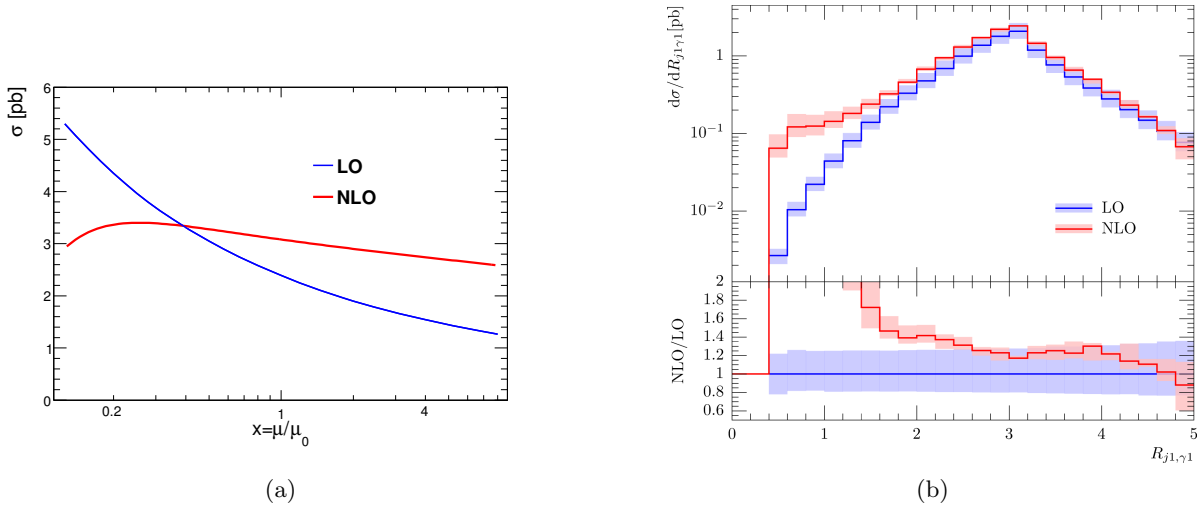
Figure 1 shows the distributions for the sum of the transverse momenta of the two leptons and the two  $b$ -jets, respectively. These observables receive large NLO corrections because most of the particles inherit their transverse momentum from a top quark pair. At LO the  $t\bar{t}$  pair has zero transverse momentum, while it can obtain transverse momentum at NLO by recoiling against the real radiation. Note that the LO scale variations cannot account for this effect and therefore the uncertainty band on the LO distribution obtained by scale variations does not include the NLO result in the tail of these distributions.

### 3.2. *Diphotons+jets*

GoSAM in combination with MadDipole/MadGraph4/MadEvent [30–35] has also been used to calculate the NLO QCD corrections to  $pp \rightarrow \gamma\gamma + 1$  jet [39] and  $pp \rightarrow \gamma\gamma + 2$  jets [40], where the former also includes the fragmentation component. The numerical results for  $pp \rightarrow \gamma\gamma + 2$  jets which are shown in Fig. 2 have been calculated at a center-of-mass energy  $\sqrt{s} = 8$  TeV. The following kinematic cuts have been applied:

$$p_T^{\text{jet}} > 30 \text{ GeV}, \quad p_T^{\gamma,1} > 40 \text{ GeV}, \quad p_T^{\gamma,2} > 25 \text{ GeV}, \\ |\eta^\gamma| \leq 2.5, \quad |\eta^j| \leq 4.7, \quad R_{\gamma,j} > 0.5, \quad R_{\gamma,\gamma} > 0.45.$$

For the photon isolation, we use the smooth cone isolation criterion [56] with  $R = 0.4$ ,  $n = 1$  and  $\epsilon = 0.05$ . Renormalization and factorization scales  $\mu$  and  $\mu_F$  have been set equal, with the central scale  $\mu_0^2 = \frac{1}{4} (m_{\gamma\gamma}^2 + \sum_j p_{T,j}^2)$ . Again, we observe a significant change of the shape at NLO, due to the extra QCD radiation in regions which are kinematically suppressed at LO.



**Figure 2.** (a) scale variations for diphoton+2 jets, (b)  $R$ -separation between the hardest jet and the hardest photon.

