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Analysis of interference effects in the di-top final state for $\mathcal{CP}$-mixed scalars in extended Higgs sectors

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Various extensions of the Standard Model predict the existence of additional Higgs bosons. If these additional Higgs bosons are sufficiently heavy, an important search channel is the di-top final state. In this channel, interference contributions between the signal and the corresponding QCD background process are expected to be important. If more than one heavy scalar is present, besides the signal-background interference effects associated with each Higgs boson also important signal-signal interference effects are possible. We perform a comprehensive model-independent analysis of the various interference contributions within a simplified model framework considering two heavy scalars that can mix with each other, taking into account large resonance-type effects arising from loop-level mixing between the scalars. The interference effects are studied with Monte Carlo simulations for the di-top production process at the LHC. We demonstrate that signatures can emerge from these searches that may be unexpected or difficult to interpret.

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1. Introduction

The Standard Model (SM) of particle physics has been remarkably successful in predicting physics observed at particle colliders starting from the earliest days of colliders in the 1970s to the present-day Large Hadron Collider (LHC). Despite the tremendous success of the SM and the discovery of a Higgs boson at about 125 GeV in 2012 [1, 2], our understanding of the universe is far from complete. Various extensions of the SM, in particular extensions of the Higgs sector, have been proposed to address its shortcomings and limitations.

Extended Higgs sector scenarios feature additional scalar bosons. Scalar bosons with a mass scale of a few hundreds of GeV (called here heavy scalars for simplicity) can be accessible to experiments at the LHC. For heavy scalars with a large top-Yukawa coupling the production via gluon fusion (proceeding through a virtual top-quark loop) and the subsequent decay to two top quarks is a very important experimental search channel. The resonant production of a heavy scalar and its subsequent decay to top pairs (the signal process) would be naively expected to manifest itself as a characteristic bump in the invariant mass distribution of the top-quark pair. However, the interference between the resonant heavy scalar production and the SM QCD background ($gg \to t\bar{t}$) results in a large destructive contribution [3–7]. This large interference with the SM QCD background leads to a characteristic peak–dip signature in the invariant mass distribution of the top pairs ($m_{t\bar{t}}$). The signal-background interference pattern depends on the $\mathcal{CP}$ nature of the heavy scalars, their masses, and their decay widths [3, 4]. These interference effects can significantly alter the exclusion limits and leave a considerable parameter region un-excluded that would appear to be ruled out if the interference effects were neglected [8–10].

In addition to the large (usually destructive) signal-background interference effect, an additional signal-signal interference contribution can appear if two heavy scalars are considered that can mix with each other. Signal-signal interferences in the di-top final state have not been investigated so far using Monte-Carlo event simulations which is a crucial ingredient for assessing the expected sensitivity of experimental searches. We will focus on the decays of heavy scalars into the $t\bar{t}$ final state because many extensions of the SM Higgs sector predict the couplings of heavy scalars to third generation fermions to be large compared to other couplings like for instance the couplings to electroweak gauge bosons [6]. In this context, it is also interesting that recently an excess in the $t\bar{t}$ final state at a mass of around 400 GeV has been observed by the CMS Collaboration based on the LHC Run 2 data that has been analysed so far [9].

2. Simplified model framework

We perform our study in a minimal simplified model (i.e., in a model-independent framework) that involves two additional $\mathcal{CP}$-mixed Higgs bosons. For our study, we parameterize the top-Yukawa part of the Lagrangian involving the two BSM $\mathcal{CP}$-mixed heavy scalars in the form

$$\mathcal{L}_{\text{yuk}} = -\sum_{j=1}^{2} \frac{y_t^{\text{SM}}}{\sqrt{2}}\, \bar{t}\left(c_{t,j} + i\gamma_5 \tilde{c}_{t,j}\right) t\phi_j\,, \tag{1}$$

where y_t^{SM} is the SM top-Yukawa coupling, ϕ_j are the two heavy scalar fields, and t and $\bar{t}$ are the top and antitop quark spinors, respectively. The parameters $c_{t,j}$ and $\tilde{c}_{t,j}$ are the Yukawa-coupling modifiers which rescale the $\mathcal{CP}$-even and $\mathcal{CP}$-odd coupling components of the heavy scalar ϕ_j to the top quark.

