A detailed comparison of QCD modelling in $pp \to t\bar{t}W^\pm$ production*

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Recent LHC measurements of $t\bar{t}W^\pm$ production either as signal or as a background to $t\bar{t}H$ production present still unexplained tensions with Standard Model predictions. Given the relevance of this process for the precision measurement of top-quark properties and searches of new physics at the LHC, the HL-LHC, and future hadron colliders (FCC-hh and CppC), we propose a comprehensive study of $t\bar{t}W^\pm$ production at hadron colliders based on next-to-leading-order (NLO) parton-shower event generators and state-of-the-art fixed-order calculations.

The production of top-quark pairs in association with electroweak gauge bosons ($t\bar{t} + V$, $V = W^\pm, Z$) can be measured at current (LHC) and future (HL-LHC, FCC-hh, CppC) hadron colliders in a multitude of decay channels and provides new avenues to test the consistency of the Standard Model (SM). At the same time, these processes represent some of the most important irreducible backgrounds for Higgs-boson precision measurements and searches of new physics beyond the Standard Model (BSM). In this context, the hadronic production of $W^\pm$ bosons in association with a top-quark pair ($t\bar{t}W^\pm$) is particularly interesting both from a phenomenological and theoretical point of view.

Indeed $t\bar{t}W^\pm$ provides one of the rarest SM signatures, namely same-sign leptons, and represents one of the leading backgrounds to searches of BSM physics for which these signatures are quite common such as, e.g., supersymmetric models [1, 2], models with Majorana neutrinos [3], as well as models with modified Higgs sectors [4]. Furthermore, the $t\bar{t}W^\pm$ processes is a crucial irreducible background in the measurements of the production of a Higgs boson in association with top quarks ($Ht\bar{t}$) in the multi-lepton decay channels, and therefore limits the accuracy of the direct measurement of the top-quark Yukawa coupling.

At the same time, the $t\bar{t}W^\pm$ hadronic process is theoretically quite interesting, both because of its unique sensitivity to higher-order QCD and EW corrections and because of its intrinsic potential to offer measurable evidence of charge asymmetry and polarization in top-quark production (other than $t\bar{t}$ production). Indeed, at hadron colliders the $t\bar{t}W^\pm$ final state is produced at leading order (LO) only via $q\bar{q}$, while at NLO additional gq and $g\bar{q}$ channels open up and greatly affects the accuracy of the theoretical predictions. The need of controlling QCD corrections beyond NLO to remove the systematic limitation of existing theoretical predictions becomes a very important question. Besides QCD, EW corrections have been shown to be quite impactful in the case of $t\bar{t}W^\pm$, due to Higgs-boson virtual exchanges that are unique to this process [7]. On the other hand, since the symmetric gg production channel only opens up at next-to-next-to-leading-order (NNLO), the top-quark charge asymmetry in $t\bar{t}W^\pm$ events is considerably larger than in $t\bar{t}$ production and $t\bar{t}W^\pm$ thus offers a better opportunity to measure such charge asymmetry [5]. In addition, the radiation of a W boson in the initial state serves as a polarizer for the top quarks. These polarization effects are further imprinted onto the leptonic decay products of the top quarks and can lead to sizable modifications of differential distributions [6].

Verifying these quite unique properties of $t\bar{t}W^\pm$ production can become a rich testing ground of our theoretical understanding of top-quark production and top-quark properties, provided state-of-the-art theoretical predictions can be used to interpret experimental data. A reason of specific concern and interest has recently been offered by a very intriguing tension between experimental data and SM theoretical predictions observed in LHC measurements of $t\bar{t}W^\pm$ as a signal [8, 9] and as a background to the measurement of the $t\bar{t}H$ signal [10] at 13 TeV.

Given the relevance of higher-order QCD corrections in the perturbative calculations of $t\bar{t}W^\pm$ production at hadron colliders, and given the importance of the accurate modelling of both production and decay (of t, $\bar{t}$, and $W^\pm$) in the generation of Monte Carlo events to be compared with experimental data, we propose to:

1. Investigate the potential impact of QCD corrections beyond NLO through a calculation that merges $t\bar{t}W^\pm$ and $t\bar{t}W^\pm + j$ including NLO QCD corrections, as well as $t\bar{t}W^\pm + 2j$ and $t\bar{t}W^\pm + 3j$ at LO QCD. Indeed, the absence of the gg channel at NLO might make the process sensitive to the modelling of initial-state radiation. In that context a study of $t\bar{t}W^\pm$ with additional jets can be illuminating (as it has been the case for $b\bar{b}W^\pm$ [11]).

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2. Assess the impact of off-shell effects, spin-correlations, and NLO QCD corrections to top-quark decays via a detailed comparison between Monte Carlo event generators and the results of fully off-shell calculations of $t\bar{t}W^{\pm}$ production+decays as recently obtained in Ref. [12, 13].

The investigation of both former aspects has never been addressed and we think it is necessary to evaluate the need for further studies which also include NLO EW corrections properly matched to parton-shower event generators as well as the full set of NNLO QCD corrections.

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