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# $t\bar{t}H$ production in the Higgs characterisation model at NLO in QCD with full off-shell effects

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In these proceedings we present results for the $t\bar{t}H$ process in the dileptonic decay channel at the Large Hadron Collider. We discuss a possible extension of the Standard Model of particle physics to allow for a $\mathcal{CP}$-odd component in the top-Higgs Yukawa interaction. Particular emphasis is placed upon the importance of higher-order corrections and full off-shell effects and on how these depend on the $\mathcal{CP}$-state of the Higgs boson. In addition, we also discuss Higgs-boson decays for the Standard Model case.

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## 1. Introduction

Even though the Higgs boson and its properties have been scrutinised extensively in the decade since its discovery, a lot of freedom remains in the $\mathcal{CP}$ phase of the Higgs boson. A pure $\mathcal{CP}$-odd state has been excluded with $3.7\,\sigma$ by CMS and $3.9\,\sigma$ by ATLAS and current measurements are in agreement with the Standard Model (SM) prediction of a $\mathcal{CP}$-even Higgs. However, the most recent CMS analysis actually favours a $\mathcal{CP}$-mixed state [1, 2]. Hence, it remains an intriguing possibility that the Higgs boson could be a $\mathcal{CP}$-mixed particle. Analysing $t\bar{t}H$ production is one of the primary ways of constraining the mixing between a $\mathcal{CP}$-even and a $\mathcal{CP}$-odd Higgs boson due to the large Yukawa coupling $y_t \sim 1$ of the top quark. Such an analysis requires precise and accurate predictions for the background and the signal processes. This should involve the calculation of NLO corrections to both the $t\bar{t}H$ production and the top quark decays as well as the inclusion of full off-shell effects. Naturally, most phenomenological studies of $t\bar{t}H$ production have been focused on the SM case. NLO QCD and EW corrections have been computed for stable $t\bar{t}H$ production including NNLL soft gluon resummation [3–8] and for fiducial $t\bar{t}H$ production with leptonically decaying top quarks including full off-shell effects [9, 10]. In contrast, the current state-of-the-art predictions for $t\bar{t}H$ production with $\mathcal{CP}$-odd admixture only incorporate NLO QCD corrections to the production and do not consider single- and non-resonant diagrams [11]. Here, we present predictions for $t\bar{t}H$ production with leptonically decaying top quarks and possible $\mathcal{CP}$ mixing in the top-Higgs Yukawa interaction including NLO QCD corrections to the production and top quark decays whilst also taking into account off-shell effects. These discussions are based on Ref. [12]. We will also briefly discuss the subsequent decay of the Higgs boson for the SM case. These results are presented in more detail in Ref. [13].

## 2. Setup

In this analysis we consider top-quark pair associated Higgs production with leptonic top quark decays, i.e. $pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu H + X$ production at order $\mathcal{O}\left(\alpha_s^3\alpha^5\right)$ for the LHC at $\sqrt{s} = 13$ TeV. For the full off-shell computation we take into account all double-, single- and non-resonant diagrams and unstable particles are treated within the complex mass scheme. In order to estimate the size of the corresponding effects, we compare the full-off shell approach to the narrow-width approximation (NWA). In the latter case only the a prior dominant double-resonant diagrams are incorporated and unstable particles are treated as on-shell particles by taking the limit $\Gamma/m \to 0$. For sufficiently inclusive observables, the off-shell effects, i.e. the differences between the two approaches, are expected to be of the order of $\Gamma_t/m_t \sim 0.8\%$. Both calculations are preformed using the HELAC-NLO framework [14, 15]. To describe the $\mathcal{CP}$ mixing in the top-Higgs Yukawa interaction, we employ the Higgs characterisation framework [16]. We choose $\kappa_{Htt\bar{t}} = 1$ for the $\mathcal{CP}$-even coupling, $\kappa_{Att\bar{t}} = 2/3$ for the $\mathcal{CP}$-odd coupling and $\kappa_{HVV} = 1$, $V = W^\pm, Z$ for the couplings between the Higgs boson and vector bosons in order to always recover the SM predictions for gluon-gluon and vector-boson fusion processes, independently of the mixing angle $\alpha_{CP}$. This mixing angle is set to 0 for the $\mathcal{CP}$-even, $\pi/4$ for the $\mathcal{CP}$-mixed and $\pi/2$ for the $\mathcal{CP}$-odd Higgs boson. Higher dimensional $HVV$ coupling and loop induced couplings of the Higgs boson to gluons or photons are not taken into account. For further details on the setup we refer to Refs. [12, 13].

