



$t\bar{t}\gamma$ Measurements at ATLAS

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LHCTopWG, CERN
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The $t\bar{t}\gamma$ Process Probes ...

Top quark charge, directly

- Indirect probing using $t\bar{t}$: exclusion of exotic top quark of charge -4/3 (
PRL98(2007)041801, PRL105(2010)101801, JHEP11(2013)031,
PRD90(2014)051101, top quark charge measurement (JHEP11(2013)031)

Structure of top-photon coupling

- Big picture: top quark neutral EW coupling to $H/Z/\gamma$
- General parametrization in terms of vector and axial couplings and electric and magnetic dipole moments (EDM/MDM): PRD71(2005)054013
- EFT model-independent parametrization in terms of O_{uW}^{33} , O_{dW}^{33} , $O_{uB\phi}^{33}$:
NPB812(2009)181

$t\bar{t}$ charge asymmetry

- Possible with full Run-2: JHEP04(2014)188, EPJC79(2019)189

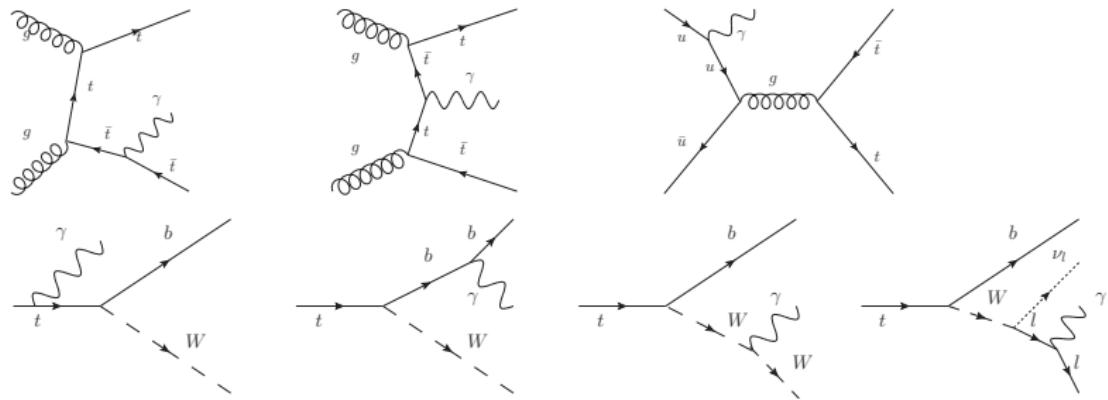
Experimental studies

- Evidence (CDF PRD84(2011)031104), observation (ATLAS 7TeV
PRD91(2015)072007, measurements (ATLAS 8TeV JHEP11(2017)086 CMS
8TeV JHEP10(2017)006, compared in last LHCTopWG)
- New ATLAS measurement at 13TeV (36 fb-1): EPJC79(2019)382

$t\bar{t}\gamma$ LO Feynman Diagrams

Radiative production: off-shell top, initial charged parton

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



- * Non-negligible prod./decay interference
- * Uninteresting photons from non-top-photon couplings

$t\bar{t}\gamma$ Modelling at ATLAS

MC: MG5_aMC (LO, $\alpha_s^2 \alpha^5$) + Pythia8

- $pp \rightarrow t\bar{t} \rightarrow e\nu\mu\nu b\bar{b}\gamma$ (single lepton channel similarly): 2→7 simulation, reserve spin correlation and prod./decay interference
- 4.6 pb xsection with cuts: isolated photon with $pT(\gamma) > 15$ GeV, $dR(\gamma, \text{charged}) > 0.2$, ...
- Systematics: Herwig7 (PS), Pythia8 A14 Var3c up/down (ISR/FSR), μ_f and μ_r up/down (scale), NNPDF eigen set (PDF)
- Off-shell/on-shell top quark photon radiation $\sim 4:1$

Normalization

- LO: [HD-THEP-98-23](#), [PRD64\(2001\)094019](#),
[PRD71\(2005\)054013](#)
- NLO QCD (used in the measurement): [PRD80\(2009\)014022](#),
[PRD83\(2011\)074013](#)
- EW correction: [PLB766\(2017\)102](#)
- Offshell and non-resonant: [JHEP10\(2018\)158](#)

NLO QCD K-factor for $t\bar{t}\gamma$ MC

NLO (parton) calculation from theoriest

- Min. pT for photon/lepton/jet
- Min. dR between (photon,lepton/jet)
- At least 4/2 jets and 2 bjets for single-lepton/dilepton channel
- 13-14% scale/pdf uncertainties

LO (particle) prediction from MC

- Reconstruct parton level objects from particle level: e.g. photon dressing for leptons to remove effect of PS
- Same selection as above
- Cannot do NLO (parton) / LO (parton): double-counting by PS

Conservative systematic variations

- Turn on/off UE/Hadronization of the LO MC: 4-6%
- Vary jet cone size of particle level jet (main): 8-11%

Background Modelling and Categorization

Top quark

- $t\bar{t}$: POWHEG (NLO) + Pythia8, “hdamp” = $1.5m_t$
- Single top: POWHEG (NLO) + Pythia6, photon radiation simulated by PS
- $t\bar{t}$ overlap removal wrt $t\bar{t}\gamma$: if the reconstructed photon originates from the hard interaction, remove the $t\bar{t}$ event

$V(+\gamma)+\text{jets}$

- $V + \text{jets}$ by Sherpa 2.2.1 + 0/1/2j@NLO, $V + \gamma$ by Sherpa 2.2.2 + 0/1j@NLO, same overlap removal

Others

- Diboson by Sherpa 2.1 + 0/1j@NLO, $t\bar{t}W/Z$ by MG5 (NLO) + Pythia8

Categorization

- Hadronic fake: photon in jet, jet mis-identified as photon, $t\bar{t} + \text{jets}$
- Electron fake: missing track, false conversion vertex, $Z \rightarrow ee$ and $t\bar{t} \rightarrow ee/e\mu$
- Prompt photon: “X“ + prompt photon, $X \neq t\bar{t}$
- Fake lepton (data-driven): fake lepton or non-prompt lepton, $t\bar{t}\gamma$ allhadronic

Object Selection

Photon

- $pT > 20\text{GeV}$, $|eta| < 2.37$, excluding crack region
- “Tight“ ID, calo/track-based isolation

Lepton

- $pT > 25\text{GeV}$, $|eta| < 2.47$ (2.5) for e (μ), w/o crack region for e
- “Tight“ electron and “Medium“ muon, $d0/z0$ significance cut

