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On the modeling of $t\bar{t}W^{\pm}$ signatures at the LHC

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Abstract

We discuss our recent progress on improving the theoretical description of the $pp \to t\bar{t}W^{\pm}$ process with particular focus on fiducial signatures that include top-quark decays. We employ a wide range of techniques from parton shower matching, narrow width approximation to full off-shell computations to assess the importance of the different modeling approaches.

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1 Introduction

The production of a W gauge boson in association with a top-quark pair is one of the rarest and most complex signatures that the Standard Model has to offer. The multiple resonant decays of top quarks and W bosons yield a plethora of different final state particles and thus a multitude of different experimental signatures. In consequence, the $t\bar{t}W^{\pm}$ process contributes as a dominant background process to many searches for Beyond the Standard Model (BSM) physics as well as to the SM measurements of the $t\bar{t}H$ and the $t\bar{t}t\bar{t}$ production process. For the latter processes, the experimental collaborations have recently reported tensions [1] when the $t\bar{t}W^{\pm}$ process is measured as a background process for multi-lepton signatures.

During the last decade a lot of progress has been made to improve the theoretical description of the $pp \to t\bar{t}W^{\pm}$ process. For the inclusive production with stable top quarks NLO QCD as well as EW corrections are well known and have been reported in Refs. [2–5]. Predictions for fiducial signatures including NLO QCD corrections to the top-quark decay have been first computed in Ref. [6] in the Narrow-Width-Approximation (NWA). Only recently, off-shell effects and non-resonant contributions have been included in the NLO QCD computation [7–9] as well as for EW corrections [10] for multi-lepton signatures. Beyond fixed-order, the resummation of soft-gluon emissions has been studied extensively in Refs. [11–15] at the inclusive and differential level. The on-shell $pp \to t\bar{t}W^{\pm}$ production process has been also matched to parton showers [16–18] and the impact of multi-jet merging has been studied for inclusive and fiducial signatures in Refs. [19–21]. Furthermore, in Ref. [22] the approximate combination of full off-shell effects and parton-shower based predictions has been proposed in an event generator independent way.

In the following we will summarize our recent efforts to explore the impact of different approximations made in the description of fiducial signatures for the $pp \to t\bar{t}W^{\pm}$ process.

2 Two same-sign lepton signature

We start our comparison by considering a two same-sign lepton signature, where we select events that fulfill

$$p_T(j) \geq 25 \text{ GeV}\,, \qquad |y(j)| < 2.5\,, \qquad p_T(\ell) > 15 \text{ GeV}\,, \qquad |y(\ell)| < 2.5\,, \tag{1}$$

and have exactly 2 same-sign leptons, at least 2 light jets as well as at least 2b jets. The theoretical predictions are obtained using the recent POWHEG-BOX implementation, which is based on one-loop amplitudes provided via NLOX [23, 24], MG5_AMC@NLO and SHERPA. We refer the reader to Ref. [18] for further details of the computational setup.

