Comparison of $t\bar{t}\gamma$ Analyses at 8 TeV

between ATLAS [arXiv:1706.03046] and CMS [JHEP10(2017)006]

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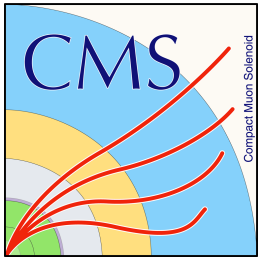
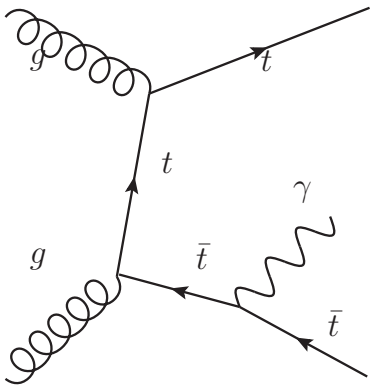
LHCTopWG meeting

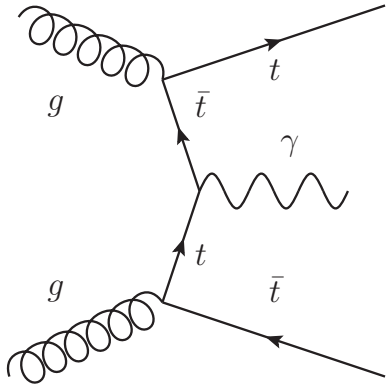
03-11-2017

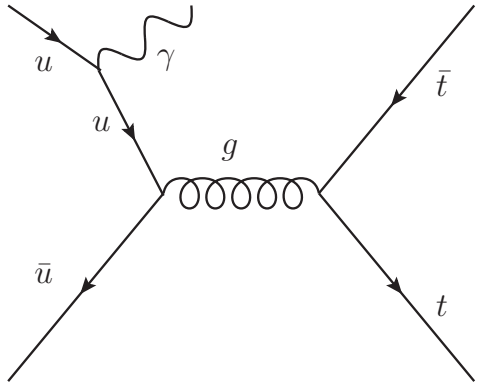


$t\bar{t}\gamma$ Process

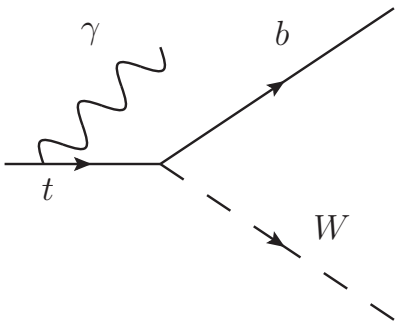
Radiative production: off-shell top, initial charged parton.

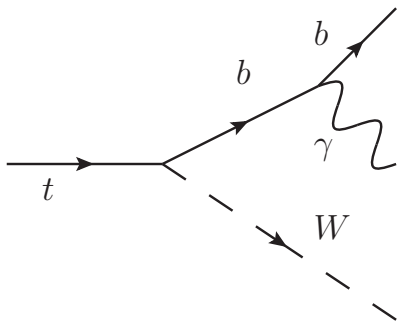


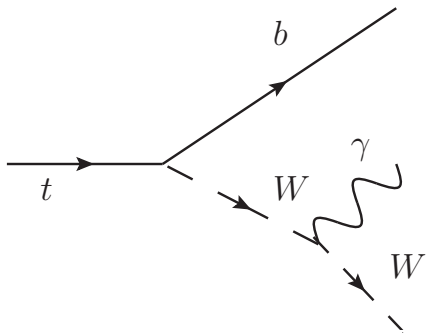


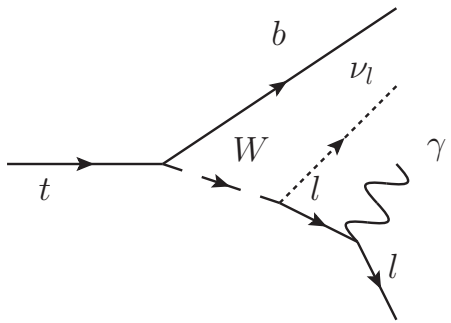


Radiative decay: on-shell top, charged top decay products.







