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

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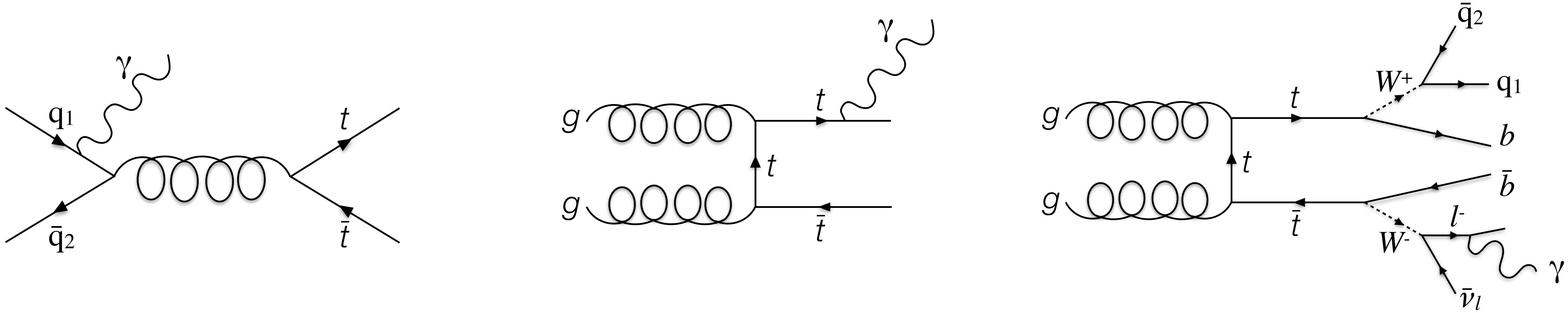
Introduction

- Cross-section measurement of $t\bar{t}\gamma$ 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:



- Event selection is optimised to enrich γ 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 η of photons, within the same fiducial volume.
- Single lepton final state

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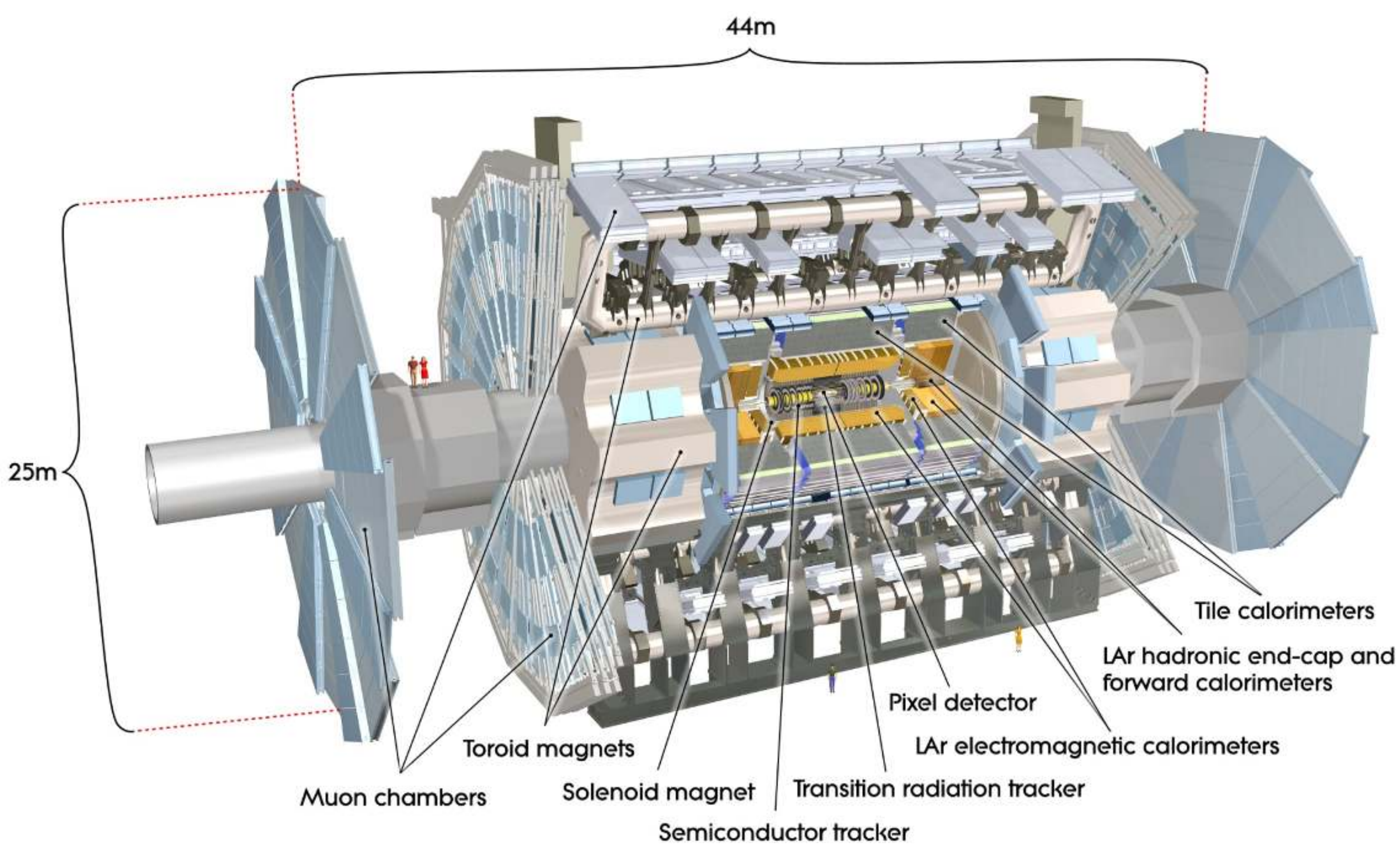
ATLAS EXPERIMENT

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 $20.2\ \text{fb}^{-1}$.
- Monte Carlo simulated $t\bar{t}\gamma$ events generated at LO by MadGraph5+Pythia6 and normalised to NLO prediction, using k-factors [PRD 91 (2015) 072007].

