Spin Polarisation of $t\bar{t}\gamma\gamma$ production at NLO+PS with GoSam interfaced to MadGraph5_aMC@NLO

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ABSTRACT: We present an interface between the multipurpose NLO Monte Carlo tool MadGraph5_aMC@NLO and the automated one-loop amplitude generator GoSam. As a first application of this novel framework, we compute the NLO corrections to $pp \rightarrow t\bar{t}H$ and $pp \rightarrow t\bar{t}\gamma\gamma$ matched to a parton shower. In the phenomenological analyses of these processes, we focus our attention on observables which are sensitive to the polarisation of the top quarks.

Contents

1. Introduction

The development of automated tools for precise calculations of total cross sections and differential distributions in high-energy collisions has undergone a dramatic acceleration in the last decade. While Leading-Order (LO) tools, based on automated tree-level calculations, have been available for a long time [1–11], the needs of the experimental analyses at the Large Hadron Collider (LHC) and a deeper understanding of the structure of scattering amplitudes [12–14] at one loop led to the development of several computer frameworks for the automated computation of loop matrix elements [15–20] and physical observables at Next-to-leading-Order (NLO) accuracy [21–27]. Moreover, techniques to properly deal with the merging of different multiplicities in the final states and the matching [28, 29] to parton shower were successfully developed [30–34] and are nowadays available.

Advanced automated calculations have been performed by embedding the codes for generating virtual corrections at NLO precision, the so called One Loop Providers (OLPs), within a Monte Carlo program (MC). The interplay between MCs programs and OLPs is controlled by means of interfaces, which allow the user to get direct access to the main features of the MC code, bypassing the need of knowing the technical details of the OLP, which is ideally an inner engine within the MC generator. Many of such interfaces are based on the standards settled by the Binoth Les Houches Accord (BLHA) [35, 36], which defines specifications of the communication between MCs and OLPs.

The LHC has recently started Run II, collecting data at an energy scale never explored before. Within this activities automated multi-purpose tools for particle collisions

simulation are of fundamental importance for comparing theoretical predictions with experimental data, thereby extracting important information about the Standard Model (SM) and exploring all traces of deviations from it. The need for flexible tools which at the same time can provide accurate predictions, both in the SM and Beyond (BSM), may become of primary relevance in the near future. It is therefore important to be able to connect different tools to increase the reliablility of results.

With this goals in mind, we present the interface between the multipurpose NLO Monte Carlo tool MADGRAPH5_AMC@NLO [27] and the automated one-loop amplitude generator GOSAM [20]. The advantage of this combination is twofold. On the one hand, this tandem allows the user of MADGRAPH5_AMC@NLO to switch between two options of OLPs, namely between the inhouse code MADLOOP [23] fully integrated directly in the MC distribution package, and GOSAM. Thus, the user can experience the evaluation of NLO virtual corrections by means of two alternative solutions corresponding to different algorithms and methods of generation and evaluation of Feynman amplitudes. On the other hand, GOSAM is interfaced to several MCs codes, like SHERPA [21], HERWIG++ [26], POWHEG [25], beside MADGRAPH5_AMC@NLO, therefore the user of the MCs can explore and compare the different features of the event generators, without being biased by the performances of the OLPs, since they all can be run using GOSAM.

As an illustration of the novel framework MADGRAPH5_AMC@NLO + GOSAM, we present its application to the NLO corrections to $pp \to t\bar{t}H$, $H \to \gamma\gamma$ and the continuum $pp \to t\bar{t}\gamma\gamma$ matched to a parton shower. The production of a Higgs Boson in association with a pair of top anti-top quarks is an important process to directly study the Yukawa coupling of the Higgs Boson with massive fermions. Such a channel, and its corresponding backgrounds, were recently the subject of detailed studies, both at LO [37–39] and NLO [40] precision. Very recently, new analyses have appeared which further extend these studies including the decay of the top and anti-top quark into bottom quarks and leptons [41], considering the production of a top-quark pair in conjunction with up to two vector bosons [42], and exploring the CP-structure of the top-Higgs coupling [43]. In the phenomenological analysis contained in this paper, we focus our attention on observables sensible to the polarization of the top quarks, such as angular variables which involve the decay of the top quark.

The paper is organized as follows: in Section 2, after a general introduction to the GOSAM and MADGRAPH5_AMC@NLO codes, we will discuss the interface between the two frameworks and its validation. In Section 3, we will present an application of the GOSAM+ MADGRAPH5_AMC@NLO interface, namely the study of NLO corrections to $pp \to t\bar{t}H$, $H \to \gamma\gamma$ and $pp \to t\bar{t}\gamma\gamma$ matched to a parton shower. Finally in Section 4, we will draw our conclusions.

2. Computational setup

For the computations contained in this paper, the automated one-loop amplitude generator GOSAM has been fully interfaced to the MADGRAPH5_AMC@NLO Monte Carlo framework.

In this section, we briefly review the main characteristics of each of these tools and describe the details of the interface between them, which allows to use one-loop amplitudes generated by GoSam within MadGraph5_aMC@NLO. Finally we discuss the validation of the interface by means of a comparison with an independent framework.

2.1 GoSam

The main idea that distinguishes the GoSam framework [20] from other codes for the automated generation of one-loop amplitudes is the combined use of automated diagrammatic generation and algebraic manipulation in $d = 4 - 2\epsilon$ dimensions, thus providing analytic expressions for the integrands, with d-dimensional integrand-level reduction techniques, or tensorial reduction. Amplitudes are automatically generated via Feynman diagrams and, according to the reduction algorithm selected by the user, are algebraically manipulated and cast in the most appropriate output [44–49]. The individual program tasks are controlled by means of a python code, while the user only needs to prepare an input card to specify the details of the process to be calculated without worrying about internal details of the code generation.

After the generation of all contributing diagrams, the virtual corrections are evaluated using the integrand reduction via Laurent expansion [50], provided by Ninja [51,52], or the d-dimensional integrand-level reduction method [53–55], as implemented in Samurai [56, 57]. Alternatively, the tensorial decomposition provided by Golem95C [58–60] is also available. The scalar loop integrals can be evaluated using OneLOop [61], Golem95C, or QCDLoop [62,63].

GoSam can be used to generate and evaluate one-loop corrections in both QCD and electroweak theory [64]. Model files for Beyond Standard Model (BSM) applications generated from a Universal FeynRules Output (UFO) [65, 66] or with LanHEP [67] are also supported. A model file which contains the effective Higgs-gluon couplings that arise in the infinite top-mass limit is also available in the current distribution and it was successfully used to compute the virtual corrections for the production of a Higgs boson in association with 2 and 3 jets [68,69].

The computation of physical observables at NLO accuracy, such as cross sections and differential distributions, requires to combine the one-loop results for the virtual amplitudes obtained with GoSam, with other parts of the calculations, namely the computation of the real emission contributions and of the subtraction terms, needed to control the cancellation of IR singularities. In some of the earlier calculations performed with GoSam [70–74], the problem was solved by means of an ad hoc adaptation of the MadDipole/Madgraph4/MadEvent framework [1,9,75,76].

Far more efficiently, this task can be performed by embedding the calculation of virtual corrections within a multipurpose Monte Carlo program (MC), that can also provide the phase-space integration, which is what is pursued in this work. In this case, the MC takes control over the different stages of the calculation, in particular the phase space integration and the event generation, and calls GoSam at runtime to obtain the corresponding value of the one-loop amplitude at the given phase space points. This approach has the great advantage of making available to the user all the advanced features that the MC generator

provides, for example to allow for parton showering, further decays of the final-state hard particles retaining spin correlation and merging of different final state multiplicities.

While in the present paper we will focus on the interface between GoSam and Mad-Graph5_aMC@NLO, it is worth mentioning that a number of phenomenological results can be found in the literature which were obtained by combining GoSam with other MC programs, in particular with Sherpa [21, 77–80], Herwig++ [26, 81], and Powheg [25, 82, 83].