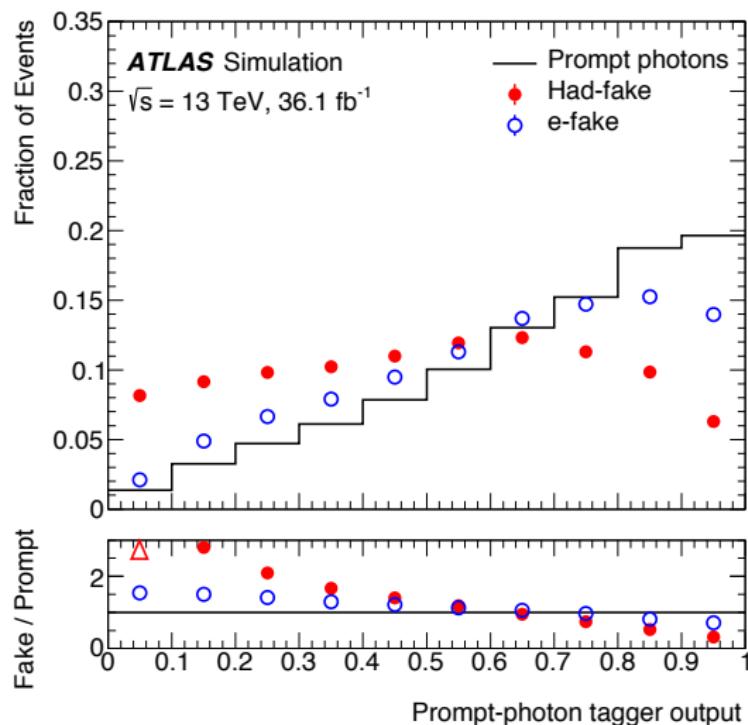
Jet

- Anti-kT with $R = 0.4$, $pT > 25\text{GeV}$, $|eta| < 2.5$, JVT
- B-tagging: 77% eff. 7(134) rejection factor for c/l-jet

Apply neural network: Prompt photon tagger (PPT)

- To discriminating prompt photon against hadronic fake
- Input (6): shower shapes in ECAL and energy leakage in HCAL
- Performance: next page
- Calibration (due to well-known issue of shower shape modelling): $Z \rightarrow \ell\ell\gamma$ CR for prompt photon and $t\bar{t} +$ hadronic fake CR for hadronic fake
- Conservative systematics: 100% of the calibration

Prompt Photon Tagger Performance



* After “tight” ID and isolation

* Shape calibrated in bins

* Shape comparison between prompt-photon, hadronic fake and electron fake

* Used for single lepton channel, as input to an event level NN

Event Selection

Common stuff

- Primary vertex, lepton trigger fired and matched

Five channels according to lepton flavor/multiplicity

- $e+jets$, $\mu+jets$, ee , $\mu\mu$, and $e\mu$

Photon and jet

- == 1 photon
- ≥ 4 (2) for single-lepton (dilepton) channels
- At least one b -tagged jet

Background suppression

- invariant mass Z veto: $m(e, \gamma)$ for $e+jets$, $m(\ell, \ell)$ and $m(\ell, \ell, \gamma)$ for ee and $\mu\mu$
- MET Z veto: ee and $\mu\mu$
- Low mass dilepton resonant suppression: $m(\ell, \ell) > 15\text{GeV}$ for all dilepton channels
- Suppress photon radiation from lepton: $dR(\gamma, \ell) > 1.0$

Event Composition after Selection

Channel	Single lepton	Dilepton
$t\bar{t}\gamma$	6490 ± 420	720 ± 34
Hadronic-fake	1440 ± 290	49 ± 27
Electron-fake	1650 ± 170	2 ± 1
Fake lepton	360 ± 200	-
$W\gamma$	1130	
$Z\gamma$		75 ± 52
Other prompt	690 ± 260	18 ± 7
Total	11750 ± 710	863 ± 78
Data	11662	902

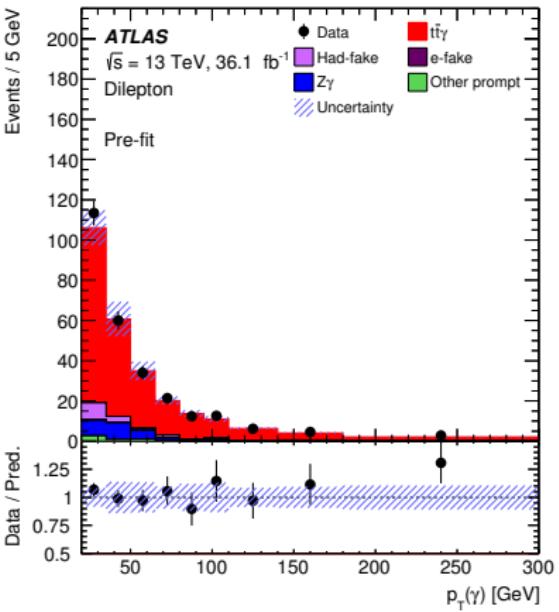
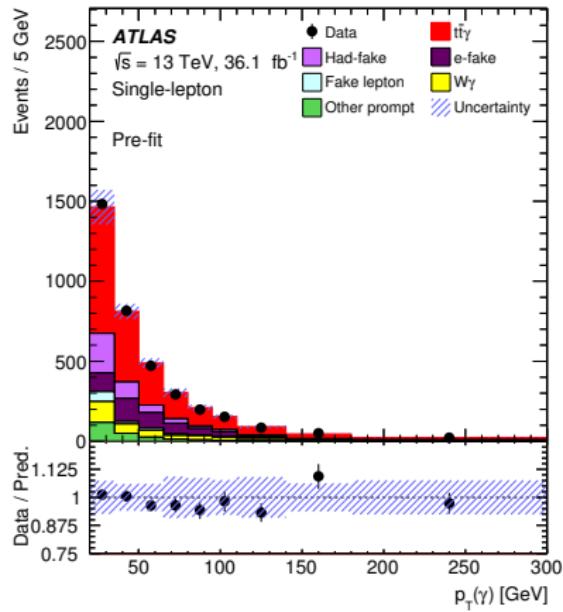
* $W\gamma$ in single-lepton channel floated in final fit, thus no uncertainty

