Higgs characterisation: NLO and parton-shower effects

Federico Demartin, Eleni Vryonidou
Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, B-1348 Louvain-la-Neuve, BELGIUM

Kentarou Mawatari
Theoretische Natuurkunde and IIHE/ELEM, Vrije Universiteit Brussel, and International Solvay Institutes, Pleinlaan 2, B-1050 Brussels, BELGIUM

Marco Zaro
Sorbonne Universités, UPMC Univ. Paris 06 and CNRS, UMR 7589, LPTHE, F-75005, Paris, FRANCE

We present the Higgs Characterisation (HC) framework to study the properties of the Higgs boson observed at 125 GeV. In this report, we focus on CP properties of the top-quark Yukawa interaction, and show predictions at next-to-leading order accuracy in QCD, including parton-shower effects, for Higgs production in association with a single top quark at the LHC.

I. INTRODUCTION

The Higgs Characterisation (HC) presented in [1], which follows the general strategy outlined in [2], provides a framework that allows one to study the Higgs boson properties, based on an effective field theory (EFT) approach. The EFT lagrangian featuring bosons with various spin-parity assignments has been implemented in the mass eigenstates in FeynRules [3], whose output in the UFO [4] can be directly passed to MadGraph5_aMC@NLO [6]. The code is publicly available online in the FeynRules repository [7]. By employing this framework, we can compute both inclusive cross sections and differential distributions matched to parton-shower programs, up to next-to-leading order (NLO) accuracy in QCD, in a fully automatic way (for the most important spin-0 scenario), and have recently studied all the main Higgs production channels (gluon fusion, weak vector-boson fusion and associated production, and $t\bar{t}H$) [8, 9], as well as the sub-dominant process, associated production with a single top quark ($tH$) [10]. In this report, we focus on $tH$ production, which is particularly interesting for Higgs characterisation.

II. HIGGS PRODUCTION IN ASSOCIATION WITH A SINGLE TOP QUARK

As in single top production in the SM, $tH$ production is always mediated by a $tWb$ vertex and therefore it entails the presence of a bottom quark either in the initial ($t$-channel and $W$-associated) or in the final state ($s$-channel).

![Feynman diagrams](image)

FIG. 1: LO Feynman diagrams for Higgs production associated with a single top quark via a $t$-channel $W$ boson in the 4F scheme (top) and in the 5F scheme (bottom).
For t-channel $tH$ production, diagrams where the Higgs couples to the top quark interfere destructively with those where the Higgs couples to the $W$ boson, making cross sections and distributions extremely sensitive to departures of the Higgs couplings from the SM predictions. To assess the possible deviations, reliable predictions and estimates for the residual uncertainties are indispensable. To this aim, we first provide the SM predictions including QCD corrections at NLO, paying particular attention to the uncertainty related to the different flavour schemes as well as the differential $K$ factors in the two schemes. See more details in [10].

In MadGraph5_aMC@NLO the code and events for t-channel $tH$ production at hadron colliders, e.g. in the 4F scheme, can be automatically generated by issuing the following commands:

> import model HC_NLO_X0
> generate p p > x0 t b^- j $\psi$ w^+ w^- [QCD]
> add process p p > x0 t^- b j $\psi$ w^+ w^- [QCD]
> output
> launch

In the HC model, the effective Lagrangian for the Higgs-top quark interaction reads

$$\mathcal{L}_0' = -\bar{\psi}_t (c_\alpha \kappa_{Ht4} g_{Htt} + i s_\alpha \kappa_{A4t} g_{Att} \gamma_5) \psi_t X_0,$$

where $X_0$ labels a generic spin-0 particle with CP-violating couplings, $c_\alpha \equiv \cos \alpha$ and $s_\alpha \equiv \sin \alpha$ are related to the CP-mixing phase $\alpha$, $\kappa_{Ht4,A4t}$ are real rescaling parameters, and $g_{Htt} = g_{Att} = m_t / v (= y_t / \sqrt{2})$. After launch, one can modify *param_card.dat* to change the parameters, e.g. $c_\alpha = 1$, $\kappa_{Ht4} = 1$ for the SM case.

