NLO CALCULATIONS WITH GOSAM

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In this talk we present the `GoSam` program package and summarize the latest development. `GoSam` has recently been used for a number of different NLO QCD computations within and beyond the Standard Model. In the first part a brief description of `GoSam` and of the interface with different external Monte Carlo programs is given, whereas in the second part the recent computations of processes of Higgs boson production in gluon-gluon fusion is presented.

1 Introduction

The latest experimental results in high energy physics presented in Moriond and contained in these proceedings show an increasing precision, never reached before, for many relevant physical observables. Furthermore, the new resonance recently discovered at the Large Hadron Collider (LHC) at CERN, resemble more and more a scalar Higgs boson. To pin down even more its properties and fully determine its nature, more precise data are still needed. On the other side, it is mandatory to reduce further the uncertainties in signal and background processes, which from the theoretical point of view, means to reduce the dependence on unphysical scales in the computation, like renormalization and factorization scales. To achieve this, Next-to-Leading Order (NLO) predictions are needed for a number different processes.

In the last decade much progress was made in the computation of NLO corrections to scattering processes both in Quantum Chromodynamics (QCD) and in the Electroweak (EW) sector of the Standard Model (SM), and also for theories Beyond the SM (BSM). In the last years it was possible to automatize the computation of NLO corrections, not only for the tree-level ingredients and the subtraction terms, but also for the virtual one-loop corrections. This process of automation allowed to achieve a high level of self-organization of the computation, which can now be organized in process-independent frameworks, directly interfaceable to Monte Carlo (MC) programs. These tools can perform a full simulation of an event, attaching a parton shower and the non-perturbative description to the initial parton-level NLO computation. This

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huge progress is often referred to as the "*NLO revolution*". `GoSam`[1] is a program package which is part of several tools leading to this big evolution. In the following we will give a short description of its functionality and present the latest developments and phenomenological progress related to it.

2 GoSam

The `GoSam` program is a framework for the automatic generation and numerical computation of one-loop amplitudes. The core program consists of a python package which generates fortran95 code for the evaluation of the desired one-loop amplitudes. The amplitudes are based upon the algebraic generation of d-dimensional integrands via Feynman diagrams, which can be evaluated both using integrand-reduction techniques and tensor integrals calculation. This approach implies also the possibility to generate and compute on-the-fly the full rational term, without the need of further ad-hoc Feynman rules. For the generation of the diagrams we use `QGRAF`[2], whereas for the algebraic manipulation of the raw amplitudes expressions we are committed to `FORM`[3] and the package `Spinney`[4]. Finally the algebraic expressions are converted to optimized fortran95 code using `Haggies`[5].

At running time the diagrams can be evaluated using `Samurai`[7], which performs a reduction at the integrand level[6] or with `Golem95` [8], which is a library for the computation of one-loop tensor integrals. The reduction method can be changed at running time. In the computations presented in the next sections `Samurai` is usually used as the default program and `Golem95` is used as rescue program whenever an instability is detected in the integrand-reduction approach. This choice is driven by the observation that the tensor integral computation is usually slightly slower but very stable.

This approach allows one to easily compute one-loop QCD and EW corrections to processes within the SM and also beyond, by simply using an appropriate model file. While for QCD corrections the whole computation is fully automatized, for EW corrections and BSM physics the user has to provide, by hand, the correct renormalization. A number of different sample processes were generated using `GoSam` and successfully compared to the literature. Since the number of processes is constantly increasing, we refer to the `GoSam` webpage for a complete list[9].

3 Full NLO computations with GoSam

For the computation of full NLO processes `GoSam` is equipped with an interface using the Binoth-Les-Houches Accord (BLHA) standards[10]. This allow an automatic interface with external MC programs. So far three different MC event generators were successfully interfaced to compute NLO cross sections and distributions for a number of different processes. For details about the working principle of BLHA interface and its standards we refer to the literature[10].