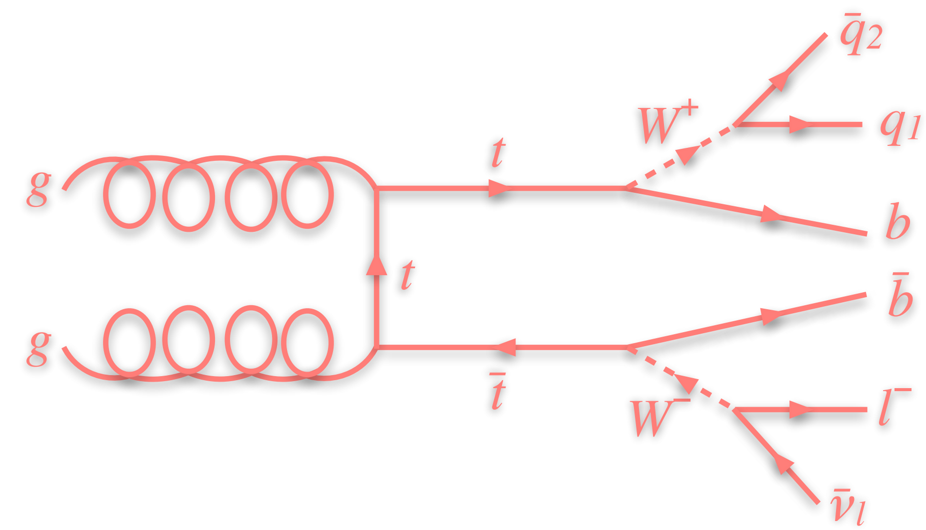
LHC

ATLAS

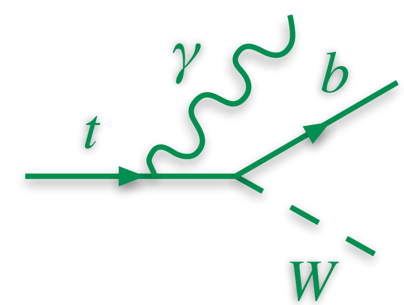


Event Selection / Fiducial Region Definition

- One lepton (e or μ), $p_{\mathrm{T}} > 25$ GeV
- $\geqslant 4$ jets, $p_{\mathrm{T}} > 25$ GeV
- $\geqslant 1$ jet tagged as b-jet (70% efficiency)
- e-channel: $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV and $m_{\mathrm{T}}^{W} > 30$ GeV
- μ-channel: $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV



- One photon, $p_{\mathrm{T}} > 15$ GeV, $|\eta| < 2.37$, no isolation requirements
- $\Delta R(\mathrm{jet}, \gamma) > 0.5$ and $\Delta R(\mathrm{lepton}, \gamma) > 0.7$
- $| m_{e\gamma} - m_Z | > 5$ GeV



➡ **1256 (1816)** candidate events selected in ***e*-channel (*μ*-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 μ-channel, cuts on E_T^{miss}, m_T^W and $m_{e\gamma}$ are not included.