The loop-level mixing between the tree-level mass eigenstates arising from loop corrections to the scalar two-point function can be incorporated via wave function normalisation factors (called "Z-factors") that in general are complex numbers [11, 12]. Defining $\{\phi_i\}(i = 1, 2)$ and relabelling (ϕ_1 with h) and (ϕ_2 with H) to be the tree-level mass eigenstates, and $\{h_a\}(a = 1, 2)$ to be the loop-corrected mass eigenstates, we can write a generic Feynman amplitude (e.g., $gg \to t\bar{t}$) involving neutral scalars as intermediate particles that mix with each other as

$$\mathcal{A} = \sum_{i,j=h,H} \hat{\Gamma}_i^X \Delta_{ij}(p^2) \hat{\Gamma}_j^Y \,. \tag{2}$$

Using the Z-factor formalism, we can rewrite this as

$$\mathcal{A} \simeq \sum_{a=1,2} \left(\sum_{i=h,H} \hat{Z}_{ai} \hat{\Gamma}_i^X \right) \Delta_a^{\mathrm{BW}}(p^2) \left(\sum_{j=h,H} \hat{Z}_{aj} \hat{\Gamma}_j^Y \right), \tag{3}$$

where Γ_i^X and Γ_j^Y are the irreducible vertex functions from the production and decay part of the amplitude, respectively. They contain the couplings of scalar i and scalar j at the scattering vertices X and Y. $\Delta_a^{\mathrm{BW}}(p^2)$ are the Breit-Wigner propagators of the mass eigenstates h_a. In practice, one can easily incorporate this formalism into the Lagrangian of Equation (1) by performing the following replacements,

$$c_{t,1} \longrightarrow Z_{11} c_{t,1} + Z_{12} c_{t,2} \,, \qquad \tilde{c}_{t,1} \longrightarrow Z_{11} \tilde{c}_{t,1} + Z_{12} \tilde{c}_{t,2} \,, \tag{4a}$$

$$c_{t,2} \longrightarrow Z_{22} c_{t,2} + Z_{21} c_{t,1} \,, \qquad \tilde{c}_{t,2} \longrightarrow Z_{22} \tilde{c}_{t,2} + Z_{21} \tilde{c}_{t,1} \,, \tag{4b}$$

where $\hat{Z}_{1h} = Z_{11}, \hat{Z}_{1H} = Z_{12}, \hat{Z}_{2h} = Z_{21}, \hat{Z}_{2H} = Z_{22}$. These Z-factors can be arranged in a non-unitary (2×2) Z-matrix. Since the Z-factors are in general complex numbers which have to be evaluated at the complex pole (imaginary parts also arise from loop integrals), this effectively renders the Yukawa-coupling modifiers to be complex. We will see that the mixing between the scalars gives rise to a rich pattern of signal-background and signal-signal interferences that can lead to important modifications of the phenomenology compared to the single-Higgs case.

3. Results

The loop-induced Higgs-gluon-gluon production vertex develops a sizeable imaginary part above the threshold where the two top quarks that couple to the Higgs boson can be on-shell. Thus, for the masses of the heavy scalars considered in this work, the limit of an infinite top-quark mass would be a poor approximation. The proper incorporation of this imaginary part is crucial for the description of interference effects. Therefore, in order to properly simulate the interference effects (and all other parts of the considered processes), we have implemented the full top-triangle loop as a form factor for our Monte-Carlo simulation, which we perform using `MadGraph` [13].

