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Cross-section measurement of $t\bar{t}\gamma$ production in pp collision at $\sqrt{s} = 8$ TeV with the ATLAS experiment

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The cross-section of top-quark pair production in association with a photon in proton-proton collisions at a center of mass energy of $\sqrt{s} = 8$ TeV is measured. The data with a total integrated luminosity of 20.2 fb^{-1} collected by the ATLAS detector in 2012 is used. The measurement is performed in the single lepton decay channel. The signal region is defined by the final state of exactly one high p_{T} lepton, large missing transverse momentum, at least four jets where at least one is being b-tagged and exactly one photon with $p_{\mathrm{T}} > 15$ GeV. The cross-section times the branching ratio is determined in a fiducial region defined in terms of the detector acceptance. In addition, the first differential cross-section measurements as a function of photon p_{T} and η are presented. The measured fiducial inclusive and differential cross sections are in good agreement with the NLO prediction.

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1. Introduction

Studies of the top-quark properties play an important role in testing the Standard Model and possible new physics scenarios. The cross-section measurement of top-quark pair production in association with a photon ($t\bar{t}\gamma$) probes the top-photon electroweak coupling, a relatively unexplored property of the top-quarks.

In the analysis described here (the complete version: [1]), the $t\bar{t}\gamma$ cross section is measured using the data set recorded with the ATLAS detector [2] in 2012 at a centre-of-mass energy of $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.2 fb^{-1}. Only the single lepton final state is considered, where one of the W bosons coming from the top-quark decays into a lepton and a neutrino and the other one into hadrons. Photons can originate from top-quarks as well as from their decay products and the incoming partons. The event selection is optimised to enrich γ radiation from top-quarks.

The cross section is measured within a fiducial volume with a maximum-likelihood fit using templates. The differential cross sections are measured within the same fiducial volume in five bins of transverse momentum (p_{T}) and pseudorapidity (η) of the photon, each, and a bin-by-bin unfolding is applied.

2. Analysis

The selected events are required to have exactly one electron or muon with $p_{\mathrm{T}} > 25$ GeV, on which the event is triggered, and at least four jets with $p_{\mathrm{T}} > 25$ GeV, among which at least one is tagged as a b-jet. The requirements on the missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) and the transverse mass of the W boson (m_{T}^{W}) are $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV for the muon channel, and $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV and $m_{\mathrm{T}}^{W} > 30$ GeV for the electron channel. Events must have exactly one photon with $p_{\mathrm{T}} > 15$ GeV. In the selected events, the angular distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ of the photon from the jets has to be greater than 0.5 and from the lepton greater than 0.7. The invariant mass of the electron and the photon ($m_{e\gamma}$) in the electron channel is required to be outside of a 5 GeV mass window around the Z boson mass.

The fiducial region is defined for the Monte Carlo simulated events at particle level (before detector simulation) by applying similar selection cuts as above, with the difference that no cuts are applied on $E_{\mathrm{T}}^{\mathrm{miss}}$, m_{T}^{W} and $m_{e\gamma}$, as an attempt to have a common fiducial region for the electron and the muon channels. The objects used in the fiducial region definition are constructed from the stable particles in the event record of the generator.

The largest background contribution for $t\bar{t}\gamma$ are the events with a fake photon from misidentified hadrons, being called hadronic fakes hereafter. This background is estimated from data, using the template fit which is being explained later.

The second largest background comes from the events with an electron misidentified as a photon. This background is also estimated from data, using two control regions: one enriched in $Z \to ee$ events and one enriched with $Z \to e + \text{fake}-\gamma$ events. The ratio of the number of events in these two control regions are taken as the fake rate. The fake rates, which are calculated as function of p_{T} and η of photons, are then applied to a modified signal region where an electron is replacing the photon in the nominal $t\bar{t}\gamma$ selection.

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Smaller background contributions come from the processes that are background to $t\bar{t}$ production, when they are produced with an additional prompt photon. Among them is the multijet production with an associated prompt photon, when one of the jets is misidentified as a lepton. This background is estimated from data, using the matrix method. The rest, which are $W\gamma$+jets, $Z\gamma$+jets, single top quark and diboson productions with an associated prompt photon, are estimated from Monte Carlo simulations.