An ad-hoc setup was used to interface with the MadGraph4-MadEvent-MadDipole family of programs. It was used to compute NLO QCD corrections to the production of $b\bar{b}b\bar{b}$ and later to assess the impact of the still missing one-loop contributions in the production of $W^+W^-\,jj$[12], both at hadron colliders. The latter process was first computed in[13], where parts of the loop contributions were neglected. More recently the same setup was used to compute NLO QCD corrections to neutralino pair production in association with one jet[14], and to study the impact of different isolation criteria in the production of $\gamma\gamma\,j$ at the LHC[15]. For this latter process a program package for the computation of the full NLO process can be downloaded from the web[9].

Using the BLHA interface `GoSam` was successfully interfaced with the `POWHEG BOX`[16]. This new interface, together with the built-in interface to MadGraph4 allows for a quick generation of new processes in the `POWHEG BOX` framework.

Thanks to the BLHA interface it was possible to link in a easy and automatic way also

Basic process	Number of extra jets	Highest number of extra jets
$W(\to l+\nu_l)$	$0,1,2$	3
$Z(\to l^+ + l^-)$	$0,1,2$	3
γ	-	$0,1,2,3$
$W(\to l+\nu_l)+b\bar{b}$	0	1
H in GGF	-	$0,1,2,3$
H in VBF	-	$2,3$
W^+W^+	2	-
W^+W^-	0	$1,2$ + loop induced
$W^+W^-b\bar{b}$	-	1
$t\bar{t}$	0	1
$H\,t\bar{t}$	-	$0,1$

Table 1: Processes available (center column) and to-appear (right column) as ready-to-use packages.

to the MC event generator `Sherpa` [17]. The two programs can exchange information about the process the user wishes to compute and generate all the needed ingredients. The user only needs to fill an input card for the two programs and, once the code is ready, the full calculation can be steered simply editing the `Sherpa` input card. A set of ready-to-use process packages with the full code for the loop computation is also available [9]. They only require the installation of `Sherpa` by the user, whereas the code for the virtual part is already generated and validated. The list of available processes and the one in phase of validation are summarized in Table 1.

4 Higgs plus jets production

In this section, we illustrate our recent computation of the NLO contributions to Higgs plus two jets production in Gluon-Gluon Fusion (GGF) at the LHC in the large top-mass limit [18], and also provide results for the one-loop virtual contribution to Higgs plus three jets production. The distributions for the former process are obtained by using the BLHA interface between `GoSam` and `Sherpa`.

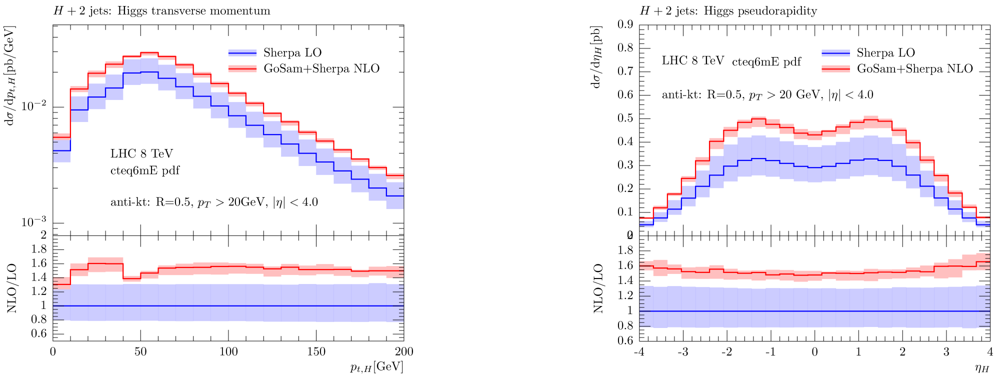

Figure 1: Transverse momentum p_T and pseudorapidity η of the Higgs boson, when produced in association with two jets.