$\Delta R = \sqrt{((\Delta\eta)^2 + (\Delta\phi)^2)}$

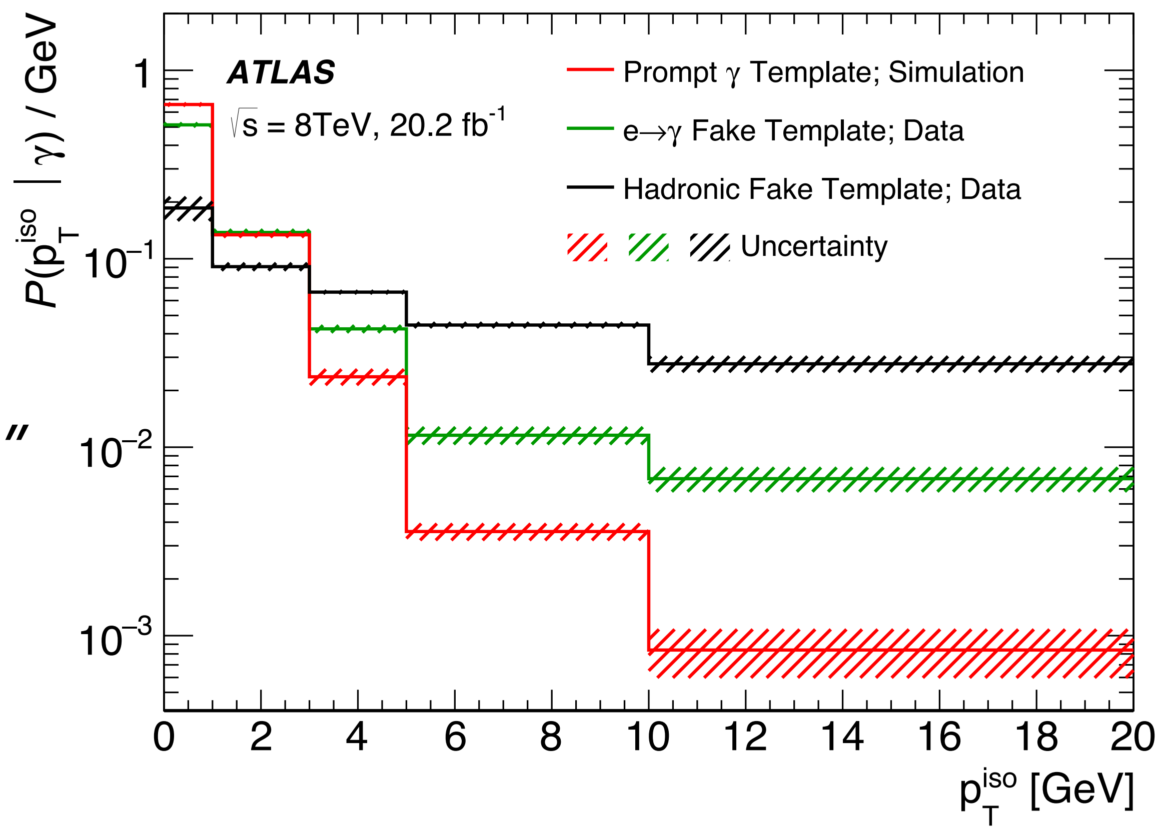
Analysis Strategy

- 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^{iso} = The sum of p_T of tracks within a cone of $\Delta R = 0.2$ around the photon.

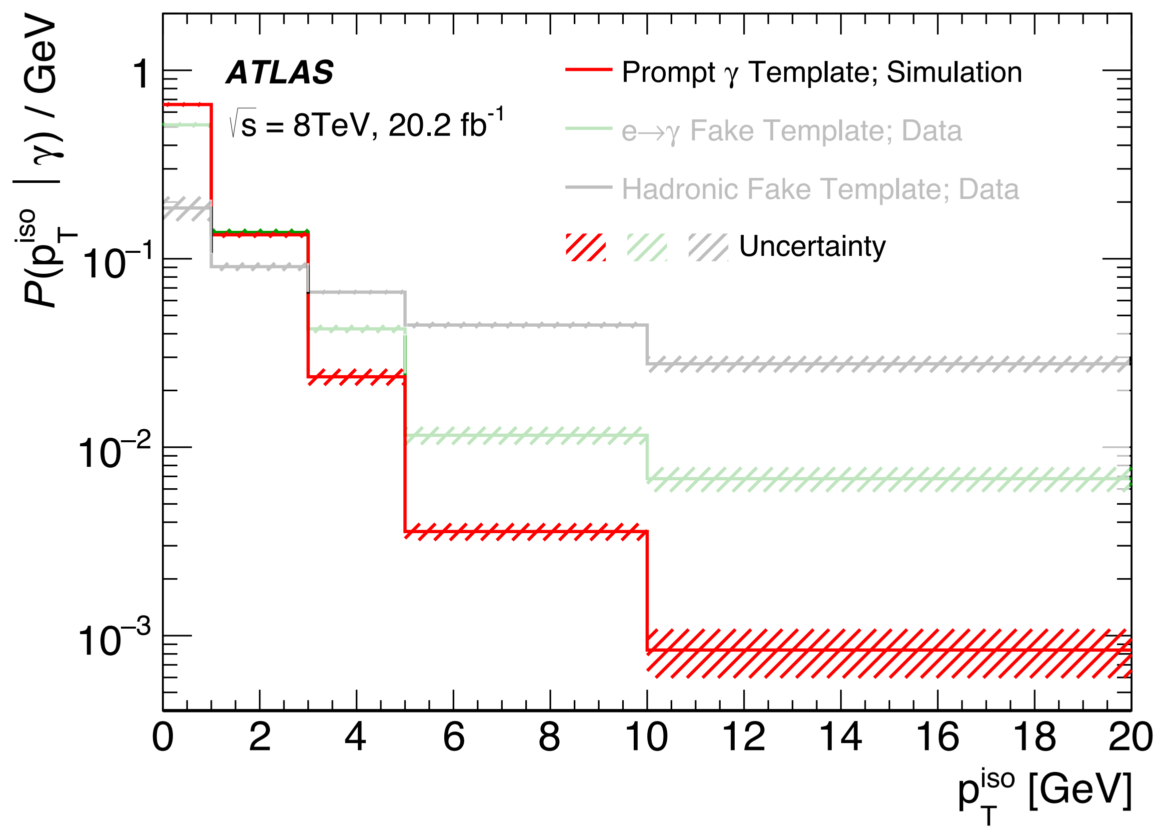
- Two **free** parameters in the fit: Number of signal events and number of hadronic-fake backgrounds. The rest of backgrounds are **fixed** in the fit to their estimated number of events.

$\Delta R = \sqrt{((\Delta\eta)^2 + (\Delta\phi)^2)}$

Prompt-Photon Template

- Events with prompt photons include both **signal** events and the **background** processes with a prompt photon: $W\gamma$+jets, $Z\gamma$+jets, …