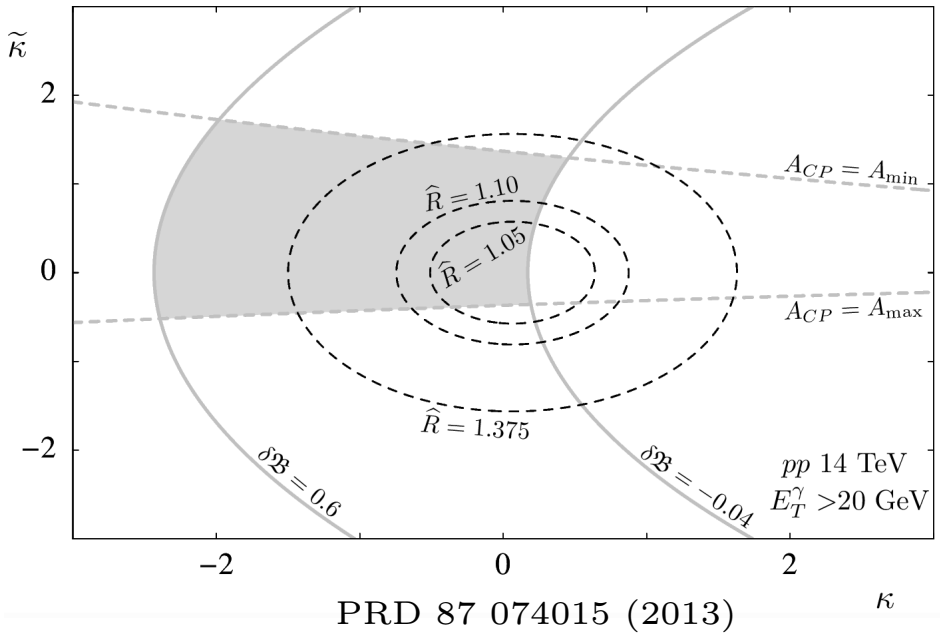


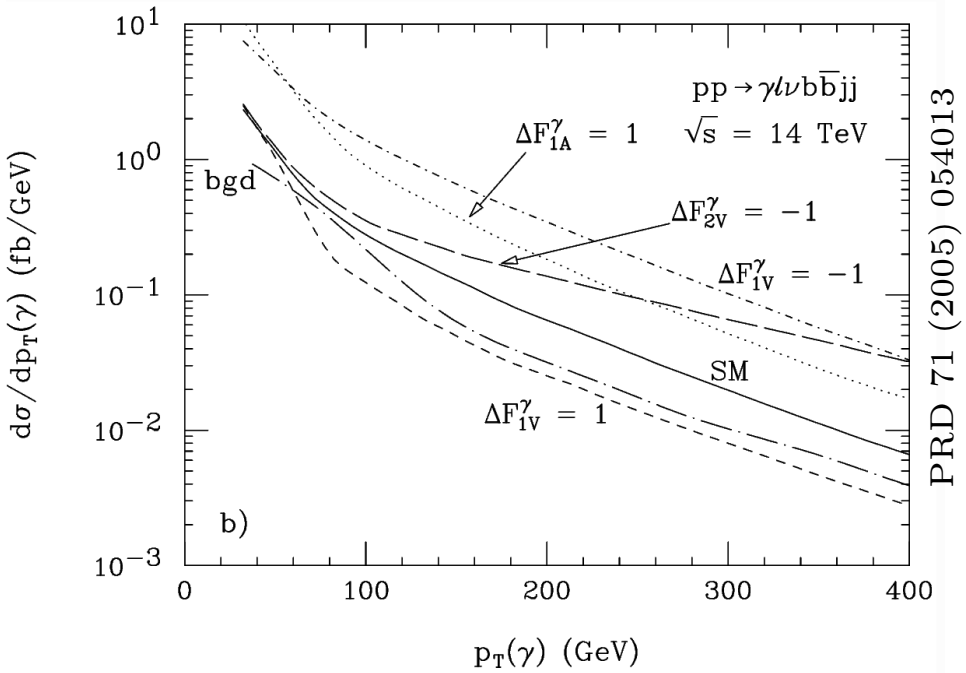
Non-negligible interference between the two.

Motivation

Probe top-γ coupling:

- Anomalous V/A coupling $\Delta F^{\gamma}_{1V,A}$ and dipole moments $\Delta F^{\gamma}_{2V,A}$ (MDM/EDM)
  $\rightarrow$ alter photon p_T spectrum.





- R $= \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}$ also sensitive to MDM/EDM (e.g. parametrised as κ and $\tilde{\kappa}$).
- Sensitivity to Top EFT operators ($O_{tW}/O_{tB}/O_{tG}$).

Important background to other measurements.

MC Samples

Experiment		ATLAS	CMS
Signal	Common	LO, MG5 + Pythia6, CTEQ6L1	
	Scale	Fixed @$2m_t$	$\sqrt{m_t^2 + \sum_{\text{parton}} p_T^2}$
	Photon	$p_T > 10$ GeV, $\lvert\eta\rvert < 5.0$	$p_T > 13$ GeV, $\lvert\eta\rvert < 3.0$
	Lepton	≥ 1 lepton with $p_T > 15$ GeV	-
	$\Delta R(\gamma, \text{charged})$	> 0.2	> 0.3
Bkg.	$t\bar{t}$	NLO, POWHEG + Pythia6, CT10	MG5, norm. to 8 TeV measurement
	V+jets	-	MG5, norm. to NNLO
	$V+\gamma$	LO, Sherpa up to 3j, CT10	MG5, norm. to NLO
	Single top	NLO, POWHEG+Pythia6, CT10, norm. to NNLO	
	Diboson	LO, Alpgen+fHerwig, CTEQ6L1, norm. to NLO	-
ME/PS choices		Diverse	Mostly MG5 / all Pythia6

Object Definitions

Experiment	ATLAS	CMS
Photon	- $p_T > 15$ GeV $\|\eta\| \in [0,1.37] \cup [1.52,2.37]$	Isolated $p_T > 25$ GeV $\|\eta\| < 1.44$
Electron	Isolated $p_T > 25$ GeV $\|\eta\| \in [0,1.37] \cup [1.52,2.47]$	Isolated $p_T > 35$ GeV $\|\eta\| \in [0,1.44] \cup [1.57,2.5]$
Loose Electron	-	Loosened isolation $p_T > 20$ GeV
Muon	Isolated $p_T > 25$ GeV, $\|\eta\| < 2.5$	Isolated $p_T > 26$ GeV, $\|\eta\| < 2.1$
Loose Muon	-	Fail "Tight" $p_T > 10$ GeV, $\|\eta\| < 2.5$
Jet	Anti-k_T cone of 0.4 $p_T > 25$ GeV, $\|\eta\| < 2.5$	Anti-k_T cone of 0.5 $p_T > 30$ GeV, $\|\eta\| < 2.4$
b-tagging	70% eff., 0.7% light jet eff.	~70% eff., 1.4% light jet eff.

Event Selection

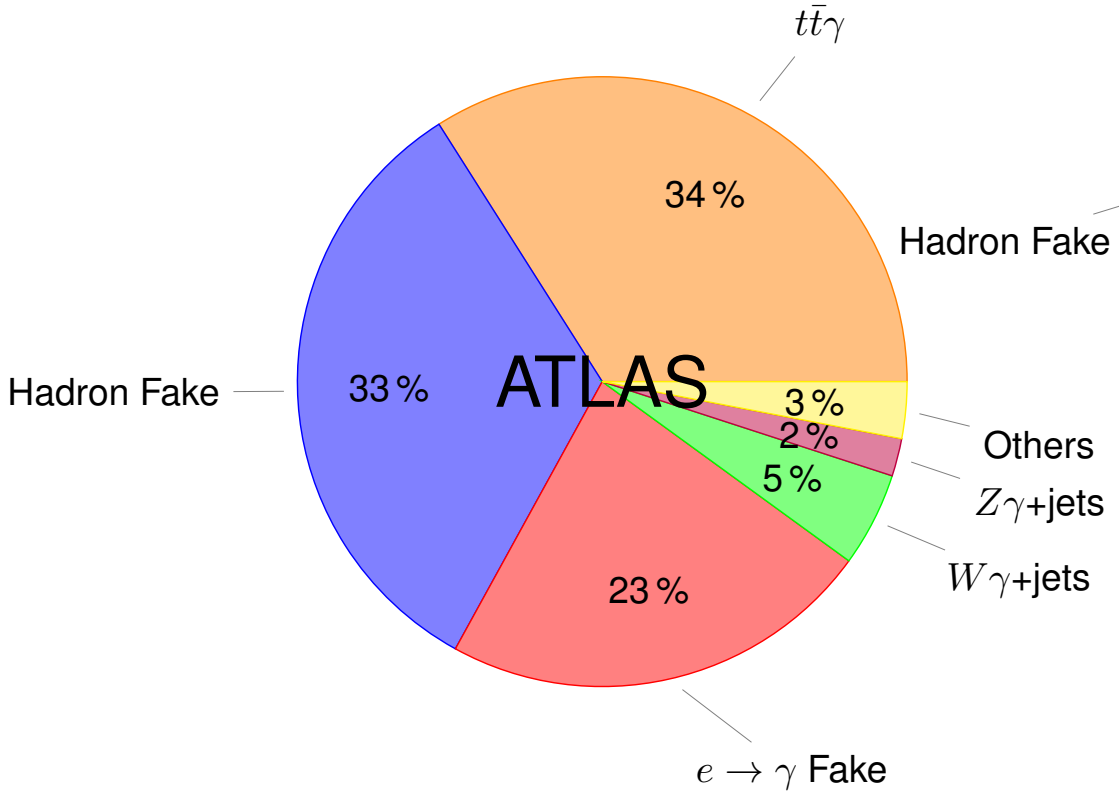
Experiment	ATLAS	CMS
Trigger	Single-lepton trigger	
ttbar	Exactly 1 lepton, trigger match, PV	
	-	No loose lepton
	$\geq$ 4 jets e+jets: $E_T^{\text{miss}} > 30$ GeV, $m_T^W > 30$ GeV μ+jets: $E_T^{\text{miss}} > 20$ GeV, $E_T^{\text{miss}} + m_T^W > 60$ GeV	$\geq$ 3 jets $p_T^{\text{miss}} > 20$ GeV
	$\geq$ 1 b jet	
Photon	== 1 photon	$\geq$ 1 photon
	Min. $\Delta R(\gamma, \text{jet}) > 0.5$ $\lvert m_{e\gamma} - m_Z \rvert > 5$ GeV for e+jets	Min. $\Delta R(\gamma, \text{jet}) > 0.7$ -
	$\Delta R(\gamma, \ell) > 0.7$	$\Delta R(\gamma, \ell) > 0.7$

