Inclusive and differential $t\bar{t}\gamma$ measurement in the dilepton channel and effective field theory interpretation

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The production cross section of $t\bar{t}\gamma$ is measured in the dilepton channel using 138 $fb^{-1}$ of proton-proton collision data recorded by the CMS experiment at $\sqrt{s} = 13$ TeV during the 2016-2018 data-taking period of the CERN LHC. A fiducial phase space is defined at the particle level in which both inclusive and differential results are provided. The $t\bar{t}\gamma$ process is sensitive to EFT operators that modify the top-photon coupling, so that tight constraints on the $c_{t\gamma}$ and $c_{t\gamma}^{(1)}$ Wilson coefficients can be extracted. Finally, the EFT interpretation is repeated on a combination of this result and a measurement of $t\bar{t}\gamma$ production in the lepton+jets channel.

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1 Introduction

Inclusive and differential measurements of $t\bar{t}\gamma$ production in the dilepton channel are presented [2]. These results were obtained using 138 fb$^{-1}$ of proton-proton collision data recorded by the CMS experiment [1] at $\sqrt{s} = 13$ TeV during the 2016–2018 data-taking period of the CERN LHC. The signal process is defined at the particle level, and includes prompt photons radiated anywhere from initial state radiation, to the final state particles originating from the decay of the top quarks. Representative diagrams for $t\bar{t}\gamma$ events where both top quarks decay into leptons are shown in Fig. 1.

As $t\bar{t}\gamma$ production is sensitive to the top-photon coupling, this measurement can be used to put constraints on modifications of this coupling. This is done in a model independent way in the framework of standard model effective field theory (SMEFT), and tight constraints on the $c_{tZ}$ and $c_{tZ}^I$ Wilson coefficients are obtained. Additionally, the SMEFT interpretation is repeated on a combination of the results of this measurement, and those of the measurement of $t\bar{t}\gamma$ in the lepton+jets channel by CMS [3].

![Figure 1: Leading-order Feynman diagrams for $t\bar{t}\gamma$ production with two leptons in the final state, where the photon is radiated by a top quark (left), by an incoming quark (middle), and by one of the charged decay products of a top quark (right).](image)

2 Event selection

Events are selected with two opposite-charge leptons, identified using a multivariate discriminator optimized to reject nonprompt leptons [4]. The invariant mass of the two-lepton system $m(ll)$ is required to be $> 20$ GeV and to fall outside of a window around the Z boson mass given by $|m(ll) - m_Z| > 15$ GeV. A similar requirement is imposed on the invariant mass of the two leptons and the photon, namely $|m(ll\gamma) - m_Z| > 15$ GeV. These last two cuts significantly reduce the contribution from the $DY$ and $Z\gamma$ background processes, and are only applied in the $ee$ and $\mu\mu$ channels. Photons are identified using cut-based identification (ID) criteria, and events are required to have exactly one photon in the barrel region of the detector, with no additional photons passing a looser version of the ID. In simulated events, selected photons are categorized as prompt or nonprompt based on a matching procedure to
the nearest generator particle with similar energy, and it is $t\bar{t}$ events decaying to two leptons with one prompt photon that make up the signal.

3 Background estimation

The backgrounds relevant to this measurement can be divided into those contributing with a prompt photon, and those that enter by a nonprompt photon being selected. Any process can contribute to the nonprompt photon background, and this category is estimated from data using an ABCD method for which a nonprompt photon enriched sideband is created by relaxing and inverting some of the photon ID criteria. The production of $Z\gamma$ forms the largest fraction of the prompt photon background in the $ee$ and $\mu\mu$ channels, while its contribution is negligible in the $e\mu$ channel. This contribution is predicted using Monte Carlo (MC) simulation, but corrections to its yield and $N_j/N_b$ distribution are derived in a control region obtained by inverting the cut applied to $m(ll\gamma)$ in the signal selection. The other, less prominent backgrounds with prompt photons are divided into Single-+$\gamma$ for single top processes, and Other+$\gamma$ for any other minor backgrounds (e.g. diboson production). These two categories are also predicted using MC simulation.

