Measurement of the $\bar{t}\gamma$ production cross section in proton-proton collisions at $\sqrt{s}=8$ TeV with the ATLAS detector

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Introduction

- Cross-section measurement of $\bar{t}t\gamma$ probes top-photon coupling.
  - BSMs (composite top, technicolor, ...), top EFT coefficients ($O_{tG}$, $O_{tB}$, ...)
- Photons can originate from top quarks, as well as from their decay products and the incoming partons:

  ![Diagram](image)

- Event selection is optimised to enrich $\gamma$ radiation from top quarks.
- Cross section is measured within a **fiducial volume**, using a **maximum-likelihood fit**.
- **First differential cross-section measurement**: as a function of $p_T$ and $\eta$ of photons, within the same fiducial volume.
- Single lepton final state
Data and Signal Simulation Sample

- Data set recorded with the ATLAS detector in 2012 at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of $20.2$ fb$^{-1}$.

- Monte Carlo simulated $\bar{t}t\gamma$ events generated at LO by MadGraph5+Pythia6 and normalised to NLO prediction, using k-factors [PRD 91 (2015) 072007].
Event Selection / Fiducial Region Definition

- One lepton ($e$ or $\mu$), $p_T > 25$ GeV
- $\geq 4$ jets, $p_T > 25$ GeV
- $\geq 1$ jet tagged as $b$-jet (70% efficiency)
- $e$-channel: $E_T^{\text{miss}} > 30$ GeV and $m_{TW} > 30$ GeV
- $\mu$-channel: $E_T^{\text{miss}} > 20$ GeV and $E_T^{\text{miss}} + m_{TW} > 60$ GeV
- One photon, $p_T > 15$ GeV, $|\eta| < 2.37$, no isolation requirements
- $\Delta R(\text{jet, } \gamma) > 0.5$ and $\Delta R(\text{lepton, } \gamma) > 0.7$
- $|m_{e\gamma} - m_Z| > 5$ GeV

$\Rightarrow$ 1256 (1816) candidate events selected in $e$-channel ($\mu$-channel).

- **Fiducial phase space** is defined for Monte Carlo events at particle level (i.e. before detector simulation).
- By cuts that mimic the selection at the reconstruction level (i.e. after detector simulation).
- To obtain a common fiducial region for $e$- and $\mu$-channel, cuts on $E_T^{\text{miss}}, m_{TW}$ and $m_{e\gamma}$ are not included.

\[ \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]
Analysis Strategy

- After the event selection, three category of events:

  1) with prompt photons
  2) with photons from hadrons, or hadrons misidentified as photons: “hadronic-fakes”
  3) with electrons misidentified as photons: “electron-fakes”

- Total and differential cross sections extracted from maximum-likelihood fit, using three templates, one for each category of events.

- Photon track isolation is used for the templates:

  \[ p_{T}^{\text{iso}} = \text{The sum of } p_T \text{ of tracks within a cone of } \Delta R = 0.2 \text{ around the photon.} \]

- Two free parameters in the fit: Number of signal events and number of hadronic-fake backgrounds. The rest of backgrounds are fixed in the fit to their estimated number of events.

\[ \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]
Events with prompt photons include both signal events and the background processes with a prompt photon: $W\gamma+\text{jets}$, $Z\gamma+\text{jets}$, ...

Prompt-photon template extracted using photons from $\bar{t}t\gamma$ signal MC sample, after full event selection.

Reconstructed photons are truth matched to particle level within $\Delta R = 0.1$.

For differential measurements, template is extracted for each bin of $p_T$ and $\eta$.