2.2 MadGraph5_aMC@NLO

The MadGraph5_aMC@NLO framework [27] has been developed to be able to generate events and compute differential cross sections with a high-level of automation. The central idea behind the code is that the structure of cross sections is essentially independent of the process under consideration. Therefore, once this structure has been set up, any cross section can be computed within the framework. For example, even though the matrix elements are process and theory dependent, they can be computed from a very limited set of instructions based on the Feynman rules.

The core of the MadGraph5_aMC@NLO framework is based on tree-level amplitude generation, since in this code the matrix elements used in both LO and NLO computations are constructed from tree-level Feynman diagrams. The generation of these amplitudes is based on three elements which are key to taming the complexity of the computation as the number of external particles increases: colour decomposition, helicity amplitudes and recycling of identical substructures between diagrams. The internal algorithms used have been described extensively in Ref. [84] and Ref. [18, 23, 27, 53, 85, 86] for the generation of tree-level and one-loop matrix elements, respectively.

Beyond the lowest order in perturbation theory, intermediate contributions to the computation of (differential) cross sections are plagued by divergences. In particular the soft/collinear divergences in the numerical phase-space integration over the real-emission (Bremstrahlung) corrections are non-trivial to deal with. In the MadGraph5_aMC@NLO framework the FKS subtraction method [87, 88] is used to factor out the singularities in order to cancel them analytically with singularities present in the virtual corrections. The FKS subtraction is based on partitioning the phase-space, in which each phase-space region has at most one collinear and one soft singularity. These singularities are subtracted before performing the numerical phase-space integration by using a straight-forward plus-description. The subtraction terms have been integrated analytically, using dimensional regularisation, once and for all, resulting in explicit poles in $1/\epsilon$ and $1/\epsilon^2$, which cancel similar poles in the virtual corrections and the PDFs.

Independently of which code one uses for the computation of the virtual corrections, for example MadLoop [23] or GoSam [20], optimisations in the phase-space integration of these contributions are used, as described in Ref. [27]. That is, during the phase-space integration an approximation of the virtual corrections based on the born matrix elements is created dynamically. These approximate virtual matrix elements are very fast to evaluate and can therefore be efficiently integrated numerically with high statistics. The small difference between the approximate and the exact virtual corrections is relatively slow to

evaluate for a given phase-space point, but given that this is a very small contribution to the final result, the requirement on the relative precision with which it needs to be computed can be relaxed. Therefore, using low statistics for this complicated contribution suffices, greatly reducing the overall computational time.

To match the short-distance matrix elements to a parton shower, the framework of MADGRAPH5_AMC@NLO employs the MC@NLO technique [28] available for Pythia 6 [89], Herwig 6 [90], Pythia 8 [91] and Herwig++ [92]. In this method, the possible double counting between the NLO corrections and the parton shower is accounted for by explicitly subtracting the parton shower approximation for the emission of a hard parton from the real-emission contributions, and the parton shower approximation of a non-emitting parton from the virtual corrections. To consistently merge various multiplicities at NLO accuracy and match them to the parton shower, the FxFx merging method [33] is available.

2.3 Interface

The interface between GOSAM and MADGRAPH5_AMC@NLO is based on the standards of the first BLHA defined in [35]. When running the MADGRAPH5_AMC@NLO interactive session, the command

$$\text{\$ set OLP GoSam}$$

changes the employed OLP from its default MADLOOP to GOSAM. Alternatively, the file

$$\texttt{input/mg5\_configuration.txt}$$

can be directly edited to include the line `OLP = GoSam`.

The BLHA order and contract file system allows for a basic communication between the two codes to exchange the most fundamental information about the number and type of subprocesses, the powers of the couplings involved in the specific process, the schemes in which the computation should be performed and also the value of parameters like masses and widths. For static parameters, which do not change at each phase space point, but stay constant during the MC integration and event generation, the information is passed via a SUSY Les Houches Accord (SLHA) parameter file. This is created by MADGRAPH5_AMC@NLO and read by GOSAM. The path to this SLHA file is specified in the order file with the key word `ModelFile`. An example generated for the computation of $t\bar{t}\gamma\gamma$ is shown in Figure 1. For parameters which instead may change at each phase space point, the BLHA 1 interface defines an array to pass the numerical value of dynamical variables. The definition and order of the parameters passed through this array is set in the order file using the keyword `Parameters`. Although in principle extendible to up to ten parameters, at present only the first entry is used, to communicate the value of α_S.

Further customization of the one-loop amplitudes which need to be generated can be achieved by editing a separate input file for GOSAM. In the file `gosam.rc`, additional information can be specified, i.e. the model, the particle content of the loop diagrams, and the number of active flavours. Here it is also possible to define ad hoc filters to remove unwanted diagrams or loop contributions which are known to be negligible or vanishing,

```
#OLE_order written by MadGraph5_aMC@NLO        # vim: syntax=olp
                                               #@OLP GoSam 2.0.0
                                               #@IgnoreUnknown True
MatrixElementSquareType CHaveraged             #@IgnoreCase False
CorrectionType          QCD                    #@SyntaxExtensions
IRregularisation        CDR                    MatrixElementSquareType CHaveraged | OK
AlphasPower             2                      CorrectionType QCD | OK
AlphaPower              2                      IRregularisation CDR | OK
NJetSymmetrizeFinal     Yes                    AlphasPower 2 | OK
ModelFile               ./param_card.dat       AlphaPower 2 | OK
Parameters              alpha_s                NJetSymmetrizeFinal Yes | OK #Ignored by OLP
                                               ModelFile ./param_card.dat | OK
                                               Parameters alpha_s | OK
# process                                      21 21 -> 22 22 6 -6 | 1 2
21 21 -> 22 22 6 -6                            2 -2 -> 22 22 6 -6 | 1 0
2 -2 -> 22 22 6 -6                             1 -1 -> 22 22 6 -6 | 1 3
1 -1 -> 22 22 6 -6                             -2 2 -> 22 22 6 -6 | 1 1
-2 2 -> 22 22 6 -6                             -1 1 -> 22 22 6 -6 | 1 4
-1 1 -> 22 22 6 -6
```

Figure 1: Example of order file (left) and contract file (right).

which may however, if kept in the calculation, introduce numerical instabilities or slow down the evaluation. Some settings are present by default, but many more can be introduced by the user. We refer to the Appendix for a more extensive list of possible options. The GoSam input file needs to be edited by hand and can be found at

Template/loop_material/OLP_specifics/GoSam/gosam.rc,

in the MadGraph5_aMC@NLO repository, or at

OLP_virtuals/gosam.rc,

in the folder that is automatically generated by MadGraph5_aMC@NLO when a new process is started. After the input file is ready, any NLO process can be generated following the general MadGraph5_aMC@NLO procedure.

The interface between MadGraph5_aMC@NLO and GoSam is available starting from MadGraph5_aMC@NLO version 2.3.2.2. The two codes can be downloaded from the following URL:

MadGraph5_aMC@NLO: http://amcatnlo.web.cern.ch/amcatnlo/

GoSam: http://gosam.hepforge.org/

2.4 NLO predictions and validation

To validate the interface, and consequently the results we present in Section 3, several cross checks were performed. The loop amplitudes of GoSam and MadLoop were compared for single phase space points and also at the level of the total cross section for a number of different processes, as presented in a dedicated table in [93]. Furthermore, for $pp \to t\bar{t}\gamma\gamma$, a fully independent check was also performed by computing the

same cross section using GoSam interfaced to Sherpa. The comparison between the results obtained with MadGraph5_aMC@NLO+GoSam, Sherpa+GoSam, and MadGraph5_aMC@NLO+MadLoop is presented Table 1, where we report the total integrated cross sections for LO and NLO at a center-of-mass energy $\sqrt{s} = 8$ TeV.

