PROCEEDINGS OF SCIENCE

Higgs interference effects in top-quark pair production in the 1HSM

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We consider a new physics model with an additional heavy Higgs boson that decays into a top-antitop pair. Its presence induces distortions in the distribution in the invariant mass of the top-antitop system in a neighbourhood of the mass of the heavy Higgs. In order to reliably assess the size of these deviations, we have developed a framework to compute all relevant corrections up to next-to-leading order (NLO) accuracy. This resulted in a code which combines the features of the NLO frameworks Helac and OpenLoops. We present some predictions for this process and, based on those, some preliminary studies of the sensitivity to the parameters of this model at the LHC and the HL-LHC.

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1. Introduction

Among the various proposals for new physics beyond the Standard Model (BSM), models with additional scalars are widely studied. These include for instance 2-Higgs doublet models. One of their general features is the occurrence of a heavier neutral Higgs boson that can decay into a top-antitop pair. This gives rise to interference effects in physical distributions involving the top-antitop pair, which can then be exploited to detect new physics contributions.

As a simplified but instructive example, we consider here the 1-Higgs-singlet model (1HSM) [1], which contains an additional Higgs boson which is a singlet under all charges in the Standard Model (SM). The most general gauge-invariant potential we can write in terms of the SM Higgs field ϕ and the additional Higgs field s is given by

$$V = \lambda\left(\phi^\dagger\phi - \frac{v^2}{2}\right)^2 + \frac{1}{2}M^2 s^2 + \lambda_1 s^4 + \lambda_2 s^2\left(\phi^\dagger\phi - \frac{v^2}{2}\right) + \mu_1 s^3 + \mu_2 s\left(\phi^\dagger\phi - \frac{v^2}{2}\right). \tag{1}$$

We restrict ourselves to models where $\mu_1 = \lambda_1 = \lambda_2 = 0$. After spontaneous symmetry breaking, we obtain two neutral spin-0 particles h_1 and h_2, as follows

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ H + v \end{pmatrix}, \qquad \begin{aligned} h_1 &= H\cos\theta - s\sin\theta\,, \\ h_2 &= H\sin\theta + s\cos\theta\,, \end{aligned} \tag{2}$$

where $v \simeq 246\,\text{GeV}$ gives the vacuum expectation value of ϕ. We interpret h_1 as the SM Higgs, with $M_{h_1} = 125\,\text{GeV}$, and h_2 as a heavier Higgs of mass M_{h_2}. Then, M_{h_2} and θ are the only free parameters of the model. The coupling of h_1 and h_2 to the top get also modified, and depend on the mixing angle θ as follows:

$$y_t^{h_1} = \sqrt{2}\cos\theta\frac{m_t}{v}\,, \qquad y_t^{h_2} = -\sqrt{2}\sin\theta\frac{m_t}{v}\,, \tag{3}$$

with m_t the top mass. Our aim is to quantitatively estimate the effect of the presence of h_2 on top-antitop ($t\bar{t}$) production, and provide a basic estimate of the sensitivity of present and future data to such effects.

2. Setup of the calculation

It is known that both top and Higgs production cross-sections receive large QCD corrections at NLO. It is therefore important to at least reach NLO accuracy not only for the background (QCD induced $t\bar{t}$ production), but also for the signal ($t\bar{t}$ production via h_1 and h_2, including interference with the SM).

While NLO corrections to the QCD background are widely established [2], NLO corrections to the signal, specifically the interference with the SM, are not included in automated NLO frameworks, mainly because the signal is loop-induced whereas QCD top production occurs at tree-level. In particular, both Higgs bosons are produced in gluon fusion through a top loop.