Modelling and experimental systematic uncertainties of the template are very small.
Hadronic-Fake Template

- Events with hadronic fakes are the largest background.
- Template extracted from a control region in data, enriched by hadronic fakes:
  - $\geq 1$ photon candidate that fails specific photon identification criteria
  - $\geq 4$ jets
  - $\Delta R(e, \gamma) > 0.1$
- Template shape shows dependency on $p_T$ and $\eta$ of hadronic fakes $\Rightarrow$ Template for fiducial cross-section is a weighted sum of templates in $p_T$ and $\eta$ bins.
- For differential measurements, template is extracted for each bin of $p_T$ and $\eta$.
- Prompt-photon contamination as systematics uncertainty:
  - Template constructed from modified photon candidates, corresponding to less prompt-photon contamination.
  - Difference w.r.t. nominal template taken as systematic.
**Electron-Fake Template**

- Events with electron fakes are the second largest background.

- Template extracted from control region in data enriched by $Z \rightarrow e+\text{fake-}\gamma$ events:
  - Back-to-back $e$ and fake-\(\gamma\)
  - $70\text{ GeV} < m_{e\gamma} < 110\text{ GeV}$
  - $p_T^e > p_T^{\gamma}$
  - $E_T^{\text{miss}} > 30\text{ GeV}$

- Backgrounds are subtracted, using a sideband fit to $m_{e\gamma}$ distribution.

- Template systematic uncertainty:
  - Variation of $E_T^{\text{miss}}$ requirement, variation of mass range
Background Estimations

- **Hadronic-fake background**: Data-driven, free parameter in template fit.

- **Electron-fake background**: Data-driven.
  - Fake rates are calculated from ratio of number of $Z \rightarrow e^+e^-\gamma$ to number of $Z \rightarrow e^+e^-$ events, as functional of $p_T$ and $\eta$ of photons.
  - The fake rates are applied to a modified signal region (electron replacing photon in $t\bar{t}\gamma$ selection).

- **Backgrounds with prompt photon**:
  - $W\gamma+$jets: MC estimation normalised by data-driven scale factors.
  - $Z\gamma+$jets, Single top+$\gamma$, Diboson+$\gamma$: MC estimation
  - Multijet+$\gamma$: Data-driven, using matrix method

### Table

<table>
<thead>
<tr>
<th>Process</th>
<th>$e$- channel</th>
<th>$\mu$-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron-fake</td>
<td>317±42</td>
<td>385±42</td>
</tr>
<tr>
<td>$W\gamma+$jets</td>
<td>65±25</td>
<td>97±25</td>
</tr>
<tr>
<td>$Z\gamma+$jets</td>
<td>35±19</td>
<td>38±20</td>
</tr>
<tr>
<td>Single top+$\gamma$</td>
<td>13±7</td>
<td>19±10</td>
</tr>
<tr>
<td>Multijet+$\gamma$</td>
<td>7.5±3.6</td>
<td>8.3±5.2</td>
</tr>
<tr>
<td>Diboson+$\gamma$</td>
<td>2.6±1.5</td>
<td>2.5±1.4</td>
</tr>
</tbody>
</table>
**Likelihood Fit**

\[ \mathcal{L} = \prod_{i,j} P(N_{i,j} | N_{i,j}^S + \sum_b N_{i,j}^b) \cdot \prod_t G(0 | \theta_t, 1) \]

- Bins of \( p_T^{\text{iso}} \) distribution
- Bins of \( p_T \) or \( \eta \)
- Differential: 5 bins
- Fiducial: 1 bin

\[ L \cdot \sigma_i \cdot C_i \cdot f_{i,j} = N_{i,j}^S \]

- Ratio of the reconstructed events to the generated events in the fiducial region in bin \( i \) of \( p_T \) or \( \eta \)
- Fraction of events in bin \( j \) of \( p_T^{\text{iso}} \) of bin \( i \) from signal template

- Events in \( e^- \) and \( \mu^- \)-channel merged in the fit \( \rightarrow \) Common parameter of interest: fiducial cross section \( \sigma_i \)

- For differential measurement \( \sigma_i \) is computed for each \( i \) bin \( \rightarrow \) **bin-by-bin unfolding** to the particle level

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Results: Fiducial Cross Section

- Fiducial cross section: $\sigma_{\text{fid}} = 139 \pm 7\text{(stat.)} \pm 17\text{(syst.)} \text{ fb} = 139 \pm 18 \text{ fb}$

- Measured fiducial cross section agrees within uncertainties with the Standard Model prediction at NLO.