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



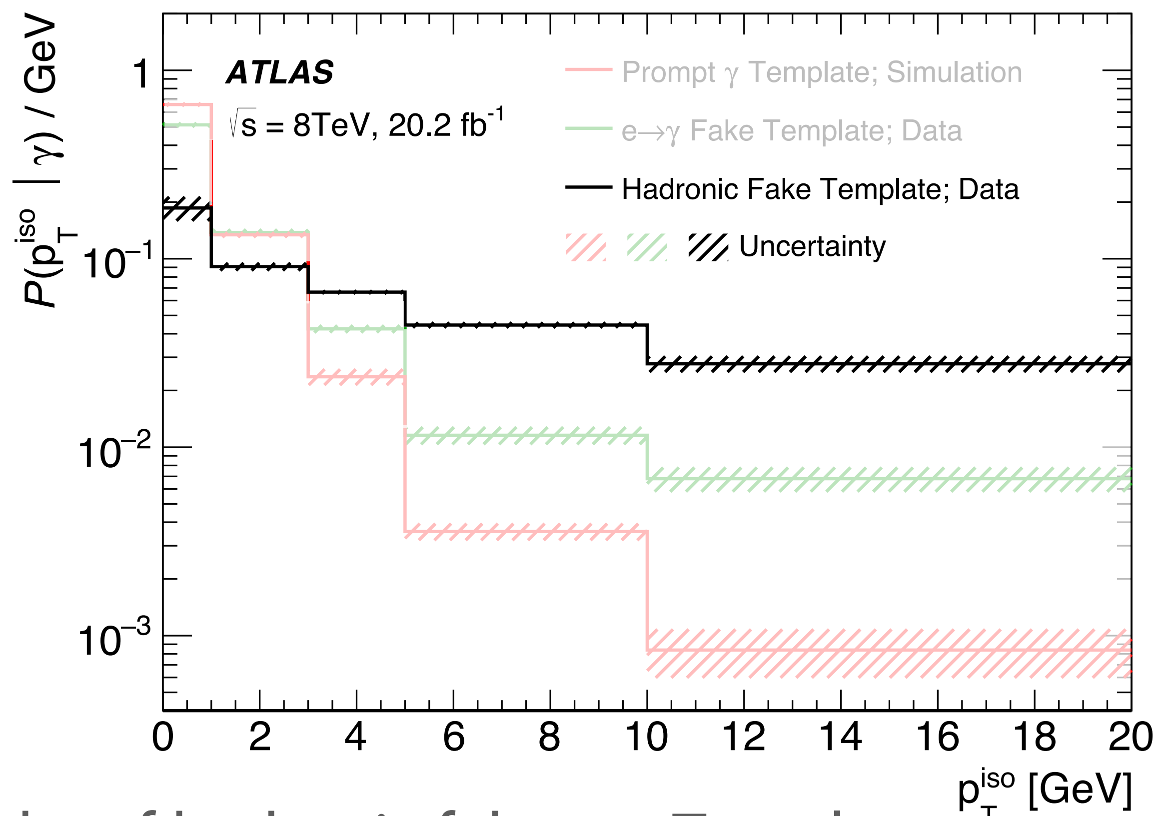
- Reconstructed photons are truth matched to particle level within $\Delta R = 0.1$.

- For differential measurements, template is extracted for each bin of p_T and η.

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

Hadronic-Fake Template

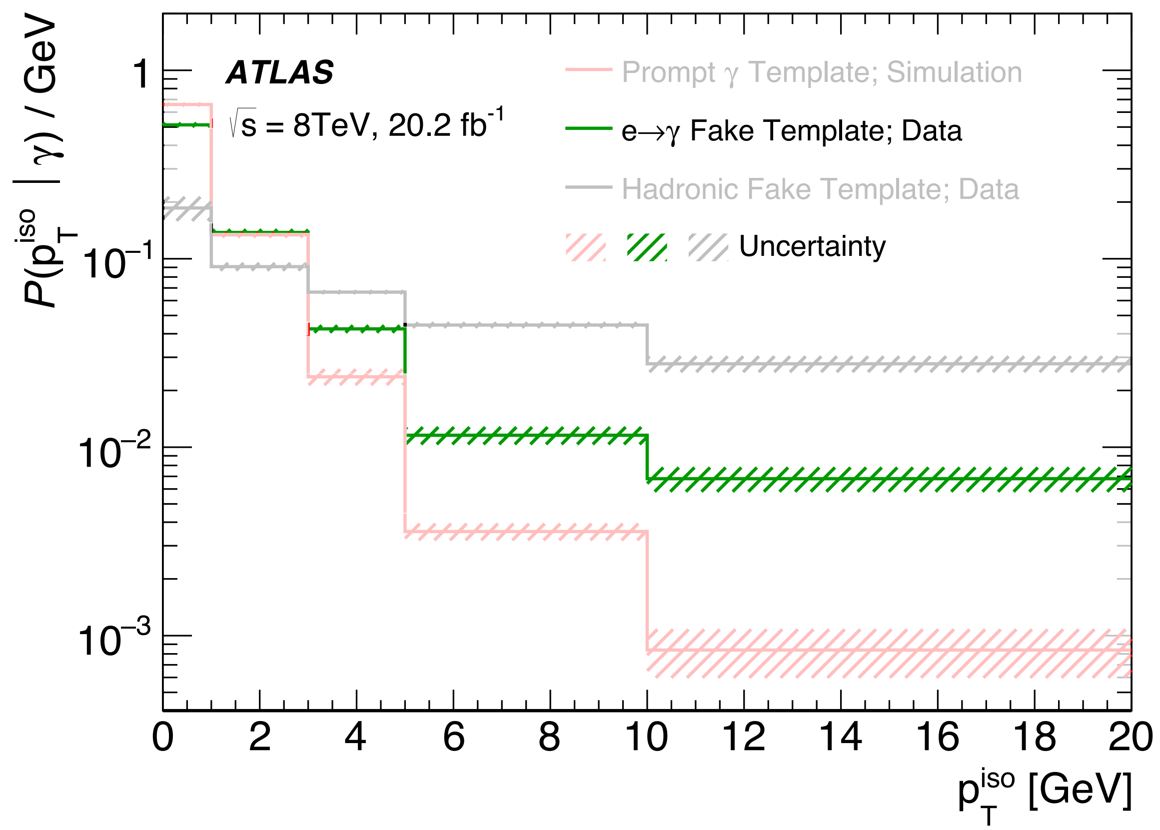
- Events with hadronic fakes are the largest background.
- Template extracted from a control region in data, enriched by hadronic fakes:
  - $\geqslant 1$ photon candidate that **fails specific photon identification criteria**
  - $\geqslant 4$ jets
  - $\Delta R(e, \gamma) > 0.1$



- Template shape shows dependency on p_T and η of hadronic fakes $\Rightarrow$ Template for fiducial cross-section is a weighted sum of templates in p_T and η bins.
- For differential measurements, template is extracted for each bin of p_T and η.
- 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

