# Parton shower effects in $t\bar{t}W^{\pm}$ production at NLO QCD

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We present a selection of results from our recent study of $pp \rightarrow t\bar{t}W^{\pm}$ production matched to partons showers at NLO QCD at the LHC. Theoretical predictions are obtained at perturbative orders $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$, where the different contributions are studied first separately at the inclusive level before being combined within a realistic two same-sign lepton signature. We investigate in detail uncertainties originating from missing higher-order corrections and from the parton-shower matching scheme employed.

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## 1. Introduction

Top-quark pair production in association with a $W$ gauge boson is one of the rarest scattering processes in the Standard Model (SM). Nonetheless, it has received much attention recently as it constitutes a large background to many SM measurements and searches for physics beyond the Standard Model (BSM). Most notably, the $pp \to t\bar{t}W^{\pm}$ process is the dominant background for SM measurements of the $t\bar{t}H$ and of the four top-quark production process in the multi-lepton signatures. However, in both cases, recent measurements of the $t\bar{t}W$ background contributions reveal tensions with the SM predictions [1].

In recent years a lot of progress has been made to improve the theoretical description of the $pp \to t\bar{t}W^{\pm}$ process. For instance, NLO QCD and electroweak (EW) corrections for predictions based on stable top-quarks are already known for some time [2–5]. Furthermore, the impact of threshold resummation on total cross sections and differential distributions has been studied in Refs. [6–10]. In addition, also the NLO QCD corrections to the decay in the NWA has been studied [11] as well as the inclusion of off-shell effects and non-resonant contributions has been addressed for the first time in Refs. [12–14] for the dominant QCD production mode as well as for the full one-loop SM corrections in Ref. [15]. Furthermore, the process has been matched to parton showers [16–18] and effects from multi-jet merging have been studied [19–21] as well. Also the approximate inclusion of full off-shell effects in parton-shower matched calculations of on-shell $t\bar{t}W$ has been investigated in Ref. [22].

In the following, we present results for theoretical predictions for the $pp \to t\bar{t}W^{\pm}$ process at $O(\alpha_s^3 \alpha)$ and $O(\alpha_s \alpha^3)$ matched to parton showers via the Powheg-Box framework.

## 2. Outline of the calculation
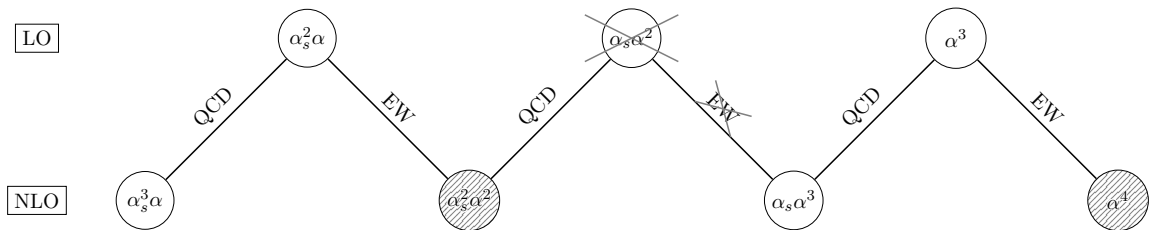


**Figure 1:** The structure of higher-order corrections for the production of the $pp \to t\bar{t}W^{\pm}$ final state.

In Fig. 1 the different perturbative orders that contribute to the $pp \to t\bar{t}W^{\pm}$ process up to the one-loop level are depicted. At the leading order only the order $O(\alpha_s^2 \alpha)$ and $O(\alpha^3)$ contribute, which correspond to the squared QCD and EW born matrix elements. The interference at $O(\alpha_s \alpha^2)$ vanishes due to color conservation, which allows to identify at the next-to-leading order the terms at $O(\alpha_s^3 \alpha)$ and $O\alpha_s \alpha^3)$ as pure QCD corrections, while the contributions at $O(\alpha_s^2 \alpha^2)$ are mixed QCD-EW and $O(\alpha^4)$ are pure EW corrections.