* All data-drive corrections and systematic uncertainties applied

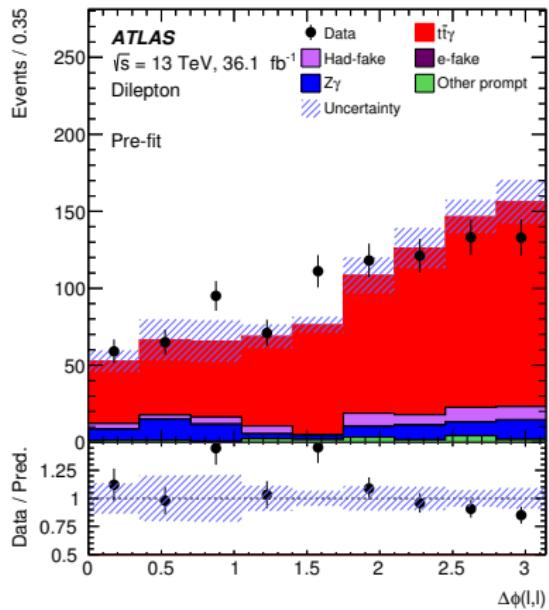
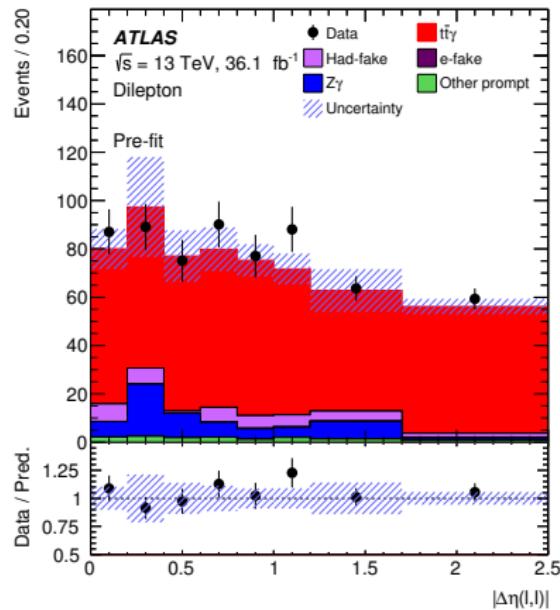
* Signal dominated

* Bkg: prompt photon > electron fake (hadronic fake) > hadronic fake (electron fake) > fake lepton for single-lepton (dilepton) channel

Kinematic Distributions after Selection



Kinematic Distributions after Selection



Data-driven Background Estimation

Hadronic fake

- ABCD method: exploit the weak correlation between photon isolation and shower shape variables of the strip layer (fine granulated)
- pT-eta binned, converted/unconverted \rightarrow SFs 0.8-3.2 (average 1.5)
- SF uncertainties > 0.5 : stat. + weak correlation + “bkg“ subtraction

Electron fake

- Measure fake rate with Z boson T&P, fit $(e,e/\gamma)$ mass to extract $n(T/P)$
- pT-eta binned \rightarrow SFs 0.8-2.1 (average 1.0)
- SF uncertainties > 0.1 : stat. + fit setup

Fake lepton

- Matrix method for $\ell+jets$ channel: define loose/tight lepton, measure real/fake eff. (loose \rightarrow tight), and apply eff. to tight/loose SR
- Dilepton channel ignored: checked in Same-Sign (SS) region

$W\gamma$ and $Z\gamma$

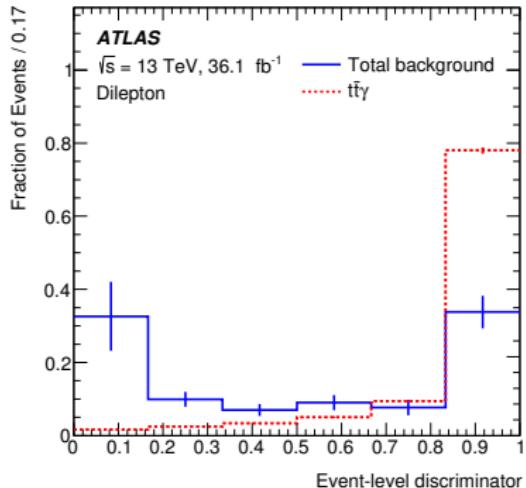
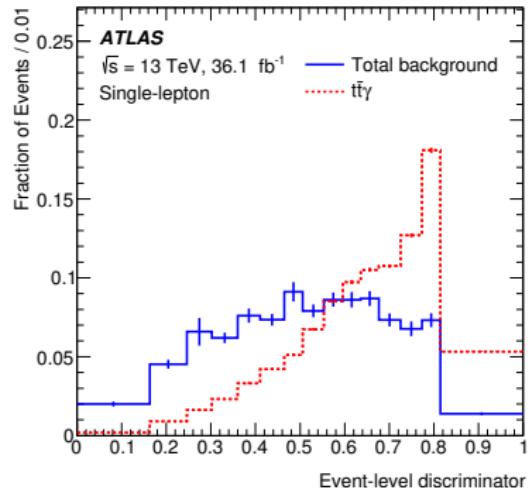
- No data-driven correction but checked in dedicated VR

Signal/Background Discrimination

Neural network trained separately for single-lepton and dilepton channels (called Event Level Discriminator)
Modelling of input variables checked in VRs

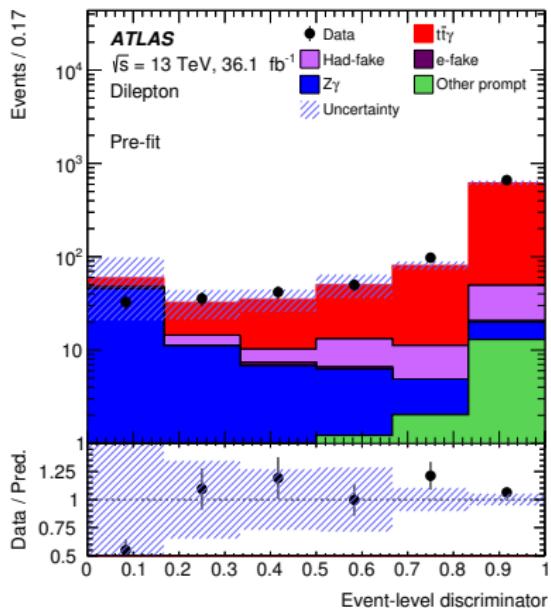
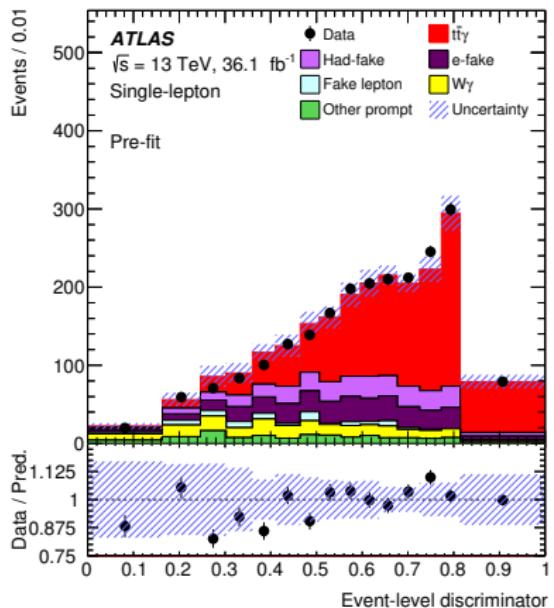
Variable	Description	Single lepton	Dilepton
PPT	Prompt-photon tagger output	✓	
H_T	Scalar sum of the p_T of the leptons and jets	✓	
$m(\gamma, \ell)$	Invariant mass of the system of the photon and the lepton	✓	
E_T^{miss}	Missing transverse energy	✓	
m_W^T	Reconstructed transverse mass of the leptonically decaying W -boson $= \sqrt{2 \times p_T(\ell) \times E_T^{\text{miss}} \times (1 - \cos(\Delta\phi(\ell, E_T^{\text{miss}})))}$	✓	✓
N_{jets}	Jet multiplicity	✓	
$p_T(j_1)$	p_T of the leading jet (ordered in p_T)	✓	✓
$p_T(j_2)$	p_T of the sub-leading jet	✓	✓
$p_T(j_3)$	p_T of the third jet	✓	
$p_T(j_4)$	p_T of the fourth jet	✓	
$p_T(j_5)$	p_T of the fifth jet	✓	
N_b -jets	b -jet multiplicity	✓	✓
$b_1(j)$	highest b -tagging score of all jets	✓	✓
$b_2(j)$	second highest b -tagging score of all jets	✓	✓
$b_3(j)$	third highest b -tagging score of all jets	✓	
$m(\ell, \ell)$	Invariant mass of the system of the two leptons		✓