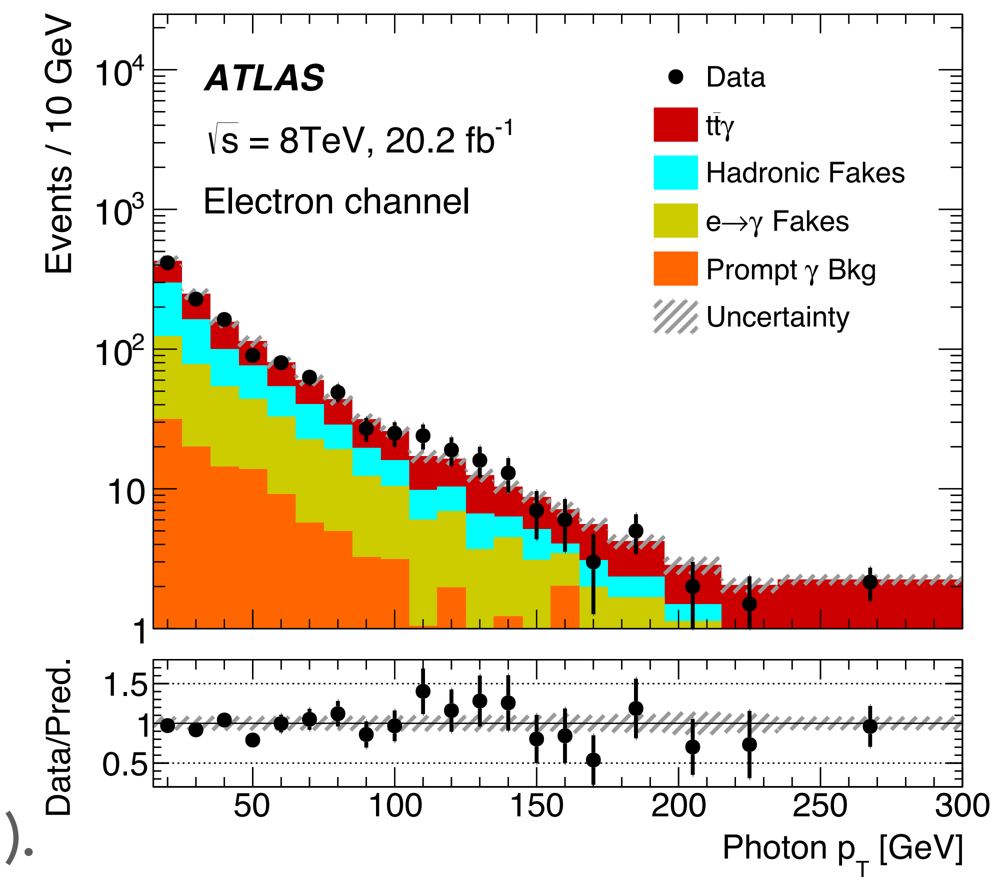
- Events with electron fakes are the second largest background.
- Template extracted from control region in data enriched by $Z \longrightarrow e$+fake-γ events:
  - Back-to-back e and fake-γ
  - $70~\text{GeV} < m_{e\gamma} < 110~\text{GeV}$
  - $p_T{}^e > p_T{}^\gamma$
  - $E_T{}^{miss} > 30~\text{GeV}$



- Backgrounds are subtracted, using a sideband fit to $m_{e\gamma}$ distribution.
- Template systematic uncertainty:
  - Variation of $E_T{}^{miss}$ 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 $Z \longrightarrow e$+fake-γ to number of $Z \longrightarrow e^{+}e^{-}$ events, as functional of p_T and η 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+γ, Diboson+γ: MC estimation
  - Multijet+γ: Data-driven, using matrix method



Process	e- channel	μ-channel
Electron-fake	317±42	385±42
$W\gamma$+jets	65±25	97±25
$Z\gamma$+jets	35±19	38±20
Single top+γ	13±7	19±10
Multijet+γ	7.5±3.6	8.3±5.2
Diboson+γ	2.6±1.5	2.5±1.4