### Source

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic-fake</td>
<td>6.3</td>
</tr>
<tr>
<td>Electron-fake</td>
<td>6.3</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>4.9</td>
</tr>
<tr>
<td>$W\gamma+$jets</td>
<td>4.0</td>
</tr>
<tr>
<td>$Z\gamma+$jets</td>
<td>2.8</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>2.2</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.1</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>5.1</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>13</td>
</tr>
</tbody>
</table>

![Graph showing ATLAS NLO prediction based on PRD 83 (2011) 074013 and comparisons with 7 TeV and 8 TeV data from PRD 91 (2015) 072007.](Graph.png)
Results: Differential Cross Section

- Measured differential cross sections agree within uncertainties with the Standard Model predictions at NLO.

**ATLAS**
\( \sqrt{s} = 8 \text{ TeV}, \ 20.2 \text{ fb}^{-1} \)
Single lepton channel

- Data (Stat.)
- Data (Stat.+Syst.)

ATLAS
\( \sqrt{s} = 8 \text{ TeV}, \ 20.2 \text{ fb}^{-1} \)
Single lepton channel

- NLO Pred.
- Data (Stat.)
- Data (Stat.+Syst.)
Summary

- Cross-section measurement of $\bar{t}t\gamma$ at $\sqrt{s} = 8$ TeV with ATLAS is presented.

- **Fiducial cross section:**
  - Dominated by systematics
  - Largest uncertainties from fake photon backgrounds
  - The precision of the measurement is reaching the accuracy of the theoretical calculations
  - Most precise $\bar{t}t\gamma$ cross-section measurement to date
  - In good agreement with theoretical prediction at NLO

- **First $\bar{t}t\gamma$ differential cross-section measurement:**
  - In good agreement with theoretical prediction at NLO within uncertainties
BACKUP
## Fiducial Region Definition

### Object level cuts:

<table>
<thead>
<tr>
<th>Object</th>
<th>Truth-info cut</th>
<th>Kinematic cut</th>
<th>Overlap removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>dresses with photons (that do not originate from hadrons) within $\Delta R=0.1$ cone</td>
<td>$p_T &gt; 25$ GeV $</td>
<td>\eta</td>
</tr>
<tr>
<td>Jet</td>
<td>$\text{anti-}k_t(\Delta R=0.4)$; $\mu/\nu$ are not included</td>
<td>$p_T &gt; 25$ GeV $</td>
<td>\eta</td>
</tr>
<tr>
<td>$b$-jet</td>
<td>if contains a $b$-hadron with $p_T &gt; 5$ GeV within $\Delta R=0.3$</td>
<td>$p_T &gt; 25$ GeV $</td>
<td>\eta</td>
</tr>
<tr>
<td>Photon</td>
<td>not originated from hadrons</td>
<td>$p_T &gt; 15$ GeV $</td>
<td>\eta</td>
</tr>
</tbody>
</table>

### Event level cuts: Exactly one lepton ($e$ or $\mu$) from $W$ boson, $\geq 4$ jets, $\geq 1$ $b$-jet, exactly one photon, $\Delta R(\text{jet}, \gamma) > 0.5$ and $\Delta R(\text{lepton}, \gamma) > 0.7$
Fake Photon Candidates To Extract Hadronic-Fake Template

- Control region to extract hadronic-fake template is requiring $\geq 1$ photon candidate that fails specific photon identification criteria:

  - At least one of the four identification criteria constructed from shower-shape variables from the first layer (strip layer) of electromagnetic calorimeter.
  - Strong discriminating power between signal and fake photon
  - Negligible correlation with photon isolation

- Modified template to estimate systematics due to prompt-photon contamination is constructed from fake photons that fails all of the four specific identification criteria, corresponding to less prompt-photon contamination.

