Measurement of the $t\bar{t}\gamma\gamma$ production cross-section in pp collisions at a center-of-mass-energy of $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC

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This analysis has been performed with data collected by the ATLAS detector during 2015 and 2016 corresponding to an integrated luminosity of 36.1 fb^{-1} at a center-of-mass-energy of $\sqrt{s} = 13$ TeV, in the single lepton channels. In the single lepton channels, one lepton and at least four jets are requested, with at least one jet being b-tagged and two isolated photons with $p_T > 20$ GeV and $|\eta| < 2.37$. The event yields and kinematic distributions are compared between data and MC in the signal region.

I. INTRODUCTION

Measurements of the top-quark properties play an important role in testing the Standard Model (SM) due to its heavy mass close to the electroweak breaking scale and short life time. It also has an important role in the study of the background processes (e.g. Higgs Boson Physics) at the Large Hadron Collider (LHC). In many scenarios beyond the SM heavier particles decay into the top quarks. Studying detailed properties of the top quarks can give handles on new physics. Since there are the large number of $t\bar{t}$ pairs produced during the LHC Run 2, this high statistics will allow to measure the properties of the top quark precisely. In particular, the production of a top-quark pair in association with two photons ($t\bar{t}\gamma\gamma$) can probe the electroweak coupling between the top quark and photons.

In this analysis a measurement of the $t\bar{t}\gamma\gamma$ production cross-section is performed with data collected by the ATLAS detector during 2015 and 2016 corresponding to an integrated luminosity of 36.1 fb^{-1} at a center-of-mass-energy of $\sqrt{s} = 13$ TeV, in the single lepton channels. The final state of the $t\bar{t}\gamma\gamma$ process is similar to the $t\bar{t}\gamma$ process, but it contains two prompt photons. Thus, this analysis is built on the single-lepton $t\bar{t}\gamma$ analysis [1] in ATLAS. In the single lepton channels, one lepton and at least four jets are requested, with at least one jet being b-tagged and two isolated photons with $p_T > 20$ GeV and $|\eta| < 2.37$. The event yields and kinematic distributions are compared between data and MC in the signal region.

II. DATA AND SIMULATION SAMPLES

This analysis has been performed with proton-proton collision data collected by the ATLAS detector during 2015 and 2016, at a center-of-mass-energy of $\sqrt{s} = 13$ TeV. The corresponding total integrated luminosity is 3.21 fb^{-1} in 2015 and 32.88 fb^{-1} in 2016, respectively. The signal sample is the $t\bar{t}\gamma$ sample which has been simulated for single lepton and dilepton channels of $t\bar{t}$ at leading-order, with the MG5-aMC@NLO generator [2], using the NNPDF2.3LO parton distribution function [3]. The showering and hadronisation is done by Pythia8, i.e. interfaced to the Pythia8[4]. The first photon of the $t\bar{t}\gamma\gamma$ process is simulated from the matrix element and the second photon by the parton shower which the second photon is selected using a truth matching in this $t\bar{t}\gamma$ sample. The production of W- and Z-bosons with an associated prompt photon as well as the other vector boson production samples (W and Z-bosons + jets) are simulated using SHERPA 2.2.2 and 2.2.1, respectively, with the NNPDF30NNLO pdf set [5]. Also for the $W\gamma\gamma$ and $Z\gamma\gamma$ processes the second photon is selected using the truth matching in the $W\gamma$ and $Z\gamma$ samples. The MC sample for the inclusive $t\bar{t}$ production is generated with POWHEG-BOX v2 interfaced to PYTHIA8, using the A14 tune [6]. The $t\bar{t}$, W+jets and Z+jets samples can contain events already taking into account by the $t\bar{t}\gamma$, $W\gamma$, $Z\gamma$ samples due to the photon by the showering. This overlap is removed using the truth matching. The single top-quark t-, s- and Wt-channel samples are produced by POWHEG-Box v1 generator. The WW-, WZ- and ZZ-diboson samples are simulated using SHERPA 2.1 with the CT10(NLO) pdf set [7]. For the single top+$\gamma\gamma$ and diboson+$\gamma\gamma$ processes two photons are simulated by the parton shower. The $t\bar{t}H$ sample is simulated with the MG5-aMC@NLO generator, using the NNPDF2.3LO parton distribution function. In the $t\bar{t}H$ process the Higgs decay to two photons.

All MC simulation samples which are the $t\bar{t}\gamma$, $t\bar{t}$, single top-quark, diboson, Wγ, Zγ, W+jets, Z+jets and $t\bar{t}H$ are normalized to the data luminosity.

