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Comparison of $t\bar{t}W$ theory predictions in the 3ℓ channel

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We report on our recent comparison of various theoretical approaches to predict fiducial signatures for $pp \to t\bar{t}W$ in the 3ℓ decay channel at $O(\alpha_s^3\alpha^6)$ and $O(\alpha_s\alpha^8)$. The comparison includes fixed-order predictions including full off-shell effects as well as predictions based only on the double-resonant contributions by employing the Narrow-Width-Approximation. Furthermore, we include parton-shower matched predictions using the MG5_aMC@NLO and Powheg-Box frameworks.

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1. Introduction

The production of top-quark pairs in association with a W boson is one of the rarest processes in the Standard Model. At the same time, it gives rise to a multitude of decay signatures of unfathomable complexity. The $pp \to t\bar{t}W$ process is one of the main backgrounds in $t\bar{t}H$ measurements and searches for the $t\bar{t}t\bar{t}$ process. Therefore, a precise understanding of the $pp \to t\bar{t}W$ process is inevitable. This is even more emphasized as recent measurements of the $t\bar{t}W$ component as part of the $t\bar{t}H$ analysis show tensions [1, 2] with the Standard Model predictions.

Due to its importance, the $pp \to t\bar{t}W$ process has received plenty of attention in the theory community. First predictions at next-to-leading order (NLO) QCD accuracy for production and decay have been reported in Ref. [3]. Subsequently, NLO EW corrections for on-shell $t\bar{t}W$ production have been computed for the first time in Refs. [4, 5]. Furthermore, mixed QCD and EW contributions have been studied in Refs. [6, 7]. Also the effects of soft-gluon resummation have been studied in detail in Refs. [8–11]. In order to describe fiducial signatures the on-shell $pp \to t\bar{t}W$ process has been matched to parton showers using either the MC@NLO [12–14] or the POWHEG [15, 16] approach. Further higher-order corrections have also been included via multi-jet merging [17, 18]. An orthogonal approach to describe fiducial signatures are fixed-order computations based on matrix elements for the fully decayed process, e.g. $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu e^+\nu_e b\bar{b} + X$, which ultimately account for all double, single and non-resonant top-quark contributions. For the three lepton decay channel both, NLO QCD predictions [19–21] as well as EW contributions [22, 23] have been studied in the literature. In this proceedings, we report on our latest study [23] that aims at comparing parton-shower and fixed-order full off-shell computations at the fiducial level. A detailed comparison of both approaches is mandatory as they include very different aspects of physics but aim to describe fiducial signatures accurately.

2. Computational setup

In our comparative study we employ the following computational approaches for the $pp \to t\bar{t}W$ process in the three-lepton decay channel.

full off-shell: We employ the calculation of Refs. [19, 23–29] for the $pp \to \ell^+\nu\ell^-\bar{\nu}\ell^\pm\nu b\bar{b}$ process that includes all double, single and non-resonant contributions.

NWA: We also employ the narrow-width-approximation (NWA),see e.g. [30], to provide predictions for $pp \to t\bar{t}W$ followed by $t \to Wb$ decays including NLO QCD corrections.

Powheg-Box; We obtain parton-shower matched results using the Powheg-Box implementation for $pp \to t\bar{t}W$ [16, 31, 32] at NLO QCD accuracy (NLOPS).

MG5_aMC@NLO: A separate NLOPS calculation using MG5_aMC@NLO [33] in conjunction with MadSpin [34] is employed.

In the case of Powheg-Box and MG5_aMC@NLO predictions we employ the Pythia8 [35, 36] parton shower, where we neglect effects from hadronization and multiple parton scattering. For a more detailed account of the differences between the various approaches as well as the computational setup refer the reader to Ref. [23].