$\sigma_{t\bar{t}\gamma\gamma}$, $\sqrt{s} = 8$ TeV	MG5_aMC + MadLoop	MG5_aMC + GoSam	Sherpa+GoSam
LO [pb]	$1.0241 \pm 5.50 \cdot 10^{-4}$		$1.0246 \pm 3.51 \cdot 10^{-4}$
NLO [pb]	$1.3507 \pm 5.85 \cdot 10^{-3}$	$1.3432 \pm 5.16 \cdot 10^{-3}$	$1.3593 \pm 1.80 \cdot 10^{-3}$

Table 1: Total cross sections in picobarns, at center-of-mass energy $\sqrt{s} = 8$ TeV, for combinations of MCs and OLPs, at LO and NLO.
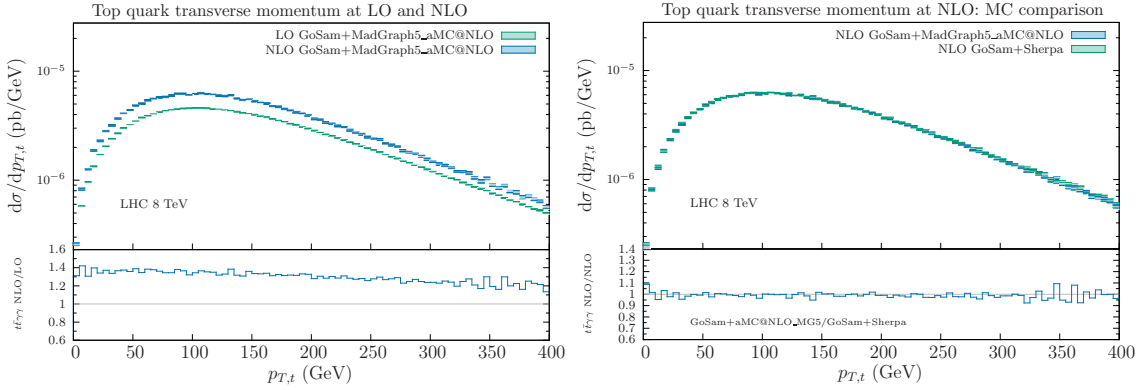
Figure 2: Transverse momentum of the top quark in $pp \rightarrow t\bar{t}\gamma\gamma$ for the LHC at 8 TeV. On the left hand side LO and NLO distributions, on the right hand side NLO comparison between GoSam+MadGraph5_aMC@NLO and GoSam+Sherpa.

The results shown in this and the following sections are computed using the following setup. The mass of the Higgs was set to $m_H = 125$ GeV, the mass of the top quark to $m_t = 173.2$ GeV. We work in the $N_f = 5$ model. The value of the electroweak coupling is set to its low energy limit $\alpha_{EW}^{-1} = 137.0$. The mass of the Z boson was set to $m_Z = 91.1876$ GeV and the value of the Fermi constant to $G_F = 1.16639 \cdot 10^{-5}$ GeV^{-2}, which fixes the electroweak scheme. For the photons, we used the isolation procedure introduced by Frixione [94] with minimal transverse momentum $p_{\gamma T\min} = 20$ GeV, radius of isolation $R_\gamma < 0.4$ and Frixione parameters $n = 1.0$ and $\epsilon_\gamma = 1.0$. Furthermore, we applied an isolation radius between the two photons $R_{\gamma\gamma} = 0.4$. In leading order calculations, we used the PDF set cteq6L1 [95]. At next-to-leading order, we instead used the PDF set CT10. The renormalisation and factorisation scales are set to $\mu_R = \mu_F = \mu_0$ with

$$\mu_0 = \frac{\hat{H}_T}{2} = \frac{1}{2} \left(\sum_{\text{final state i}} m_{T,i} \right) \tag{2.1}$$
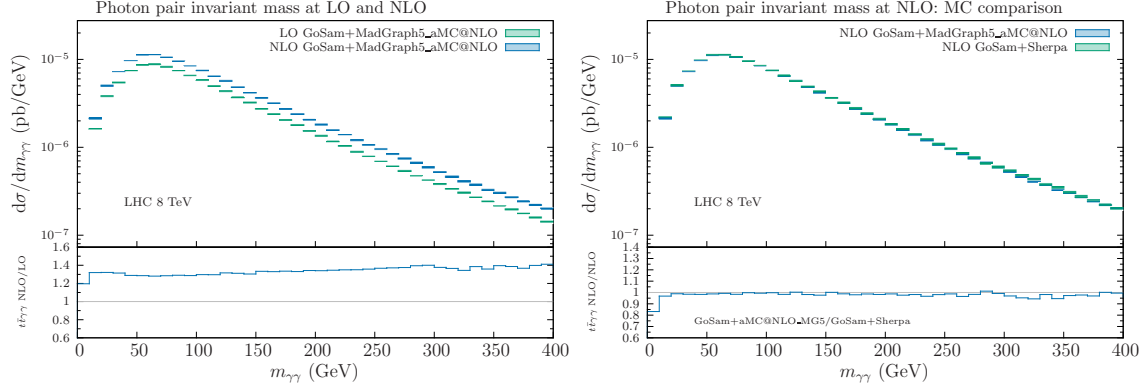
Figure 3: Photon pair invariant mass distribution in $pp \to t\bar{t}\gamma\gamma$ for the LHC at 8 TeV. On the left hand side LO and NLO distributions, on the right hand side NLO comparison between GoSam+MadGraph5_aMC@NLO and GoSam+Sherpa.

In Figure 2, on the left, we compare LO and NLO predictions for the transverse momentum of the top quark obtained with GoSam+MadGraph5_aMC@NLO, while on the right we compare the same NLO predictions with results obtained using GoSam+Sherpa. In Figure 3 we do the same for the photon pair invariant mass. All predictions are computed for a center of mass energy of 8 TeV.

3. Results

In this section we present results at NLO+PS level for the LHC at 8 TeV and compare the *background* process $t\bar{t}\gamma\gamma$, where the photons are directly radiated from the quarks, with the *signal* process $t\bar{t}H$ in which the Higgs boson decays to two photons. We will refer to the latter simply as "$t\bar{t}H$"; it should be understood that we consider only the process with the photonic Higgs decay $t\bar{t}H$, $H \to \gamma\gamma$.

The study is performed using NLO predictions for $t\bar{t}H$ and continuum $t\bar{t}\gamma\gamma$ production. The top and anti-top quarks are subsequently decayed semi-leptonically $t \to W^+(\to \bar{l}\,\nu_l)b$, $\bar{t} \to W^-(\to l, \bar{\nu}_l)\bar{b}$ with MadSpin [96,97], taking into account spin correlation effects, and then showered and hadronised with Pythia 8.2, using its default parameters, but with underlying event turned off. The short-distance events were generated and compared with two slightly different sets of cuts in order to verify that they had no impact on the results at the level of the analysis. Apart from the kinematical requirements on the reconstructed objects, which we will describe below, we use identical model parameters, renormalisation and factorisation scales, PDFs and photon isolation as described in Section 2.4.

Note that for the background process we neglect effects of photon bremsstrahlung from the charged top decay products, which can at least partially be reduced by applying proper kinematical cuts. For the spin correlation observables, on which we will focus our attention in the last part of this section, a LO study [37] showed that the impact of neglecting these contributions is present but not drammatic.

The analysis cuts are designed to increase the signal over the background, but are by no means optimised to maximise the enhancement. The two photons from the Higgs decay (or the two hard photons in the $t\bar{t}\gamma\gamma$ process) are required to be isolated and fulfill

$$p_{T,\gamma} \; > \; 20 \text{ GeV}, \quad |\eta_\gamma| \; < \; 2.5, \quad 123 \text{ GeV} \; < \; m_{\gamma\gamma} \; < \; 129 \text{ GeV}, \qquad (3.1)$$

where the invariant mass requirement selects a window around the Higgs boson mass, which reduces the background significantly without altering the signal strength. Furthermore, we require the events to have two oppositely charged leptons and two b-jets coming from the top and anti-top decays. The leptons are selected requiring

$$p_{T,l^\pm} \; > \; 10 \text{ GeV}, \quad |\eta_{l^\pm}| \; < \; 2.7. \qquad (3.2)$$

The b-jets are defined to be jets containing at least one lowest lying B meson. The jets themselves are defined by clustering all stable hadrons and photons, but excluding the two photons selected using Eq. (3.1), using the anti-k_T algortithm as implemented in the code FASTJET [98–100], with

$$\Delta R = 0.4, \quad p_{T,j} \; > \; 20 \text{ GeV}, \quad |\eta_j| \; < \; 4.7. \qquad (3.3)$$

We use MC truth information to select the photons from the Higgs decay (signal) or hard events (background) as well as the leptons and b-jets coming from the top and anti-top decays. As reconstructed (anti-)top quark, we use the four-momentum of the (anti-)top quark just before it decays, as provided in the Pythia 8 event record. In the presence of these analysis cuts, we obtain the cross-sections reported in Table 2.