III. EVENT SELECTION

In the single lepton channels, the $t\bar{t}\gamma\gamma$ final state contains two isolated photons with high-p_T, an isolated lepton (e^- or μ) with a large p_T, large missing transverse momentum originating from the neutrino in the leptonic decay of a W boson, two jets from

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the hadronic decay of the other W boson, and two b-quark jets. For e+jets (μ+jets) channels: Exactly one electron (muon) with $p_T > 25$ GeV is required and two reconstructed photons satisfying the Tight identification criteria and being isolated are required with $p_T > 20$ GeV and $|\eta_{clus}| < 2.37$. At least four reconstructed jets with $p_T > 25$ are required. At least one jet has to be b-tagged jet. For e+jets channel: An invariant mass $m(\gamma, e)$ between each prompt photon and electron has to be outside a 5 GeV mass window around the Z boson mass. Distance between each prompt photon and the lepton must be greater than 1.0. This is to limit the contribution from the photons originating from top decay products in the radiative top decay process. Event double counting removal: To avoid a double counting with the W$\gamma\gamma$, Z$\gamma\gamma$, $t\bar{t}\gamma\gamma$, the events with two prompt photons in the W+jets, Z+jets and $t\bar{t}$ MC samples are removed by using the truth matching which identifies the origin and the type of the truth particle corresponding to the reconstructed photon.
In the TABLE I the events passing above selection are shown. Selection yields a total of 28 ± 5.29

TABLE I: The event yields for each sample and e+jets(μ+jets) channel. Only statistical uncertainties are included.

Process	e+jets	μ+jets
$t\bar{t}\gamma\gamma$	11.15 ± 0.75	12.52 ± 0.84
W$\gamma\gamma$	0 ± 0	0.37 ± 0.37
Z$\gamma\gamma$	0.60 ± 0.60	0.57 ± 0.36
Single top+$\gamma\gamma$	0 ± 0	0 ± 0
Diboson+$\gamma\gamma$	0 ± 0	0 ± 0
$t\bar{t}$H	1.41 ± 0.17	1.04 ± 0.15
Fake Photon	3.82 ± 0.51	2.31 ± 0.66
Fake Lepton	1.10 ± 2.58	0 ± 0.84
Total	18.08 ± 2.80	16.81 ± 1.46
Data	28 ± 5.29	17 ± 4.12

and 17 ± 4.12 data events with statistical errors in the electron and muon channels, respectively. From simulation studies with the $t\bar{t}\gamma\gamma$ signal sample, 11.15 ± 0.75 and 12.52 ± 0.84 signal events with statistical errors are predicted in the electron and muon channels, respectively. Those predicted events are normalized to the total integrated luminosity of 36.1 fb^{-1} and weighted with the pile-up, MC weight and scale factors per photon, lepton, jet, b-tag.

A. Kinematic distributions

FIG.1 shows the distributions of the transverse momentum of each prompt photon with $p_T > 20$ GeV in the e+jets and μ+jets channel, respectively.

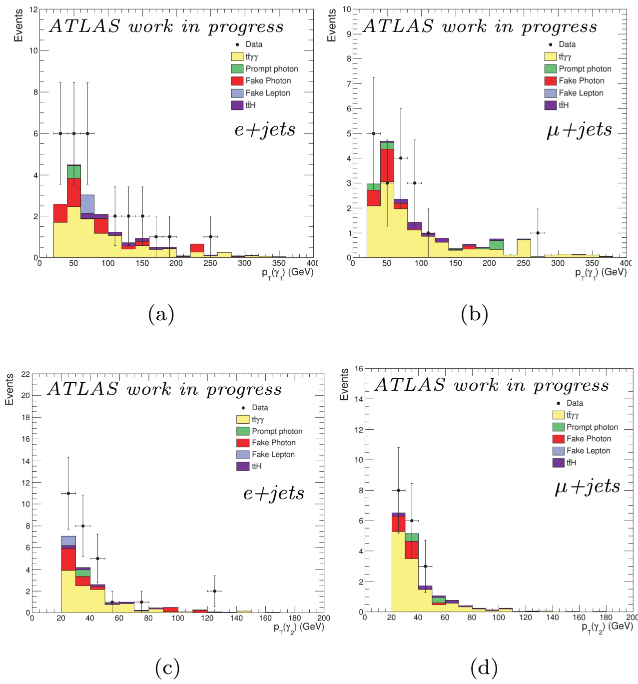

FIG. 1: The distributions of the transverse momentum of the first and second prompt photon.

