$t\bar{t}W$ Production: a very complex process

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These Monte Carlo studies describe the impact of higher order effects in both QCD and EW $t\bar{t}W$ production. Both next-to-leading inclusive and multileg setups are studied for $t\bar{t}W$ QCD production.

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1 Introduction

The $t\bar{t}W$ process is very interesting from the phenomenological point of view \cite{1}. It is for instance a main background for some beyond the Standard Model (SM) searches and other rare top SM processes such as $t\bar{t}H$ and $t\bar{t}t\bar{t}$. Moreover, $t\bar{t}W$ production rates have been measured at the LHC by CMS and ATLAS as inclusive cross–sections \cite{2,3} and those measurements yield larger values than the SM predictions from the CERN Yellow Report 4 \cite{4}. This motivates the in–depth study of this process.

For these Monte Carlo (MC) studies, the event selection is as follows: the $t\bar{t}$ pair is decayed semileptonically and the associated $W$ boson is decayed leptonically, being both leptons of the same charge. In addition, the following particle level jet cuts $p_T(j) > 25$ GeV and $|\eta| < 2.5$ are applied. Forwards jets are defined in the $2.5 < |\eta| < 4.5$ region.

2 Disentanglement of Higher Order Effects

Higher order effects (in the quantum chromodynamic (QCD) strong coupling constant $\alpha_S$ and the electro–weak (EW) coupling constant $\alpha$) are very important for $t\bar{t}W$ production and can significantly modify leading order cross–sections. Figure 1 shows the Born level diagrams due to these higher order corrections that enter the MC simulations.

The MG5\_AMC@NLO \cite{5} generator is used interfaced with the PYTHIA8 \cite{6} parton shower (PS) for both multileg and inclusive setups. The following items are explored: scale variations of the renormalisation and factorisation scales ($\mu_R$ and $\mu_F$) in the matrix elements (ME) (for inclusive setups), where up to three different functional forms are used; multileg setups (with the FxFx \cite{7} algorithm), using NLO–accurate matrix elements for up to one additional jet and LO–accurate matrix elements for up
to two additional jets \((t\bar{t}W + 0,1jNLO + 2jLO)\); *parameter variations* that impact the FxFx matching algorithm.

### 3 QCD Production

The QCD corrections have been studied with both NLO inclusive and multileg merged setups. Figure 2 shows the studies performed at NLO QCD accuracy for the three points mentioned in the previous section. The following conclusions may be extracted:

- (a): there is a 10% increase in the cross-section between the (green) default dynamical scale used in MG5_aMC@NLO and the (blue) fixed scale used in the CERN YR4. For all functional forms, there is a big dependence of the cross-section with the chosen value of the scale with \(\sigma(\mu_i,0/4)/\sigma(\mu_i,0) \sim 1.4\).

- (b): the nominal multileg (FxFx) sample has a merging scale \(\mu_Q = 30\text{ GeV}\) and a \(p_T^{\text{min}}(j) = 8\text{ GeV}\). No significant shape effects and a cross-section difference of about 2% is observed when changing the merging scale. This configuration yields a cross-section of \(\sigma_{FxFx}^{t\bar{t}W} = 614.2^{+12\%}_{-13\%}\) fb.

- (c) and (d): there is good agreement between both MG5_aMC@NLO and SHERPA2.2.8 [8, 9] multileg setups inside the uncertainty bands. These show correlated scale variations in the ME and PS.

### 4 “tree–level” EW Production

The EW corrections to the \(t\bar{t}W\) process have been recently calculated to increase the cross-section by around 10\% [10] which is much bigger than naively expected. This is caused by the appearance of \(t\bar{t}W \rightarrow t\bar{t}W\) scattering diagrams \((\mathcal{O}(\alpha_S\alpha^3))\), as those on the bottom right of Figure 1. Such corrections and their effects are shown in Figure 3 from which the following conclusions may be extracted:

- (a): in addition to the strong \(\mu_R\) and \(\mu_F\) scale dependance, the EW corrections predict a 10% increase in the cross-section throughout for all scale values. A similar study has been performed using SHERPA2.2.8 where the effect on the cross-section is of about 5%.

- (b) to (d): shape effects of around a 20% are observed for events in the high central and forward jet multiplicity regions, as well as in the high pseudo rapidity region \((2.5 < |\eta| < 4.5)\) where the extra jet in \(t\bar{t}W \rightarrow t\bar{t}W\) scattering is expected.
5 Conclusions

From these studies including higher order effects in both QCD and EW it is clear that we still don’t have the whole picture for the $t\bar{t}W$ process. The choice of the functional
Figure 3: (a): Cross-section dependence with two functional forms of the $\mu_R$ and $\mu_F$ scales. (b) to (d): Effect of the “tree-level EW” contribution for MG5_aMC@NLO for some kinematic variable distributions. The vertical error lines show the 7-point scale variations for (a), while for the rest they indicate the MC statistical uncertainty and the shaded bands represent these scale variations. Figures from Ref. [11].

form of the $\mu_R$ and $\mu_F$ scales as well as their values can change the predictions substantially. The addition of multileg setups and EW corrections also have a 10% impact on the cross-section values. The former seem to be in agreement across
different MC generators and also consistent within relevant parameter variations (such as $\mu_Q$); while the latter further increase the cross-section and have considerable shape effects in some kinematic distributions. These results are documented in Ref. [11].

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References

[1] F. Maltoni, M. L. Mangano, I. Tsinikos and M. Zaro, Phys. Lett. B 736 (2014), 252-260 doi:10.1016/j.physletb.2014.07.033 [arXiv:1406.3262 [hep-ph]].

[2] CMS Collaboration, JHEP 08 (2018), 011 doi:10.1007/JHEP08(2018)011 [arXiv:1711.02547 [hep-ex]].

[3] ATLAS Collaboration, Phys. Rev. D 99 (2019) no.7, 072009 doi:10.1103/PhysRevD.99.072009 [arXiv:1901.03584 [hep-ex]].

[4] D. de Florian et al. [LHC Higgs Cross Section Working Group], doi:10.23731/CYRM-2017-002 [arXiv:1610.07922 [hep-ph]].

[5] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli and M. Zaro, JHEP 07 (2014), 079 doi:10.1007/JHEP07(2014)079 [arXiv:1405.0301 [hep-ph]].

[6] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen and P. Z. Skands, Comput. Phys. Commun. 191 (2015), 159-177 doi:10.1016/j.cpc.2015.01.024 [arXiv:1410.3012 [hep-ph]].

[7] R. Frederix and S. Frixione, JHEP 12 (2012), 061 doi:10.1007/JHEP12(2012)061 [arXiv:1209.6215 [hep-ph]].

[8] E. Bothmann et al. [Sherpa], SciPost Phys. 7 (2019) no.3, 034 doi:10.21468/SciPostPhys.7.3.034 [arXiv:1905.09127 [hep-ph]].

[9] C. Gütschow, J. M. Lindert and M. Schönherr, Eur. Phys. J. C 78 (2018) no.4, 317 doi:10.1140/epjc/s10052-018-5804-2 [arXiv:1803.00950 [hep-ph]].

[10] R. Frederix, D. Pagani and M. Zaro, JHEP 02 (2018), 031 doi:10.1007/JHEP02(2018)031 [arXiv:1711.02116 [hep-ph]].

[11] ATLAS Collaboration, ATL-PHYS-PUB-2020-024, url: https://cds.cern.ch/record/2730584

[12] ATLAS Collaboration, 2008 JINST 3 S08003