$\sqrt{s} = 8$ TeV	$pp \to t\bar{t}H,\, H \to \gamma\gamma$	$pp \to t\bar{t}\gamma\gamma$
LO [pb]	$8.83(6) \cdot 10^{-7} \; {}^{+27\%}_{-20\%} \; {}^{+10\%}_{-11\%}$	$1.44(2) \cdot 10^{-7} \; {}^{+25\%}_{-18\%} \; {}^{+10\%}_{-12\%}$
NLO [pb]	$11.17(7) \cdot 10^{-7} \; {}^{+6\%}_{-8\%} \; {}^{+11\%}_{-12\%}$	$2.17(5) \cdot 10^{-7} \; {}^{+10\%}_{-10\%} \; {}^{+10\%}_{-11\%}$
K-factor	$1.26(5)$	$1.50(7)$

Table 2: Cross sections in picobarns, at a center-of-mass energy of $\sqrt{s} = 8$ TeV and in the presence of the analysis cuts described in the text. The two sets of uncertainties following the cross-section correspond to the scale and PDF variations respectively.

In the next section we focus our attention on some relevant observables related to a single particle, whereas in Section 3.2 we will concentrate on observables which can directly probe correlation effects due to the top quark polarisation.

In what follows and unless specified otherwise, the plots will always consist of four distributions. The top curves show the differential cross sections for a given observable and for both the signal and the background process. The two middle insets display the relative uncertainty of the $t\bar{t}H$ and $t\bar{t}\gamma\gamma$ predictions respectively. The scale dependence (transparent band) is estimated by taking the envelope of the nine predictions obtained by the separate
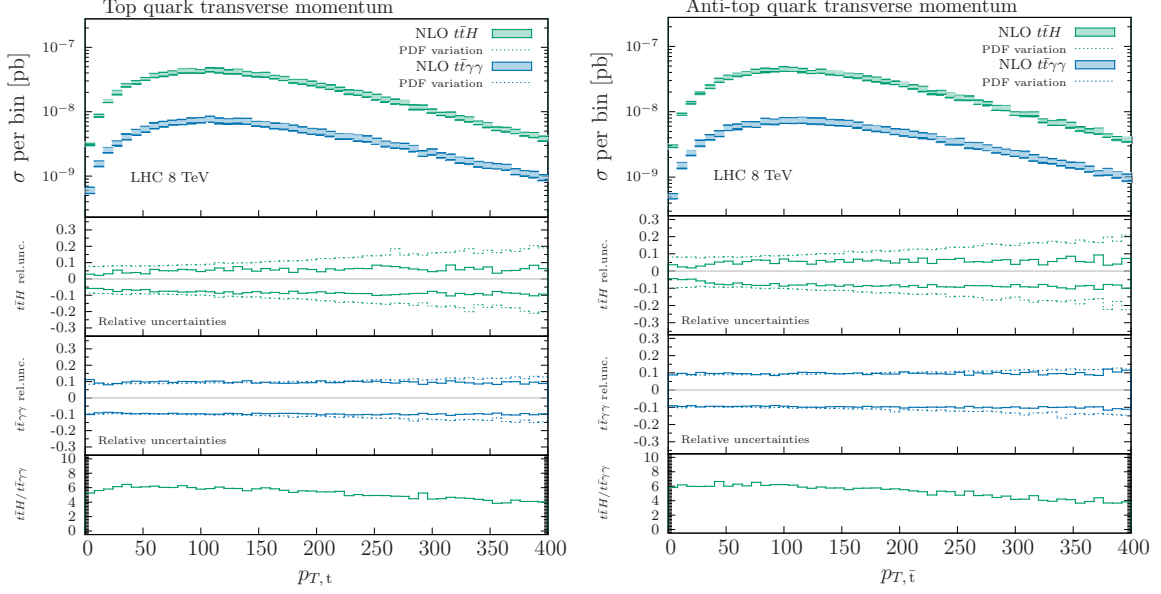
Figure 4: Transverse momentum distribution of the top quark (left) and anti-top quark (right).

variation of renormalisation and factorisation scales by factors of 0.5 and 2 around the central scale μ_0 defined in Equation (2.1). For estimating the PDF uncertainty (dotted lines), we use the Hessian method. Finally, the bottom inset highlights the differential signal-to-background ratio.

3.1 Single particle observables

We start comparing the transverse momentum distribution of the reconstructed top and anti-top quarks, which is shown in Figure 4. For either the signal or background process, the shapes of the top and anti-top quark p_T distributions are very similar, as expected, and therefore the same is true for the signal-to-background ratio. In both cases, it reaches a maximum between 50 and 100 GeV and than decreases slightly in the high transverse momentum tail. It is also worth noting that the uncertainty due to the PDF variation is larger in $t\bar{t}H$, due to the dominant gluon-channel production, and is increasing for larger transverse momenta. At $p_T \approx 400$ GeV the PDF uncertainty for $t\bar{t}H$ is around 20%, whereas it stays below 15% for $t\bar{t}\gamma\gamma$.

Figure 5 shows the transverse momentum and the rapidity of the photon pair, which for the signal process corresponds to the one of the reconstructed Higgs boson. Since in $t\bar{t}\gamma\gamma$ the photon pair does not originate from a massive particle decay, its transverse momentum is softer and the spectrum falls off faster for large p_T. The signal-to-background rapidity curve shows that photons coming from the decay of the Higgs boson are generally produced more centrally. This is not surprising given that such a decay does not feature a collinear enhancement, contrary to the case of $t\bar{t}\gamma\gamma$.