**Table 1:** *Integrated fiducial cross-sections as calculated in the NWA, NWA with LO top-quark decays and full off-shell approach for $\alpha_{CP} = 0, \pi/4$ and $\pi/2$. Table was taken from [12].*

| $\alpha_{CP}$ | | Off-shell | NWA | Off-shell effects |
|---|---|---|---|---|
| 0 (SM) | $\sigma_{\rm LO}$ [fb] | $2.0313(2)^{+0.6275\,(31\%)}_{-0.4471\,(22\%)}$ | $2.0388(2)^{+0.6290\,(31\%)}_{-0.4483\,(22\%)}$ | −0.37% |
| | $\sigma_{\rm NLO}$ [fb] | $2.466(2)^{+0.027\,(1.1\%)}_{-0.112\,(4.5\%)}$ | $2.475(1)^{+0.027\,(1.1\%)}_{-0.113\,(4.6\%)}$ | −0.36% |
| | $\sigma_{\rm NLO_{LOdec}}$ [fb] | – | $2.592(1)^{+0.161\,(6.2\%)}_{-0.242\,(9.3\%)}$ | |
| | $\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$ | 1.21 | 1.21 (LOdec: 1.27) | |
| $\pi/4$ | $\sigma_{\rm LO}$ [fb] | $1.1930(2)^{+0.3742\,(31\%)}_{-0.2656\,(22\%)}$ | $1.1851(1)^{+0.3707\,(31\%)}_{-0.2633\,(22\%)}$ | 0.66% |
| | $\sigma_{\rm NLO}$ [fb] | $1.465(2)^{+0.016\,(1.1\%)}_{-0.071\,(4.8\%)}$ | $1.452(1)^{+0.015\,(1.0\%)}_{-0.069\,(4.8\%)}$ | 0.89% |
| | $\sigma_{\rm NLO_{LOdec}}$ [fb] | – | $1.517(1)^{+0.097\,(6.4\%)}_{-0.144\,(9.5\%)}$ | |
| | $\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$ | 1.23 | 1.23 (LOdec: 1.28) | |
| $\pi/2$ | $\sigma_{\rm LO}$ [fb] | $0.38277(6)^{+0.13123\,(34\%)}_{-0.09121\,(24\%)}$ | $0.33148(3)^{+0.11240\,(34\%)}_{-0.07835\,(24\%)}$ | 13.4% |
| | $\sigma_{\rm NLO}$ [fb] | $0.5018(3)^{+0.0083\,(1.2\%)}_{-0.0337\,(6.7\%)}$ | $0.4301(2)^{+0.0035\,(0.8\%)}_{-0.0264\,(6.1\%)}$ | 14.3% |
| | $\sigma_{\rm NLO_{LOdec}}$ [fb] | – | $0.4433(2)^{+0.0323\,(7.3\%)}_{-0.0470\,(11\%)}$ | |
| | $\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$ | 1.31 | 1.30 (LOdec: 1.34) | |

## 3. Phenomenological results

In Table 1 we list the integrated fiducial cross-section results for the three considered mixing angles in the off-shell approach and the NWA at LO and NLO in QCD. For the NWA we also calculate results where only the NLO QCD corrections to the production are taken into account ($\text{NLO}_{\text{LOdec}}$). Overall, the SM results are about 5 times as large as those for the $\mathcal{CP}$-odd Higgs boson while the $\mathcal{CP}$-mixed ones fall almost exactly in the middle of the two others. Higher-order corrections are consistent between the NWA and the full off-shell calculation and amount to around 20% for the $\mathcal{CP}$-even and -mixed scenarios. They are slightly larger for the $\mathcal{CP}$-odd Higgs boson but still within the LO scale uncertainties. The results without QCD corrections to the decays exhibit slightly larger $\mathcal{K}$-factors and thus overestimate the full NLO result by 3 – 5%. Off-shell effects are below 1% and thus of the expected order for the $\mathcal{CP}$-even and -mixed cases. However, for the $\mathcal{CP}$-odd Higgs boson, the effects increase to 14% at NLO which is more than an order of magnitude larger than for the other cases and well above the NLO scale uncertainties of 7%. This means that even at the level of integrated fiducial cross-sections, the inclusion of off-shell effects is