Likelihood Fit

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

Bins of p_T^{iso} distribution

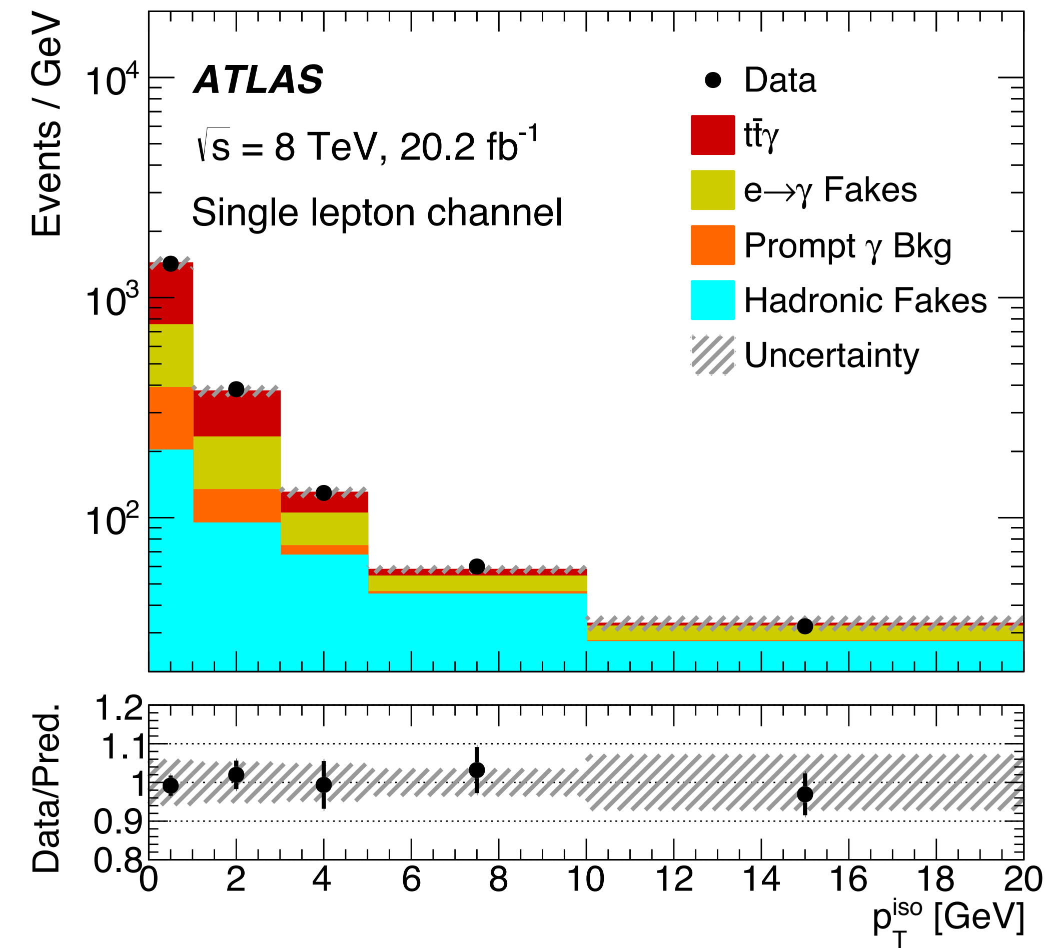
Systematic uncertainties

Bins of p_T or η
Differential: 5 bins
Fiducial: 1 bin

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

Ratio of the reconstructed events to the generated events in the fiducial region in bin i of p_T or η

Fraction of events in bin j of p_T^{iso} of bin i from signal template



Post-fit p_T^{iso} distribution for inclusive measurement

- Events in e- and μ-channel merged in the fit ⟶ Common parameter of interest: fiducial cross section σ_i
- For differential measurement σ_i is computed for each i bin ⟶ **bin-by-bin unfolding** to the particle level

Results: Fiducial Cross Section

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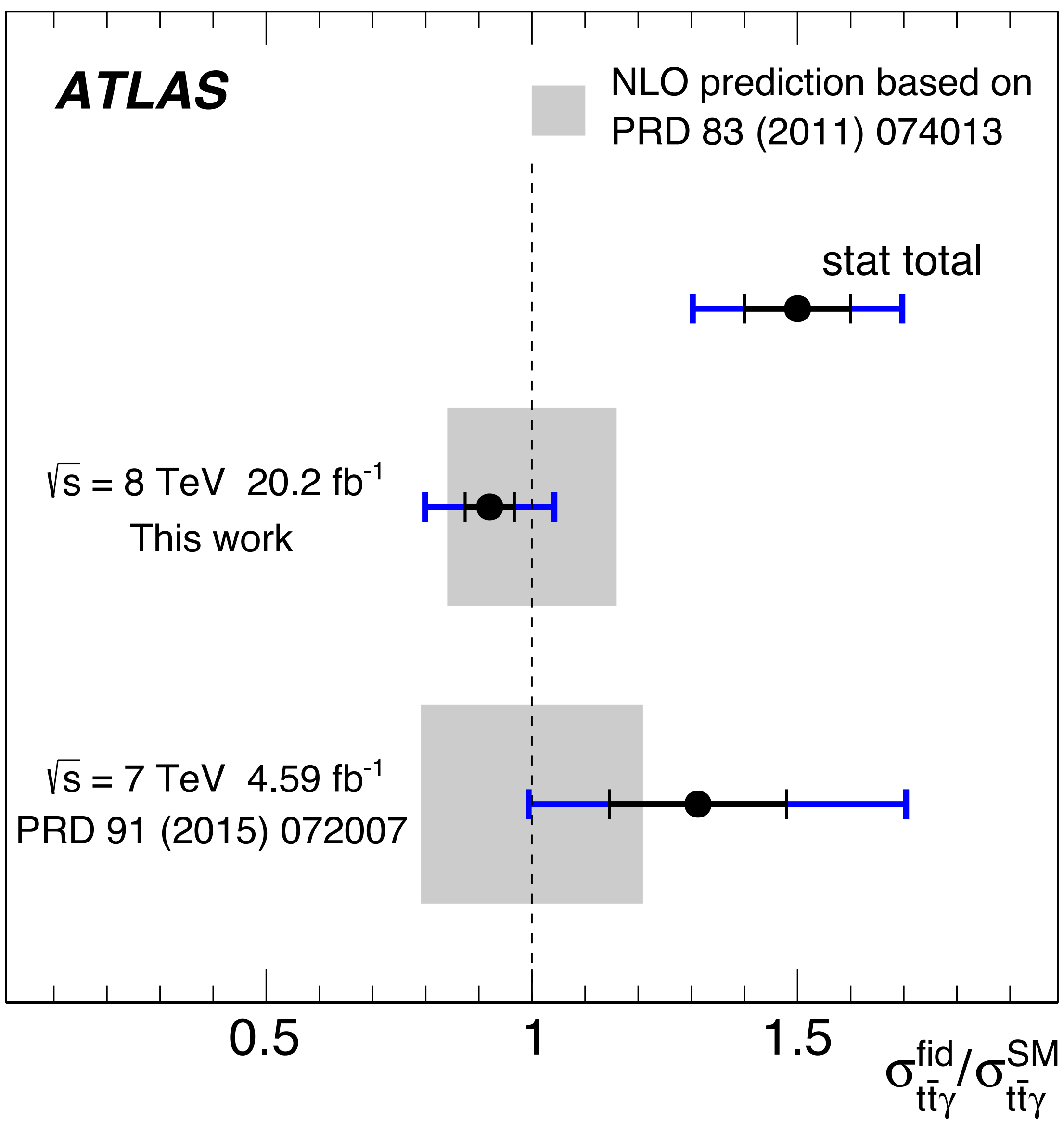
- Fiducial cross section: $\sigma_{\mathrm{sl}}^{\mathrm{fid}} = 139 \pm 7(\mathrm{stat.}) \pm 17(\mathrm{syst.})\ \mathrm{fb} = 139 \pm 18\ \mathrm{fb}$
- Measured fiducial cross section agrees within uncertainties with the Standard Model prediction at NLO.



