NLO QCD corrections to the production of top–antitop pairs in association with a W boson including leptonic decays

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We present the QCD radiative corrections to the full off-shell $t\bar{t}W^+$ production, considering a final state with three charged leptons, two $b$ jets and missing energy. All interferences, off-shell effects and spin correlations are included in the calculation. Beyond presenting integrated and differential results for the full off-shell process, we compare them with those obtained applying a double-pole approximation to the virtual corrections.

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1 Introduction

An accurate theoretical modelling is needed for the top-antitop production in association with a W boson at the LHC. Beyond its own importance both as a probe of the Standard Model (SM) and as a window to new physics effects, such a process represents a relevant background to the $t\bar{t}H$ production.

Recent experimental results show significant deviations from the SM in the modelling of $t\bar{t}W$ production [1], and much effort is being put to improve the theoretical description of the process in order to compare with present and future LHC data. The next-to-leading-order (NLO) corrections (QCD and electroweak) are known since several years for the inclusive $t\bar{t}W$ production both for on-shell top quarks and in the narrow-width approximation [2], and the matching to parton-shower [3], soft-gluon resummation [4] and multi-jet merging [5] have also been tackled for this process.

The first full off-shell calculations of $t\bar{t}W$ production in the three-lepton decay channel have appeared very recently [6, 7]. In these proceedings, we briefly describe the calculation of Ref. [7] and present the most relevant results at the integrated and differential level, including a comparison between full off-shell results and those obtained with a double-pole approximation.

2 Description of the calculation

We consider the complete NLO QCD corrections to off-shell $t\bar{t}W^+$ production at the LHC@13TeV in the channel $pp \rightarrow e^+\nu_e \mu^-\bar{\nu}_\mu \tau^+\nu_\tau b\bar{b}$, including all off-shell effects, spin-correlations and interferences. At leading-order [LO, $O(\alpha_s^2\alpha^6)$], this process receives contributions from quark-induced partonic channels only. At NLO QCD [$O(\alpha_s^3\alpha^6)$], also the $gq/g\bar{q}$ channels open up. While the virtual corrections feature up to seven-point one-loop functions to be evaluated (see Fig. 1), the challenging part of the calculation are the real corrections, as they involve a large-multiplicity final state ($2 \rightarrow 9$ process, with four external coloured partons). Tree-level and one-loop amplitudes are computed with RECOLA [8], and the numerical integration is per-
formed with the MoCaNLO Monte Carlo code, which uses the dipole formalism \cite{9} for the subtraction of soft and collinear singularities. Unstable particles are treated in the complex-mass scheme \cite{10}. For the details on the SM input parameters and the fiducial setup we refer to Sect. 3.1 of Ref. \cite{7}.

3 Integrated and differential results

We present the fiducial cross-sections for five different central-scale choices, both fixed and dynamical. Numerical results are shown in Table 1. The dynamical scales are based either on the $H_T$ observable, defined as

$$H_T = p_{T,\text{miss}} + \sum_{i=\ell,b} p_{T,i},$$

or on the geometrical average of the two top-quark transverse masses,

$$(M_{T,\ell} M_{T,t})^{1/2} = \left(\sqrt{p_{T,\ell}^2 + M_{T,\ell}^2} \sqrt{p_{T,t}^2 + M_{T,t}^2}\right)^{1/2},$$

where the ambiguity in the selection of the top-quark is solved choosing the decay products whose invariant mass is the closest to top-quark pole mass.

The different scale choices lead to NLO QCD corrections between $+7\%$ and $+25\%$ to the fiducial cross-section in the fiducial region. Furthermore the theory uncertainties from renormalization- and factorization-scale variations are sizeably reduced at NLO: while they are at the 20\% level at LO, they are reduced to 5\% at NLO QCD.

The choice of a dynamical scale gives flatter corrections than with a fixed scale at the differential level in most of the analyzed observables. However, moderate shape distortions owing to NLO corrections can be found even using a dynamical scale. This