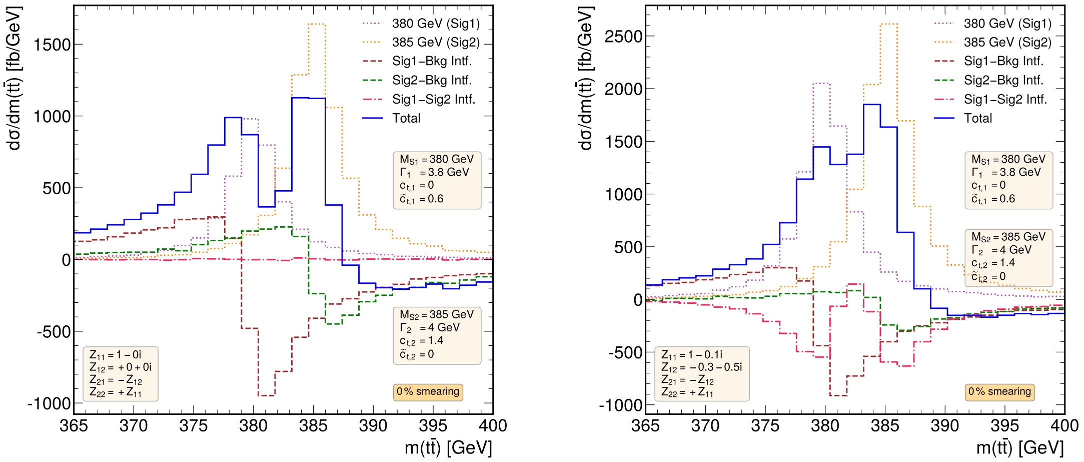
In Figures 1 to 3 we present results of our analysis for differential cross sections as a function of the invariant mass of the top-quark pair after subtracting the QCD background distribution. The purple dotted curve in each plot shows the resonance contribution corresponding to the signal of the lighter one of the two scalars, while the yellow dotted curve shows the signal resonance of the heavier scalar. The brown dashed curve shows the signal-background interference for the lighter scalar, while the green dashed curve shows the signal-background interference for the heavier scalar. The red dash-dotted curve displays the signal-signal interference between the two scalars. The solid blue curve shows the total contribution arising from the sum of all the signal and interference contributions in each plot. Gaussian smearing is applied in order to account for the effects of a finite experimental resolution (thus, the plots where "0%" smearing is indicated correspond to an idealistic situation with infinite experimental resolution).

The masses of the heavy scalars, the decay widths and the values of the Yukawa-coupling modifiers are input parameters and are specified in the plot panels. The total decay width is chosen such that it is at least as large as the partial decay width in the $t\bar{t}$ channel. For the entries of the (2×2) Z-matrix exemplary values are chosen as input parameters, which are also displayed in the plot panels. In a UV-complete model the elements of the Z-matrix can be predicted from the other model parameters, see e.g. Refs. [11, 12]. We impose the following approximate relations: the diagonal elements are approximately equal to each other, and the off-diagonal terms are approximately the negative of each other. For the case of negligible higher-order contributions the Z-matrix is a (2×2) identity matrix.

As examples for our numerical results we focus in the following on three scenarios. In the first one, shown in Figure 1, the chosen lowest-order couplings indicate that the two scalars at lowest order are a pure $\mathcal{CP}$-even and a pure $\mathcal{CP}$-odd state, while a loop-level mixing can be induced via the Z-matrix (such a situation occurs e.g. in the MSSM with complex parameters). In the two plots the case where the Z-matrix is a (2×2) identity matrix (Figure 1a) is compared with the case of a non-trivial Z-matrix (Figure 1b). While as expected no signal-signal interference contribution occurs in Figure 1a, the loop-level mixing induced by the Z-factors gives rise to the signal-signal interference contribution shown in Figure 1b. As a result of this mixing, the two separate peaks in Figure 1a merge into a single broad peak in Figure 1b even for the idealistic case where no experimental smearing is applied.

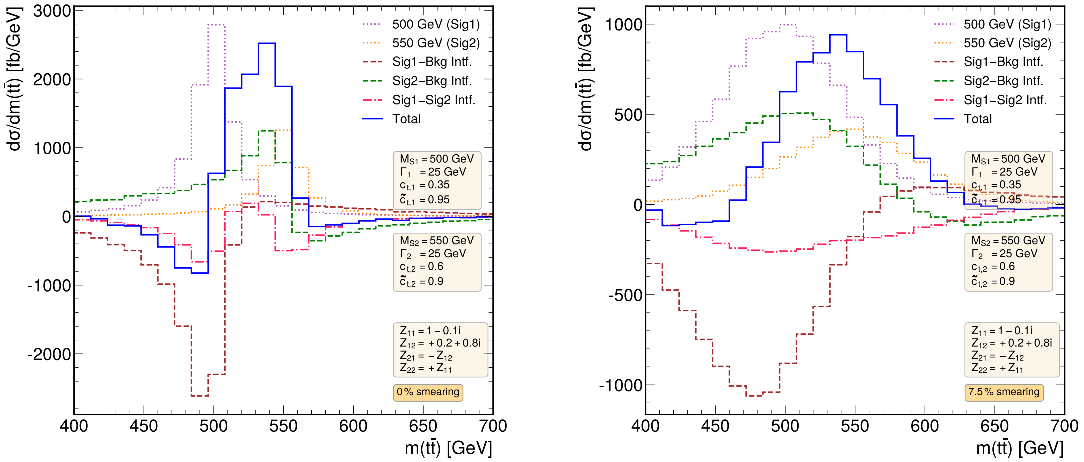
The effect of a finite experimental resolution is investigated in Figure 2, where the case of no smearing is compared with a Gaussian smearing of 7.5% that resembles the resolution of the CMS analysis of Ref. [9]. While for the case of no smearing a dip-peak structure is visible (Figure 2a), the total contribution (blue curve) for this scenario with two Higgs bosons that are separated in mass by 50 GeV (Figure 2b) resembles the case of a single resonance peak (rather than a peak-dip or dip-peak structure).