Since we are interested in the production of a heavy Higgs above the $t\bar{t}$ threshold, we cannot approximate Higgs production as arising from an effective contact interaction between two gluons and a Higgs, but rather we need to keep the full mass dependence in the top loop. This implies that virtual NLO corrections to the signal arise from two-loop diagrams. These are of two kinds. On the one hand, we have factorisable corrections, i.e. two-loop corrections to the gluon-gluon-Higgs amplitude, as well as one-loop corrections to top-production. The latter are already present in OpenLoops [3], and we have implemented the former in OpenLoops as form factors, whose explicit expressions can be found in [4]. On the other hand, we have non-factorisable corrections, in which a gluon is exchanged between a gluon in the initial state and a top quark in the final state. An analytic calculation of these corrections is beyond today's loop technology. We have therefore employed an approximation, which involves rescaling one-loop non-factorisable corrections in the heavy-top limit with the exact Born amplitude. This approximation is exact in the limit in which the exchanged gluon is soft, and therefore allows the cancellation of infrared singularities between real and virtual contributions.

Real NLO corrections arise from Higgs production plus one extra parton at one loop. These can be produced using the standard features of OpenLoops. In particular, we have computed exactly both factorisable and non-factorisable real corrections.

In order to combine real and virtual corrections in an NLO event generators, we have used the Helac framework. In particular, Helac-Dipoles [5] provided the appropriate counterterms for real and virtual corrections using Catani-Seymour dipole subtraction [6, 7]. The so-upgraded real and virtual contributions can be computed numerically, as the cancellation of infrared singularities of both real and virtual singularities is performed against the corresponding counterterms beforehand. This procedure is standard for NLO calculations. The phase space is generated using Kaleu [8], also part of the Helac framework. The corresponding code, which we refer to as Helac+OpenLoops, has been used to obtain the numerical predictions presented in the next section. We remark that the calculation is performed with stable tops, and we leave the inclusion of top decay to future work.

3. Numerical predictions

In [9], we considered eight benchmark scenarios, corresponding to two values of θ and four values of M_{h_2}, as in table 1. Here, for illustrative purposes, we show results for the differential

M_{h_2} [GeV]	700	1000	1500	3000
$\theta = \theta_1$	$\pi/15$	$\pi/15$	$\pi/22$	$\pi/45$
$\theta = \theta_2$	$\pi/8$	$\pi/8$	$\pi/12$	$\pi/24$

Table 1: The benchmark values of θ and M_{h_2} considered in and presented here.

distribution in $M_{t\bar{t}}$, the invariant mass of the top-antitop pair. This is displayed in figure 1 for $\theta = \theta_1$ (left) and $\theta = \theta_2$, for the four values of M_{h_2} in table 1. The numerical predictions shown there have been obtained for the LHC with $\sqrt{s} = 13$ TeV, using the NLO PDF set `PDF4LHC15_nlo_mc` [10]. We observe that QCD background constitutes by far the largest part of the cross-section. Deviations from the SM are small, and, as expected, occur for values of $M_{t\bar{t}}$ in a neighbourhood of the mass of the heavy Higgs. We then identified some invariant mass windows, one for each benchmark scenario, where deviations from the SM are more prominent, and that can be used for sensitivity studies. The largest deviations occur for $M_{h_2} = 700\,\text{GeV}$, and the corresponding predictions are reported in figure 2. Around the mass of the heavy Higgs we observe a peak-dip structure which