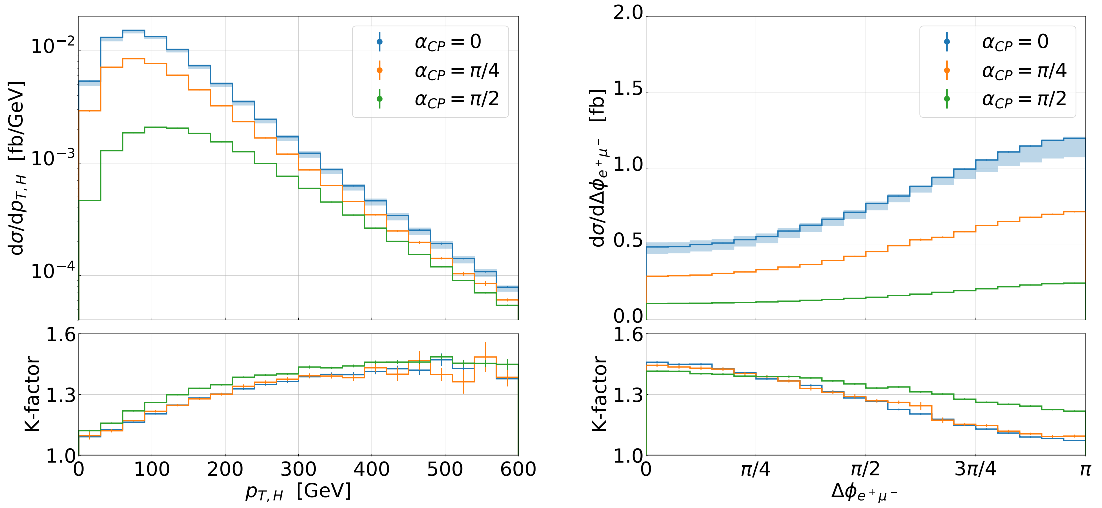


**Figure 1:** *Differential distributions for the observables $p_{T,H}$ and $\Delta\phi_{e^+\mu^-}$ at NLO in QCD. The lower panels show the differential $\mathcal{K}$-factors. Figures were taken from [12].*