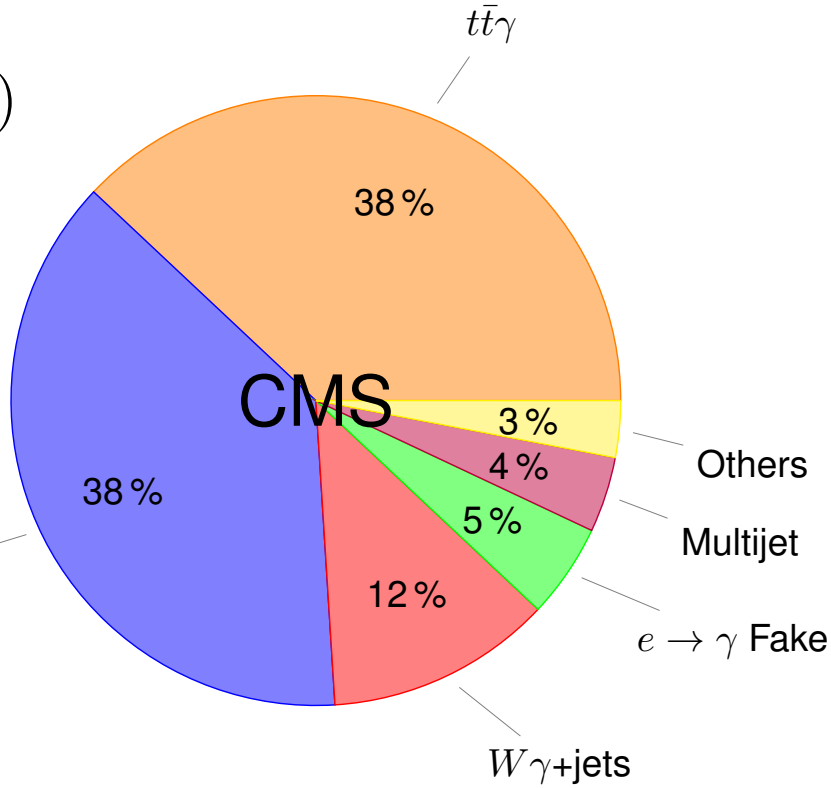
Event Categorisation

Acc. to Photon	Description	Contribution	Estimation	
			ATLAS	CMS
Prompt	Promptly produced, nonhadronic sources	$t\bar{t}\gamma$ (main)	Free	
		$W\gamma$ (main)	d-d	Free
		$Z\gamma$	MC	
		Single top	MC	
		Multijet	d-d	
		VV	MC	-
$e \to \gamma$ **Fake**	Missing track or hard brem. or nearby random track	$t\bar{t} \to ee/e\mu$ (main)	d-d	
		$Z \to ee$ (main)		
		Single top		
Hadronic Fake	Misidentified hadron or from hadron decay	$t\bar{t}$+jets (main)	Free	
		W+jets (main)		
		Z+jets		
		Multijet	d-d	

Event Categorisation

- Post-fit ATLAS numbers (3072 data)
- Pre-fit CMS numbers (2071 data)





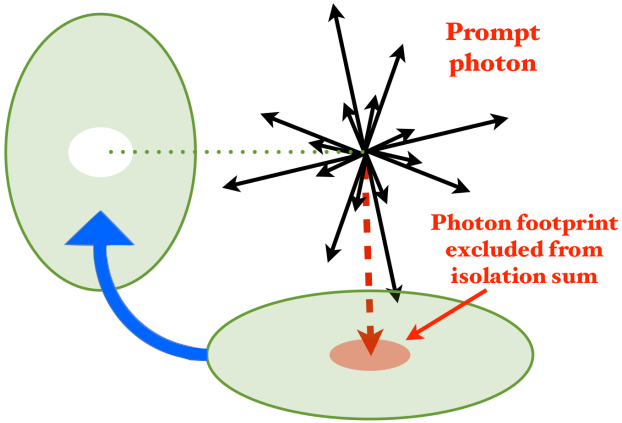
- ATLAS asks for more jet $\to$ less $W\gamma$
- ATLAS includes photon in high $|\eta| \to$ more $e \to \gamma$ fake