The transverse momentum distribution for the single photons (ordered according to their p_T) is shown in Figure 6. The shoulder in the $t\bar{t}H$ signal distribution stemming from the presence of the Higgs boson resonance is also visible in the background shape, albeit less
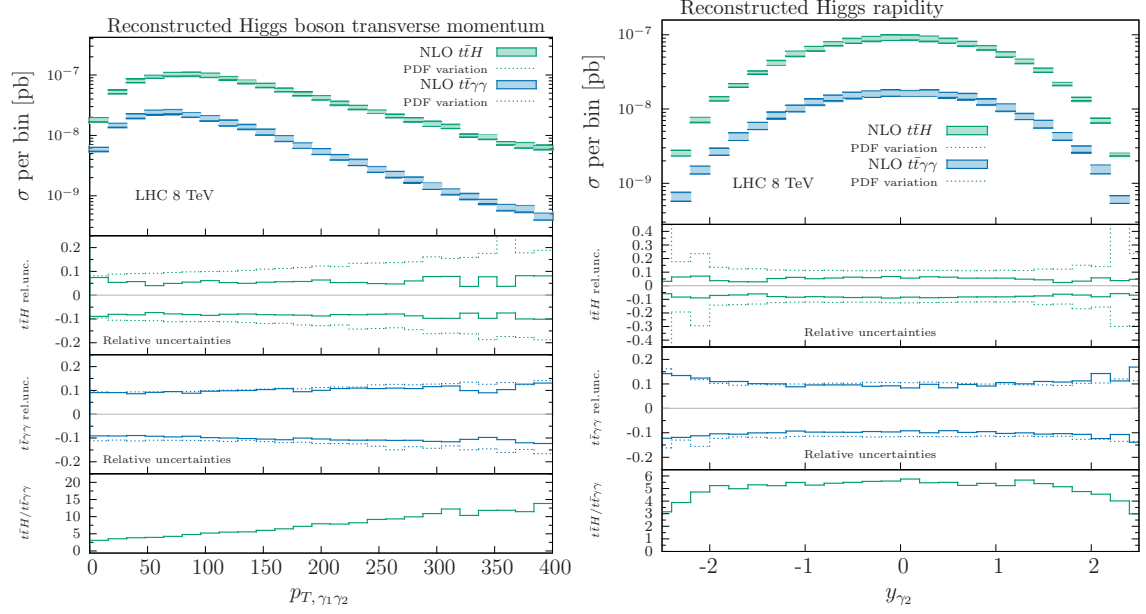
Figure 5: Transverse momentum (left) and rapidity (right) distributions of the reconstructed Higgs boson.
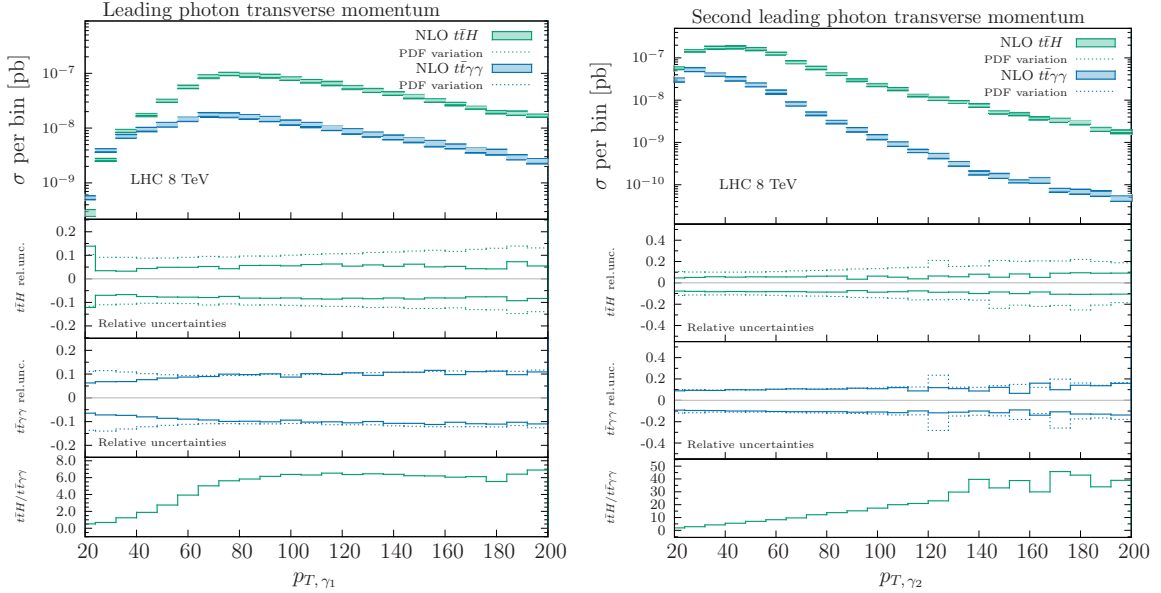
Figure 6: Transverse momentum distribution of the leading (left) and second leading photon (right).

pronounced, given the invariant mass cut on the photon pair. As expected, the shoulder is shifted towards lower transverse momenta for the case of $t\bar{t}\gamma\gamma$, because of the initial state collinear enhancement.

It is particularly interesting to compare the rapidities of the top and anti-top quarks (Figure 7) and of their decay products. This highlights the well known difference between
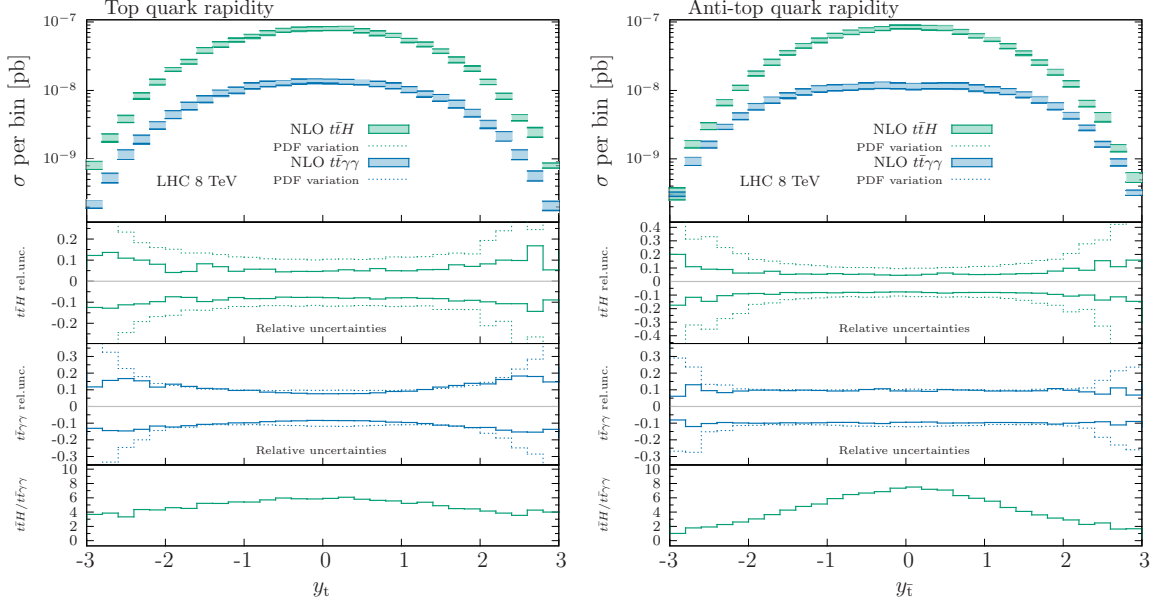
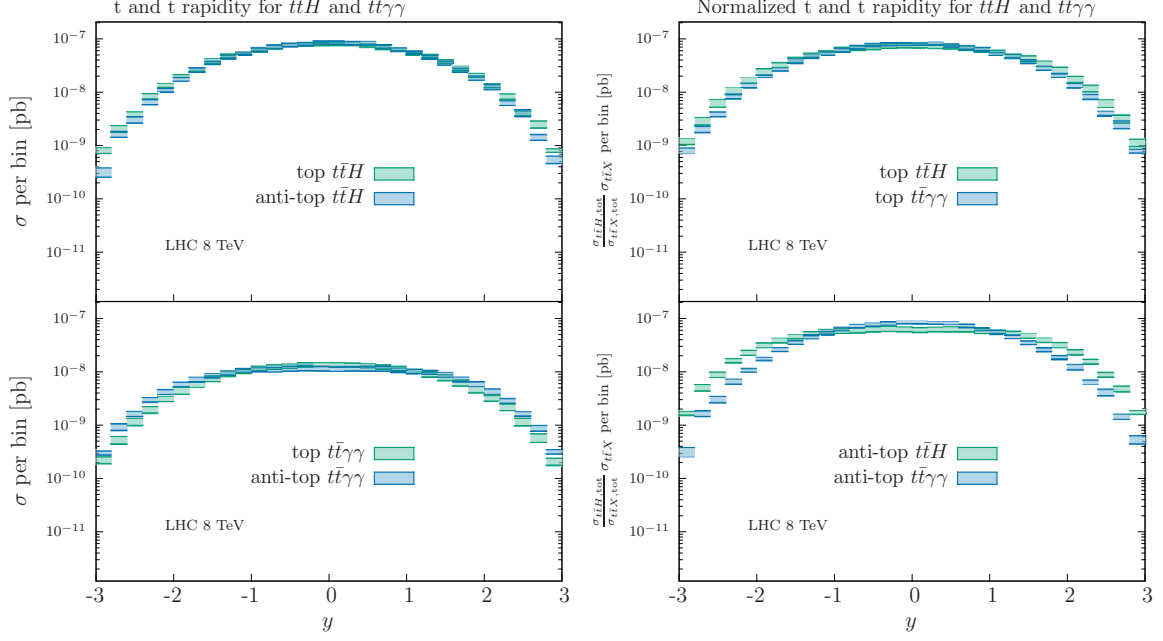**Figure 7:** Rapidity distribution of the top quark (left) and anti-top quark (right).

the broadness of the respective top and anti-top quark rapidity distribution and it can be used to improve on background discrimination. This difference is known as the *charge asymmetry* and is usually quantified by the following observable:

$$A_{\mathrm{t\bar{t}}}^{\mathrm{C}} = \frac{\sigma\left(\Delta|y| > 0\right) - \sigma\left(\Delta|y| < 0\right)}{\sigma\left(\Delta|y| > 0\right) + \sigma\left(\Delta|y| < 0\right)} \, , \tag{3.4}$$

where $\Delta|y| = |y_{\mathrm{t}}| - |y_{\mathrm{\bar{t}}}|$. This observable has been measured at the LHC by both the ATLAS [101,102] and the CMS [103–105] collaboration in the context of top-quark studies.