4 Results

An inclusive differential cross section is obtained within the fiducial phase space using a maximum likelihood fit to the photon $p_T$ distribution, with a value of

$$174.4 \pm 2.5 \text{ (stat)} \pm 6.1 \text{ (syst)} \text{ fb}$$ (1)

This value is compatible with the next-to-leading order standard model prediction of $153 \pm 27 \text{ fb}$ within the uncertainties. In this fit the various sources of systematic uncertainties are implemented as nuisance parameters, which can modify both the shape and yield of the predicted distributions. Several differential results are obtained for variables ranging from photon, lepton, and jet kinematics, to the angles between these objects. Fig. 2 shows two of these results, namely for the transverse momentum of the photon and the pseudorapidity difference between the two leptons. The obtained distributions are compared to two theory predictions obtained using different parton shower models, and the paper includes both absolute and normalized differential results. These differential results are obtained using an unregularized unfolding procedure for which the TUnfold package is used. The response matrices have a binning that is twice as fine at the generator level than at the reconstruction level, and the binning itself is optimized for each variable in order to minimize bin-to-bin migrations.
5 Effective field theory interpretation

From the measurement of $t\bar{t}\gamma$ production constraints can be put on SMEFT operators that could modify electroweak dipole moments of the top quark. We parametrize the shape and yield of the signal as a function of $c_{tZ}$ and $c_{I_{tZ}}$, of which the corresponding operators are linear combinations of the $O_{uB}^{33}$ and $O_{uW}^{33}$ operators as given in the Warsaw basis. The definition used in these results involves setting $c_{33}^{uW} = 0$ given that the Wtb vertex can be better probed in measurements of W helicity fractions. The hypothetical contributions of these operators are suppressed by a fixed $\Lambda = 1$ TeV parameter, which means that any effects are expected to appear in the high energy tail of the $p_T(\gamma)$ distribution. The parametrization is in practice performed by reweighting the nominal simulation after the full analysis selection using weights obtained by taking the ratio of simulated distributions with nonzero values for the Wilson coefficients to the nominal case at the particle level. Fits to the photon $p_T$ distribution similar to what is used for the extraction of the inclusive cross section are the performed as a function of the Wilson coefficients. This can be done both for operators individually (setting the other Wilson coefficient to zero), or for both coefficients simultaneously. The result of the latter is given in the left plot of Fig. 3. The same approach and operators are used in the lepton+jets analysis [3], so that a combination of these two results can be readily performed. Overlap between the events in the two analyses is found to be minimal, and systematic uncertainties are correlated where necessary.
Given that the lepton+jets analysis benefits from significantly higher statistics in the high $p_T(\gamma)$ tail, better constrains are obtained than using dilepton information. Nevertheless, the most stringent constraints are obtained in the combination of the two, for which the 2D likelihood scan is shown in the right plot of Fig. 3.

Figure 3: Result from the two-dimensional scan of the Wilson coefficients $c_{tZ}$ and $c_{lZ}$ using the photon $p_T$ distribution from this analysis (left) or the combination of this analysis with the lepton+jets analysis.

References

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[2] CMS Collaboration, “Measurement of the inclusive and differential $t\bar{t}\gamma$ cross section and EFT interpretation in the dilepton channel at $\sqrt{s} = 13$ TeV ”, CMS-PAS-TOP-21-004, CERN 2021.

[3] CMS Collaboration, “Measurement of the inclusive and differential $t\bar{t}\gamma$ cross sections in the single-lepton channel and EFT interpretation at $\sqrt{s} = 13$ TeV ”, arXiv:2107.01508 (accepted by JHEP).

[4] CMS Collaboration, “Inclusive and differential cross section measurements of single top quark production in association with a $Z$ boson in proton-proton collisions at $\sqrt{s} = 13$ TeV ”, arXiv:2111.02860 (submitted to JHEP)