Event Level Discriminator



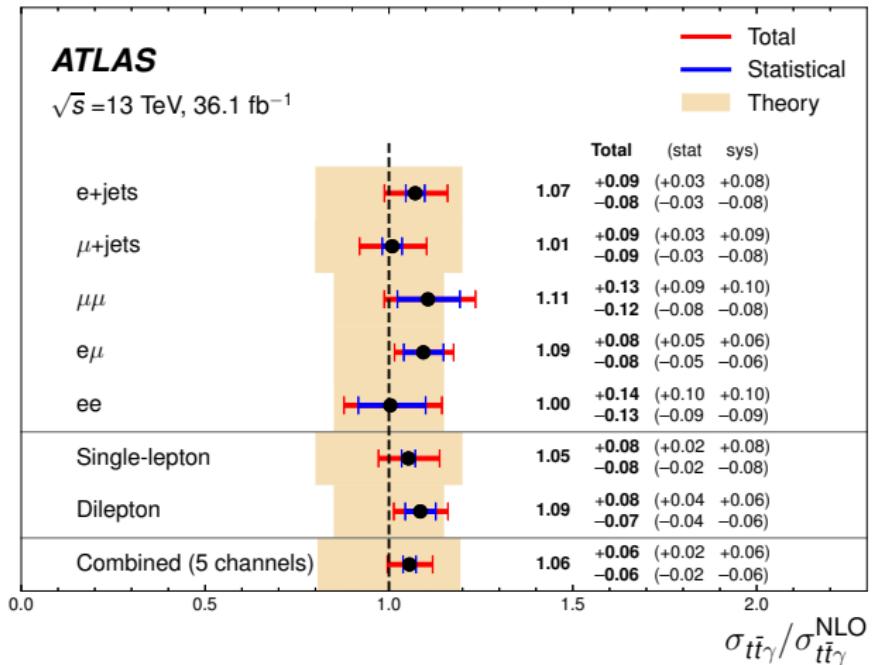
* Used to construct likelihood fit to extract signal strength

Event Level Discriminator



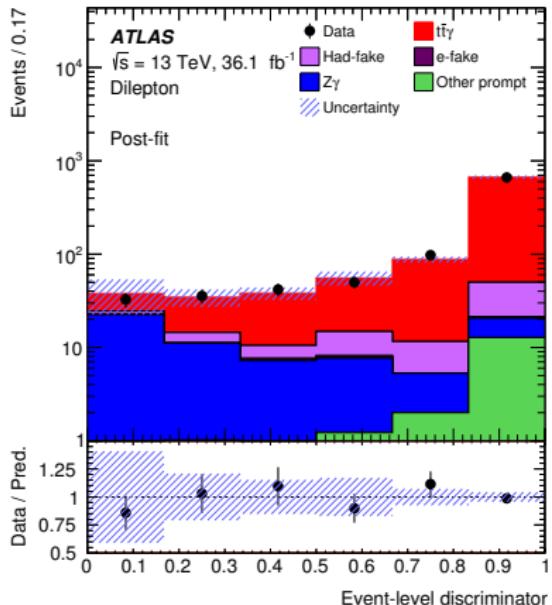
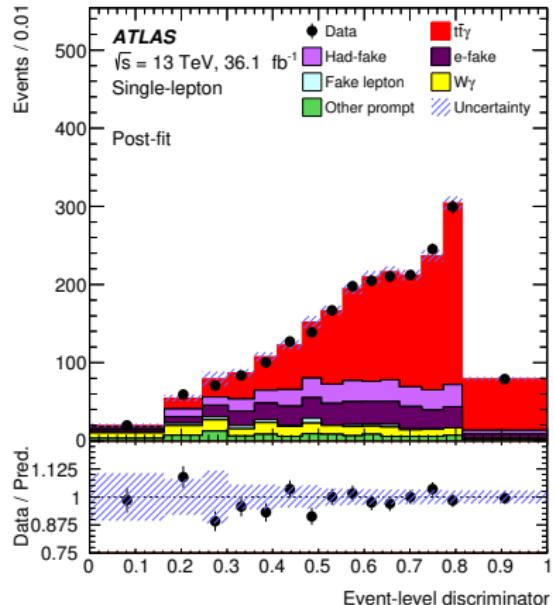
* Large deviation in the 1st bin of dilepton channel: large weighted $Z\gamma$ event

Fiducial Cross-section



- * Single-lepton channel mainly limited by systematic uncertainty,
- * Dilepton channel has comparable uncertainties of stat. and sys.

Postfit Distribution



* Systematic error bands shrunk significantly

Systematics

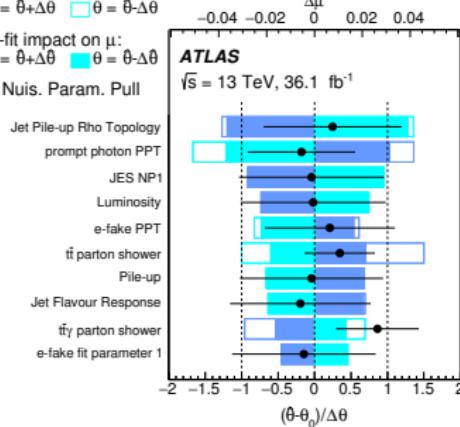
Pre-fit impact on μ :

□ $\theta = \theta + \Delta\theta$ □ $\theta = \theta - \Delta\theta$

Post-fit impact on μ :