The measurement of the total and differential cross sections is based on a likelihood fit, using three different templates: 1) prompt-photon template, 2) template for hadronic fakes 3) template for fake photons from electrons. The variable used for the templates is p_{T}^{iso}, the sum of p_{T} of the tracks within a cone of $\Delta R = 0.2$ around the photon.

The prompt-photon template is extracted from the $t\bar{t}\gamma$ signal Monte Carlo simulation. After performing the signal event selection, the reconstructed photons that are geometrically matched to a particle level photon are used for the template. The prompt-photon template is used in the fit for the signal events, as well as for the background events with a prompt photon.

The hadronic-fake template is extracted from a control region in data enriched with hadronic fakes. The control region is selected by requiring at least four jets, at least one photon which fails some special photon identification criteria, and $\Delta R(e, \mathrm{fake}{-}\gamma) > 0.1$. The differences of the p_{T} and η distributions of the hadronic fakes in this control region and in the signal region are taken into account and the template is re-weighted accordingly. The prompt-photon contamination is also taken into account, in the form of a systematic uncertainty.

The template for the fake photons from electrons is extracted from the $Z \to e + \mathrm{fake}{-}\gamma$ control region in data, after the backgrounds are subtracted.

The three templates for the inclusive cross-section measurement are shown in Figure 1. For the differential cross-section measurements, all the templates are extracted for each of the bins of the p_{T} and η of the photons.

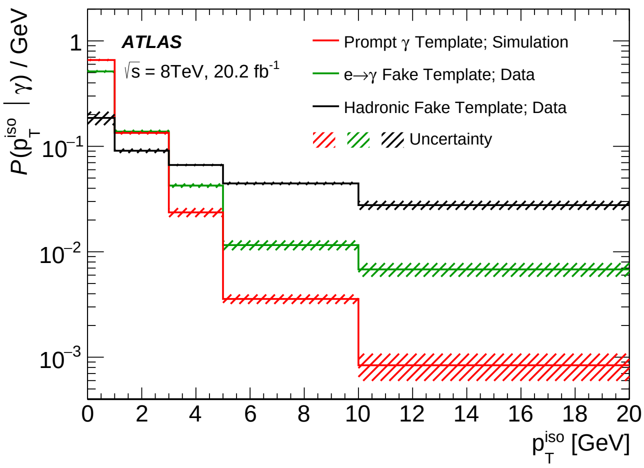

Figure 1: The templates for the inclusive cross-section measurement for prompt photons, hadronic fakes and the fake photons from electrons [1]. The distributions are normalised to unity and the last bins contain the overflows. The dashed bands show the total uncertainty in each template.

The likelihood fit function employed on the observed binned p_{T}^{iso} distribution is defined as

$$\mathscr{L} = \prod_{i,j} P(N_{i,j} | N^s_{i,j} + \sum_b N^b_{i,j}) \cdot \prod_t G(0|\theta_t, 1). \quad (2.1)$$

where j denotes the bins of p_{T}^{iso} distribution and i denotes the bins of p_{T} or η used for the differential cross-section measurement. In the Poisson function, $N_{i,j}$ is the observed number of events while $N^s_{i,j}$ and $N^b_{i,j}$ are the expected numbers of signal and background events, respectively. The Gaussian function $G(0|\theta_t, 1)$ models the systematic uncertainty t.

There are two free parameters in the fit: the total number of signal events and the total number of background events with hadronic fakes. For the rest of the backgrounds, the mean values in the Poisson probability distribution are fixed to their corresponding estimated total number of events.

Moreover, the fiducial inclusive and differential cross sections, σ_i, are related to the number of signal events by

$$N^s_{i,j} = L \cdot \sigma_i \cdot C_i \cdot f_{i,j}, \quad (2.2)$$

where L is the integrated luminosity, $f_{i,j}$ is the fraction of the signal events falling into bin j of p_{T}^{iso} of bin i, and C_i is the ratio of the number of reconstructed events to the number of generated events in the fiducial region in bin i.

In the term C_i, the denominator (the number of generated events in the fiducial region in bin i) also can be expressed as the number of reconstructed events falling into the fiducial region in bin i, multiplied by the signal efficiency. Therefore, C_i corrects for the migration of events between the fiducial and the non-fiducial region, or, in the case of differential cross-section measurement, between different i bins. This means the differential cross-section measurements are computed in each bin i with a bin-by-bin unfolding to the particle level.

Events from electron and muon channels are merged together to have σ_i as the common parameter of interest in the maximum-likelihood fit.