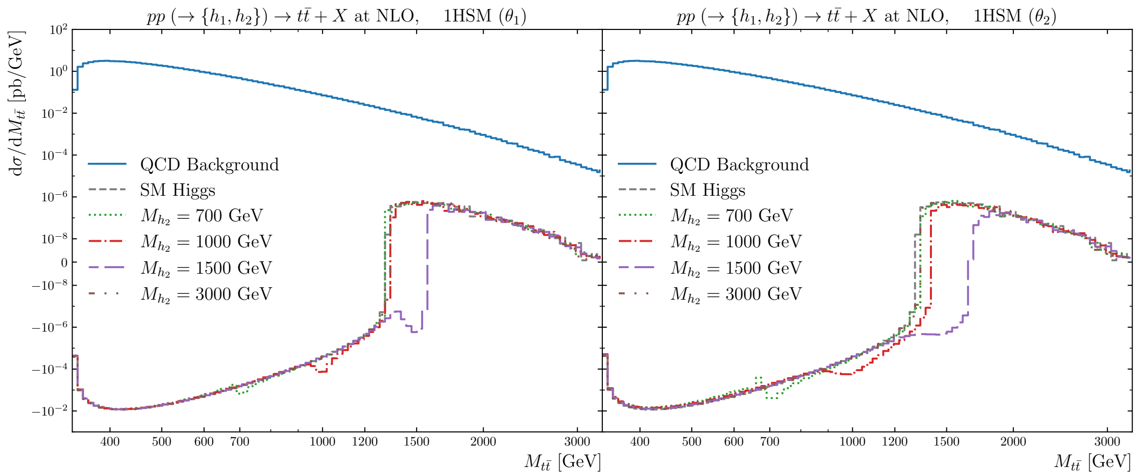

Figure 1: Distribution in $M_{t\bar{t}}$ at the LHC with $\sqrt{s} = 13$ TeV, corresponding to $\theta = \theta_1$ (left) and $\theta = \theta_2$ (right).

is typical for an invariant mass distribution around a resonance. Note that the deviations from the QCD background are generally quite small, reaching at most 0.5%.

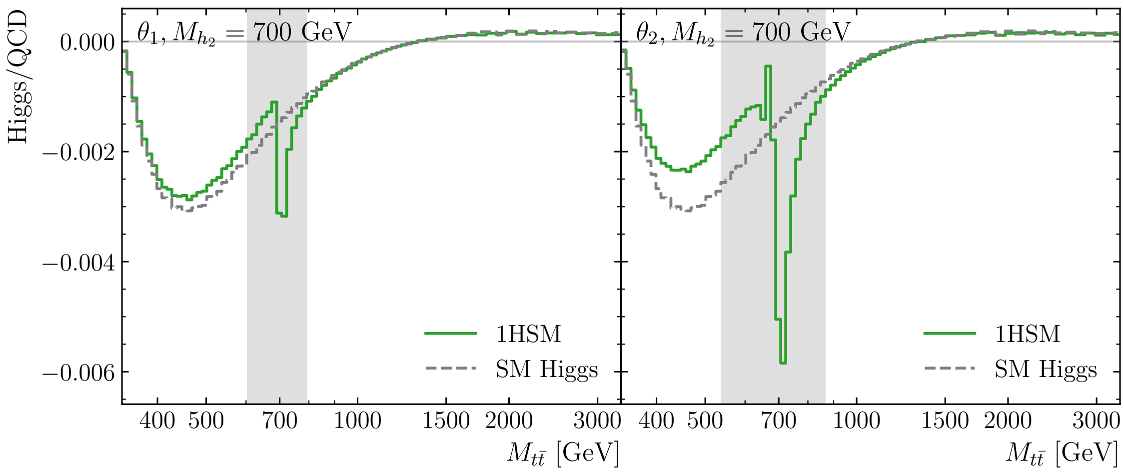

Figure 2: Ratio between the Higgs contribution to the $M_{t\bar{t}}$ distribution for $\theta = \theta_1$ (left) and $\theta = \theta_2$ (right) and for $M_{h_2} = 700$ GeV. The mass windows used for sensitivity studies in [9] correspond to the shaded areas in the figure.

It is also instructive to zoom into the selected mass windows (the shaded areas in figure 2), and appreciate the impact of NLO corrections. This is illustrated in figure 3. We observe that NLO corrections are quite large, and give rise to sizeable distortions of the $M_{t\bar{t}}$ distribution around the mass of heavy Higgs. This is not only due to the overall size of the NLO corrections, but also to the effect of real radiation which is not included in $M_{t\bar{t}}$ by definition, thus causing an imbalance between real and virtual corrections. Whether it is possible to devise observables that are less sensitive to real radiation is an interesting question which we leave to future work.