Analysis Strategy

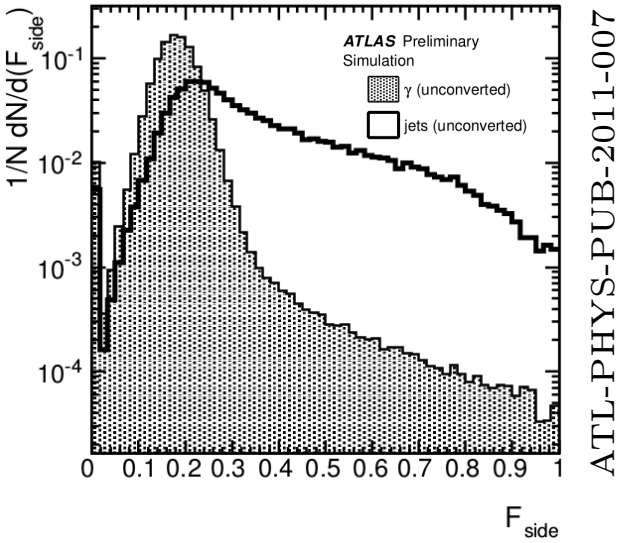
Exp.	ATLAS	CMS
Likelihood	$\mathcal{L}(\mathrm{N}_{t\bar{t}\gamma}, \mathrm{N}_{\mathrm{jet}\to\gamma} \vert p^{\mathrm{iso}}_{T,\mathrm{data}}) = (\mathrm{N}_{t\bar{t}\gamma} + \mathrm{N}_{other\gamma}) \times p^{\mathrm{iso}}_{T,\gamma} + \mathrm{N}_{\mathrm{jet}\to\gamma} \times p^{\mathrm{iso}}_{T,\mathrm{jet}\to\gamma} + \mathrm{N}_{e\to\gamma} \times p^{\mathrm{iso}}_{T,e\to\gamma}$	$\chi^2(\mathrm{SF}_{t\bar{t}\gamma}, \mathrm{SF}_{V\gamma}, \mathrm{SF}_{\mathrm{jet}\to\gamma}) = (\pi^{\mathrm{data}}_{e\gamma} - \pi^{\mathrm{MC}}_{e\gamma})^2/\sigma^2_{\pi_{e\gamma}} + (\pi^{\mathrm{data}}_{t\bar{t}} - \pi^{\mathrm{MC}}_{t\bar{t}})^2/\sigma^2_{\pi_{t\bar{t}}} + (N^{\mathrm{data}} - N^{\mathrm{MC}})^2/\sigma^2_N$
Features	**3 isolation templates:** $p^{\mathrm{iso}}_{T,\gamma}$ / $p^{\mathrm{iso}}_{T,\mathrm{jet}\to\gamma}$ / $p^{\mathrm{iso}}_{T,e\to\gamma}$ **2 free parameters:** $\mathrm{N}_{t\bar{t}\gamma}$ / $\mathrm{N}_{\mathrm{jet}\to\gamma}$	**2 template fits:** photon isolation $\to$ photon purity: $\pi^{\mathrm{data}}_{e\gamma} \pm \sigma_{\pi_{e\gamma}}$ tri-jet mass $M_3 \to$ top purity: $\pi^{\mathrm{data}}_{t\bar{t}} \pm \sigma_{\pi_{t\bar{t}}}$ **1 χ^2 fit:** $\pi^{\mathrm{MC}}_{e\gamma}$, $\pi^{\mathrm{MC}}_{t\bar{t}}$, and N^{MC} are functions of the 3 SFs
Similarity	Photon isolation used to discriminate hadronic fake	
Difference	$V\gamma$ fixed in ATLAS / floated in CMS	

Isolation Templates

Experiment	ATLAS	CMS
Definition	$\sum p_T$ of **all tracks** around the photon with $\Delta R \leq 0.2$	$\sum p_T$ of **all charged-hadrons** around the photon with $\Delta R \leq 0.3$, not within the photon footprint
Prompt Photon	MC based $Z \to ee \to e\gamma$ control region	"Random Cone" method
$e \to \gamma$ Fake		
Hadronic Fake	Reverse ≥ 1 of 4 ID flags	Shower shape sideband

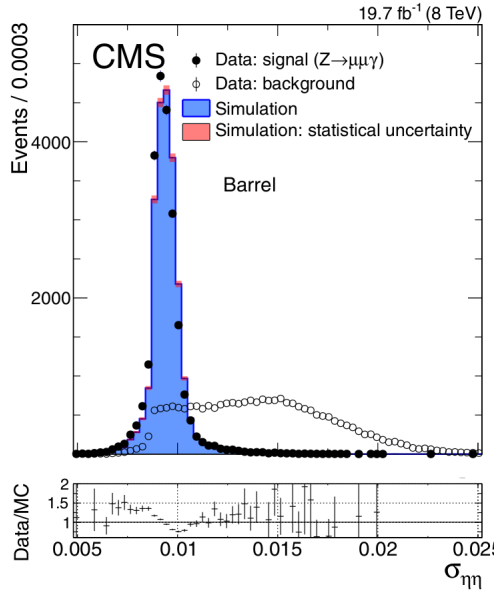


from Marco Peruzzi



ATL-PHYS-PUB-2011-007

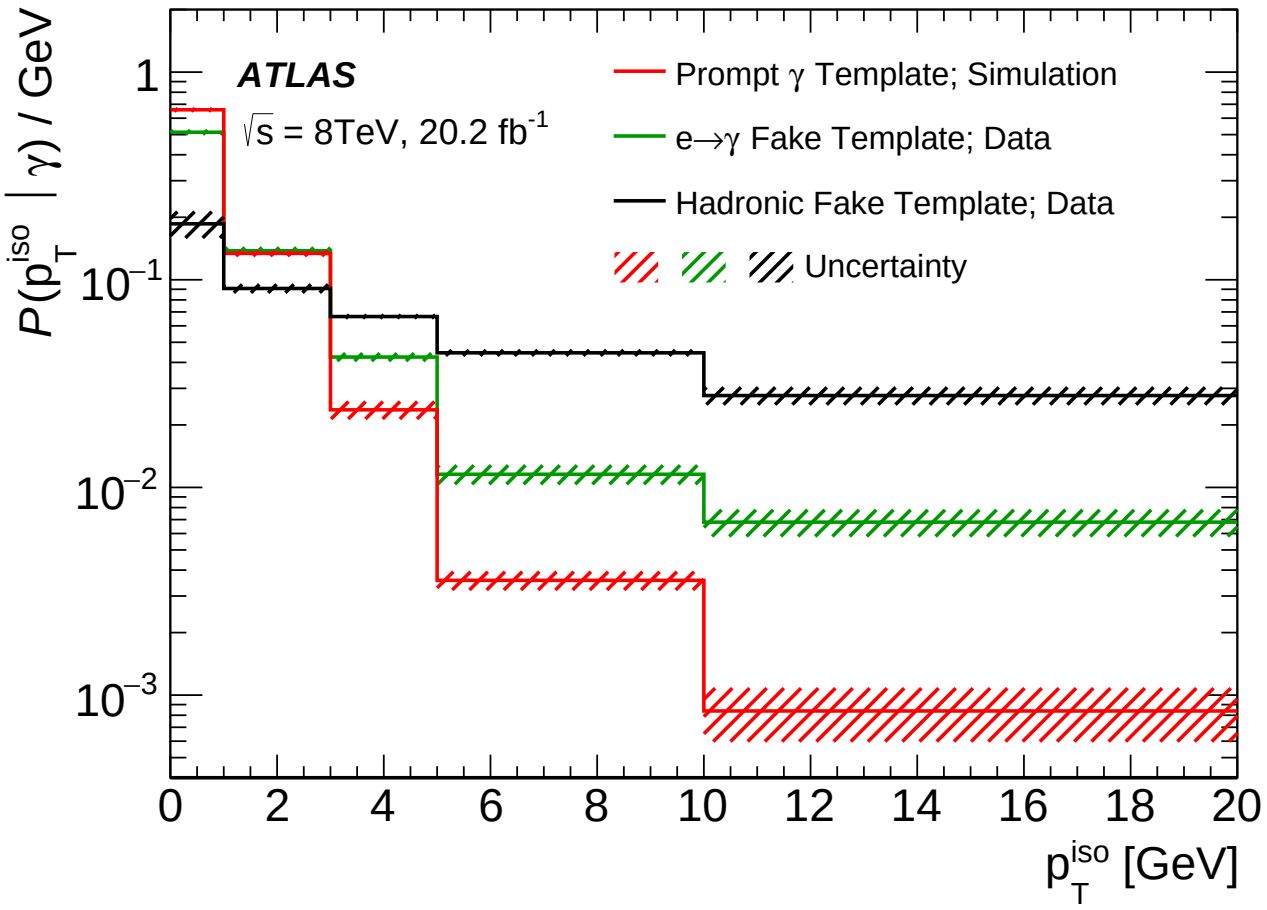
(3 others: w_{s3}, ΔE, E_{ratio})