For top-pair production at the LHC $A_{\mathrm{t\bar{t}}}^{\mathrm{C}}$ is positive, i.e. top quarks are produced at larger rapidities compared to anti-top quarks [106]. It is however known that the presence of a photon reverses the sign of $A_{\mathrm{t\bar{t}}}^{\mathrm{C}}$ already at tree-level [107]. This change in the rapidity distributions of the top and anti-top quarks, due to additional photon radiation, can clearly be seen in the plots of Figure 8, which compare y_{t} and $y_{\mathrm{\bar{t}}}$ individually for $t\bar{t}H$ and $t\bar{t}\gamma\gamma$. In the signal process the additional presence of a Higgs boson in the final state does not change the qualitative result, as compared to simple $t\bar{t}$-production. This can be seen in the upper left plot of Figure 8, which shows that top quarks are produced at slightly higher rapidities, as compared to anti-tops, which are more central, leading to a positive $A_{\mathrm{t\bar{t}}}^{\mathrm{C}}$. In the lower left plot, instead, the effect is reversed. The presence of the additional photons causes the top quarks to be more central compared to the anti-tops.

This effect is even more visible when comparing directly the distributions for $t\bar{t}H$ with the ones for $t\bar{t}\gamma\gamma$. To better appreciate the change in the shape, only marginally visible in Figure 7, we plot the same distribution normalized to the inclusive $t\bar{t}H$ cross section on the right hand side of Figure 8. From the upper plot it becomes clear that the top quark rapidities have very similar shape in both the signal and the background process, although in the latter the tops are produced at slightly higher rapidities. This means that despite

Figure 8: On the left: rapidity distribution comparison between the top and anti-top quark for $t\bar{t}H$ (above) and $t\bar{t}\gamma\gamma$ (below). On the right: normalized top (above) and anti-top (below) rapidity distribution for signal and background.

the top being produced at higher rapidities as compared to the anti-top in $t\bar{t}H$, overall, they are still slightly more central than in $t\bar{t}\gamma\gamma$. The opposite is true for the anti-top quark rapidity, and, therefore, the difference is even more visible in the lower right plot of Figure 8.

Analogous conclusions can be derived by looking at the rapidities of the top decay products. They are shown in Figure 9 and 10, where the rapidities of the b- and $\bar{b}$-jets and the charged leptons are shown respectively.

In Figure 11 we compare the rapidities of the leading and second leading photon. Not surprisingly, the photon coming form the Higgs boson decay are produced more centrally as compared to the ones radiated from the partons.

3.2 Spin polarisation observables

In this section we focus on observables that allow for investigating polarisation effects of the top and anti-top quarks as well as in their decay products. This can be done by studying angular variables which involve the decay products of the top and anti-top quarks; both top quarks are considered to decay semileptonically (same as in the previous section). We stress that a similar analysis was already performed at LO in Ref. [37].

Typically, for hadronic $t\bar{t}$-production, very specific kinematic frames are defined [108–110]. In the following we will consider the three-dimensional opening angle θ_{ll} between the leptonic decay products of the top (l^{+}) and anti-top quarks (l^{-}), defined in three different frames. The most straightforward possibility is to define θ_{ll} in the laboratory frame (referred to as lab-frame in the following). The results for this case are shown in Figure 12.
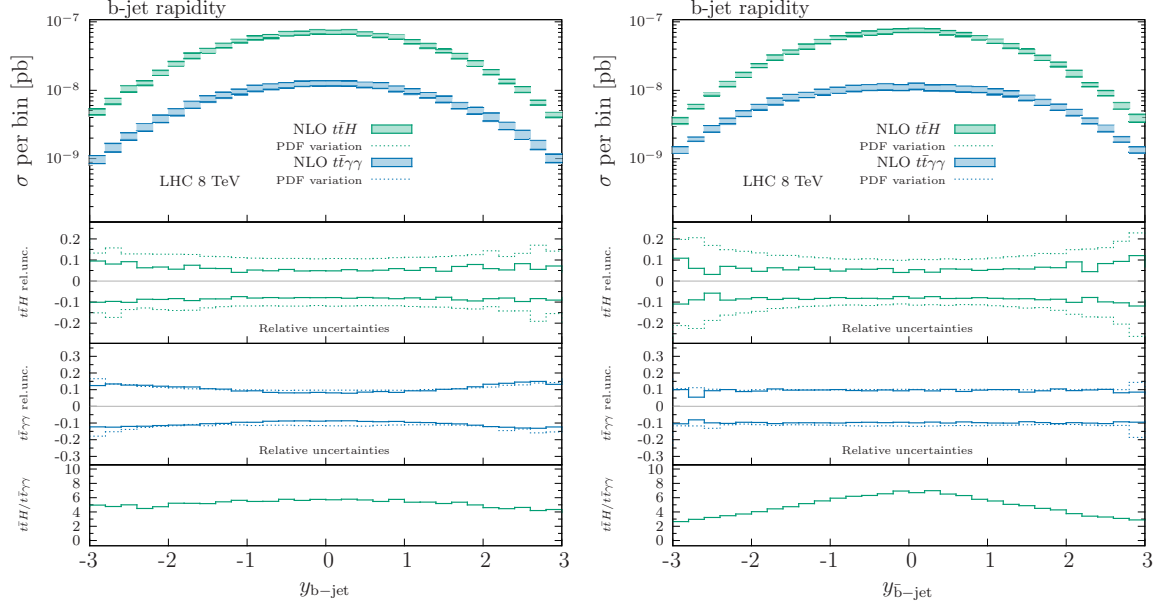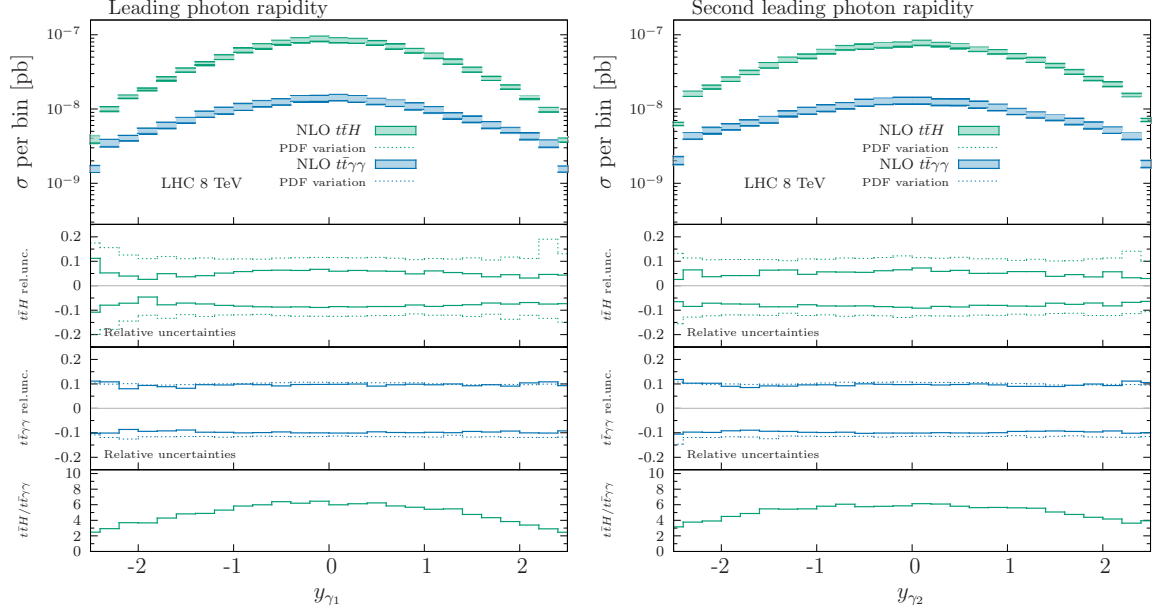
Figure 9: Rapidity distribution distribution of the b-jet (left) and anti-b jet (right) produced in the decay of the top and anti-top quark respectively.
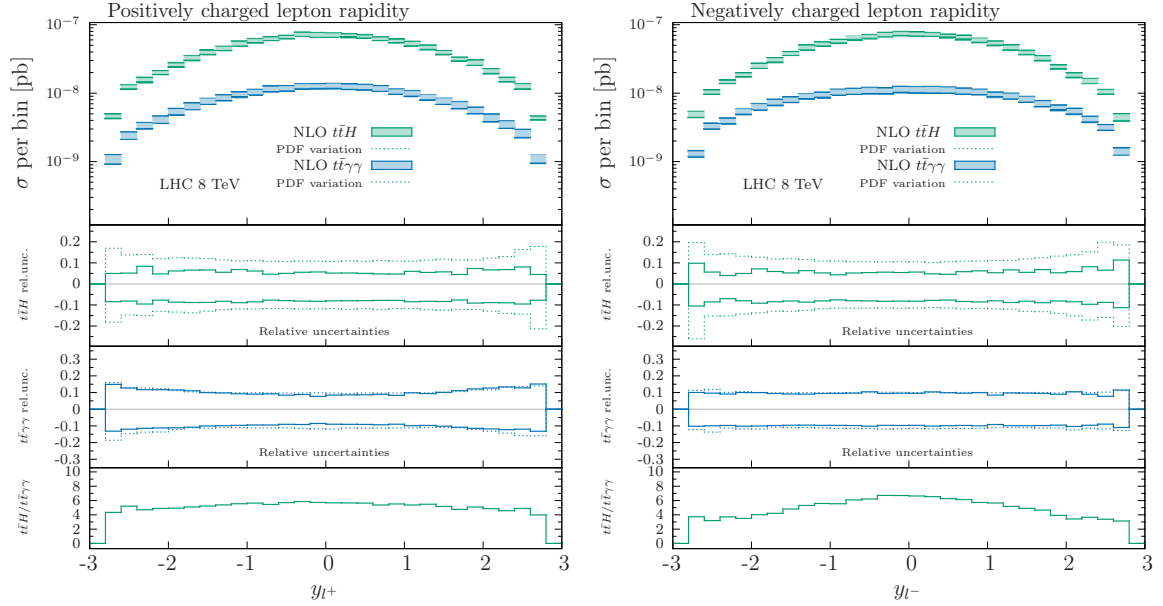