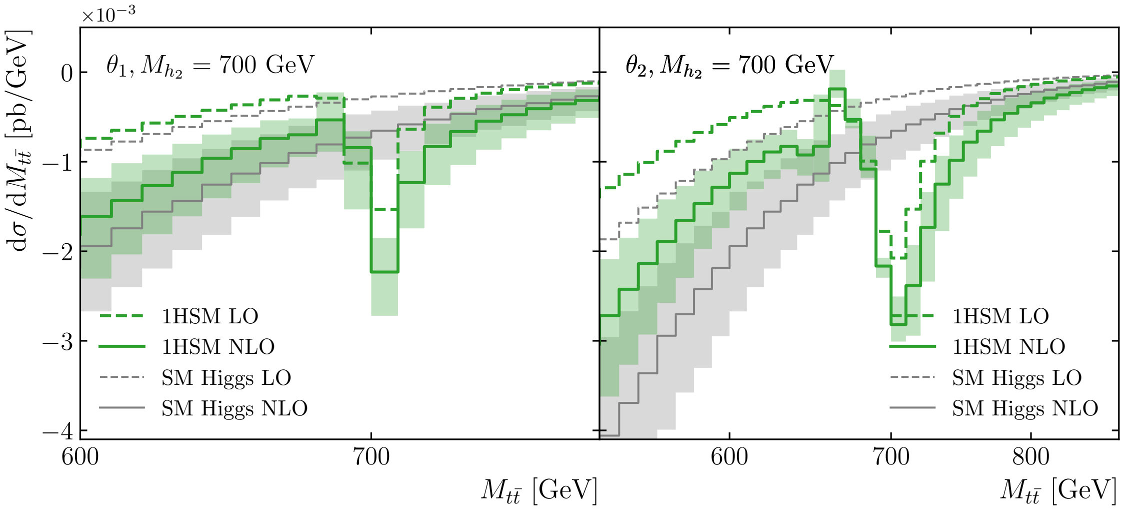

Figure 3: LO and NLO contributions to the $M_{t\bar{t}}$ distribution arising from a SM Higgs and from both Higgs bosons in the 1HSM, for $\theta = \theta_1$ (left) and $\theta = \theta_2$ (right), and for $M_{h_2} = 700$ GeV.

4. BSM sensitivity and outlook

Based on the predictions described in the previous section, in [9] we investigated the sensitivity of current and future LHC data to the presence of a heavy Higgs in the 1HSM. For each benchmark scenario, we select an appropriate $M_{t\bar{t}}$ window around the mass of the heavy Higgs. As a significance measure, we use $(|S|/\sqrt{B}) \times \sqrt{\mathrm{Br}_{2\ell 2\ell'}}$, where $|S|$ is the sum of the absolute values of the Higgs contribution to the number of events in the selected mass window, B is the number of QCD background events, and $\mathrm{Br}_{2\ell 2\ell'}$ the branching ratio for $t\bar{t}$ decaying into a final state with two leptons with different flavours. This significance measure is overly optimistic. In fact, it is based only on statistics and ignores completely systematic uncertainties. We conventionally consider a benchmark point to have the potential to be excluded if the above significance is larger than 2. We then find that only benchmark points with $\theta = \theta_1$ and $M_{h_2} = 700$ GeV or $M_{h_2} = 1000$ GeV can be barely excluded at the HL-LHC.

To have a more realistic understanding, one needs to include the decay of the top quarks. This can be performed by implementing the BSM model we have considered in a NLO accurate Monte Carlo event generator such as POWHEG [11]. The inclusion of top decays will give access to more complicated observables, for instance correlations between the leptons, whose features could be exploited to reduce the overwhelming QCD background.

Also, even if the 1HSM will not give promise to be excluded at the LHC, the framework we have developed could be used for other BSM models with additional scalars, both CP-even and CP-odd.

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