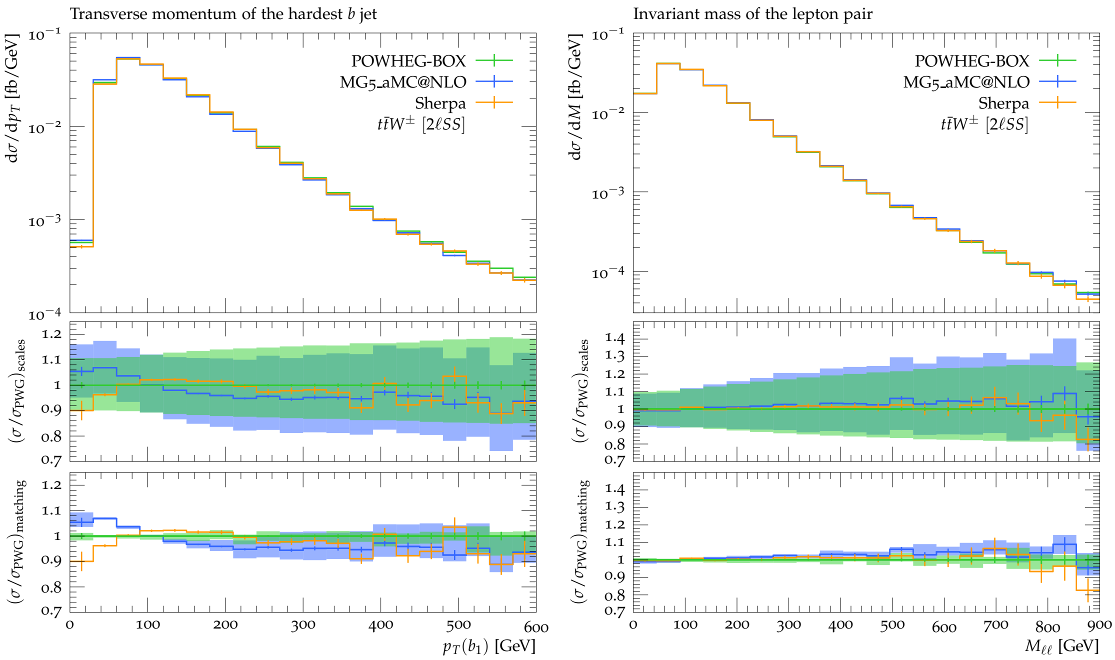

Figure 1: Differential cross section distribution in the two same-sign lepton fiducial region as a function of the transverse momentum of the hardest b jet (l.h.s) and of the invariant mass of the lepton pair (r.h.s). Figures taken from Ref. [18].

In Fig. 1 we show the transverse momentum of the hardest b jet and the invariant mass of the same-sign lepton pair. Both observables are computed from top-quark decay products, thus allowing to compare the different decay algorithms employed in the event generators. For the transverse momentum of the hardest b jet shown on the left we observe good agreement between the various frameworks with only minor shape modifications below 10%. It is well known, that differences in the treatment of radiation from heavy quarks can account for these effects. Nonetheless, within the estimated theoretical uncertainties of 10% − 20% that are dominated by missing higher-order corrections all predictions are compatible with each other.

In the case of the invariant mass of the two same-sign lepton pair we observe even better agreement between the considered Monte Carlo event generators. Due to its leptonic nature the observable is only marginally affected by less than 5% due to the parton shower evolution. Thus, matching uncertainties are negligible over the whole range. The scale uncertainties start at 10% and increase up to 25% in the tail of the distribution.

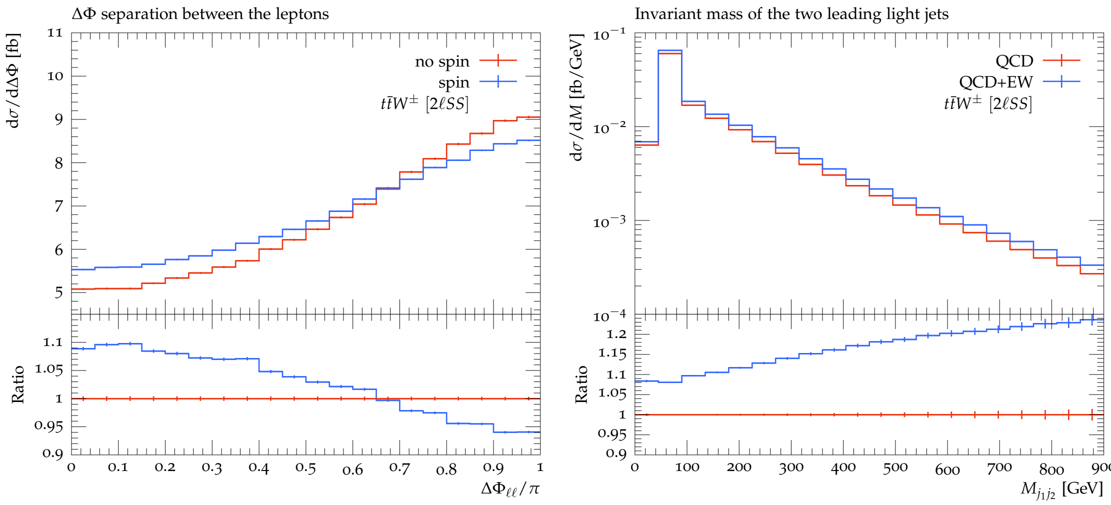

Figure 2: Differential cross section distribution in the two same-sign lepton fiducial region as a function of the azimuthal angle between the two leptons (l.h.s) and of the invariant mass of the two hardest light jets (r.h.s). Figures taken from Ref. [18].