■ $\theta = \theta + \Delta\theta$ ■ $\theta = \theta - \Delta\theta$

● Nuis. Param. Pull



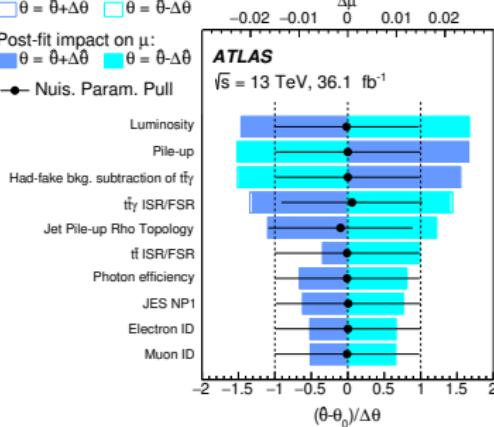
Pre-fit impact on μ :

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Post-fit impact on μ :

■ $\theta = \theta + \Delta\theta$ ■ $\theta = \theta - \Delta\theta$

● Nuis. Param. Pull



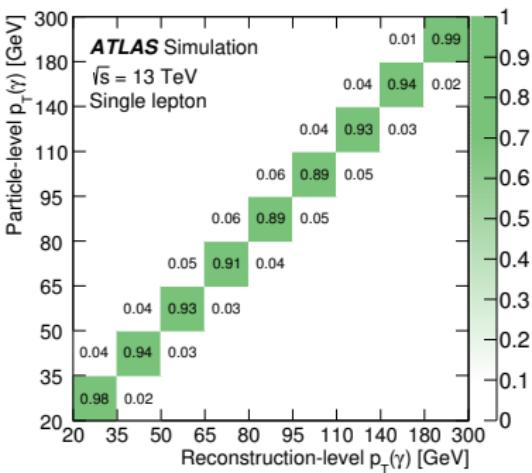
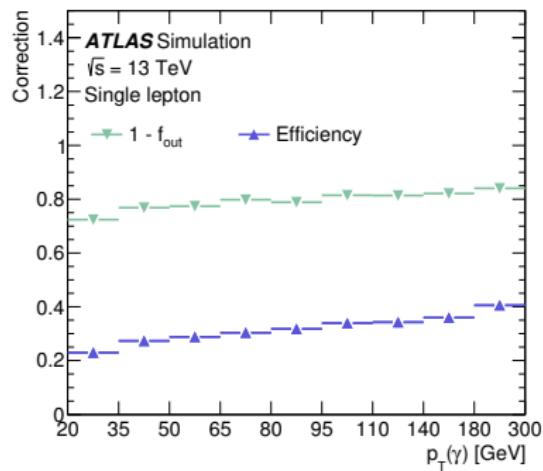
- * Single-lepton channel: JES, PPT, lumi., PU, $t\bar{t} / t\bar{t}\gamma$ PS
- * Dilepton channel: lumi., PU, h-fake, $t\bar{t} / t\bar{t}\gamma$ ISR/FSR
- * $t\bar{t}\gamma$ PS pull shows data favors alternative shower model (H7)

Unfolding

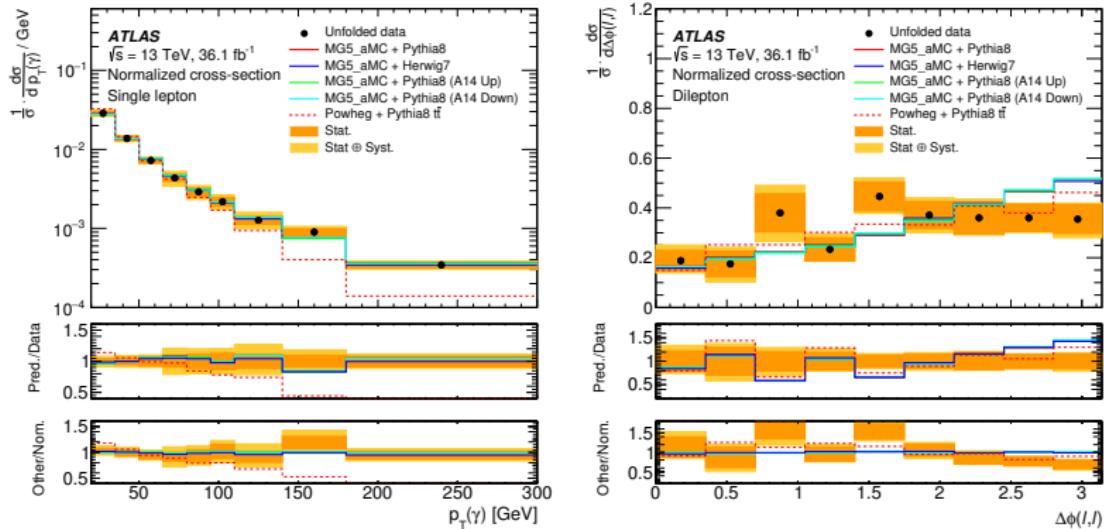
Iterative Bayesian, 3 iterations, normalized to unity

$$\sigma_k = \frac{1}{L} \times \frac{1}{\epsilon_k} \times \sum_j M_{jk}^{-1} \times (N_j^{\text{obs}} - N_j^b) \times (1 - f_{\text{out},j}) .$$

No likelihood fit to avoid entangled postfit systematics

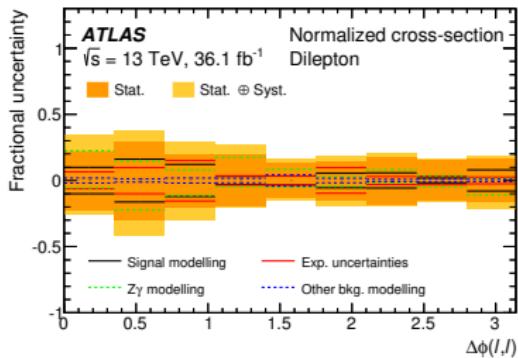
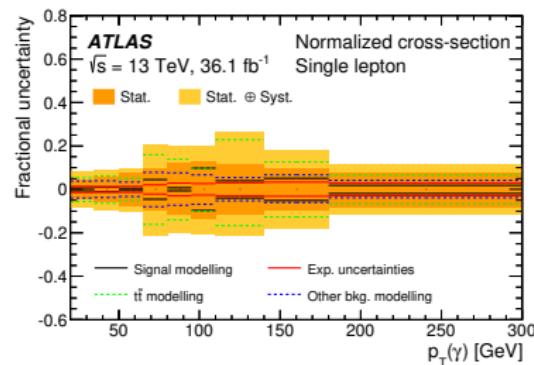


Normalized Differential Cross-section



- * Other observables: $(|\eta(\gamma)|)$, $dR(\gamma, \ell)$, $|d\eta(\ell, \ell)|$
- * PS simulated photon radiation disfavored ($t\bar{t}$ MC)
- * Small deviation (1.5 sigma) in spin-correlation sensitive $\Delta\phi(\ell, \ell)$

Differential Systematics



- * Single-lepton channel: 10-20%, $t\bar{t}$ modelling sys dominates, followed by statistical uncertainty and others
- * Dilepton channel: 20-40%, statical uncertainty dominates, followed by $Z\gamma$ modelling sys and others
- * Uncertainties are larger than fiducial xsection due to not using likelihood fit

Other $t\bar{t}\gamma$ Studies

HL-LHC projection

- Expected uncertainty reduced by a factor of more than 2
- EFT limits expected to be narrowed by a factor of 2 to more than 10

NN to separate top-quark radiated photon from photons of other sources

- Master thesis of Andreas Kirchhoff: a first study

Full Run-2 analyses

- Ongoing ...

