Modelling of top quark decays in $t\bar{t}\gamma$ production at the LHC

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In this proceedings we briefly report on the state-of-the-art NLO QCD computation for the $pp \rightarrow t\bar{t}\gamma$ process in the di-lepton channel. We describe higher-order corrections to the $e^+\nu_e \mu^-\nu_\mu b\bar{b}\gamma$ final state at the LHC with $\sqrt{s} = 13$ TeV. Off-shell top quarks, double-, single- as well as non-resonant top-quark contributions along with all interference effects are consistently incorporated at the matrix element level. Results are presented in the form of fiducial integrated and differential cross sections. The impact of top quark modelling is scrutinised by an explicit comparison with the results in the narrow-width approximation. Both types of predictions are now available in the HELAC-NLO framework.

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1 Introduction

Top quark pair production in association with an additional photon provides particularly promising means for a direct measurement of the top quark electric charge, which governs the coupling strength of the $t\bar{t}\gamma$ interaction. The $t\bar{t}\gamma$ process can probe, however, not only the strength but also the structure of the $t\bar{t}\gamma$ vertex. A generic way for the parameterisation of new physics effects is provided by an effective field theory (EFT). The Lagrangian of the EFT is expressed in terms of the Standard Model (SM) Lagrangian and a non-SM part, which is dominated by the contributions due to operators of dimension six. Such contributions can be translated into top quark magnetic and electric dipole moments [1,2] and measured at the LHC. Since the top quark is the heaviest quark, effects of physics beyond the SM on its couplings are larger than for any other fermion, thus, deviations with respect to SM predictions for this process should be easier to detect. Furthermore, $t\bar{t}\gamma$ production can be used to obtain predictions for integrated and differential $t\bar{t}\gamma/t\bar{t}$ cross section ratios [3]. Such cross section ratios are more stable against radiative corrections and have reduced scale dependence. Consequently, they have enhanced predictive power. They can, therefore, be used to study the $t\bar{t}\gamma$ process with a higher precision. Finally, the integrated and differential top quark charge asymmetries and lepton charge asymmetry can be investigated in $t\bar{t}\gamma$ production at the LHC. They provide complementary information to the measured charge asymmetries in $t\bar{t}$ production [4–7].

For an accurate comparison with LHC data, reliable theoretical predictions, which include higher order effects, are mandatory. NLO QCD corrections for the $t\bar{t}\gamma$ process have been calculated in Ref. [5,8], whereas NLO electroweak corrections have been considered in Ref. [9]. In both cases, top quarks are treated as stable particles. For more realistic studies, however, top quark decays are required. First attempts in this direction have been carried out in Ref. [10], where NLO QCD predictions for $t\bar{t}\gamma$ have been matched to parton shower programs. In this study top quark decays are treated in the parton shower approximation omitting spin correlations and photon emission in parton shower evolution. Fully realistic theoretical predictions for $t\bar{t}\gamma$ at NLO in QCD have been presented in Ref. [11]. In this case, top quark decays are included using the narrow width approximation (NWA). Consequently, spin correlations of final state particles are maintained at the NLO level and photon radiation off top quark decay products is incorporated. Finally, in Ref. [12] a complete description of $pp \rightarrow t\bar{t}\gamma$ in the di-lepton top quark decay channel has been presented. In this case, all resonant and non-resonant diagrams, interferences, and off-shell effects of the top quarks and the $W$ gauge bosons are consistently taken into account. These state-of-the-art theoretical predictions for $t\bar{t}\gamma$ have been compared to the NWA case in Ref. [13] using the HELAC-NLO common framework [14].

In this proceedings we briefly summarise the state-of-the-art theoretical predictions for $t\bar{t}\gamma$ production at the LHC and analyse the applicability of the NWA approach for this process.

2 Results

We present results for the $pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu\bar{b}b\gamma$ process for the LHC Run II energy of $\sqrt{s} = 13$ TeV. Our calculation uses CT14 parton distribution functions (PDFs) [15] and employs the
Table 1: LO and NLO integrated cross sections for various approaches to the modelling of top quark decays. We additionally provide theoretical uncertainties as obtained from the scale dependence. All results are provided for $\mu_0 = H_T/4$.

| Modelling Approach | $\sigma^{\text{LO}}$ [fb] | $\sigma^{\text{NLO}}$ [fb] |
|--------------------|----------------------------|----------------------------|
| full off-shell     | $7.32^{+2.45}_{-1.71}$ (33%) | $7.50^{+0.11}_{-0.45}$ (1.0%) |
| NWA                | $7.18^{+2.39}_{-1.68}$ (33%) | $7.33^{+0.43}_{-0.24}$ (5.9%) |
| NWA$_{\gamma-\text{prod}}$ | $3.89^{+1.29}_{-0.90}$ (33%) | $4.15^{+0.12}_{-0.21}$ (2.3%) |
| NWA$_{\gamma-\text{decay}}$ | $3.35^{+1.10}_{-0.77}$ (33%) | $3.18^{+0.31}_{-0.03}$ (9.7%) |
| NWA$_{\text{LO decay}}$ | $4.63^{+0.44}_{-0.52}$ (9.5%) |