In Fig. 2 we show the azimuthal angle between the leptons as well as the invariant mass of the two hardest light jets. Both observables are sensitive to the modeling details of the signature. For instance, in the case of the azimuthal angle between the two same-sign leptons we observe sizable effects due to spin-correlations in the top-quark decays. The shape of the distribution is altered at the level of 10%. However, for non-leptonic observables we have not found any indications of spin-correlation effects. When considering the invariant mass of the two hardest light jets, shown on the right panel of Fig. 2, we observe multiple features. For instance, the peak of the distribution is centered around the W boson resonance, which indicates that the majority of events are dominated by jets originating from the hadronic W decay. This decay, however, is modeled at leading-order accuracy in all event generators. Including higher-order QCD corrections to these decays is of utmost importance to achieve a better description of the fiducial signature. Furthermore, we observe that the impact of the EW contributions increases for larger values of the invariant mass because the observable becomes sensitive to jets generated in the forward region. Nonetheless, for the majority of studied observables the EW production modes yields a constant +10% correction at the differential level.

3 Multi-lepton signatures

In the following we compare two different fixed-order approaches to describe fiducial signatures. We compute the full off-shell process, i.e. the computation is based on matrix elements for the $pp \to e^+\nu_e\mu^-\nu_\mu e^+\nu_e b\bar{b}$ process. These amplitudes take all double, single and non-resonant contributions together with all interference effects at the matrix element level into account. In Fig. 3 we show some representative Feynman diagrams for each class of contribution. The computation is performed in the HELAC-NLO framework [25] that consists out

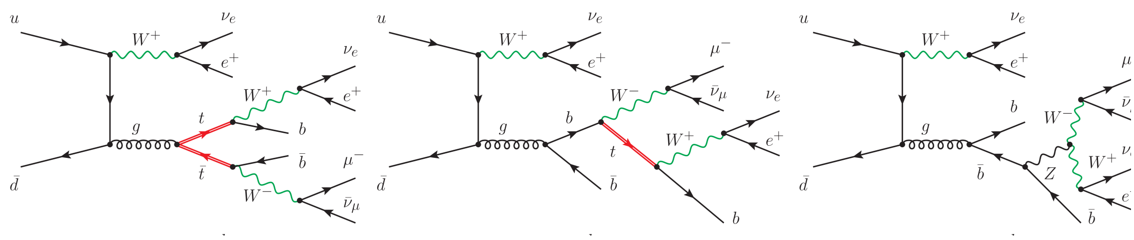

Figure 3: Representative Feynman diagrams for the double, single and non-resonant contributions to the $pp \to e^+ \nu_e \mu^- \nu_\mu e^+ \nu_e b\bar{b}$ amplitude. Figure taken from Ref. [7].

of HELAC-1LOOP [26] and HELAC-DIPOLES [27–29] and which has been already applied to various off-shell processes [30–33].

On the other hand, the narrow-width-approximation (NWA), which has been recently automated in our framework [34], is applied to the process under consideration to simply greatly the computation. In the NWA only the leading double-resonant contribution is kept by applying the following relation to the Breit-Wigner propagators of top quarks and W bosons

$$\frac{1}{(p^2-m^2)^2+m^2\Gamma^2} \to \frac{\pi}{m\Gamma}\delta(p^2-m^2)+\mathcal{O}\left(\frac{\Gamma}{m}\right). \tag{2}$$

Nonetheless, the NWA allows to systematically include NLO QCD corrections in the production and decay stage with exact spin correlations. For more details on the computation we refer to Refs. [7,8]. The different approaches allow to quantify the importance of NLO QCD corrections to the decay as well as of the single and non-resonant contributions.