Outlook

What to improve

- Hadronic fake photon discrimination for single lepton channel
- Suppression of photon radiation from non-top sources
- Differential NLO QCD correction
- MC modelling with higher order precision
- Include EW correction
- Single top + photon modelling (ongoing)

What else to measure

- Direct measurement/limit of top quark MDM(g-2)/EDM
- Ratio of radiative production over radiative decay
- Ratio $t\bar{t}\gamma / t\bar{t}$: predicted with high precision 1-3% ([JHEP01\(2019\)188](#)), constrain EW dipole moments ([EPJC76\(2016\)no.8,466](#))

Backup

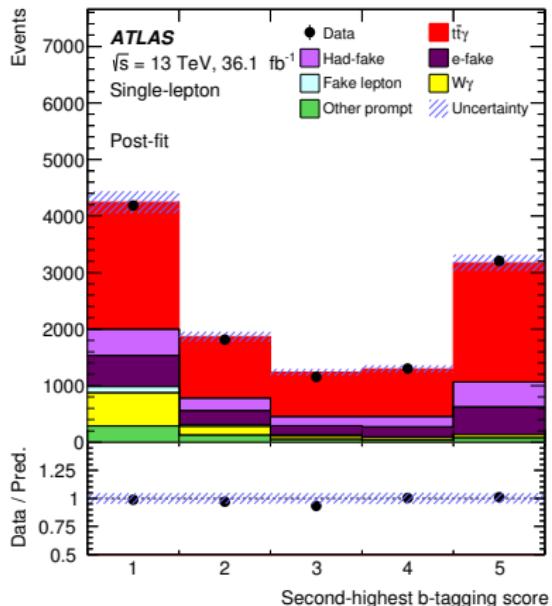
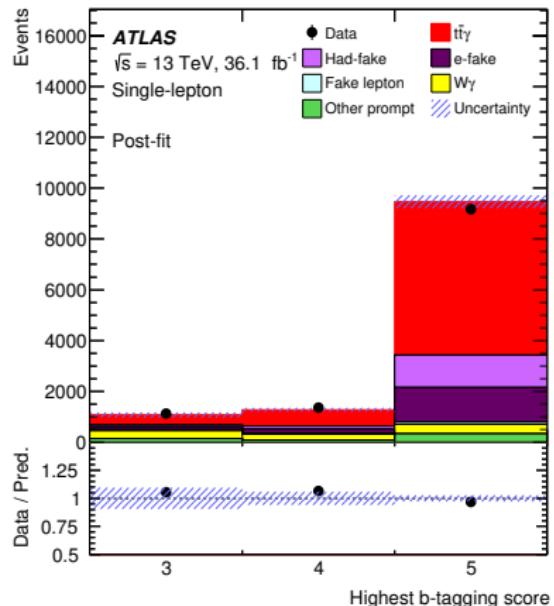
Shower Shape

Name	Description
Hadronic leakage	
R_{had} or $R_{\text{had}1}$	Transverse energy leakage in the hadronic calorimeter normalized to transverse energy of the photon candidate in the ECAL. In the region $0.8 \leq \eta \leq 1.37$, the entire energy of the photon candidate in the HCAL is used (R_{had}), while in the region $ \eta < 0.8$ and $ \eta > 1.37$ the energy of the first layer of the HCAL is used ($R_{\text{had}1}$).
Energy ratios and width in the second layer of ECAL	
R_η	Energy ratio of 3×7 to 7×7 cells in the $\eta \times \phi$ plane.
R_ϕ	Energy ratio of 3×3 to 3×7 cells in the $\eta \times \phi$ plane.
w_{η_2}	Lateral width of the shower, using a window of $\eta \times \phi = 3 \times 5$ cells.
Energy ratios and widths in the first (strip) layer of ECAL	
w_{s3}	Shower width along η , using 3 strips around the largest energy deposit.
$w_s \text{ tot}$	Shower width along η , using 20×2 strip cells in the $\eta \times \phi$ plane.
F_{side}	Energy outside the 3 central strips but within 7 strips, normalized to the energy within the 3 central strips.
E_{ratio}	Ratio between difference of the first and second energy maximum divided by their sum ($E_{\text{ratio}} = 1$ if there is no second maximum).
ΔE	Difference between the second energy maximum and the minimum found between first and second maximum ($\Delta E = 0$ if there is no second maximum).

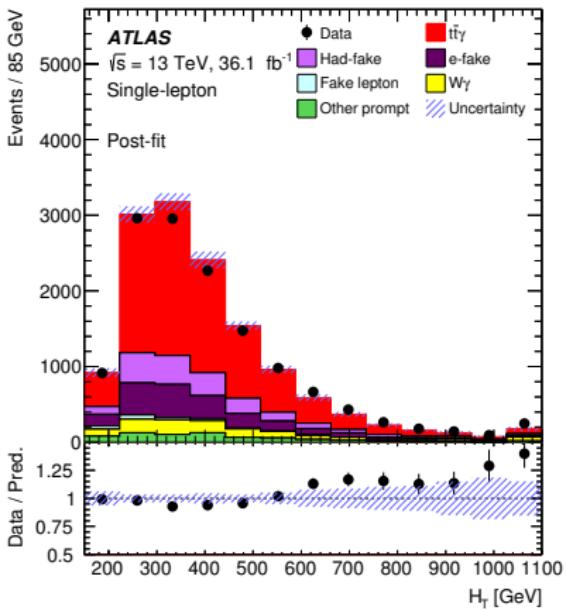
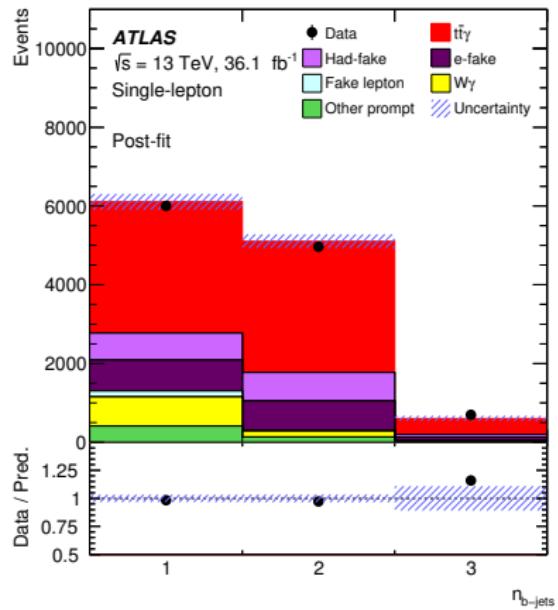
* PPT: R_η , R_ϕ , w_{η_2} , w_{s3} , F_{side} , and R_{had}