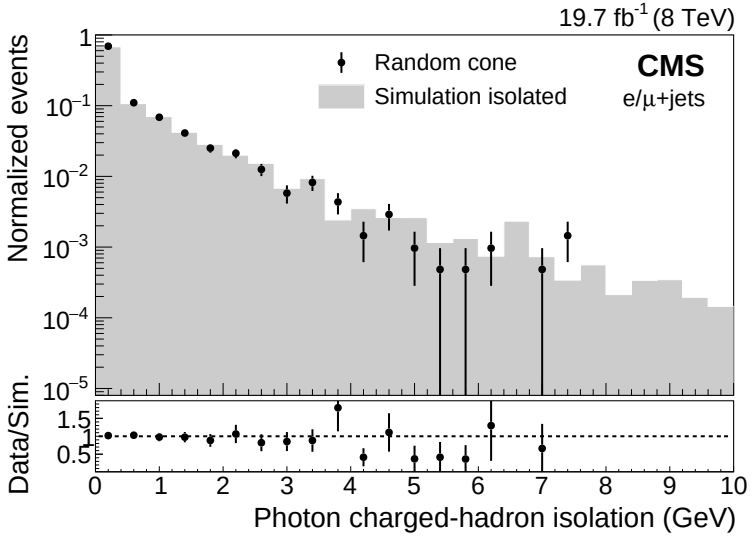
arXiv 1502.02702

Isolation Template (ATLAS)

Hadronic fake features long isolation tail.
$e \to \gamma$ fake is slightly less isolated than prompt photon.



Isolation Template (CMS)

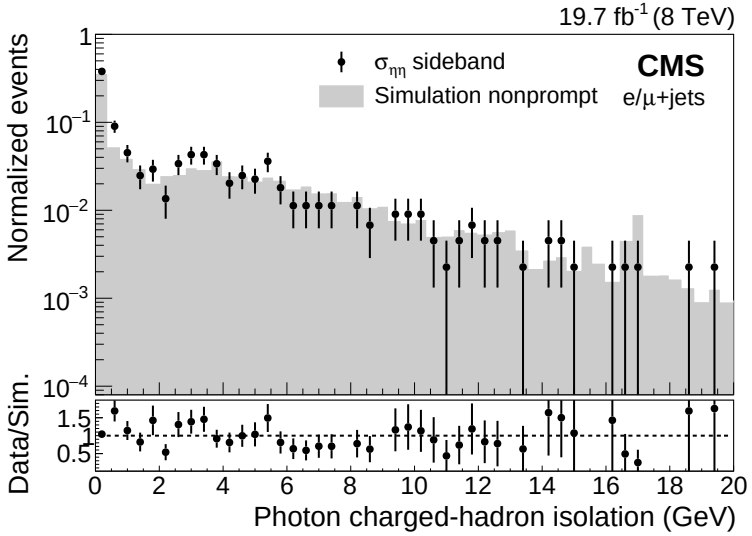


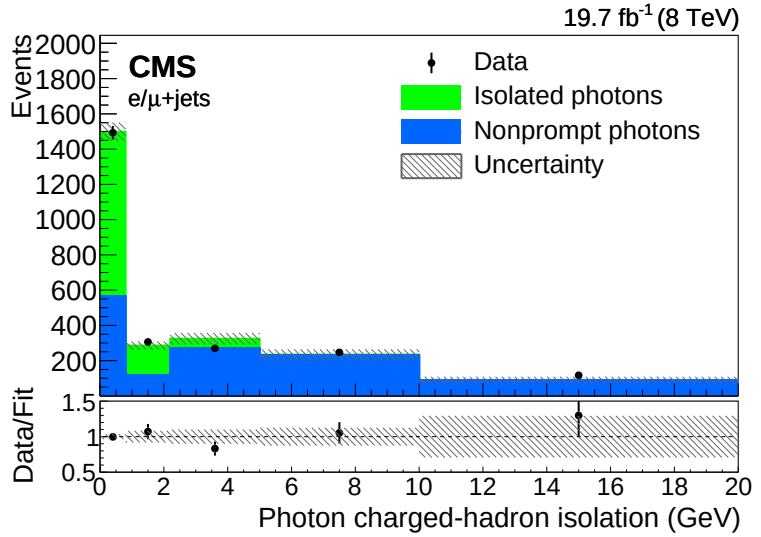
Used to fit "photon purity" ($e \to \gamma$ **fake counted as "photon"**)

Isolation cut temporarily removed

$\pi_{e\gamma}$	e+jets	μ+jets
Measured	0.57 ± 0.06	0.53 ± 0.06
MC	0.58 ± 0.03	0.57 ± 0.02

Stat. err.





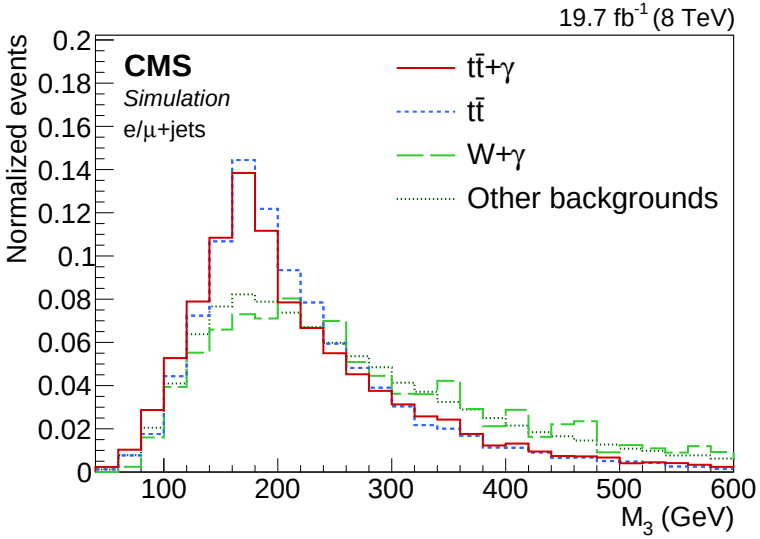
Tri-jet Mass Template (CMS)