3. Phenomenological results

We start the discussion of our findings at the level of inclusive cross sections, since we can establish some global differences between the computations already here. In Tab. 1 the inclusive

$\sigma^{\rm NLO}_{\rm QCD}$	$t\bar{t}W$ 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: Inclusive cross sections for $t\bar{t}W$ QCD ($O(\alpha_s^3\alpha^6)$) and for $t\bar{t}W$ EW ($O(\alpha_s\alpha^8)$) at NLO QCD accuracy.

fiducial cross sections including the estimated theoretical uncertainties are shown for the five different calculations employed in our study. First, we observe that the subleading EW contributions amount to roughly 13% of the leading QCD cross section. Furthermore, for $t\bar{t}W$ EW the difference between the full off-shell and the full NWA calculation is of the order of 9%. This is surprisingly large because these effects are expected to be of the order of $\Gamma_t/m_t \sim 0.8\%$. We also observe that for $t\bar{t}W$ QCD the theoretical uncertainty is reduced if NLO QCD corrections for the top-quark decays are included. This is not the case for $t\bar{t}W$ EW, as the corrections are dominated by the $pp \to t\bar{t}Wj$ production matrix elements. Finally, we find that the NLOPS predictions are in very good agreement with each other but yield a 11 − 34% reduced cross section with respect to the full off-shell calculation. The origin of this reduction is due to multiple radiation in the resonant top-quark decays during the shower evolution.

Let us now turn to the discussion of differential cross sections. As an example, we present in

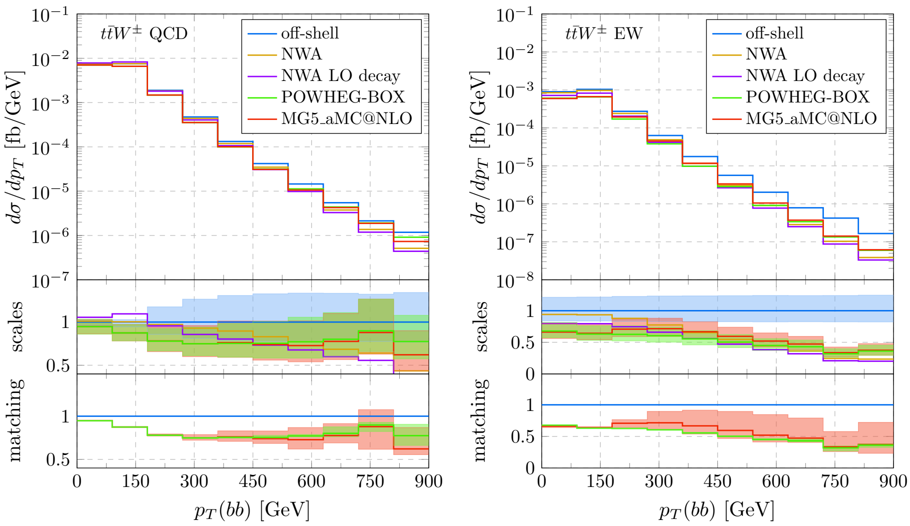

Figure 1: Differential distribution of the transverse momentum of the two hardest b jets for $t\bar{t}W$ QCD (left) and $t\bar{t}W$ EW (right). Figure taken from Ref. [23].

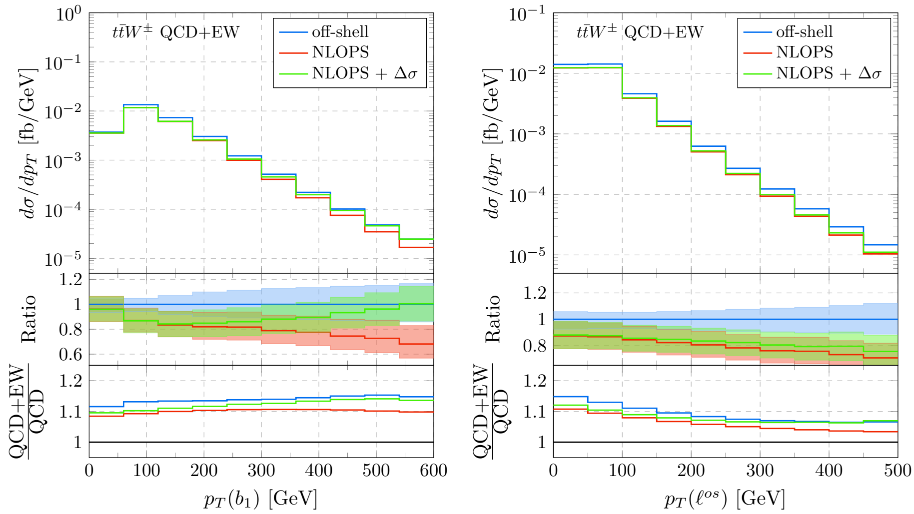

Figure 2: Differential distribution of the transverse momentum of the hardest b jet (left) and of the opposite-sign lepton ℓ^{os} (right). Figure taken from Ref. [23].