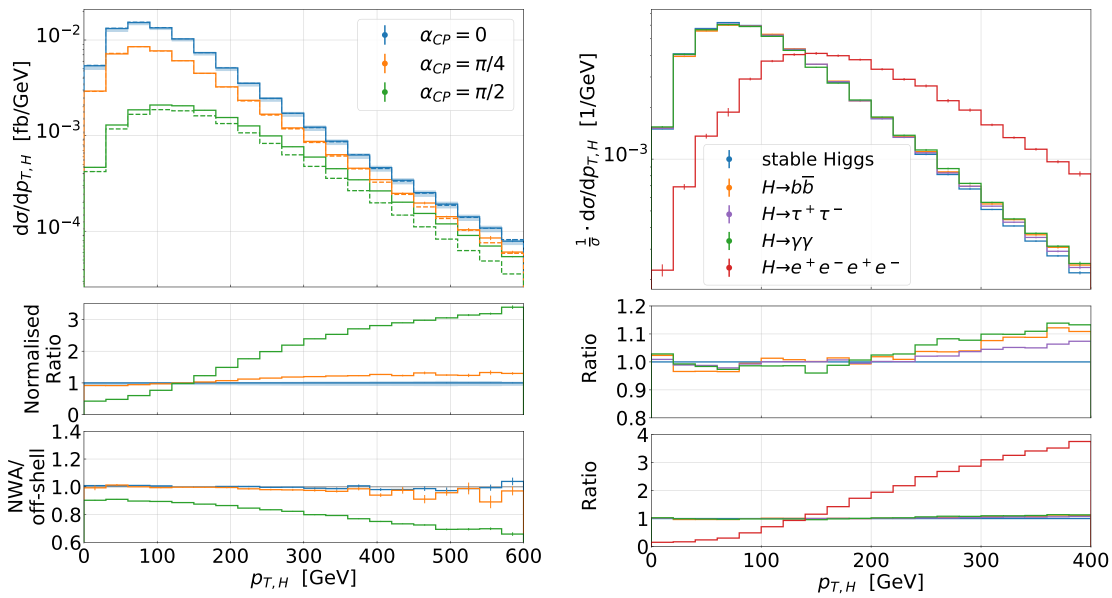


**Figure 2:** *Left: Differential distributions at NLO in QCD for $p_{T,H}$ for the full off-shell case (solid lines) and the NWA (dashed lines). The ratio to $\alpha_{CP}=0$ of the normalised differential distributions for the full off-shell case is shown in the middle panel, the ratio NWA/off-shell is given in the lower one. Figure was taken from [12].*
*Right: Normalised differential distributions for the SM case at NLO in QCD for $p_{T,H}$ for various Higgs decay channels. The two lower panels display the ratio to the stable Higgs. Figure was taken from [13].*

indispensable. Both NLO QCD corrections and off-shell effects are even more significant at the differential level. In Figure 1 we compare the differential cross-section distributions in $p_{T,H}$ and

**Table 2:** *Integrated fiducial cross section at LO and NLO QCD for various Higgs boson decay channels. Table was taken from [13].*

| | $\sigma_{\text{LO}}$ [fb] | $\sigma_{\text{NLO}}$ [fb] | $\mathcal{K}$ |
|---|---|---|---|
| Stable Higgs | $2.2130(2)^{+30.1\%}_{-21.6\%}$ | $2.728(2)^{+1.1\%}_{-4.7\%}$ | 1.23 |
| $H \to b\bar{b}$ | $0.8304(2)^{+44.4\%}_{-28.7\%}$ | $0.9456(8)^{+2.5\%}_{-9.5\%}$ | 1.14 |
| $H \to \tau^+\tau^-$ | $0.11426(2)^{+30.0\%}_{-21.6\%}$ | $0.1418(1)^{+1.2\%}_{-4.8\%}$ | 1.24 |
| $H \to \gamma\gamma$ | $0.0037754(8)^{+30.0\%}_{-21.6\%}$ | $0.004552(4)^{+0.9\%}_{-4.1\%}$ | 1.21 |
| $H \to e^+e^-e^+e^-$ | $1.0083(7) \cdot 10^{-5}{}^{+30.2\%}_{-21.6\%}$ | $1.313(4) \cdot 10^{-5}{}^{+1.8\%}_{-6.2\%}$ | 1.30 |

$\Delta\phi_{e^+\mu^-}$ at NLO in QCD for the three different $\mathcal{CP}$ states. The respective differential $\mathcal{K}$-factors are shown in the lower panels. For $p_{T,H}$, the NLO QCD corrections are largest for the $\mathcal{CP}$-odd case throughout the entire spectrum which is consistent with the results at the integrated level. However, the shape of the $\mathcal{K}$-factors is almost identical between the three $\mathcal{CP}$ states. This means that even though the overall size of the corrections depends on the mixing angle, the shape distortions are independent of it. This particular behavior is mimicked by most observables we have considered. A notable exceptions to this rule are observables that involve decay products from both top quarks, like e.g. $\Delta\phi_{e^+\mu^-}$. For these observables, the differential $\mathcal{K}$-factor is flatter in the $\mathcal{CP}$-odd case than for the other two which results in smaller corrections for small opening angles and high-$p_T$ regions. This is a result of the harder Higgs boson radiation in the $\mathcal{CP}$-odd case which can be observed in the $p_{T,H}$ distribution. The harder Higgs boson radiation suppresses the effects from real radiation contributions at NLO in QCD which typically lead to large $K$-factors in high-$p_T$ regions or for small opening angles. On the left side of Figure 2 we again display the differential cross-section distributions in $p_{T,H}$ but this time we compare these distributions to the results in the NWA (dashed lines). The ratio between the two approaches is depicted in the lower panel. Just like at the level of integrated fiducial cross-sections, the off-shell effects for the $\mathcal{CP}$-even and -mixed cases are rather small and do not exceed a few percent, even in the high-$p_T$ region. In contrast, the effects increase to more than 30% for the $\mathcal{CP}$-odd Higgs boson which again underlines the importance of incorporating full off-shell effects. Let us note that the large size of off-shell effects in this case is a result of an enhancement of single-resonant contributions for the $\mathcal{CP}$-odd Higgs boson compared to the $\mathcal{CP}$-even case.

