Theory advances for $t\bar{t}W$ multi-lepton predictions

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We report on recent theoretical advances in the description of the $pp \rightarrow t\bar{t}W$ process. First, we discuss a comparison of many state-of-the-art predictions for multi-lepton signatures including the leading QCD contributions at $\mathcal{O}(\alpha_s^3\alpha^6)$ as well as subleading EW contributions at $\mathcal{O}(\alpha_s\alpha^8)$. Furthermore, we briefly discuss recent improvements using multi-jet merging techniques.

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1 Introduction

The production of $t\bar{t}W$ final states is one of the rarest processes at the LHC. At the same time, the various decay channels constitute one of the most important backgrounds in $t\bar{t}H$ measurements as well as in searches for $t\bar{t}H$ signatures. In recent years, the production of top-quark pairs along with a $W^{\pm}$ gauge boson has received much attention as tensions between data and theoretical predictions have been reported [1,2].

While the first calculation for on-shell $t\bar{t}W$ appeared a decade ago [3], more refined predictions have emerged recently. Besides electroweak effects [4–7] also the resummation of soft gluons has been addressed in Refs. [8–11]. The $pp \rightarrow t\bar{t}W$ process has been also matched to parton showers using both, the MC@NLO [12–14] as well as the POWHEG method [15, 16]. Additionally, also the impact of multi-jet merging has been studied in Refs. [17, 18]. Beyond the stable top-quark approximation the size of off-shell effects and non-resonant contributions have been investigated. First for the leading QCD corrections [19–21] and afterwards also for the electroweak contributions [22,23].

Here, we will briefly summarize the recent progress made in the field at hand of two examples from Refs. [18,23].

2 Phenomenological Results

First we discuss the recent comparison of many state-of-the-art Standard Model predictions. For details of the comparison we refer to Ref. [23]. In Tab. 1 the fiducial cross sections are listed. First, we note that the parton-shower based predictions agree well with each other, while they predict consistently lower cross sections as comparable fixed-order approaches. This difference originates from multiple emissions in the top-quark decays that effects the acceptance efficiency in the fiducial volume. Furthermore, we observe that for $t\bar{t}W$ QCD the theoretical uncertainty of parton shower event generators are larger than in the case of the full off-shell or narrow-width approximation (NWA) predictions due to missing higher-order corrections in the decays.

| $\sigma_{\text{QCD}}^{\text{NLO}}$ | $t\bar{t}W$ QCD [fb] | $t\bar{t}W$ EW [fb] |
|---------------------------|----------------|------------------|
| full off-shell            | 1.58$^{+3\%}_{-6\%}$ | 0.206$^{+22\%}_{-17\%}$ |
| full NWA                  | 1.57$^{+3\%}_{-6\%}$ | 0.190$^{+22\%}_{-16\%}$ |
| NWA with LO decays        | 1.66$^{+10\%}_{-10\%}$ | 0.162$^{+22\%}_{-16\%}$ |
| POWHEG-Box                | 1.40$^{+11\%}_{-11\%}$ | 0.133$^{+21\%}_{-16\%}$ |
| MG5_AMC@NLO               | 1.40$^{+11\%}_{-11\%}$ | 0.136$^{+21\%}_{-16\%}$ |

Table 1: Fiducial cross sections for $t\bar{t}W$ at $\mathcal{O}(\alpha_s^3\alpha_6)$ (QCD) and for $\mathcal{O}(\alpha_s\alpha_8)$ (EW).
For $t\bar{t}W$ EW predictions all the effects are much more pronounced because even the full NWA performs badly and off-shell effects are already of the order of 9% at the level of inclusive cross sections. Even though the theoretical uncertainties are much larger for $t\bar{t}W$ EW and modeling issues are prominent they only play a minor role in the end as the EW production mode only contributes 13% of the leading QCD cross section.

Figure 1: Differential cross sections for various Standard model predictions. Plots taken from Ref. [23].

On the left side of Fig. 1 the transverse momentum of the leading $b\bar{b}$ pair is shown for various theoretical predictions. While even at the differential level the parton shower based results are very consistent with each other, none of the predictions resembles the shape of the full off-shell calculation. While the full NWA still agrees in the bulk of the distribution, all predictions deviate strongly in the tail which is dominated by single-resonant contributions that are only included in the full off-shell prediction. The right plot of Fig. 1 depicts improved predictions for the transverse momentum of the leading $b$ jet. Here, parton shower matched calculations are supplemented with single and non-resonant contributions via

$$
\frac{d\sigma^{\text{th}}}{dX} = \frac{d\sigma^{\text{NLOPS}}}{dX} + \frac{d\Delta \sigma_{\text{off-shell}}}{dX}, \quad \frac{d\Delta \sigma_{\text{off-shell}}}{dX} = \frac{d\sigma^{\text{NLO}}_{\text{off-shell}}}{dX} - \frac{d\sigma^{\text{NLO}}_{\text{NWA}}}{dX}
$$

and denoted with NLOPS + $\Delta \sigma$. First of all, we note that the parton shower matched predictions (NLOPS) differ with respect to the full off-shell result up to 35% in the tail.
of the distribution. However, once single and non-resonant contributions are taken into account via the differential corrections $d\Delta\sigma_{\text{off-shell}}/dX$ the improved predictions agree well with the full off-shell calculation. The bottom panel also shows that the electroweak contribution receives a sizable correction in the tail of the distribution.

3 Multi-jet Merging

An orthogonal approach to increase the accuracy of theoretical predictions is multi-jet merging, where multiple parton-shower matched calculations for $pp \rightarrow t\bar{t}W$, $pp \rightarrow t\bar{t}Wj$ and $pp \rightarrow t\bar{t}Wjj$ are combined into a single prediction. Here we want to briefly mention the improved FxFx [24] merging for $pp \rightarrow t\bar{t}W$ [18]. The main advancement

![Figure 2: Differential distribution for the transverse momentum of the leading $b$ jet and the muon. Plots taken from Ref. [18].](image)

of Ref. [18] relies on the identification of so-called QCD and electroweak jets. Here, QCD jets originate from QCD splittings such as $q \rightarrow qg$, while EW jets are formed by EW splittings such as $q \rightarrow Wq'$. The latter splittings are finite for small transverse momenta and therefore a resummation via parton showers is not necessary.

Based on this improvement, we show in Fig. 2 improved FxFx predictions for $t\bar{t}W$. In particular the transverse momentum of the leading $b$ jet and the muon is shown. It is evident from the bottom panel that the inclusion of higher jet multiplicities introduces large corrections between 30 – 40%. Therefore, the inclusion of additional
hard jet radiation is necessary to obtain an accurate description of $t\bar{t}W$ in fiducial volumes.

4 Conclusions

We have summarized recent progress for theoretical predictions for the $pp \rightarrow t\bar{t}W$ process. The main conclusions that can be drawn are as follows:

- The theoretical uncertainties of currently available parton-shower matched predictions might be reduced by including QCD corrections to top-quark decays.
- Multiple radiation in the top-quark decays has a strong impact in fiducial volumes.
- Contributions from additional hard jets are sizable and should be included.
- Tails of dimensionful distributions are often dominated by single and non-resonant contributions.

All these observations essentially point to the fact that the $pp \rightarrow t\bar{t}W$ process needs to be computed at the NNLO accuracy including top-quark decays via the narrow-width approximation. Furthermore, a full off-shell calculation for $t\bar{t}W$ matched to parton showers is highly desirable to include further corrections.

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