3. Results

The inclusive fiducial cross-section times the branching ratio is measurement to be:

$$\sigma^{\mathrm{fidu}}_{\mathrm{sl}} = 139 \pm 7(\mathrm{stat.}) \pm 17(\mathrm{syst.})\ \mathrm{fb} = 139 \pm 18\ \mathrm{fb}, \quad (3.1)$$

The most important systematics sources and their effect on the measured inclusive cross-section are listed in Table 1. In Figure 2 this result is compared to the Standard Model prediction at NLO accuracy and to the measurement performed at $\sqrt{s} = 7$ TeV [3]. A good agreement between the measurement and the theory prediction is observed.

In addition, the results of first differential cross-section measurements are summarised in Figure 3, for five bins of p_{T} and five bins of η of the photons. The migration between the individual bins is found to be smaller than 7% and a bin-by-bin unfolding is applied. The comparison with the NLO theory prediction shows a good agreement.

Table 1: Five most dominant systematic uncertainties and their effects on the measurement of the inclusive cross section.

Source	Relative uncertainty [%]
Hadronic-fake template shape	6.3
Fake γ from electron (template shape and normalisation)	6.3
Jet energy scale	4.9
$W\gamma$+jets (normalisation)	4.0
$Z\gamma$+jets (normalisation)	2.8

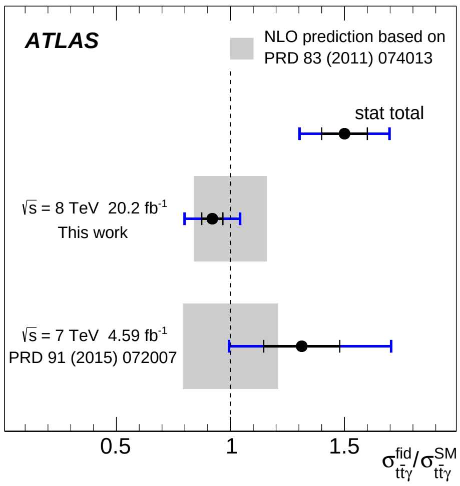

Figure 2: Summary of $t\bar{t}\gamma$ fiducial cross-section measurements in pp collisions at $\sqrt{s} = 7$ TeV [3] and $\sqrt{s} = 8$ TeV [1], normalised to the expected cross section at NLO [4].

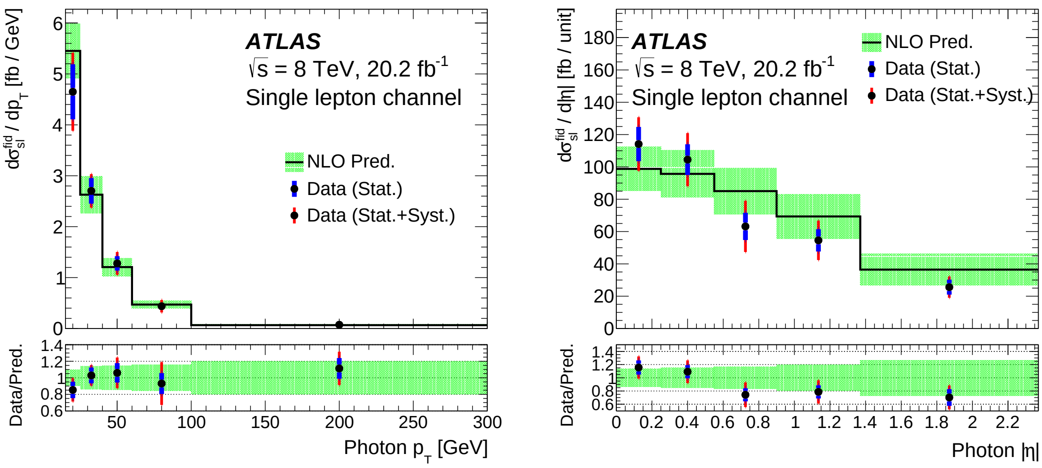

Figure 3: Measured $t\bar{t}\gamma$ differential cross section in terms of photon p_{T} (left) and $|\eta|$ (right) and their theoretical prediction [1].

References

[1] ATLAS Collaboration, arXiv:1706.03046 [hep-ex].

[2] ATLAS Collaboration, JINST 3 (2008) S08003.

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