Our calculation takes into account the dominant higher-order corrections at the perturbative orders $O(\alpha_s^3 \alpha)$ and $O(\alpha_s \alpha^3)$. The implementation of the dominant QCD corrections in the Powheg-Box is based on virtual amplitudes provided via NLOX [23, 24]. We compare results obtained

with the PoWHEG-Box to those obtained with MG5_AMC@NLO [25] as well as the SHERPA framework [26, 27]. Spin-correlated top-quark decays are, depending on the framework employed, taken into account in the study of the two same-sign lepton signature according to Refs. [28–30]. Theoretical predictions based on the PoWHEG-Box and MG5_AMC@NLO are interfaced with the PYTHIA8 parton shower, while for SHERPA its own Catani-Seymour shower is used. Thus, our comparison allows to compare different parton-shower matching schemes as well as different parton showers. Further details on the specific setup of the comparison can be found in Ref. [18].

## 3. Inclusive $t\bar{t}W$ production

First we compare the different Monte Carlo generators at the fully inclusive level with stable top quarks and $W$ gauge bosons. Jets are defined via the anti-$k_T$ jet algorithm with a separation parameter of $R = 0.4$ and we require jets to fulfill the following constraints

$$p_T(j) > 25 \text{ GeV}, \qquad |y(j)| < 2.5, \qquad N_{\text{jets}} \geq 0. \tag{1}$$
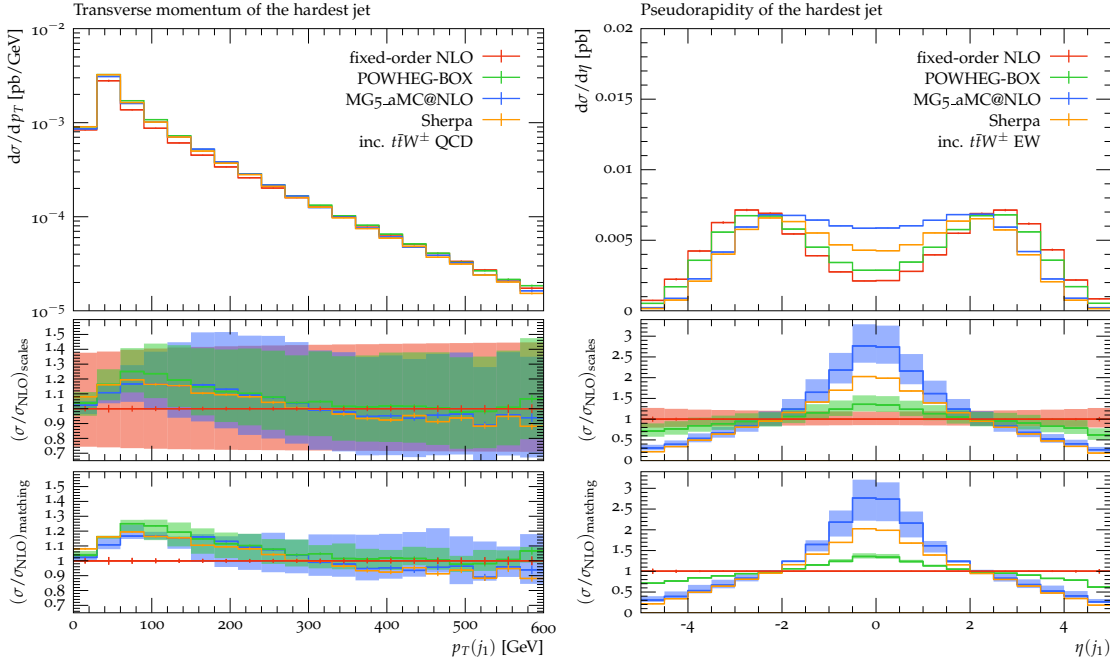


**Figure 2:** Differential cross section distribution as a function of the transverse momentum of the hardest jet at $O(\alpha_s^3 \alpha)$ (l.h.s) and of the rapidity of the hardest jet at $O(\alpha_s \alpha^3)$ (r.h.s).