* ABCD: F_{side} , w_{s3} , ΔE , and E_{ratio}

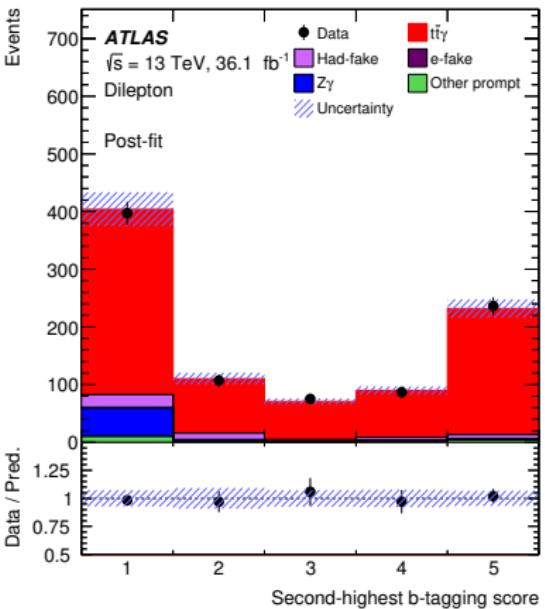
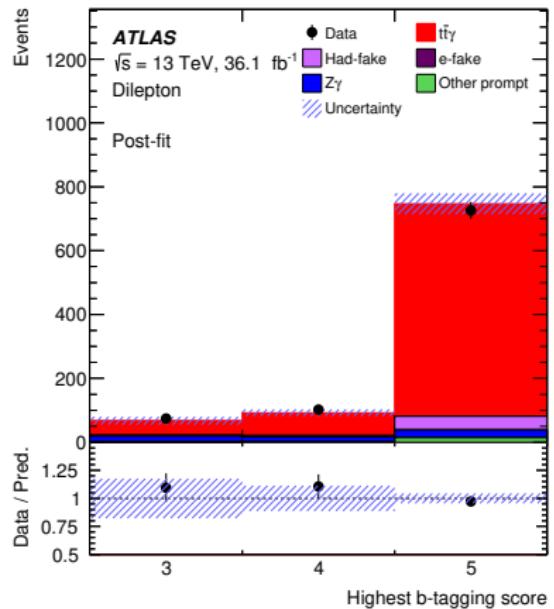
ELD Input (SL)



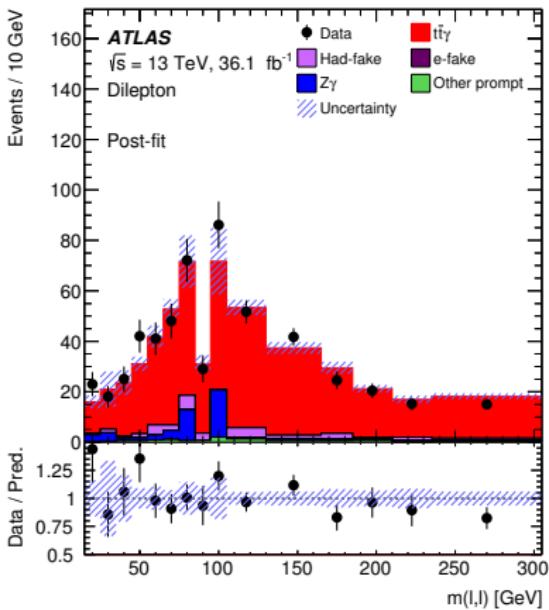
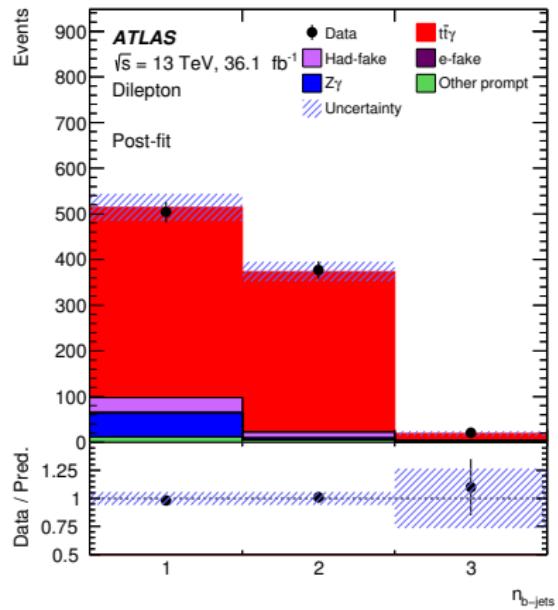
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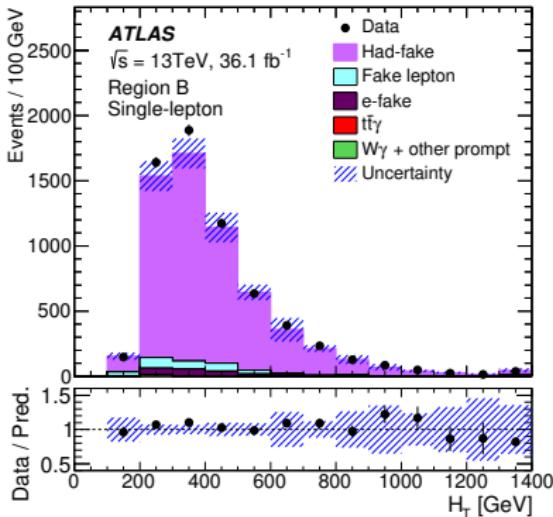
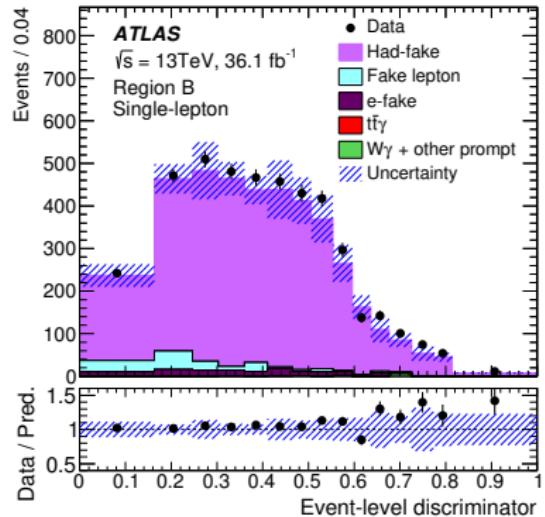
ELD Input (DL)