The SM NLO rates and distributions with theoretical uncertainties are presented in fig. 2 (as well as in tables [11] for the explicit values of the rates), where the flavour-scheme combined prediction is defined by

$$\sigma_{NLO} = (\sigma^+ + \sigma^-)/2, \quad \delta_{\mu+FS} = (\sigma^+ - \sigma^-)/2,$$

with

$$\sigma^+ = \max_{\mu \in [\mu_0/2, 2\mu_0]} \{ \sigma_{NLO}^{4F}(\mu), \sigma_{NLO}^{5F}(\mu) \}, \quad \sigma^- = \min_{\mu \in [\mu_0/2, 2\mu_0]} \{ \sigma_{NLO}^{4F}(\mu), \sigma_{NLO}^{5F}(\mu) \}.$$
### TABLE I: NLO cross sections and uncertainties for t-channel $tH$ production at the 13-TeV LHC. NNPDF2.3 PDFs [12] have been used (NNPDF2.1 for $m_b$ uncertainty in 5F). The integration uncertainty in the last digit(s) (in parentheses) as well as the scale (plus combined flavour-scheme) dependence and the combined PDF + $\alpha_s + m_b$ uncertainty (in %) are reported.

| t-channel | $\sigma_{NLO}^{(4F)}$ [fb] | $\delta_\mu^{(4F)}$ | $\delta_{\text{PDF}}^{(4F)}$ | $\sigma_{NLO}^{(5F)}$ [fb] | $\delta_\mu^{(5F)}$ | $\delta_{\text{PDF}}^{(5F)}$ | $\sigma_{NLO}^{(4F+5F)}$ [fb] | $\delta_\mu^{(4F+5F)}$ | $\delta_{\text{PDF}}^{(4F+5F)}$ |
|-----------|-------------------|-----------------|-----------------|-------------------|-----------------|-----------------|-------------------|-----------------|-----------------|
| 4F        | 45.90(7)          | +3.6            | +2.3            | 46.67(8)          | +4.3            | +1.9            |                    |                  |                  |
| $tH$      | 23.92(3)          | +4.2            | +2.5            | 24.47(5)          | +4.4            | +2.5            |                    |                  |                  |
| $tH + iH$ | 69.81(11)         | +3.2            | +2.8            | 71.20(11)         | +4.3            | +3.0            |                    |                  |                  |
| 5F        | 48.80(5)          | +7.1            | +2.8            | 47.62(5)          | +7.4            | +3.0            |                    |                  |                  |
| $iH$      | 25.68(3)          | +6.8            | +3.4            | 25.07(3)          | +7.4            | +3.2            |                    |                  |                  |
| $tH + iH$ | 74.80(9)          | +6.8            | +3.0            | 72.70(7)          | +7.4            | +3.9            |                    |                  |                  |
| 4F+5F     | 47.64(7)          | ±9.7            | ±2.9            | 47.47(6)          | ±7.7            | ±3.1            |                    |                  |                  |
| $tH$      | 24.88(4)          | ±10.2           | ±2.6            | 24.86(3)          | ±8.3            | ±3.3            |                    |                  |                  |
| $tH + iH$ | 72.55(10)         | ±10.1           | ±3.1            | 72.37(10)         | ±8.0            | ±2.9            |                    |                  |                  |