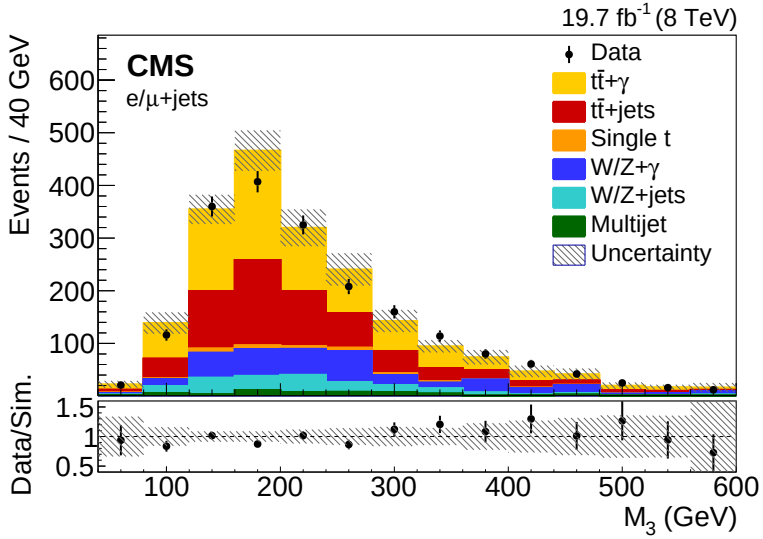
Used to fit "top purity", fraction of top quark events in all events

- Invariant mass of the 3 jets giving highest p_T sum
- $W\gamma$ is free (since it has distinguishing M_3 shape)
- A similar fit is performed, after $t\bar{t}$ selection stage, to measure $\sigma_{t\bar{t}}$

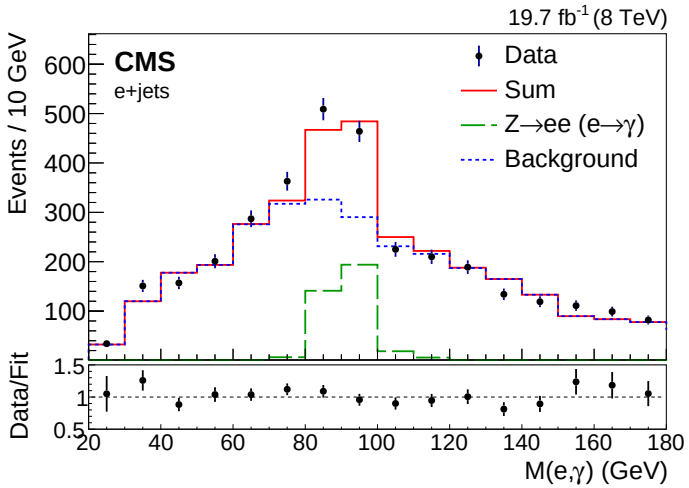
$\pi_{t\bar{t}}$	e+jets	μ+jets
Measured	0.70 ± 0.08	0.68 ± 0.06
MC	0.70 ± 0.03	0.72 ± 0.02

Stat. err.





$e \to \gamma$ Fake Background

Exp.	ATLAS	CMS
Method	Fully data-driven	Data-driven correction
Details	1. Define $Z \to e\gamma$ CR $\Rightarrow$ $N_{e\gamma}$, define $Z \to ee$ CR $\Rightarrow$ N_{ee}, calculate **fake rate** FR $= \frac{N_{e\gamma}}{N_{ee}}$ in electron p_T-η bins 2. Define **modified SR**, $SR_{\ell\gamma\to\ell e}$, by replacing γ with electron (a pool of $e \to \gamma$ candidates) 3. Apply FR to $SR_{\ell\gamma\to\ell e}$ (SR_{ee} gets applied twice)	1. Loosen SR cut $\to$ remove b-tag 2. **Fit** $M_{e\gamma}$ $\Rightarrow$ **SF** $= \frac{N_{e\gamma}^{data}}{N_{e\gamma}^{MC}}$ 3. Apply SF to correct MC in SR 
Results	FR $\in$ [0.04,0.21]	SF $= 1.45 \pm 0.20$

Multijet Background

Exp.	ATLAS	CMS
Method	"Matrix Method"	Sideband + template fit
Details	1. Relax lepton ID cuts to define **"loose" sample** w.r.t. SR, the **"tight" sample** 2. $N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$ $N^{tight} = \epsilon_{real} N^{tight}_{real} + \epsilon_{fake} N^{tight}_{fake}$ 3. $\epsilon_{real}/\epsilon_{fake}$: "loose" $\rightarrow$ "tight" **efficiency** for real/fake 4. Solve **matrix equation** in (2) estimated multijet in SR = $\frac{\epsilon_{fake}}{\epsilon_{real}-\epsilon_{fake}}(\epsilon_{real} N^{loose} - N^{tight})$	1. **Sideband** for shape: reverse lepton iso. cut (if e+jets, also ID) remove non-multijet by MC 2. **Fit** $p_T^{\mathbf{miss}}$ for normalization: multijet template from (1) non-multijet from MC

Other Backgrounds

<table>
<tr><th>Exp.</th><th>ATLAS</th><th>CMS</th></tr>
<tr><td rowspan="3">$W\gamma$</td><td>Data-driven correction</td><td rowspan="3">Free</td></tr>
<tr><td>CR modified from SR:
1. $N_{jet} \geq 4 \rightarrow N_{jet} \in [1,3]$
2. $N_{bjet} \geq 1 \rightarrow N_{bjet} = 1$
3. $m_{\ell\gamma} < 40$ GeV</td></tr>
<tr><td>$SF_{e+jets} = 0.69 \pm 0.16$
$SF_{\mu+jets} = 0.76 \pm 0.14$</td></tr>
<tr><td rowspan="3">Z+jets</td><td rowspan="3">None</td><td>Data-driven correction</td></tr>
<tr><td>Dedicated for $\sigma_{t\bar{t}}$ measurement</td></tr>
<tr><td>CR defined at $t\bar{t}$ selection stage, by modifying $t\bar{t}$ single lepton selection to same-flavor dilepton selection</td></tr>
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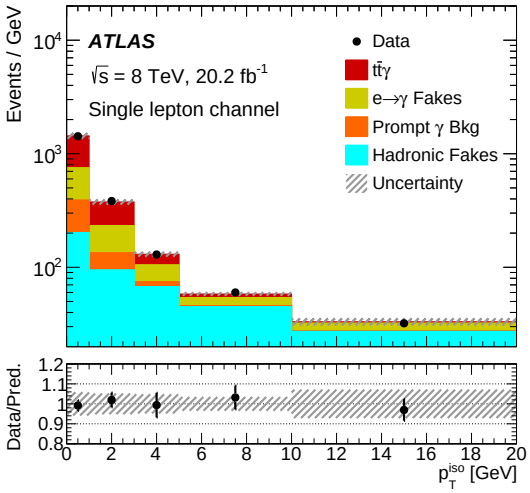
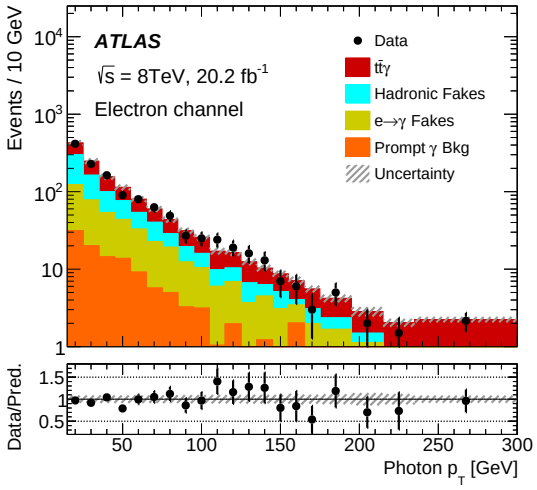
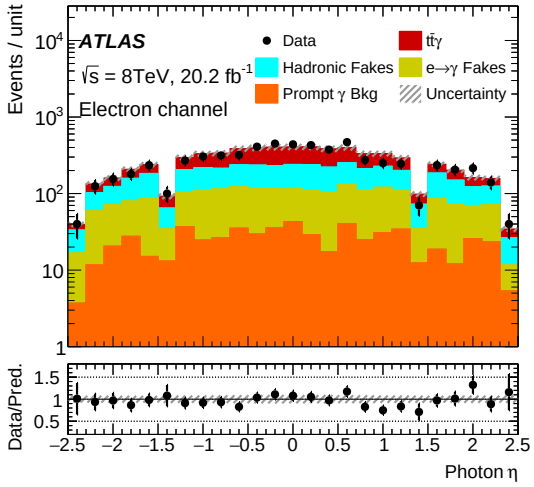
Post-fit Distributions