## Post-Fit Event Yields

<table>
<thead>
<tr>
<th>Range</th>
<th>$t\bar{t}\gamma$</th>
<th>Hadronic fake</th>
<th>$e \to \gamma$ fake</th>
<th>$W\gamma$+jets</th>
<th>$Z\gamma$+jets</th>
<th>Single top$\gamma$</th>
<th>Multijet$\gamma$</th>
<th>Diboson+$\gamma$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1060 ± 130</td>
<td>1020 ± 90</td>
<td>710 ± 90</td>
<td>160 ± 40</td>
<td>73 ± 32</td>
<td>32 ± 15</td>
<td>16 ± 6</td>
<td>5.1 ± 2.4</td>
<td>3072</td>
</tr>
<tr>
<td>$15 \leq p_T &lt; 25$ GeV</td>
<td>280 ± 40</td>
<td>360 ± 40</td>
<td>240 ± 35</td>
<td>47 ± 13</td>
<td>23 ± 10</td>
<td>7 ± 4</td>
<td>4.4 ± 2.3</td>
<td>1.3 ± 0.7</td>
<td>966</td>
</tr>
<tr>
<td>$25 \leq p_T &lt; 40$ GeV</td>
<td>309 ± 34</td>
<td>233 ± 26</td>
<td>171 ± 7</td>
<td>37 ± 10</td>
<td>22 ± 10</td>
<td>6.4 ± 3.3</td>
<td>3.8 ± 2.4</td>
<td>1.8 ± 0.9</td>
<td>783</td>
</tr>
<tr>
<td>$40 \leq p_T &lt; 60$ GeV</td>
<td>220 ± 40</td>
<td>205 ± 21</td>
<td>111 ± 30</td>
<td>28 ± 8</td>
<td>13 ± 6</td>
<td>10 ± 5</td>
<td>1.6 ± 1.9</td>
<td>0.5 ± 0.3</td>
<td>589</td>
</tr>
<tr>
<td>$60 \leq p_T &lt; 100$ GeV</td>
<td>160 ± 40</td>
<td>116 ± 16</td>
<td>100 ± 40</td>
<td>24 ± 7</td>
<td>10 ± 5</td>
<td>8 ± 4</td>
<td>3.4 ± 2.1</td>
<td>1.0 ± 0.6</td>
<td>420</td>
</tr>
<tr>
<td>$100 \leq p_T &lt; 300$ GeV</td>
<td>150 ± 25</td>
<td>71 ± 10</td>
<td>50 ± 20</td>
<td>23 ± 7</td>
<td>4 ± 2</td>
<td>0.9 ± 0.7</td>
<td>0.8 ± 1.0</td>
<td>0.3 ± 0.2</td>
<td>298</td>
</tr>
</tbody>
</table>

$|\eta| < 0.25$ | 246 ± 34 | 121 ± 21 | 93 ± 24 | 18 ± 6 | 9 ± 4 | 4.0 ± 2.2 | 5.2 ± 1.8 | 1.0 ± 0.6 | 497 |

$0.25 \leq |\eta| < 0.55$ | 260 ± 40 | 130 ± 20 | 116 ± 29 | 29 ± 8 | 11 ± 6 | 3.7 ± 2.1 | 0.0 ± 0.4 | 1.5 ± 0.8 | 552 |

$0.55 \leq |\eta| < 0.90$ | 180 ± 40 | 198 ± 27 | 150 ± 40 | 31 ± 9 | 16 ± 7 | 2.2 ± 1.3 | 4.0 ± 1.8 | 0.4 ± 0.2 | 578 |

$0.90 \leq |\eta| < 1.37$ | 200 ± 40 | 233 ± 33 | 169 ± 50 | 35 ± 10 | 17 ± 8 | 9 ± 5 | 5.7 ± 2.1 | 1.0 ± 0.5 | 663 |

$1.37 \leq |\eta| < 2.37$ | 150 ± 40 | 344 ± 33 | 200 ± 12 | 48 ± 13 | 19 ± 9 | 13 ± 6 | 5.4 ± 2.5 | 1.4 ± 0.7 | 782 |