Figure 10: Rapidity distribution of the lepton (left) and anti-lepton (right) produced in the decay of the top and anti-top quark respectively.

The definition of two other frames, introduced for the first time in [109], became customary in polarisation studies, since they capture particularly well spin correlation effects.

For these particular frames, we define θ_{ll} to be the angle between the direction of flight of l^+, measured in frame where the *top quark* is at rest, and the direction of flight of l^-, measured in the frame where the *anti-top quark* is at rest. Since two rest frames

Figure 11: Rapidity distribution of the leading (left) and second leading photon (right).
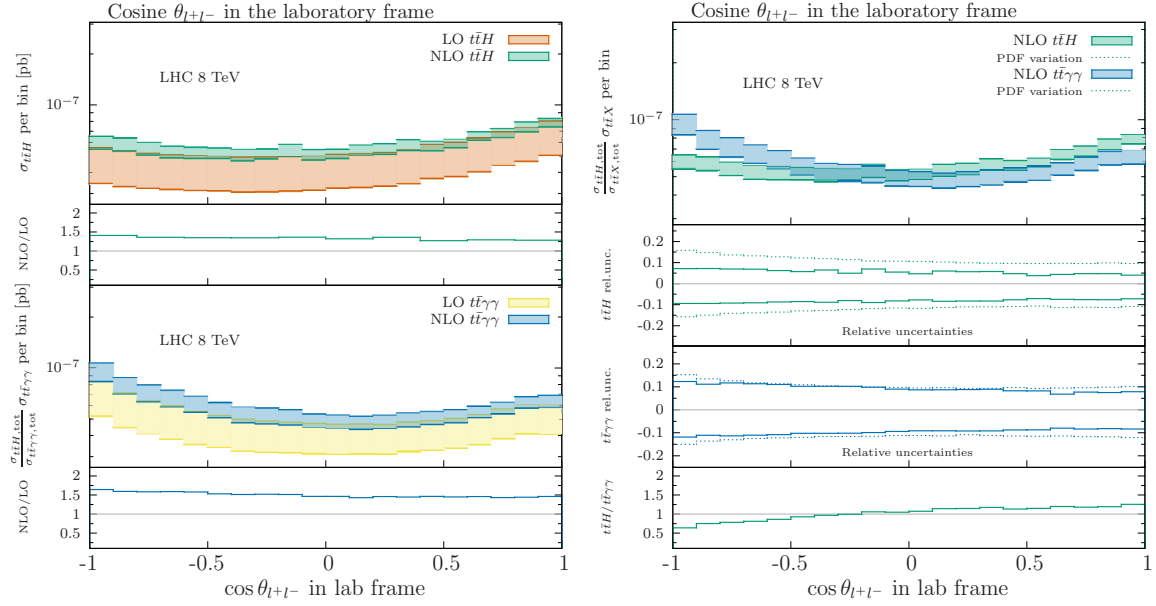
Figure 12: $\cos\theta_{ll}$ distribution for the signal ($t\bar{t}H$) and background ($t\bar{t}\gamma\gamma$) processes in the laboratory frame. The exact definition of the angle θ is given in the text. The $t\bar{t}\gamma\gamma$ prediction is normalized to the $t\bar{t}H$ inclusive cross-section. On the left hand side, we compare LO with NLO predictions and show their K-factor separately for $t\bar{t}H$ and $t\bar{t}\gamma\gamma$ in bottom insets. On the right hand side, we show NLO relative uncertainties with the signal-to-background ratio as the last bottom inset.