| central scale | LO    | NLO QCD | $K$-factor |
|---------------|-------|---------|------------|
| $\mu_0^{(a)} = M_t + M_W/2$ | $0.2042(1)^{+23.8\%}_{-18.0\%}$ | $0.2452(7)^{+4.5\%}_{-6.8\%}$ | 1.20 |
| $\mu_0^{(b)} = H_T/2$ | $0.1931(1)^{+23.0\%}_{-17.5\%}$ | $0.2330(9)^{+4.2\%}_{-6.5\%}$ | 1.21 |
| $\mu_0^{(c)} = H_T/3$ | $0.2175(1)^{+24.2\%}_{-18.2\%}$ | $0.2462(8)^{+2.8\%}_{-5.8\%}$ | 1.13 |
| $\mu_0^{(d)} = \left(M_{T,\ell} M_{T,t}\right)^{1/2}$ | $0.1920(1)^{+23.0\%}_{-17.5\%}$ | $0.2394(6)^{+5.4\%}_{-7.2\%}$ | 1.25 |
| $\mu_0^{(e)} = \left(M_{T,\ell} M_{T,t}\right)^{1/2}/2$ | $0.2360(1)^{+24.9\%}_{-18.7\%}$ | $0.2535(8)^{+3.4\%}_{-5.2\%}$ | 1.07 |

Table 1: Fiducial cross-sections and $K$-factors for different central-scale choices for the process $pp \rightarrow e^+\nu_e\mu^-\tau^+\nu_\tau b\overline{b}$ at the LHC@13TeV \cite{7}. Numerical errors are shown in parentheses, and scale uncertainties are given in percentages.
is the case for the azimuthal distance between the positron and the muon, considered in Fig. 2 (left). Despite the usage of the resonance-aware dynamical scale $\mu_0^{(d)}$, the NLO $K$-factor diminishes from 1.5 (at $\Delta \phi_{e^+\mu^-} \approx 0$) to 1.15 (at $\Delta \phi_{e^+\mu^-} \approx \pi$).

Another interesting aspect of this process is given by the very large corrections that characterize some distribution tails, in particular those depending on the $b$ jets. As an example, the transverse momentum of the two-b-jet system, shown in Fig. 2 (right), features 100% corrections already at moderate values. These effects signal that the NLO QCD corrections are dominated by real radiation. This is confirmed by the scale-uncertainty bands that are larger than the LO ones for $p_{T,bb} > 200$ GeV.

We have compared the full off-shell results with those obtained via a double-pole approximation (DPA) for the top-antitop resonances. More specifically, we have performed two calculations using the DPA: we have either applied the DPA to the virtual QCD corrections only, or both to the virtual corrections and to the $I$-operators of the integrated dipoles, which by construction subtract the explicit infrared poles of the virtual corrections and therefore should be treated in the same way as the virtual corrections themselves.

The fiducial cross-sections read (the central scale $\mu_0^{(d)}$ is understood):

$$\sigma_{\text{NLO}}^{\text{full}} = 0.2394(6) \text{fb}, \quad \sigma_{\text{NLO}}^{\text{DPA,V}} = 0.2395(7) \text{fb}, \quad \sigma_{\text{NLO}}^{\text{DPA,V+I}} = 0.2422(7) \text{fb}. \quad (3)$$

The agreement between the full off-shell calculation and the one obtained applying the DPA to the virtual contributions only is impressive, thanks to the fact that virtual corrections are small for this process. If the DPA is applied also to the $I$-operators
of the integrated dipoles, a 1% discrepancy is found at the integrated level.

Larger discrepancies can be observed in more exclusive phase-space regions, where the contributions of resonant top and antitop quarks are not dominant anymore, and off-shell effects are sizeable. In Fig. 3 we consider again the transverse momentum of the two-b-jet system. If the DPA is applied to the virtual corrections only, the discrepancy w.r.t. the off-shell result reaches 3% at large values, while 10% effects appear if also integrated dipoles are treated in the same way. The DPA results show that the \( t\bar{t}W \) resonant structure is dominant in most of the fiducial phase space and for sufficiently inclusive observables, while the full off-shell modelling is definitely needed in suppressed phase-space regions.

4 Conclusion

The NLO QCD corrections to \( t\bar{t}W^+ \) production at the LHC are about 20% for the fiducial cross-section and sizeably reduce the scale uncertainties. Mild differences show up when using different renormalization and factorization scales. An improved perturbative convergence is obtained using a dynamical scale, which gives flatter differential \( K \)-factors than the typical fixed scale. Very large \( K \)-factors are found in exclusive phase-space regions, in particular where the process is dominated by hard QCD radiation. A comparison of the full off-shell results with those obtained applying a double-pole approximation to virtual corrections gives a percent agreement at the level of the fiducial cross-section. Larger discrepancies (up to 10%) characterize phase-space regions which are not dominated by the \( t\bar{t} \) resonance structure.
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