Fig. 1 the transverse momentum distribution of the two hardest b jets. For the $t\bar{t}W$ QCD predictions on the left, we observe that the NWA is a very good approximation of the full off-shell calculation in the bulk of the distribution. Only in the tail of the spectrum considerable deviations are visible. The parton shower predictions, on the other hand, have a very different shape over the whole range of the distribution. Nonetheless, all generators are consistent with each other within the estimated uncertainties. The theoretical uncertainties are also dominated by missing higher-order corrections. In contrast, the $t\bar{t}W$ EW contributions, shown on the right plot, show a very different behavior. Not even the NWA performs well in this case. For transverse momenta larger than roughly 450 GeV all predictions deviate more than 50% from the full off-shell calculation. The predictions also become quickly incompatible with each other within the uncertainties. The exception is MG5_aMC@NLO as its uncertainties are severely inflated due to matching uncertainties.

As the full off-shell calculation is not yet matched with parton showers we propose to improve the currently available on-shell NLOPS calculations by a simple procedure. We add off-shell corrections to NLOPS predictions via

$$\frac{d\sigma^{\text{th}}}{dX} = \frac{d\sigma^{\text{NLOPS}}}{dX} + \frac{d\Delta\sigma_{\text{off-shell}}}{dX}\,, \qquad \frac{d\Delta\sigma_{\text{off-shell}}}{dX} = \frac{d\sigma^{\text{NLO}}_{\text{off-shell}}}{dX} - \frac{d\sigma^{\text{NLO}}_{\text{NWA}}}{dX}\,. \tag{1}$$

The definition of $\Delta\sigma_{\text{off-shell}}$ removes approximately the double counting between the double-resonant $t\bar{t}W$ contributions. It, therefore, adds single and non-resonant contributions as well as interference effects. The impact of these corrections are shown in Fig. 2, where on the left the transverse momentum of the leading b jet and on the right of the opposite-sign lepton ℓ^{os} is shown. In the case of $p_T(b_1)$, we find that the off-shell corrections are sizable in the tail of the distribution. This is expected as this phase space region is dominated by associated single-top production. In addition, we observe that the EW contributions receive sizable corrections. However, the combined predictions, NLOPS + $\Delta\sigma$, reproduce the tails of the full off-shell predictions to a very good extent.

On the other hand, for $p_T(\ell^{os})$ we find only minor corrections. The reason for this is that the distribution is described in an excellent way by the NWA. Therefore, we obtain only very

PoS(ICHEP2022)896

small corrections $d\Delta\sigma/dX$ over the whole plotted range. The residual corrections originate from the EW contributions as can be deduced from the bottom panel. The two shown differential distributions illustrate that the $\Delta\sigma$ correction terms indeed only have an effect if single and non-resonant contributions become sizable.

4. Summary

We presented some selected results from our recent comparison of theoretical predictions for $pp \to t\bar{t}W$ in the multi-lepton decay channel. We find that fixed-order full off-shell and on-shell $t\bar{t}W$ NLOPS predictions are overall in good agreement with each other within the estimated theoretical uncertainties. Nonetheless, parton-shower based predictions have considerable shape differences in comparison to fixed-order approaches. The observed differences are enhanced in the case of the $t\bar{t}W$ EW contributions, which however is itself of the order of 10% of the leading QCD prediction. Therefore, differences in the $t\bar{t}W$ EW predictions only have a minor impact on the final predictions.

In the future NLOPS predictions for the full off-shell calculation as well as predictions including NNLO QCD corrections for on-shell $pp \to t\bar{t}W$ will become necessary.

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