### 3.3. Associated Higgs production

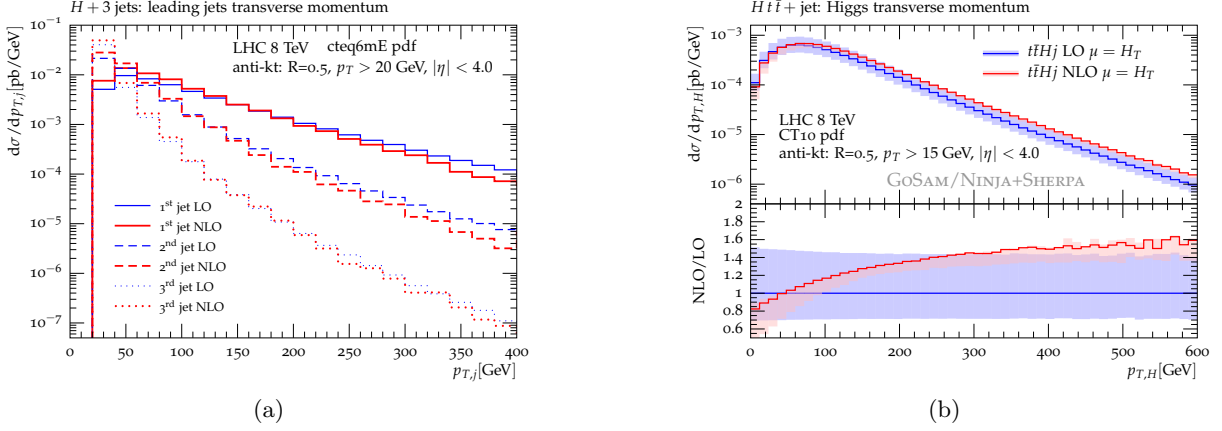
After the recent discovery of a Higgs boson at the LHC, being able to disentangle signal processes from background ones and also the different production channels of the SM Higgs boson became of central relevance. The developments in GOSAM allowed recently to compute the NLO QCD corrections to the production of  $H + 2$  jets [47] and  $H + 3$  jets [49] (in gluon-gluon fusion in the  $m_{top} \rightarrow \infty$  limit) and also of  $Ht\bar{t}$  and  $Ht\bar{t}$ +jet [48] for the LHC at 8 TeV.  $H + 2$  jets and the processes involving the top quark were computed using a fully automated interface to the Sherpa MC event generator, based on the BLHA, whereas for  $H + 3$  jets a hybrid setup combining the virtual part generated by GOSAM with MadDipole/Madgraph4/MadEvent and Sherpa was used. The virtual corrections for  $Ht\bar{t}(j)$  were computed using a new reduction algorithm based on an integrand decomposition via Laurent expansion [57], which was implemented in the library NINJA.

In the calculation of  $H + 3$  jets the cteq6L1 and cteq6mE parton-distribution functions were used for LO and NLO respectively, and a minimal set of cuts based on the anti- $k_T$  jet algorithm with  $R = 0.5$ ,  $p_{T,min} > 20$  GeV and  $|\eta| < 4.0$  was applied. For  $Ht\bar{t}(j)$  we used CT10 at NLO and a minimum transverse momentum cut of  $p_{T,min} > 15$  GeV.

Figure 3(a) shows the transverse momentum distributions at LO and NLO for the three leading jets in  $H + 3$  jets. We observe that the NLO corrections drag the  $p_T$ -spectra towards smaller  $p_T$  values, as expected as an effect of additional QCD radiation. Figure 3(b) displays the transverse momentum distribution of the Higgs boson in  $Ht\bar{t}j$  at LO and NLO. In this case the NLO corrections become larger with increasing  $p_T$ . Furthermore the scale uncertainty is reduced by 60-70% in going from LO to NLO.

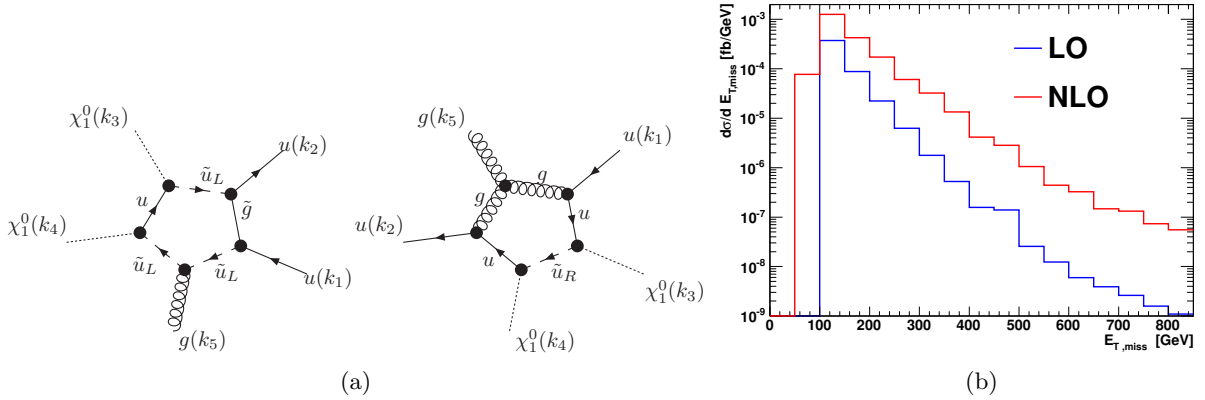
### 3.4. SUSY-QCD corrections to neutralino pair plus jet production

GOSAM also has been used to calculate the NLO Susy-QCD corrections to the production of a pair of the lightest neutralinos plus one jet at the LHC at 8 TeV, appearing as a monojet signature in combination with missing energy. We fully included all non-resonant diagrams, i.e. we did not use the simplifying assumption that production and decay factorise. Examples of pentagon diagrams occurring in the virtual corrections, as well as the missing transverse energy distribution, are shown in Fig. 4. We observe that the NLO corrections are large, mainly due



**Figure 3.** (a) transverse momentum distributions of the leading jets in  $H + 3$  jets production, (b) transverse momentum distribution of the Higgs boson in  $Ht\bar{t}$ +jet production.