The two-photon invariant mass distributions are shown in the FIG.2. The invariant mass of two photons are calculated using the energy and momentum of each prompt photon.

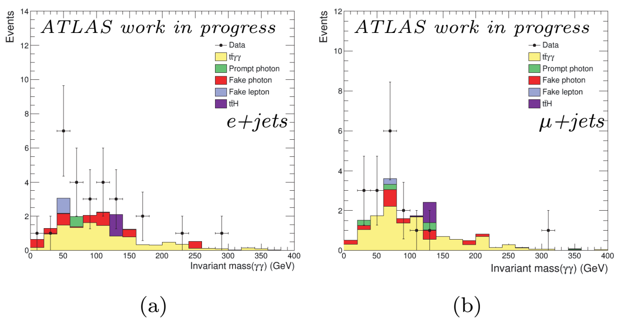

FIG. 2: The two-photon invariant mass distributions.

IV. BACKGROUND DESCRIPTIONS

There are several background contributions which come from events with prompt photon, fake photon and fake lepton in this analysis. One of the largest background contribution to the $t\bar{t}\gamma\gamma$ process is from events with fake photons. This contribution is cate-

gorized as follows: Photons originated from hadron decay (Hadronic fakes), electrons misidentified as photons (Electron fakes), events with at least one fake photon. The contribution of the hadronic fakes background comes from events the two photons coming from hadron decay. Similarly, the contribution from events with electrons misidentified as photons is considered as electron fakes background. Since the single-lepton $t\bar{t}\gamma\gamma$ final states contains two photons, one of these photons can be originating from hadron decay and another one coming from electron fakes. In this case this contribution from events with one hadronic fake and one electron fake is included in the events with at least one fake photon.
In addition, the contributions of the fake lepton or QCD background which comes from fake leptons, the prompt photon background which is from non-$t\bar{t}$ events with two prompt photons and the $t\bar{t}H$ background are considered in this analysis. The TABLE II summarizes all background contributions to the $t\bar{t}\gamma\gamma$ process.

TABLE II: All background contributions to the $t\bar{t}\gamma\gamma$ process in the e+jets (μ+jets) channel. The numbers are normalized to the total integrated luminosity of 36.1 fb^{-1}. Only statistical uncertainties are included.

Process	e+jets	μ+jets
Hadronic fakes	0.48 ± 0.31	0.42 ± 0.40
Electron fakes	0 ± 0	0 ± 0
Event with at least one fake	3.34 ± 0.40	1.89 ± 0.53
Prompt Photon	0.60 ± 0.60	0.94 ± 0.52
Fake Lepton	1.10 ± 2.58	0 ± 0.84
$t\bar{t}H$	1.41 ± 0.17	1.04 ± 0.15

V. FIDUCIAL CROSS SECTION MEASUREMENT

The number of generated events in the fiducial region is derived by subtracting background events from data and applying of the correction factor [1]. To calculate the fiducial cross section, this number is divided by the integrated luminosity. Using the expression 4.3, the fiducial cross section can be calculated. Index i runs over the single lepton channels:

$$\sigma_i^{fid} = \frac{N_{data,i} - N_{bkgs,i}}{L \times C_i} \quad (1)$$

where $N_{data,i}$ - number of data events corresponding to the i channel, $N_{bkgs,i}$ - total number of background events corresponding to the i channel, L - total integrated luminosity, C_i - correction factor corresponding to the i channel. The correction factor is used to unfold the number of signal selected at reconstruction level $N_{reco,i}$ in channel i to the number of generated signal events in the fiducial region $N_{gen}^{fid,i}$ corresponding to channel i [1].

$$C_i = \frac{N_{reco,i}}{N_{gen}^{fid,i}} \quad (2)$$

The predicted fiducial cross section can be calculated using the total cross section from theory prediction:

$$\sigma_i^{pred.fid} = \sigma_{theory}^{tot} \times A_i \quad (3)$$

where A_i - signal acceptance corresponding to the i channel, σ_{theory}^{tot} - total cross section from theory prediction. The signal acceptance is defined as the fraction of events falling into the fiducial region out of the total generated [1]:

$$A_i = \frac{N_{gen}^{fid,i}}{N_{gen}^{all}} \quad (4)$$

where N_{gen}^{all} is the total number of generated events and $N_{gen}^{fid,i}$ is the number of events inside the fiducial region i, with i running over the single lepton channel. The predicted fiducial cross sections for the $t\bar{t}\gamma\gamma$ process are calculated using the higher order cross section of $t\bar{t}\gamma$ process of 5.36 pb. The predicted values for the $t\bar{t}\gamma\gamma$ fiducial cross sections are a total of 1.44 fb in the e+jets channel and 1.34 fb in the μ+jets channel, respectively. The following table summarizes the predicted values and measured fiducial cross sections.