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

Results: Differential Cross Section

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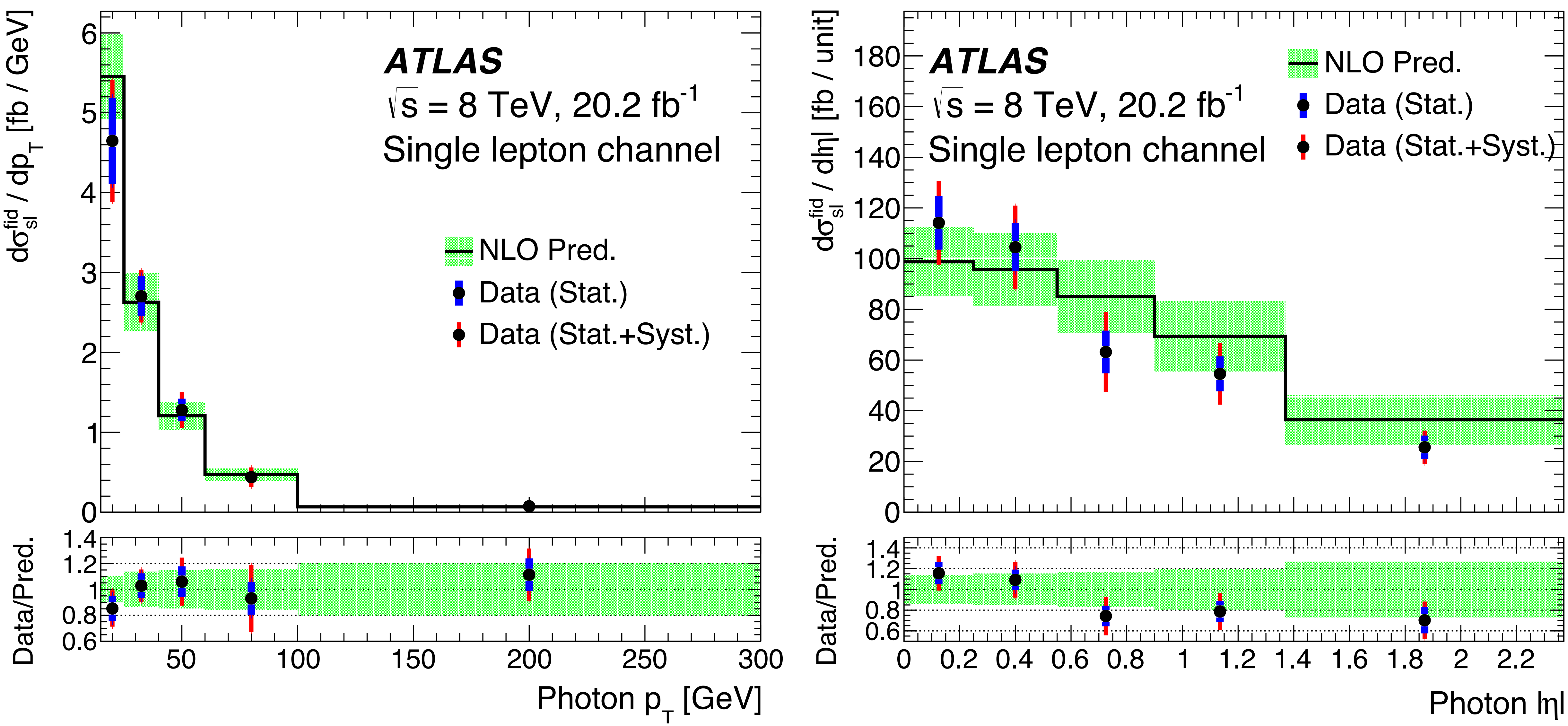
- Measured differential cross sections agree within uncertainties with the Standard Model predictions at NLO.



Summary

- Cross-section measurement of $t\bar{t}\gamma$ 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 $t\bar{t}\gamma$ cross-section measurement to date
  - In good agreement with theoretical prediction at NLO
- **First $t\bar{t}\gamma$ differential cross-section measurement**:
  - In good agreement with theoretical prediction at NLO within uncertainties