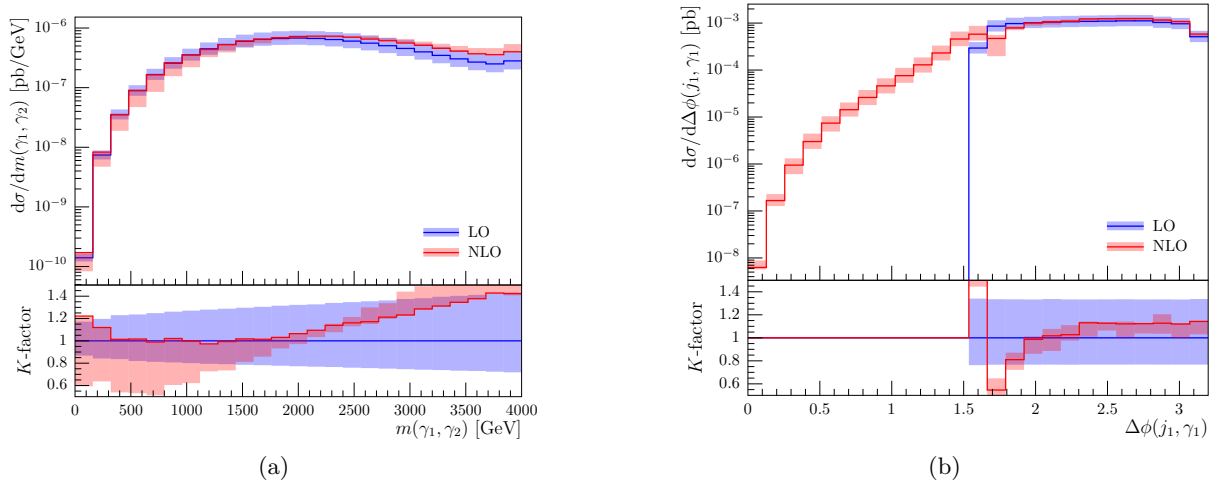
to additional channels opening up at NLO. The detailed setup can be found in [41].



**Figure 4.** (a) Two illustrative pentagon diagrams, (b) missing transverse energy  $E_T^{\text{miss}}$  for the process  $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + \text{jet}$  at  $\sqrt{s} = 8$  TeV.

### 3.5. GOSAM and extra dimensions

Another computationally intense calculation based on GOSAM+ MadDipole/MadGraph4/MadEvent are the NLO QCD corrections to the production of a graviton in association with one jet [42], where the graviton decays into a photon pair, within ADD models of large extra dimensions [58, 59]. The calculation is quite involved due to the complicated tensor structure introduced by spin-2 particles, and the non-standard propagator of the graviton, coming from the summation over very densely distributed Kaluza-Klein modes. As can be seen from Fig. 5, the K-factors turn out *not* to be uniform over the range of the diphoton invariant mass distribution. As the latter in general is used to derive exclusion limits, the differential NLO corrections should be taken into account. For details we refer to [42].



**Figure 5.** (a) NLO QCD corrections to the invariant mass distribution of the photon pair stemming from graviton decay within the ADD model for  $\delta = 4$  large extra dimensions. The bands show the scale variations by a factor of two around the central scale  $\mu_0^2 = \mu_F^2 = \frac{1}{4} (m_{\gamma\gamma}^2 + p_{T,jet}^2)$ . (b) Azimuthal angle distribution between the leading photon and the leading jet. The region  $\Delta\Phi < \pi/2$  is kinematically inaccessible at LO.

#### 4. Code development

We are working on a number of new features concerning code generation as well as integrand reduction. For instance, we implemented a new strategy to produce optimized `fortran95` code based on `FORM` version 4 [26] rather than `haggies` [18], leading to faster code generation and more compact code. Further, the possibility of parallelisation at diagram level, the option to have numerical polarisation vectors and the option to sum diagrams sharing the same propagators algebraically at `FORM` level lead to an enormous gain in code generation time and reduction of code size. Concerning the amplitude reduction, we implemented integrals where the rank exceeds number of propagators. An alternative reduction based on the Laurent expansion method developed in [57] also has been implemented and used successfully in [48].

A version `GOSAM 2.0` where all these new features are publicly available is in preparation.

#### 5. Conclusions

We have presented applications of the program `GOSAM` which can generate and evaluate one-loop matrix elements for multi-particle processes in an automated way. The program is publicly available at <http://projects.hepforge.org/gosam/> and can be used to produce NLO corrections within QCD, electroweak theory, or other models which can be imported via an interface to `FeynRules`. Monte Carlo programs for the real radiation are linked via the `BLHA` (Binoth Les Houches Accord) interface. This way `GOSAM` is a very flexible and widely applicable tool for the automated calculation of multi-particle observables at next-to-leading order.

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