We finally turn to a scenario with two nearly mass-degenerate scalars that is characterised by a large compensation between the signal contributions of the two scalars and the signal-signal interference contribution. The latter is driven in particular by a large imaginary part in the off-diagonal term of the Z-matrix. As shown in Figure 3 the overall effect in this "nightmare"-type scenario for experimental searches is just a rather flat distribution in the di-top invariant mass. While without smearing (Figure 3a) a small dip is visible, this feature is significantly washed out if Gaussian smearing is taken into account (Figure 3b; it should be noted that the scale of the y-axis in this plot is different from the other one). In such a situation other search channels like the production of three or four top-quarks can provide important complementary information.



(a) without loop-level mixing between the scalars **(b)** with loop-level mixing between the scalars

Figure 1: The effect of loop-level mixing, induced by the Z-factors, for the case of two heavy scalars which are pure $\mathcal{CP}$-even and $\mathcal{CP}$-odd states at lowest order.

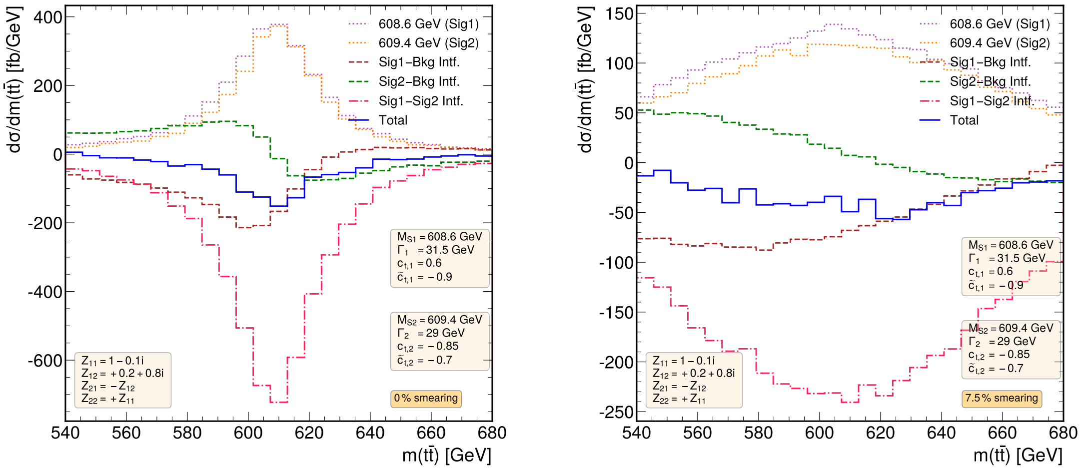


(a) without Gaussian smearing **(b)** with Gaussian smearing

Figure 2: The effect of a finite experimental resolution on the $m_{t\bar{t}}$ distribution.

4. Conclusions

In this work, we investigated the impact of interference effects in extended Higgs sectors in a model-independent analysis with loop-level mixing between the scalars. We considered two heavy scalars with masses above the di-top threshold and large branching ratios into top quarks. The loop-level mixing between the two scalars has been taken into account via the “Z-factor” formalism. We discussed possible patterns in the $m_{t\bar{t}}$ distribution that can arise as a consequence of the combined effect of the signal-background and signal-signal interference contributions. In addition, we discussed the impact of the finite experimental resolution. We pointed out that the scenario of two additional Higgs states that are close together in mass and can mix with each other gives rise to a very rich phenomenology, resulting in $m_{t\bar{t}}$ distributions that may be difficult to



(a) without Gaussian smearing

(b) with Gaussian smearing

Figure 3: A “nightmare scenario” with two nearly mass-degenerate scalars giving rise to a large destructive contribution from the signal-signal interference.

interpret. In such a situation the complementarity with searches targeting three- and four-top final states should be exploited.

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