BACKUP

Fiducial Region Definition

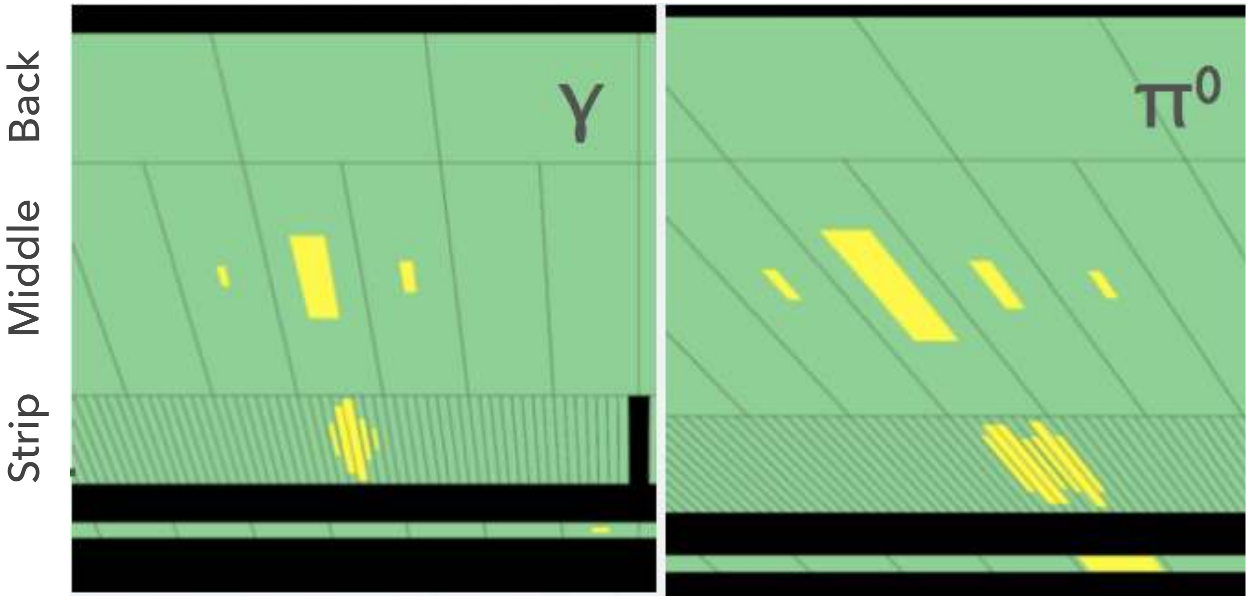
- **Object level cuts:**

Object	Truth-info cut	Kinematic cut	Overlap removal
Lepton	dresses with photons (that do not originate from hadrons) within ΔR=0.1 cone	$p_{\mathrm{T}} > 25$ GeV $\lvert\eta\rvert < 2.5$	μ if $\Delta R(\mathrm{jet}, \mu) < 0.4$
Jet	anti-k_t (ΔR=0.4) ; μ/ν are not included	$p_{\mathrm{T}} > 25$ GeV $\lvert\eta\rvert < 2.5$	jet if $\Delta R(\mathrm{jet}, e) < 0.2$ or $\Delta R(\mathrm{jet}, \gamma) < 0.1$
b-jet	if contains a b-hadron with $p_{\mathrm{T}} > 5$ GeV within ΔR=0.3		
Photon	not originated from hadrons	$p_{\mathrm{T}} > 15$ GeV $\lvert\eta\rvert < 2.37$	---

- **Event level cuts:** Exactly one lepton (e or μ) from W boson, $\geqslant 4$ jets, $\geqslant 1$ b-jet, exactly one photon, $\Delta R(\mathrm{jet}, \gamma) > 0.5$ and $\Delta R(\mathrm{lepton}, \gamma) > 0.7$

Fake Photon Candidates To Extract Hadronic-Fake Template

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



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20100721/display-photons/index.html

- *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

Range	$t\bar{t}\gamma$	Hadronic fake	$e \to \gamma$ fake	$W\gamma$+jets	$Z\gamma$+jets	Single top+γ	Multijet+γ	Diboson+γ	Data
Total	1060 ± 130	1020 ± 90	710 ± 90	160 ± 40	73 ± 32	32 ± 15	16 ± 6	5.1 ± 2.4	3072
$15 \leq p_{\mathrm{T}} < 25$ GeV	280 ± 40	360 ± 40	240 ± 35	47 ± 13	23 ± 10	7 ± 4	4.4 ± 2.3	1.3 ± 0.7	966
$25 \leq p_{\mathrm{T}} < 40$ GeV	309 ± 34	233 ± 26	171 ± 7	37 ± 10	22 ± 10	6.4 ± 3.3	3.8 ± 2.4	1.8 ± 0.9	783
$40 \leq p_{\mathrm{T}} < 60$ GeV	220 ± 40	205 ± 21	111 ± 30	28 ± 8	13 ± 6	10 ± 5	1.6 ± 1.9	0.5 ± 0.3	589
$60 \leq p_{\mathrm{T}} < 100$ GeV	160 ± 40	116 ± 16	100 ± 40	24 ± 7	10 ± 5	8 ± 4	3.4 ± 2.1	1.0 ± 0.6	420
$100 \leq p_{\mathrm{T}} < 300$ GeV	150 ± 25	71 ± 10	50 ± 20	23 ± 7	4 ± 2	0.9 ± 0.7	0.8 ± 1.0	0.3 ± 0.2	298
$\lvert\eta\rvert < 0.25$	246 ± 34	121 ± 21	93 ± 24	18 ± 6	9 ± 4	4.0 ± 2.2	5.2 ± 1.8	1.0 ± 0.6	497
$0.25 \leq \lvert\eta\rvert < 0.55$	260 ± 40	130 ± 20	116 ± 29	29 ± 8	11 ± 6	3.7 ± 2.1	0.0 ± 0.4	1.5 ± 0.8	552
$0.55 \leq \lvert\eta\rvert < 0.90$	180 ± 40	198 ± 27	150 ± 40	31 ± 9	16 ± 7	2.2 ± 1.3	4.0 ± 1.8	0.4 ± 0.2	578
$0.90 \leq \lvert\eta\rvert < 1.37$	200 ± 40	233 ± 33	169 ± 50	35 ± 10	17 ± 8	9 ± 5	5.7 ± 2.1	1.0 ± 0.5	663
$1.37 \leq \lvert\eta\rvert < 2.37$	150 ± 40	344 ± 33	200 ± 12	48 ± 13	19 ± 9	13 ± 6	5.4 ± 2.5	1.4 ± 0.7	782