following SM parameters: $G_\mu = 1.166378 \times 10^{-5}$ GeV$^{-2}$, $m_W = 80.385$ GeV, $\Gamma_W = 2.0988$ GeV, $m_Z = 91.1876$ GeV and $\Gamma_Z = 2.50782$ GeV. The electroweak coupling is derived from the Fermi constant. For the emission of the isolated photon, however, $\alpha_{\text{QED}} = 1/137$ is used instead. The top quark mass is set to $m_t = 173.2$ GeV. The top quark width is calculated using formulas from Ref. [16]. All other QCD partons including $b$ quarks as well as leptons are treated as massless. The final state jets are constructed using the IR-safe anti-$k_T$ jet algorithm [17] with $R = 0.4$. We require at least two jets for our process, of which exactly two must be bottom flavoured jets. Furthermore, we request two charged leptons, missing transverse momentum and an isolated hard photon. For the latter, we use the Frixione photon isolation prescription, which is based on a modified cone approach [18]. We apply basic selection cuts to these final states to ensure that they are observed inside the detector and are well separated from each other, see [13] for more details. We utilise the following scale $\mu_R = \mu_F = \mu_0 = H_T/4$ where $H_T$ is defined as

$$H_T = p_T(e^+) + p_T(\mu^-) + p_T^{\text{miss}} + p_T(b_1) + p_T(b_2) + p_T(\gamma),$$

with $p_T(b_1)$ and $p_T(b_2)$ being bottom-flavoured jets and $p_T^{\text{miss}}$ the missing transverse momentum from the two neutrinos. The scale systematics is evaluated by varying $\mu_R$ and $\mu_F$ independently in the range between $\mu_0/2$ and $2\mu_0$. For comparisons, in the case of the $t\bar{t}\gamma$ cross section results in the NWA also the fixed scale $\mu_0 = m_t/2$ is used. Our results for the integrated fiducial cross sections for $t\bar{t}\gamma$ production are summarised in Table 1. We compare the full off-shell results with the calculations in the NWA. For the NWA case two versions are examined: the full NWA and the NWA$_{\text{LO decay}}$. The former comprises NLO QCD corrections to the production and top quark decays as well as photon radiation from all charged particles. The latter includes the NWA predictions with LO decays of top quarks and photon radiation in the production stage only. In Table 1 we additionally quote results for the LO and NLO QCD cross sections where photon radiation occurs either in the production or in the decay stage.

A few comments can be made here. First, we observe that the NLO QCD corrections are
small of the order of a few percent only. We can also assess the size of the non-factorizable top quark corrections for our setup. These effects, which imply a cross-talk between production and decays of top quarks, change the NLO cross section by less than 3%. For both the full off-shell and NWA case, theoretical uncertainties due to the scale dependence are consistently at the 6% when higher order effects are incorporated. Using results from Table 1, we can additionally see that 57% of all isolated photons are emitted in the production stage either from the initial state light quarks or off-shell top quarks that afterwards go on-shell. Thus, 43% are emitted in the decay stage, either from on-shell top quarks or its (charged) decay products. Not only is the contribution from photon emission in top quark decays substantial but NLO QCD corrections to decays are also relevant. Therefore, it is not surprising that NWA_{LOdecay} results can not reproduce the correct normalisation. The discrepancy with respect to the full NWA approach amounts to almost 60%. NLO QCD corrections to top quark decays are negative and at the level of 12% when $\mu_0 = H_T/4$ is employed. Furthermore, theoretical uncertainties increase up to 11% in this case.

The situation changes for the full NWA case once differential cross sections are examined instead. In Figure 1 we present two examples of differential fiducial cross section distributions where off-shell effects are particularly sizeable. Specifically, we show the minimum invariant mass of the positron and bottom-jet and the (averaged) transverse momentum of the $b$-jet.

Figure 1: Differential cross section distributions as a function of the minimum invariant mass of the positron and bottom-jet and the (averaged) transverse momentum of the $b$-jet. NLO QCD results for various approaches to the modelling of top quark production and decays are shown.
Figure 2: Differential cross section distributions in function of $H_T$ and the transverse momentum of the isolated photon. NLO QCD predictions in the full NWA are shown together with fractions of events originating from photon radiation in the production and in decays.

The upper plots show absolute NLO QCD predictions for the same three different theoretical descriptions. The ratios to the full off-shell result including its scale uncertainty band is plotted in the middle and bottom plots. When the full off-shell and NWA results are compared, non-factorizable top quark corrections up to $50\% – 60\%$ can be noticed in the specific phase space regions. At the same time, we can see that the NWA_{\text{LO decay}} predictions are unable to correctly describe these observables in the whole plotted range. Among all observables that we have examined, only dimensionful observables are sensitive to non-factorizable top quark corrections. They can be divided into two categories: observables with kinematical thresholds or edges and observables in high $p_T$ regions.

We have also studied the composition of photon emissions at the differential level. As an example, in Figure 2, differential cross section distributions in function of $H_T$ and $p_T(\gamma)$ are given at NLO in QCD. We present predictions in the full NWA together with fractions of events originating from photon radiation in the production and in decays. For low values of the transverse momentum, the differential distributions are dominated by photon emission in the decay stage. However, once the high $p_T$ regions of these observables are probed, photon emission from the production part of the $t\bar{t}\gamma$ process dominates completely the full results. Based on our findings, selection criteria can be developed to reduce such contributions that constitute a background for the measurement of the anomalous couplings in the $t\bar{t}\gamma$ vertex.

Last but not least, our state-of-the-art theoretical predictions for the $t\bar{t}\gamma$ process in the $e\mu$ channel at 13 TeV have already been compared to the LHC data [19].
3 Summary

In this proceedings, we have briefly described a comparison between the complete off-shell and NWA calculations for the $e^+\nu_e \mu^-\tau_\mu b\bar{b}\gamma$ final state at the LHC. We underlined the importance of the higher order corrections and photon emission in top quark decays. Furthermore, we have shown that dimensionful observables are sensitive to the non-factorizable top quark corrections in the high $p_T$ regions and close to kinematical thresholds or edges. This shows that proper modelling of the top quark production and decays is essential already now in the presence of inclusive cuts and it will become even more important in the presence of more exclusive cuts and in the high luminosity phase of the LHC.

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