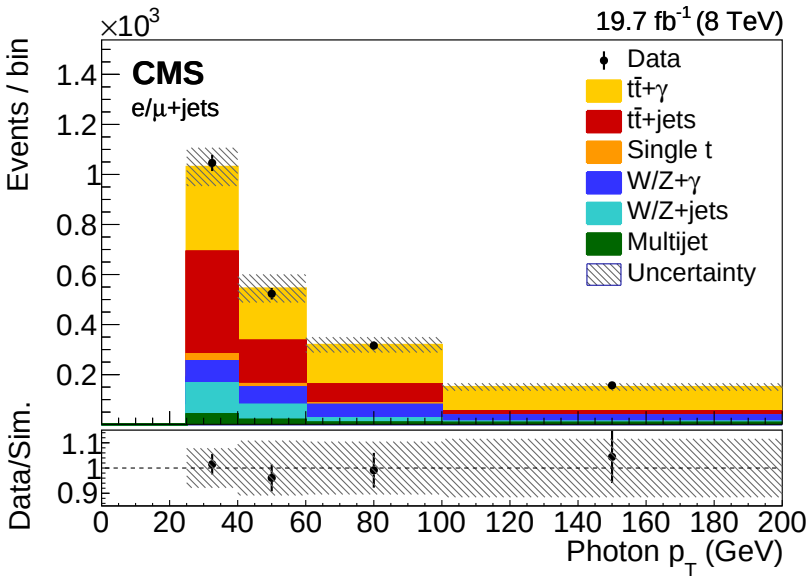
ATLAS

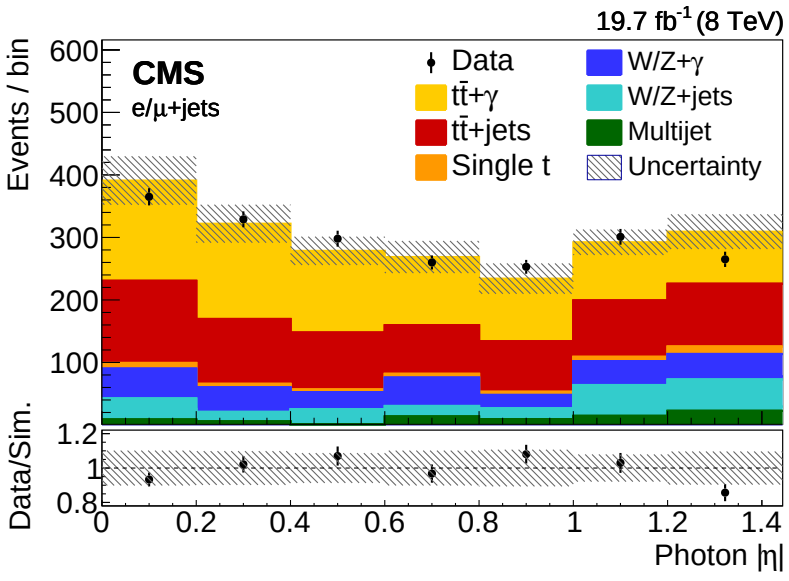






CMS





Fiducial Region

Experiment		ATLAS	CMS
$t\bar{t}$ decay channel		e+jets or μ+jets	
Object	Photon	$E_T > 15$ GeV, $\|\eta\| < 2.37$	$p_T > 25$ GeV, $\|\eta\| < 1.44$
	Electron	$p_T > 25$ GeV, $\|\eta\| < 2.5$	$p_T > 35$ GeV, $\|\eta\|\in[0,1.44]\cup[1.56,2.5]$
	Muon		$p_T > 26$ GeV, $\|\eta\| < 2.5$
	Jet	$p_T > 25$ GeV, $\|\eta\| < 2.5$	$p_T > 30$ GeV, $\|\eta\| < 2.4$
	b-jet	Ghost match, b-hadron	-
	E_T^{miss} or p_T^{miss}	-	$\sum p_T$ of all neutrinos
Event	Photon	Exactly 1	
	Lepton	Exactly 1	
	Jet	≥ 4 jets, ≥ 1 b-jet	≥ 3 jets
	E_T^{miss} or p_T^{miss}	-	$p_T^{\text{miss}} > 20$ GeV
	ΔR	$\Delta R(\text{jet},\gamma)_{min} > 0.5$ $\Delta R(\ell,\gamma) > 0.7$	-
Acc. e+jets (μ+jets)		14% (13%)	24% (26%)
Eff. e+jets (μ+jets)		28% (48%)	12% (13%)