For Hjj production, the following minimal set of processes are computed: $gg \to Hgg$, $gg \to Hq\bar{q}$, $q\bar{q} \to Hq\bar{q}$, $q\bar{q} \to Hq'\bar{q}'$. The remaining processes are obtained by performing the appropriate symmetry transformation. We work in the dimensional reduction scheme (DRED) and UV divergences have been renormalized in the $\overline{\text{MS}}$ scheme. Our results are in agreement with [19] and MCFM (v6.4) [20].

As an illustration of possible analyses that can be performed with the `GoSam-Sherpa` automated setup, in Fig. 1 we present the distribution of the transverse momentum p_T of the Higgs boson and its pseudorapidity η, for proton-proton collisions at the LHC at $\sqrt{s} = 8$ TeV. For details about the setup we refer to the original publication [18]. The bands show the impact of varying renormalization and factorization scale by factors of 2 around its central value, set to $\hat{H}_t = \sqrt{M_H^2 + p_{t,H}^2} + \sum_j p_{t,j}$, where $p_{t,H}$ and $p_{t,j}$ are the transverse momenta of the Higgs boson and the jets. Both distributions show a K-factor between the LO and the NLO distribution of about $1.5 - 1.6$ and a decrease of the scale uncertainty of about 50%.

All independent processes contributing to $Hjjj$ can be obtained by adding one extra gluon to the final state of the processes listed in the case of Hjj. Accordingly, we generated the codes for the virtual corrections to the processes $gg \to Hggg$, $gg \to Hq\bar{q}g$, $q\bar{q} \to Hq\bar{q}g$, $q\bar{q} \to Hq'\bar{q}'g$. Some representative one-loop diagrams are depicted right in Figure 2.

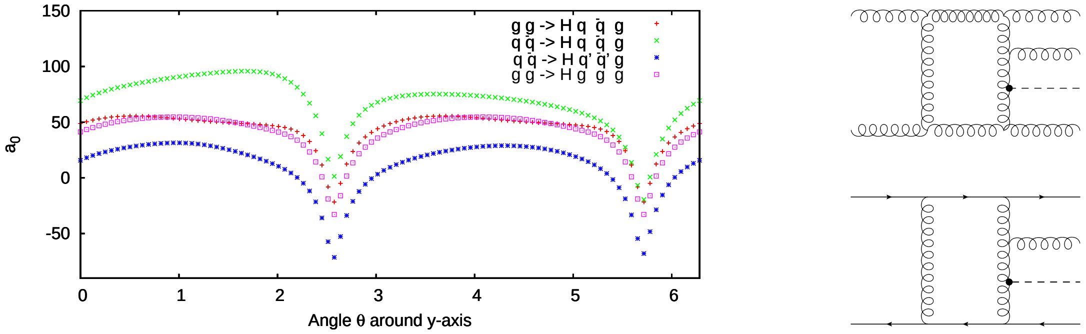

Figure 2: Left: Finite-term of the virtual matrix elements for $gg \to Hq\bar{q}g$ (red), $q\bar{q} \to Hq\bar{q}g$ (green), $q\bar{q} \to Hq'\bar{q}'g$ (red), $gg \to Hggg$ (purple). Right: sample hexagon diagrams which enter in the six-parton one-loop amplitudes for $gg \to Hggg$ and $q\bar{q} \to Hq\bar{q}g$. The dot represents the effective ggH vertex.

Choosing the momenta of the initial partons along the z-axis, we show in Figure 2 the effect on the finite parte of the virtual amplitude of rotating a phase space point through an angle θ about the y-axis.

Furthermore we verified that the values of the double and the single poles conform to the universal singular behavior of dimensionally regulated one-loop amplitudes.

5 Conclusions

`GoSam` is a very flexible tool for the automatic computation of one-loop amplitudes. Work is in progress to increase the generation and the running speed and to decrease the size of the generated codes. These new features will be part of new release of the code, planned for the second half of the current year.

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