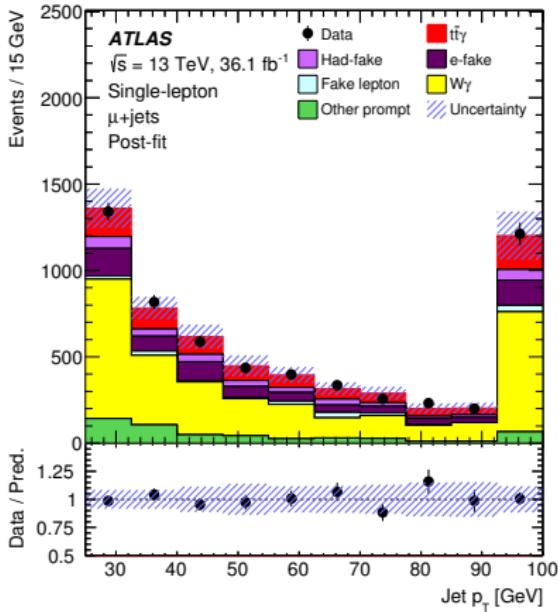
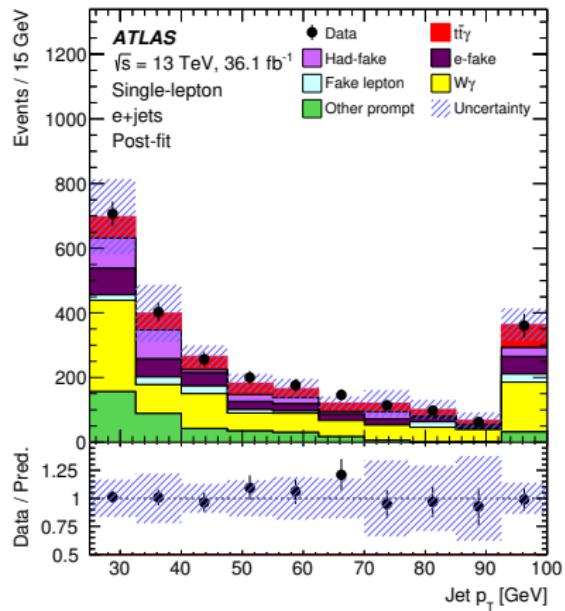
ELD Input (DL)



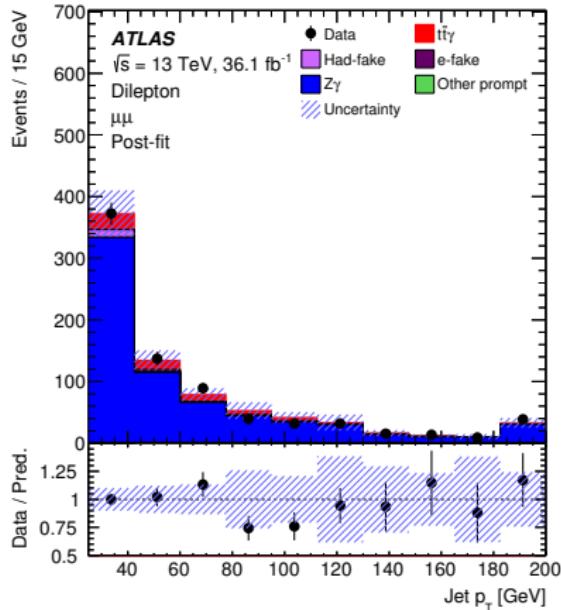
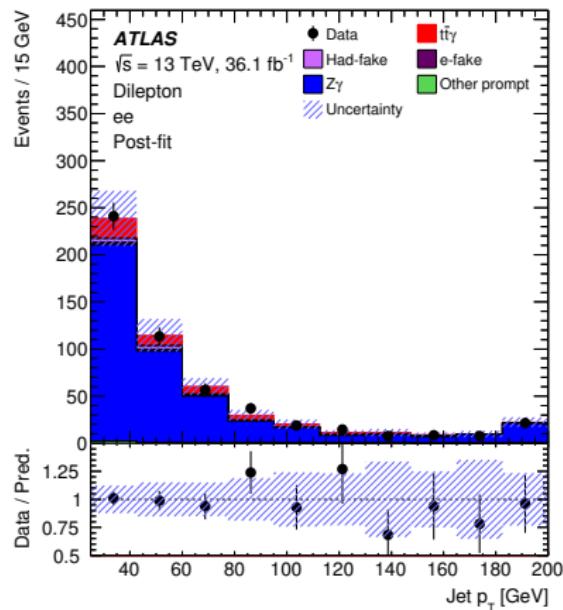
Hadronic Fake CR



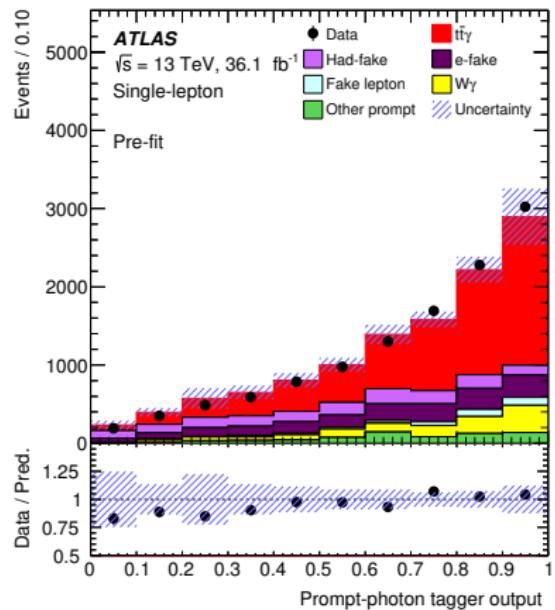
$W\gamma$ VR



$Z\gamma$ VR



Prompt Photon Tagger Distribution



Event Selection Summary

$e + \text{jets}$	$\mu + \text{jets}$	ee	$\mu\mu$	$e\mu$
Primary vertex				
1 e	1 μ	2 e , OS	2 μ , OS	1 $e + 1 \mu$, OS
Trigger match				
≥ 4 jets			≥ 2 jets	
≥ 1 b -jet				
1 γ				
$ m(e, \gamma) - m(Z) > 5$ GeV			-	
-		$m(\ell, \ell) \notin [85, 95]$ GeV		-
-		$m(\ell, \ell, \gamma) \notin [85, 95]$ GeV		-
-		$E_T^{\text{miss}} > 30$ GeV		-
-		$m(\ell, \ell) > 15$ GeV		
$\Delta R(\gamma, \ell) > 1.0$				