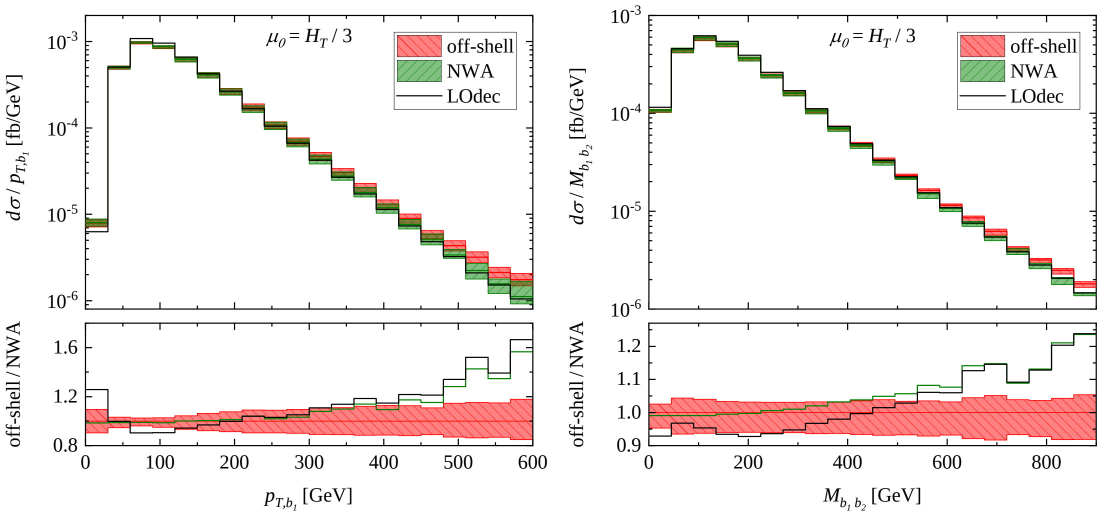

Figure 4: Differential cross section distribution in the three lepton fiducial region as a function of the transverse momentum of the hardest b jet (l.h.s) and of the invariant mass of the two hardest b jets (r.h.s). Figures taken from Ref. [7].

In Fig. 4 we illustrate the impact of the various approximations to the full off-shell computation. For the transverse momentum of the hardest b jet, shown on the left panel, we observe differences up to 60% between the full off-shell and the full NWA prediction in the tail of the distribution. This can be attributed to sizable single-resonant contribution in this phase space region. The size of these effects even outgrow the scale uncertainties that are below 20%. If additionally NLO QCD corrections in the top-quark decays are omitted in the NWA we observe effects at the 10% level even in the bulk of the distribution. Similar effects are observed in the case of the invariant mass of the two hardest b jets. The size of single-resonant contributions are below 30%. However, also scale uncertainties are smaller and are below 10%. The impact of QCD corrections to the decay is, as in the previous case, at the 10% level. Therefore, both contributions, i.e. NLO QCD corrections to top-quark decays as well as single and non-resonant contributions are important for a reliable description of the fiducial volume.