In Fig. 2 we highlight the transverse momentum of the leading jet for the QCD production mode of $pp \rightarrow t\bar{t}W^{\pm}$ at $O(\alpha_s^3 \alpha)$ and the rapidity of the leading jet for the EW production channel at $O(\alpha_s \alpha^3)$. Even though the presented observables have only leading-order accuracy they serve as a good representation of our findings also for inclusive NLO accurate observables. We refer to Ref. [18], where we have studied more distributions for both production channels. For the transverse momentum distribution we find very good agreement between all employed generators. All predictions including parton-shower effects align very well with the fixed-order NLO QCD result

in the tail of the distribution. This is expected, since the hard matrix elements are reliable for hard emissions and shower corrections are small in this region. On the other hand, we find differences between shower based and fixed-order predictions at the level of 20% at the beginning of the spectrum, which is dominated by soft and collinear emissions. These differences can be attributed to the leading logarithmic resummation performed by the parton showers. Missing higher-order corrections dominate the uncertainties for most of the plotted range. Only at the beginning of the distribution matching uncertainties become comparable in size. On the contrary, we observe large differences in the EW predictions at $O(\alpha_s\alpha^3)$ as can be seen in the rapidity distribution on the right of Fig. 2. None of the parton-shower based predictions is in agreement with fixed-order calculation. To be specific, we find deviations of the order of 50% for the POWHEG-BOX, 100% for SHERPA and more than 200% for MG5_AMC@NLO. As indicated by the large matching uncertainties of the MG5_AMC@NLO prediction the resulting curve depends crucially on the choice of the initial shower scale.

## 4. Two same-sign lepton signature

Turning now to the comparison for a realistic two same-sign lepton signature at the fiducial level. Final-state particles are subject to the following phase space cuts

$$p_T(\ell) > 15 \text{ GeV} , \qquad |\eta(\ell)| < 2.5 , \qquad p_T(j) > 25 \text{ GeV} , \qquad |\eta(j)| < 2.5 , \qquad (2)$$

where jets are formed using the anti-$k_T$ jet algorithm with $R = 0.4$. Additionally, we require exactly 2 same-sign leptons, at least 2$b$ jets and at least 2 light jets. Predictions shown in the following correspond to the sum of $t\bar{t}W^+$ and $t\bar{t}W^-$ processes as well as the combination of $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$ contributions.