are involved in this definition, a common initial frame needs to be specified, from which the (rotation-free) Lorentz boost can be applied in order to transform the system to the t and $\bar{t}$ rest frames. We choose two possible starting points, which we label as *frame-1* and
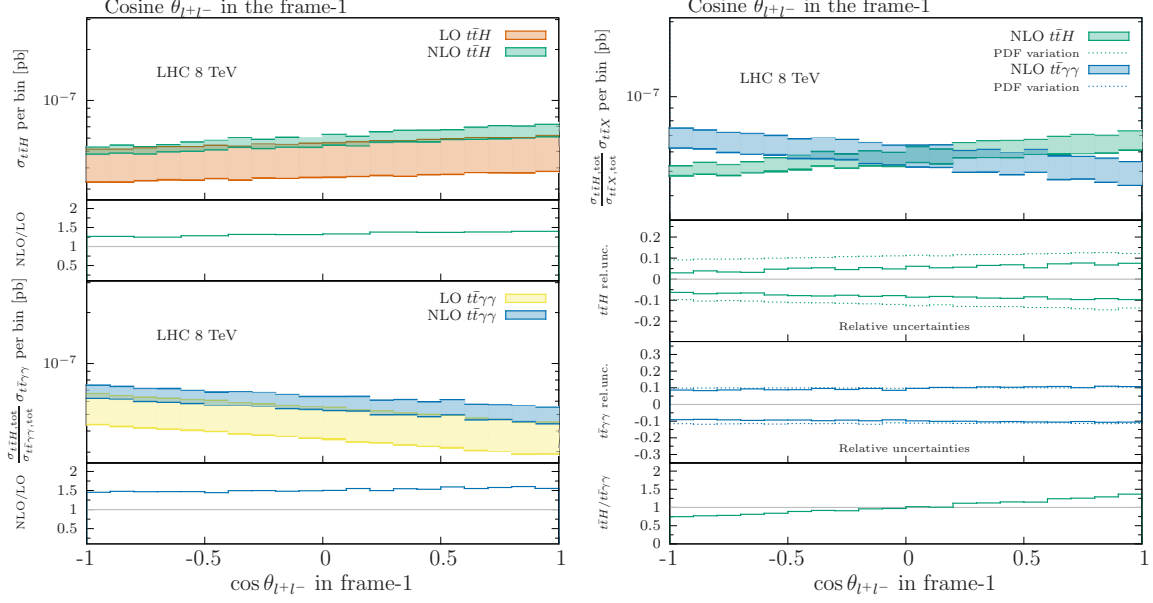
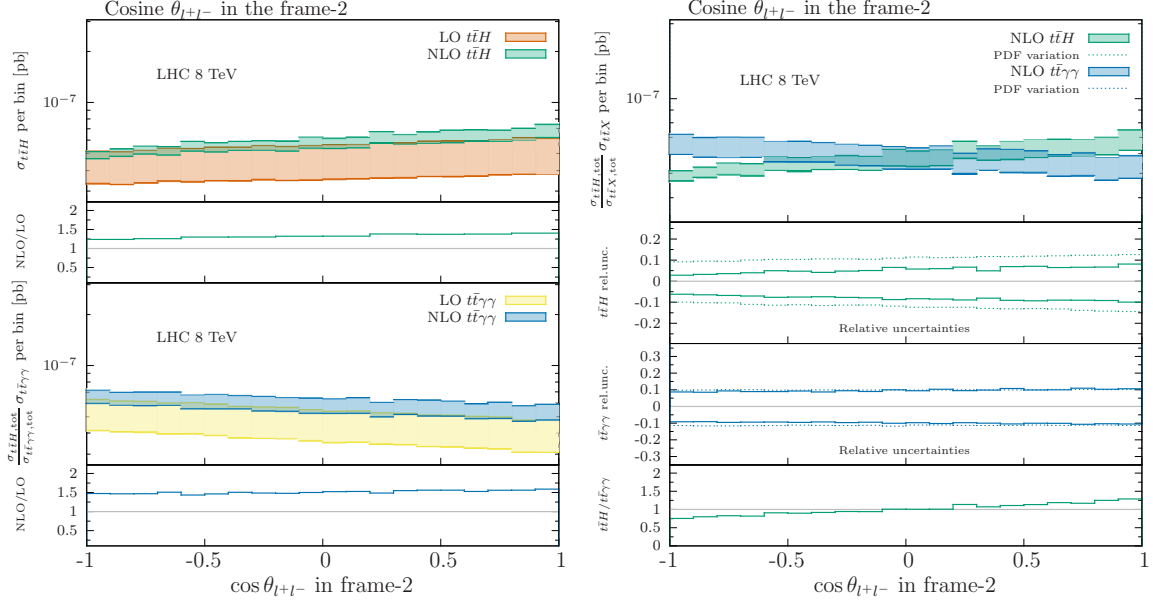**Figure 13:** Same as Figure 12, but for reference frame-1.

frame-2, defined as follows:

- *frame-1*: the Lorentz boosts to bring t and $\bar{t}$ separately at rest are defined with respect to the $t\bar{t}$-pair center-of-mass frame,

- *frame-2*: the Lorentz boosts to bring t and $\bar{t}$ separately at rest are defined with respect to the lab-frame.

These two frames are designed to be maximally sensitive to the different polarisation structures of the top-pair in the final state. Furthermore, as already demonstrated at LO [37], considering the spin information in the decay of the top and anti-top quark is crucial to disentangle the two different final states, which otherwise look identical, being characterized by a completely flat distribution in both cases.

In Figure 12 we show the behaviour of $\cos\theta_{ll}$ in the lab-frame. To highlight shape differences, the background predictions have been normalized to the inclusive $t\bar{t}H$ cross section. The left hand side of Figures 12-14 presents the comparison of the LO and NLO predictions for $t\bar{t}H$ and $t\bar{t}\gamma\gamma$ separately and shows their respective differential K-factors. The right hand side histograms compare results for the signal and background processes, with their ratio and respective relative uncertainty in the bottom insets.

This is to be compared with the plots in Figures 13-14, where the same observable is shown in frame-1 and frame-2. In the two latter frames a difference in the sign of the slope emerges, while in the lab frame, despite a clear difference in the slopes, the curves have an analogous trend. By comparing the two ratio plots at the bottom of the right plots in Figures 13 and 14, we conclude that the frame-1 offers the best signal-to-background ratio. It is also worth stressing that, while in the lab frame the K-factors tend to decrease slightly when $\cos\theta_{ll} \to 1$, in frame-1 and frame-2, the NLO corrections feature an almost perfectly

Figure 14: Same as Figure 12, but for reference frame-2.

flat K-factor which agrees with the inclusive cross section K-factor reported in Table 1. A comparison of the LO and NLO predictions reveals the anticipated reduction of the scale uncertainties.

Let us finally remark that the results shown here for the background, only consider photon radiation from the initial state and from the top and anti-top quark, but not from their decay products. This is opposite to the case of the signal, where photons always originate from the decay of the Higgs boson. By considering more general cases and using top tagging techniques without relying on MC truth is expected to decrease the purity of the signal. A more quantitative analysis of these effects is beyond the scope of the present work.

4. Conclusions

The event generator MADGRAPH5_AMC@NLO and the one-loop amplitudes provider GoSam have been interfaced to provide the user with a framework implenting the most advanced techniques for the evaluation of cross sections and differential distributions at next-to-leading order (NLO) accuracy.

In this work, the integration of the two codes has been applied for the first time to the NLO corrections to the production of a Higgs Boson in association with a pair of top-antitop quarks, as well as to the background process where two hard photons are produced directly. We compared several key distributions to disentangle the two processes and focused in particular on observables designed to study spin correlation effects. We found that NLO corrections give a sizable contribution, which however distorts the shape of the distributions only very mildly. Moreover, we observed a clear reduction of the theoretical uncertainties.

The high-level of flexibility and reliability of the joined technologies of the two codes make of MADGRAPH5_AMC@NLO+GOSAM an ideal tool for the high-precision studies and the hunt for deviations from known-physics signals which characterise the Run II programme at the LHC.

Acknowledgments

A. The GoSam input card

We report here a copy of the default GoSam input card with a brief explanation of the different options. For a more detailed overview we refer to the GoSam papers [17, 20] and the GoSam manual which can be found online [111] and is continuously updated. The default `gosam.rc` file is the following:

```
##################################################
# Copy this file to setup.in in order to set
# some common options for all examples.
###################
# physics options #
###################
# Model specs.:
model=smdiag_mad
model.options=GF: 0.0000116639, mZ: 91.188, mW: 80.419, Nf: 4

# Parameters set to zero algebraically:
zero=me,mmu,mU,mD,mC,mS,wB,wT

# Symmetries:
symmetries=family,generation

# Filter for scale-less loop integrals:
filter.nlo=lambda d: (not (d.isScaleless()))


###################
# program options #
###################
form.bin=tform
form.threads=4
form.tempdir=/tmp
fc.bin=gfortran -O2
##################################################
```

This input file needs to be modified if the computation is performed within the 5-flavour scheme. The b-quark mass can be set algebraically to zero by adding `mB` to the list `zero`:

`zero=me,mmu,mU,mD,mC,mS,mB,wB,wT`.

Furthermore the number of light quarks `Nf` has to be set equal to 5.

The tag `symmetries` specifies some further symmetries in the calculation of the amplitudes. The information is used when the list of helicities is generated. Possible options are:

- `flavour`: does not allow for flavour changing interactions. When this option is set, fermion lines are assumed not to mix.

- `family`: allows for flavour-changing interactions only within the same family. When this option is set, fermion lines 1-6 are assumed to mix only within families. This

means that e.g. a quark line connecting an up with down quark would be considered, while a up-bottom one would not.

- `lepton`: means for leptons what "flavour" means for quarks.

- `generation`: means for leptons what "family" means for quarks.

Furthermore it is possible to fix the helicity of particles. This can be done using the command `%<n>=<h>`, where $< n >$ stands for a PDG number and $< h >$ for an helicity. For example `%23=+-` specifies the helicity of all Z-bosons to be "+" and "-" only (no "0" polarisation).

The filter

```
filter.nlo=lambda d: (not (d.isScaleless()))
```

removes possible scaleless loop diagrams which may be generated by `QGRAF`. Several predefined filters to select only subsets of diagrams exist and can be used in this tag. The full list and some examples can be found in [111].

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