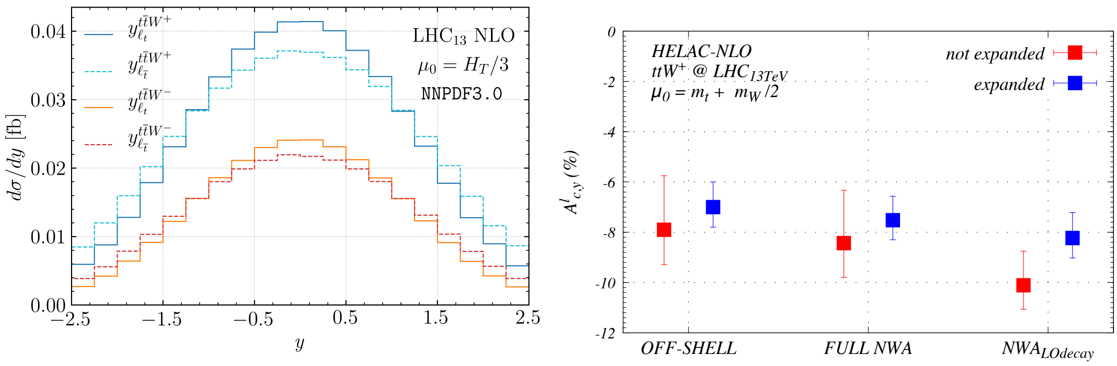

Figure 5: Differential cross section distribution in the three lepton fiducial region as a function of the rapidity of the lepton originating from the top and anti-top quark (l.h.s) and the inclusive charge asymmetry for various approaches to describe the fiducial volume (r.h.s). Figures taken from Ref. [8].

We also explored the impact of the various computational approaches in the context of the charge asymmetry defined via top decay products. On the left panel of Fig. 5 we show the rapidity distributions of the lepton originating from the top and anti-top quark separately for $t\bar{t}W^+$ and $t\bar{t}W^-$. It is clearly visible that for each production mode the leptons are produced asymmetrically. The inclusive charge asymmetry can be computed via

$$A_c^\ell = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\,, \qquad \sigma^\pm = \int d\sigma\,\theta(\pm\Delta|y|)\,, \qquad \Delta|y| = |y_{\ell_t}| - |y_{\ell_{\bar{t}}}|\,. \tag{3}$$

Our obtained predictions are illustrated on the right panel of Fig. 5. We find that the full off-shell computation predicts a charge asymmetry of $A_c^\ell = -7.9\%$, while the full NWA gives slightly larger results of $A_c^\ell = -8.43\%$. If NLO QCD corrections to the decay are omitted they increase further to $A_c^\ell = -10.11\%$. Even though all theoretical predictions are compatible with each other within the estimated uncertainties a clear trend is visible. In addition, if we expand A_c^ℓ to NLO accuracy via

$$A^\ell_{c,exp} = \frac{\Sigma^-_{\rm LO}}{\Sigma^+_{\rm LO}}\left(1 + \frac{\delta\Sigma^-_{\rm NLO}}{\Sigma^+_{\rm LO}} - \frac{\delta\Sigma^+_{\rm NLO}}{\Sigma^+_{\rm LO}}\right)\,, \qquad \Sigma^\pm = \sigma^+ \pm \sigma^-\,, \tag{4}$$

we can estimate the impact of uncontrolled higher-order corrections. Also in this case we observe that the full off-shell computation shows the smallest dependence on higher-order terms. We conclude that modeling of the fiducial phase space volume has a non-negligible effect on the extracted charge asymmetry. In Ref. [8] we studied more asymmetries also at the differential level.

4 Summary & Outlook

We studied several aspects of the modeling of fiducial signatures for the $pp \to t\bar{t}W^\pm$ process at the LHC. In the case of the two same-sign lepton signature we compared various parton-shower matched predictions and explored the impact of subleading EW contributions as well as spin-correlated top-quark decays at the differential level. Generally speaking good agreement between the various event generators have been observed. The subleading EW production channels contribute at the level of 10%. However, their size can increase up to 25% if the considered observable is sensitive to forward jet production. Spin-correlation effects have only been found in leptonic observables, where they can change the shapes of distributions by roughly 10%.

On the other hand, for multi-lepton signatures we considered fixed-order predictions that allows to include also single and non-resonant contributions as well as NLO QCD corrections to top-quark decays. By comparing the full off-shell calculation to the predictions obtained in the NWA we were able to quantify the impact of those effects at the differential level. We found that corrections in the top-quark decay have a visible impact at the 10% level even in the bulk of the distribution. On the contrary, the single and non-resonant contributions can become sizable in the tail of dimensionful observables and can be as large as 60%.

To improve the theoretical description of fiducial signatures even further a signature-by-signature approach has to be considered. For multi-lepton signatures the NNLO QCD corrections to the production part will be of utmost importance. In the presence of hadronic W decays however the inclusion of NLO QCD corrections to the decay might be more relevant in the near future.

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