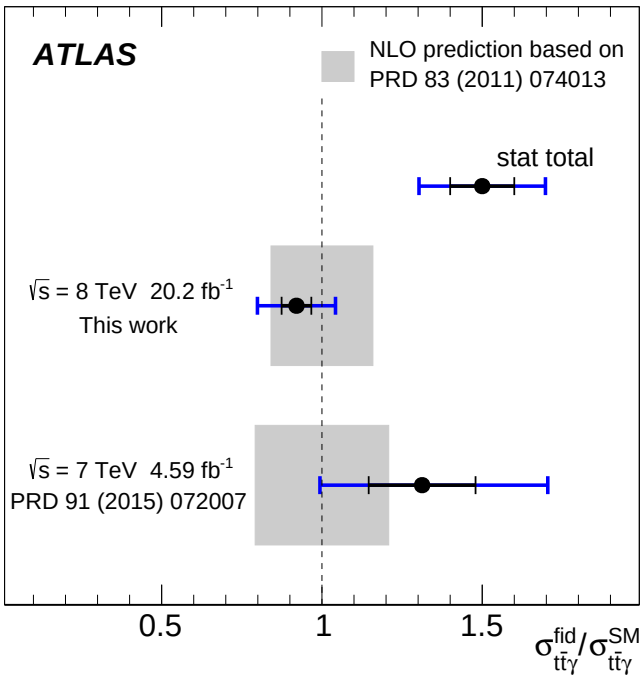
Cross Section

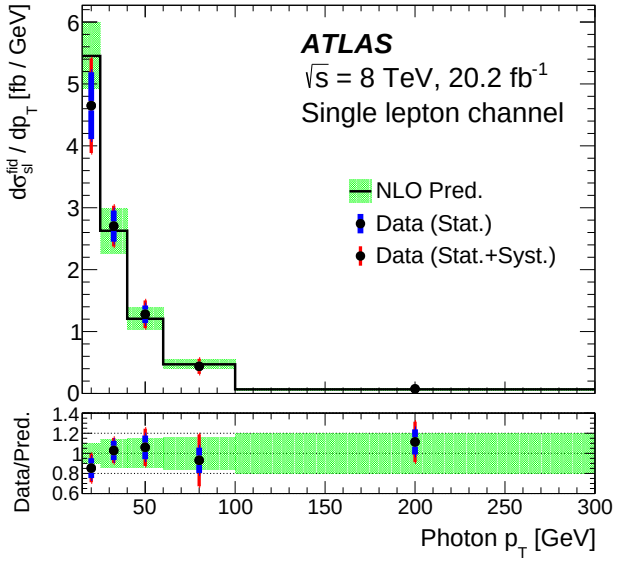
Exp.	ATLAS	CMS		
Channel	e+μ	e	μ	Average
N(signal)	1060 ± 130	338 ± 53 (stat)	442 ± 69 (stat)	-
$\mathbf{R} = \frac{\sigma^{\mathbf{fidu}}_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}$	-	$\frac{N_{t\bar{t}\gamma}}{Eff_{t\bar{t}\gamma}} \frac{Eff_{t\bar{t}}Acc_{t\bar{t}}}{N_{t\bar{t}}}$		
		$(5.7 \pm 1.8) \cdot 10^{-4}$	$(4.7 \pm 1.3) \cdot 10^{-4}$	$(5.2 \pm 1.1) \cdot 10^{-4}$
$\sigma^{\mathbf{fidu}}_{t\bar{t}\gamma}$	$\frac{N_{t\bar{t}\gamma}}{L \cdot Eff}$	R $\times$ $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}$ from another dedicated measurement)		
	139 ± 18 fb	138 ± 45 fb	115 ± 32 fb	127 ± 27 fb
Theo. (NLO)	151 ± 24 fb	-		
Ratio	0.92 ± 0.19	-		
$\sigma_{t\bar{t}\gamma}$	-	$\sigma^{fidu}_{t\bar{t}\gamma}$/Acc		
		582 ± 187 fb	453 ± 124 fb	515 ± 108 fb
Theo. (NLO)	-	592 ± 71 (scales) ± 30 (PDFs) fb		
Ratio	-	0.98 ± 0.34	0.77 ± 0.23	0.87 ± 0.21

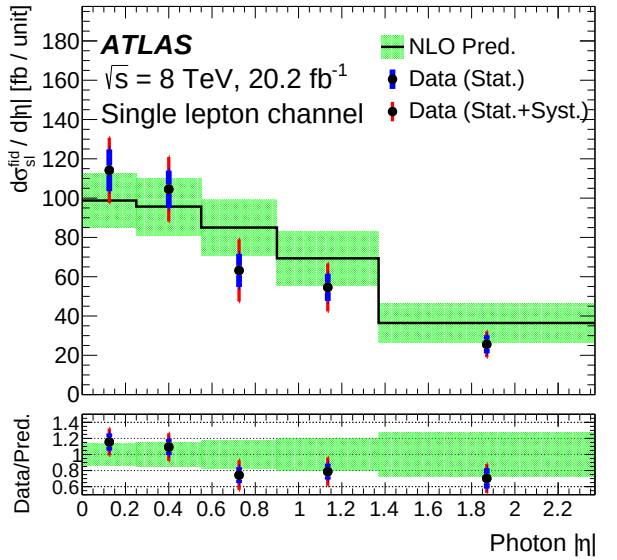
Cross Section (ATLAS)

7 TeV and 8 TeV measurements are compared

Differential cross section measured via bin-by-bin unfolding







Systematic Uncertainties

ATLAS ($\sigma^{\text{fidu}}_{t\bar{t}\gamma}$)	
Source	Uncert. [%]
Hadron-fake template	6.3
$e \to \gamma$ **fake**	6.3
JES	4.9
$W\gamma$+jets	4.0
$Z\gamma$+jets	2.8
ISR/FSR	2.2
Luminosity	2.1
Photon	1.4
Single top+γ	1.2
Muon	1.2
Electron	1.0
Scale uncertainty	0.6
Parton shower	0.6
Statistical uncertainty	5.1
Total uncertainty	13

CMS ("R")	
Source	Uncert. (%)
Statistical likelihood fit	15.5
Top quark mass	7.9
JES	6.9
Fact. and renorm. scale	6.7
ME/PS matching threshold	3.9
Photon energy scale	2.4
JER	2.3
Multijet estimate	2.0
Electron misid. rate	1.3
Z+jets scale factor	0.8
Pileup	0.6
Background normalization	0.6
Top quark p_T reweighting	0.4
b tagging scale factor	0.3
Muon efficiency	0.3
Electron efficiency	0.1
PDFs	0.1
Muon energy scale	0.1
Electron energy scale	0.1
Total	20.7

Summary

8 TeV ATLAS/CMS $t\bar{t}\gamma$ measurements are compared in details.

13 TeV $t\bar{t}\gamma$ analysis status

- ATLAS: NN, all non-hadronic channels, more differential.
- CMS: all non-hadronic channels, add differential.

Future plan

- ATLAS: TopEFT, charge asymmetry, $t\bar{t}$+diphoton.
- CMS: TopEFT, charge asymmetry, top charge.

Other ideas ?

- ATLAS/CMS combination (diff. binning, common MC).
- Set limit to anomalous V/A-coupling, no direct constrain.
- Set limit to dipole moments, no direct constrain (the EDM is of special interest since it's highly suppressed in SM and CP-violating).
- Include EW correction.

Backup

Scale Choice (ATLAS)