TABLE III: The predicted and measured $t\bar{t}\gamma\gamma$ fiducial cross section in the e+jets (μ+jets) channel. Also data events, predicted signal events and total backgrounds are shown.

	e+jets	μ+jets
N_{data}	28 ± 5.29	17 ± 4.12
N_{bkgs}	6.93 ± 2.70	3.75 ± 1.20
N_{sig}	11.15 ± 0.75	12.52 ± 0.84
Signal Acceptance	(2.7×10^{-4}) $\pm(1.07 \times 10^{-5})$	(2.5×10^{-4}) $\pm(8.4 \times 10^{-6})$
Correction Factor	0.21 ± 0.02	0.25 ± 0.02
Predicted $\sigma_{t\bar{t}\gamma\gamma}^{fid}$	1.44 ± 0.06 fb	1.34 ± 0.05 fb
Measured $\sigma_{t\bar{t}\gamma\gamma}^{fid}$	2.78 ± 0.82 fb	1.47 ± 0.49 fb

VI. SYSTEMATIC UNCERTAINTIES

Three sources of systematic uncertainties are considered in the $t\bar{t}\gamma\gamma$ cross section measurement. All sources are from the modelling uncertainties of the signal in the single lepton channel. The TABLE IV summarizes all systematic uncertainties on the correction factor and signal acceptance with the statistical uncertainties.

TABLE IV: The systematic uncertainties on the signal acceptance and correction factor due to the up and down variation of the initial and final state radiation uncertainty sources.

Sources	Correction Factor	Signal Acceptance
	e+jets	
Showering uncertainty [%]	14.2 ± 13.9	30.6 ± 5.9
ISR/FSR uncertainty [%]	9.5 ± 13.5	3.7 ± 9.6
Scale variation uncertainty [%]	17.0 ± 8.5	26.9 ± 4.3
Total uncertainty [%]	25.9 ± 10.6	41.9 ± 5.19
	μ+jets	
Showering uncertainty [%]	4.7 ± 11.8	28.6 ± 5.9
ISR/FSR uncertainty [%]	4.0 ± 14.0	4.0 ± 9.4
Scale variation uncertainty [%]	7.1 ± 8.8	28.0 ± 4.3
Total uncertainty [%]	20.3 ± 5.0	41.1 ± 5.12

VII. SUMMARY AND OUTLOOK

In this analysis the fiducial cross section measurements of the $t\bar{t}\gamma\gamma$ production are performed with data collected by the ATLAS detector during 2015 and 2016 corresponding to an integrated luminosity of 36.1 fb^{-1} at a center-of-mass-energy of $\sqrt{s} = 13$ TeV, in the single lepton channels. A total of 28 ± 5.29 and 17 ± 4.12 data events are observed, and from simulation studies 11.15 ± 0.75 and 12.52 ± 0.84 signal events with statistical uncertainties are predicted in the electron and muon channels, respectively. Considering the fake photon, fake lepton and prompt photon backgrounds the background estimation is done. The largest contribution to the $t\bar{t}\gamma\gamma$ process comes from events with at least one fake photon which contribute to the fake photon background. The total uncertainties for the $t\bar{t}\gamma\gamma$ fiducial cross sections are found to be 25.9 % and 20.3 % in the electron and muon channel, respectively. The $t\bar{t}\gamma\gamma$ fiducial cross sections within fiducial region are measured as:

e+jets channel:

$$\sigma^{fid}_{t\bar{t}\gamma\gamma} = (2.79 \pm 0.82|_{stat} \pm 0.89|_{sys})\ \text{fb}$$

μ+jets channel:

$$\sigma^{fid}_{t\bar{t}\gamma\gamma} = (1.47 \pm 0.49|_{stat} \pm 0.25|_{sys})\ \text{fb}$$

The fiducial measurement in the muon channel is in good agreement with the predicted fiducial cross section within experimental uncertainties. But the measured fiducial cross section in the electron channel is larger than the predicted value. Further, the $t\bar{t}\gamma\gamma$ total cross sections will be measured.

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