Single top, W and Higgs associated production

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We study the associated production of a single top quark plus a W and a Higgs bosons ($tWH$) at the LHC, at NLO-QCD accuracy. We show results obtained with the technique known as Diagram Removal to treat the event generation in the NLO real-emission $tWbH$ channel, where $tWH$ interferes with $ttH$. We provide NLO results for $tWH$ total and differential cross sections at 13 TeV, also matching the matrix element for the hard scattering to a parton shower. Finally, we show the sensitivity of this process to a generic CP-mixed (i.e. BSM) Yukawa interaction between the Higgs and the top quark.

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1. Introduction

Despite its small cross section at the LHC, $tWH$ production is an interesting case of study for two reasons: (1) rare processes where the Higgs is produced with a single top quark are more sensitive than $ttH$ to study departures of the top Yukawa coupling from the SM prediction (see [1] and references therein), and (2) at NLO-QCD the $tWH$ (singly resonant) and $ttH$ (doubly resonant) processes interfere in the real-emission $tWbH$ channel (fig. 1), thus their separation is not trivial. The same situation is present also in the SM cases of $tW$/$tt$ production [2, 3] and $tWZ/ ttZ$, and in beyond-Standard-Model (BSM) processes [4–7]. This problem can be avoided with a full simulation of $WbWbH$ production at NLO [8]; however, this is highly non-trivial. Moreover, efficient generation of singly-resonant events ($tWH$) require to run separately the $tWH$ and $ttH$ processes. To this purpose, approximate techniques known as Diagram Removal and on-shell Diagram Subtraction are used to treat the $tWbH$ channel. Our results are obtained within the MADGRAPH5_AMC@NLO framework [9].

![Diagram](image)

**Figure 1:** Examples of “$ttH$” doubly resonant amplitudes $A_2$ (left), “$tWH$” singly resonant amplitudes $A_1$ (center) and non resonant amplitudes $A_0$ (right) contributing to the same $WbWbH$ final state.

In the $tWbH$ channel, the Diagram Removal (DR) matrix elements without (DR1) and with interference (DR2) are

$$M_{DR1} = |A_1|^2 \quad \text{and} \quad M_{DR2} = |A_2 + A_1|^2 - |A_2|^2,$$

where the indices 1 and 2 indicate the number of on-shell top quarks in the diagrams. Both DR1 and DR2 are not guaranteed to preserve gauge invariance. We find a significant difference between DR1 and DR2, because the doubly-singly interference $A_2 A_1^*$ contribution is large compared to the singly resonant contribution $|A_1|^2$. Non-resonant contributions from $A_0$ (“+0r”) are numerically negligible.

We have also investigated results obtained using on-shell Diagram Subtraction (DS)

$$M_{DS} = |A_2 + A_1|^2 - C_{DS} = \sum_{\{q_i^{OS}\}} \frac{(m_t \Gamma_t)^2}{(p_{Wb} - m_t)^2 + (m_t \Gamma_t)^2} |A_2(\{q_i^{OS}\})|^2,$$

where $m_t$ and $\Gamma_t$ are the mass and the width of top quark, while the external momenta reshuffling $\{p_i\} \rightarrow \{q_i^{OS}\}$ puts on-shell the internal top propagator, to preserve gauge invariance (at least in the limit $\Gamma_t/m_t \rightarrow 0$). We have found a significant dependence on how the on-shell reshuffling $\{p_i\} \rightarrow \{q_i^{OS}\}$ is performed; further investigations about the substantiality of this issue are ongoing.

2. $tWH$ production at NLO+PS

The NLO cross section for $tWH$ production at 13 TeV, computed with DR2, amounts to 15.6 fb and shows significantly reduced uncertainties compared to LO (table 1). The impact of $tWH/ ttH$
interference can be estimated by taking the difference with the DR1 result (∼ 5 fb), and amounts to about one third of the NLO cross section. Interference affects significantly also the shape of distributions of the top quark and the W boson, while the effect is milder for the Higgs (fig. 2).

<table>
<thead>
<tr>
<th>$tWH$</th>
<th>$\sigma$ [fb]</th>
<th>$\delta^\mu$</th>
<th>$\delta^\text{PDF}$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>16.15(3)</td>
<td>$^{+12.9}_{-12.8}$</td>
<td>$^{\pm11.1}_{-}$</td>
<td>-</td>
</tr>
<tr>
<td>NLO DR1</td>
<td>20.65(3)</td>
<td>$^{+5.0}_{-3.2}$</td>
<td>$^{\pm3.0}$</td>
<td>1.28</td>
</tr>
<tr>
<td>NLO DR2</td>
<td>15.61(3)</td>
<td>$^{-4.6}_{-6.1}$</td>
<td>$^{\pm2.7}$</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Table 1: Total cross sections at the 13-TeV LHC for $pp \to tW^-H+W^+H$, in the 5F scheme at LO and NLO accuracy (NLO results are obtained with Diagram Removal). We also report the scale and PDF uncertainties, as well as the NLO $K$ factor. The dynamic scale $\mu = H_T/4$ has been used throughout the simulation.

Figure 2: Transverse momentum distributions of the Higgs boson (left), the top quark (center) and the W boson (right) at NLO+PYTHIA8.

Figure 3: Total cross section with scale uncertainty for $t$-channel $tX_0$ (blue), $ttX_0$ (red) and $ttX_0 + tWX_0$ production computed with DR2 (orange), as a function of the CP-mixing angle $\alpha$ in the HC Lagrangian. The point $\alpha = 0^\circ$ corresponds to the SM scenario, while $\alpha = 180^\circ$ corresponds to $y_t = -y_t(SM)$. 

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Finally, we go beyond the Standard Model employing the Higgs Characterisation model ($H \rightarrow X_0$), where the Higgs-top Yukawa interaction is described by the Lagrangian

$$\mathcal{L}_t^0 = -\overline{\psi}_t (c_\alpha \kappa_{Ht} g_{Ht} + i s_\alpha \kappa_{Ht} g_{Ht} \gamma_5) \psi_t X_0. \quad (2.1)$$

The SM case is reproduced when $c_\alpha \equiv \cos \alpha = 1$ and $\kappa_{Ht} = 1$. The sensitivity of the $tWX_0$ rate to the CP-mixing angle $\alpha$ is presented in fig. 3, together with $ttX_0$ and $t$-channel $tX_0$ for reference.

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References