Finally, we want to briefly discuss the possible inclusion of Higgs boson decays in the case of the SM Higgs. These decays are performed in the NWA for the Higgs boson, i.e. only the Higgs boson is on-shell. We include decays into $b\bar{b}$, $\tau^+\tau^-$, $\gamma\gamma$ and $e^+e^-e^+e^-$. In the case of $b\bar{b}$, NLO QCD corrections to the Higgs decay are also taken into account. The results for the integrated fiducial cross-sections are listed in Table 2. The values are essentially ordered according to the corresponding branching ratios with slight deviations resulting from the cuts applied on the final state particles. $\mathcal{K}$-factors are of the same order for all cases with slightly smaller corrections for the decay in to $b\bar{b}$ due to the additional inclusion of QCD corrections to the Higgs decay. We should note that the results for the stable Higgs boson are different from the numbers shown in Table 1 because of different input parameters and cuts on the final state particles. On the right hand side of Figure 2 we compare the transverse momentum of the Higgs boson for the various decay channels. Most of the distributions behave quite similarly to each other and only deviate from the stable Higgs distribution by up to 15%. The only exception is the decay into $e^+e^-e^+e^-$ for which the cut on the lepton $p_T$ results in a distribution that is shifted towards higher transverse momenta.

## 4. Summary

In these proceedings we have presented some of our results for $t\bar{t}H$ production in the dilepton decay channel at NLO in QCD with possible $\mathcal{CP}$ mixing in the top-Higgs interaction. We have demonstrated that both NLO QCD corrections and off-shell effects are necessary for adequately modelling this process, in particular at the differential level. Off-shell effects are especially large for the $\mathcal{CP}$-odd Higgs boson due to an enhancement of single resonant contributions in this case. Finally, we have also touched upon the possible inclusion of Higgs boson decays into various final states for the SM Higgs boson. For additional information we refer the reader to Refs. [12, 13].

## References

[1] CMS Collaboration, `arXiv:2208.02686`.

[2] ATLAS Collaboration, *Phys. Rev. Lett.* **125** (2020) 061802.

[3] A. Kulesza, L. Motyka, T. Stebel and V. Theeuwes, *JHEP* **03** (2016) 065.

[4] A. Broggio, A. Ferroglia, B. D. Pecjak, A. Signer and L. L. Yang, *JHEP* **03** (2016), 124.

[5] A. Broggio, A. Ferroglia, B. D. Pecjak and L. L. Yang, *JHEP* **02** (2017) 126.

[6] A. Kulesza, L. Motyka, T. Stebel and V. Theeuwes, Phys. Rev. D **97** (2018) 114007.

[7] A. Broggio *et al.*, *JHEP* **08** (2019) 039.

[8] A. Kulesza *et al.*, *Eur. Phys. J.* C **80** (2020) 428.

[9] A. Denner and R. Feger, *JHEP* **11** (2015) 209.

[10] A. Denner, J.-N. Lang, M. Pellen and S. Uccirati, *JHEP* **02** (2017) 053

[11] F. Demartin, F. Maltoni, K. Mawatari, B. Page, M. Zaro, *Eur. Phys. J. C* **74** (2014) 3065.

[12] J. Hermann, D. Stremmer, M. Worek, *JHEP* **09** (2022) 138.

[13] D. Stremmer, M. Worek, *JHEP* **02** (2022) 196.

[14] G. Bevilacqua *et al.*, *Comput. Phys. Commun.* **184** (2013) 986.

[15] G. Bevilacqua, H. B. Hartanto, M. Kraus, T. Weber, M. Worek, *JHEP* **03** (2020) 154.

[16] P. Artoisenet *et al.*, *JHEP* **11** (2013) 043.