Representative of our full findings in Ref. [18] we show the transverse momentum distribution of the leading $b$ jet on the left and the invariant mass distribution of the two hardest light jets on the right of Fig. 3. The hardest $b$ jet predominantly originates from the top-quark decay and therefore allows for a comparison of the different approaches to model spin-correlated decays in the event generators. We find very good agreement between the various predictions with differences less than 5% for most of the plotted range. In the beginning of the distribution differences are slightly larger at the level of 10%. This, however, can be attributed to the different treatment of radiation from heavy quarks. Over the whole plotted range we also find that scale uncertainties dominate the theoretical uncertainties and are of the order of 10% − 20%. From the invariant mass distribution of the two hardest light jets, as depicted on the right of Fig. 3, we can draw multiple conclusions. First of all, we notice the that the peak of the distribution is located around the $W$ boson resonance, i.e. the leading jets originate from the hadronic decaying $W$ boson that is described at leading-order accuracy for all generators. Furthermore, we see that the EW production mode starts as a +10% correction that increases towards the end of the spectrum up to +25%. Generally, the EW contribution becomes sizable if the considered observable is sensitive to forward jets. However, for most observables we studied the inclusion of the $O(\alpha_s\alpha^3)$ contribution constitutes a constant +10% correction at the differential level.
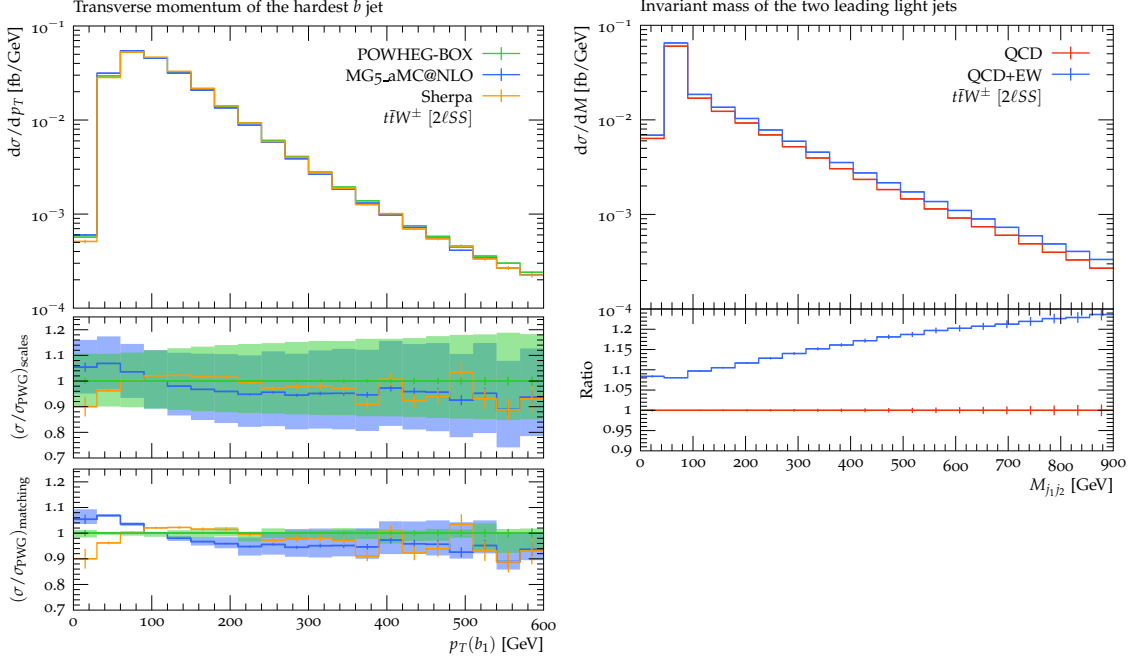
**Figure 3:** Differential cross section distribution as a function of the transverse momentum of the hardest *b* jet (l.h.s) and of the invariant mass of the two hardest light jets (r.h.s).

## 5. Summary

We presented results of our recent comparison [18] of the $pp \rightarrow t\bar{t}W^{\pm}$ process for a two same-sign lepton signature. We find overall very good agreement between the various generators employed in the case of the QCD production mode at $O(\alpha_s^3\alpha)$. On the contrary, for the EW production of the $pp \rightarrow t\bar{t}W^{\pm}$ final state we observe sizable differences between the generators. Nonetheless, the less accurate modeling of the EW contribution has only a small impact once QCD and EW contributions are combined because the latter are generally a 10% effect on top of the dominant QCD contribution. Only in phase space regions dominated by forward jets the EW contributions becomes sizable. Furthermore, we investigated spin-correlation effects in the top-quark decay modeling, which can also modify the shape of leptonic observables at the 10% level.

Further improvements in the realistic description is highly signature dependent. For instance, in multi-lepton signatures the NNLO QCD corrections to the $pp \rightarrow t\bar{t}W^{\pm}$ production process are of utmost importance. For multi-lepton signatures also the matching of the full off-shell computation to parton showers will further improve the description of fiducial phase space volumes. However, for signatures involving the hadronic *W* boson decays the inclusion of NLO QCD corrections in the decay is inevitable.

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