### TABLE II: Same as table I but with MSTW2008 PDFs [13].

| t-channel | $\sigma_{NLO}^{(4F)}$ [fb] | $\delta_\mu^{(4F)}$ | $\delta_{\text{PDF}}^{(4F)}$ | $\sigma_{NLO}^{(5F)}$ [fb] | $\delta_\mu^{(5F)}$ | $\delta_{\text{PDF}}^{(5F)}$ | $\sigma_{NLO}^{(4F+5F)}$ [fb] | $\delta_\mu^{(4F+5F)}$ | $\delta_{\text{PDF}}^{(4F+5F)}$ |
|-----------|-------------------|-----------------|-----------------|-------------------|-----------------|-----------------|-------------------|-----------------|-----------------|
| 4F        | 45.91(9)          | +3.7            | +2.1            | 47.00(7)          | +3.4            | +2.1            |                    |                  |                  |
| $tH$      | 23.61(3)          | +3.1            | +2.4            | 24.10(5)          | +4.6            | +2.2            |                    |                  |                  |
| $tH + iH$ | 69.43(7)          | +4.9            | +2.5            | 71.29(10)         | +3.8            | +2.2            |                    |                  |                  |
| 5F        | 48.28(6)          | +7.0            | +2.6            | 47.17(6)          | +7.0            | +2.9            |                    |                  |                  |
| $iH$      | 24.99(3)          | +6.4            | +2.7            | 24.41(3)          | +7.1            | +3.2            |                    |                  |                  |
| $tH + iH$ | 73.45(8)          | +7.0            | +3.0            | 71.54(7)          | +7.0            | +2.8            |                    |                  |                  |
| 4F+5F     | 47.30(8)          | ±9.2            | ±2.7            | 47.18(6)          | ±7.0            | ±2.9            |                    |                  |                  |
| $tH$      | 24.17(4)          | ±10.0           | ±2.8            | 24.26(3)          | ±7.7            | ±3.2            |                    |                  |                  |
| $tH + iH$ | 71.99(11)         | ±9.2            | ±3.1            | 71.48(9)          | ±7.3            | ±2.8            |                    |                  |                  |

### TABLE III: Same as table I but with CT10 PDFs [14].

| t-channel | $\sigma_{NLO}^{(4F)}$ [fb] | $\delta_\mu^{(4F)}$ | $\delta_{\text{PDF}}^{(4F)}$ | $\sigma_{NLO}^{(5F)}$ [fb] | $\delta_\mu^{(5F)}$ | $\delta_{\text{PDF}}^{(5F)}$ | $\sigma_{NLO}^{(4F+5F)}$ [fb] | $\delta_\mu^{(4F+5F)}$ | $\delta_{\text{PDF}}^{(4F+5F)}$ |
|-----------|-------------------|-----------------|-----------------|-------------------|-----------------|-----------------|-------------------|-----------------|-----------------|
| 4F        | 45.03(6)          | +3.4            | +1.6            | 46.00(8)          | +3.4            | +1.3            |                    |                  |                  |
| $tH$      | 22.78(2)          | +3.8            | +1.4            | 23.34(4)          | +3.8            | +1.2            |                    |                  |                  |
| $tH + iH$ | 67.09(8)          | +3.9            | +1.7            | 69.02(10)         | +4.5            | +1.9            |                    |                  |                  |
| 5F        | 47.91(6)          | +7.0            | +2.7            | 46.76(6)          | +7.1            | +2.5            |                    |                  |                  |
| $iH$      | 24.53(2)          | +6.5            | +3.7            | 23.94(3)          | +7.3            | +3.7            |                    |                  |                  |
| $tH + iH$ | 72.36(9)          | +6.6            | +2.9            | 70.71(8)          | +7.1            | +2.7            |                    |                  |                  |
| 4F+5F     | 46.78(6)          | ±9.6            | ±2.8            | 46.54(6)          | ±7.6            | ±2.5            |                    |                  |                  |
| $tH$      | 23.71(4)          | ±10.2           | ±3.9            | 23.70(3)          | ±8.4            | ±3.8            |                    |                  |                  |
| $tH + iH$ | 70.29(11)         | ±9.8            | ±3.0            | 70.21(9)          | ±7.9            | ±2.8            |                    |                  |                  |
Finally, we go beyond the SM Higgs coupling to the top quark, and present the dependence on the CP-mixing angle $\alpha$ for the $tH$ and $t\bar{t}H$ production cross sections in fig. 3. The nature of the top quark Yukawa coupling also affects the loop-induced Higgs coupling to gluons and photons. In the figure, to keep the SM gluon-fusion production cross section, the rescaling parameters are set to $\kappa_{Htt} = 1$ and $\kappa_{Att} = 2/3$. The LO cross sections for loop-induced $HZ$ [15] and $HH$ [16] production via gluon fusion are also shown as a reference.

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