Measurements of inclusive and differential cross-sections of $t\bar{t}\gamma$ production in the $e\mu$ channel at 13 TeV

(ATLAS-CONF-2019-042)

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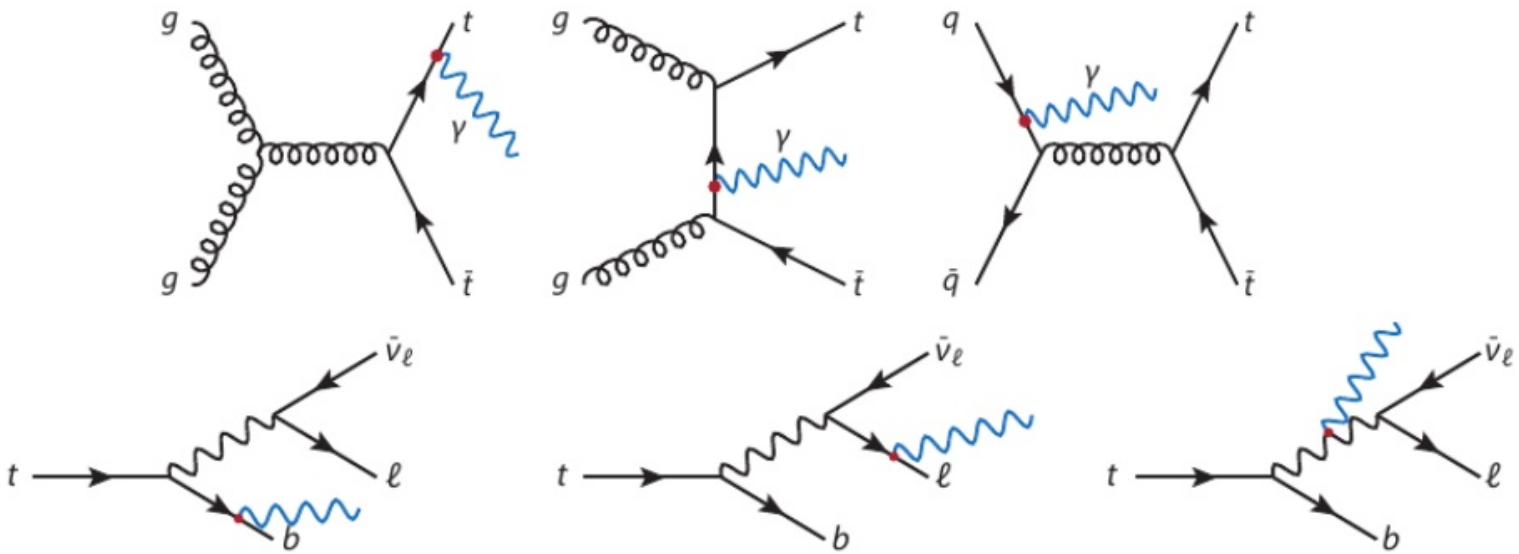
LHC Top Working Group

Studying the $t\bar{t}\gamma$ process: what and why?

- Several contributions to final states with a top quark pair and a photon



- Radiative production: probe structure of $t\gamma$ coupling
- Sensitive to new physics: top quark anomalous dipole moments, EFT interpretations (dim-6 operators)
- Enhanced $t\bar{t}$ charge asymmetry in $t\bar{t}\gamma$ process

$t\bar{t}\gamma$ cross section measurements: what and why?

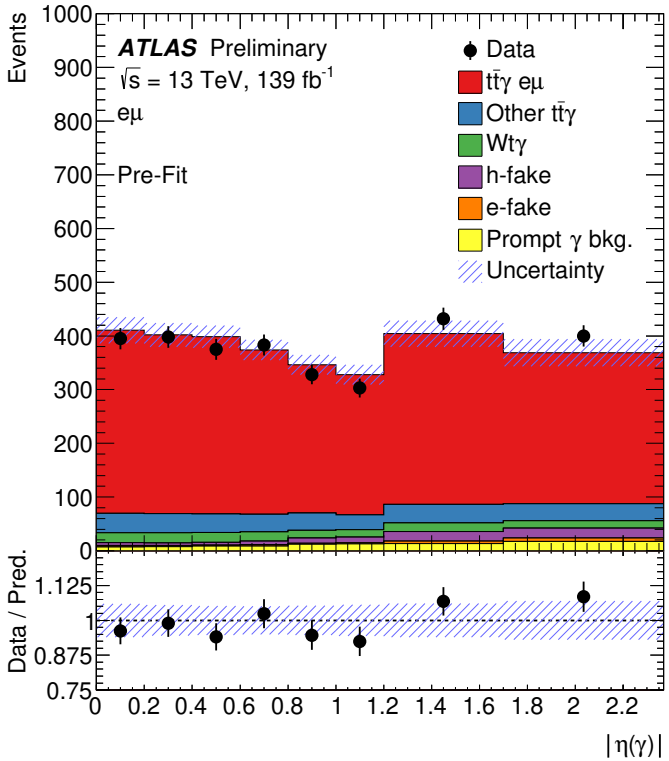
- Previous measurement: 36.1 fb^{-1} of data, single and dilepton channel, inclusive and differential cross sections at particle level (EPJC79 (2019)382) [1]
- Newest results: Inclusive and differential parton-level cross-section measurements
- Full Run 2 data (139 fb^{-1}), focus on $e\mu$ channel only
  - Cleanest $t\bar{t}$ decay channel
  - Small BR but large dataset ($\sim$2500 signal events) $\rightarrow$ allows for precision measurements
- Compare to latest theory prediction: full NLO calculation for $pp \rightarrow e\mu\nu\nu bb\gamma$ (M. Worek et al., JHEP 1810 (2018) 158)
  - Requires unfolding to parton level
  - Also measuring absolute differential cross section
  - Only events prompt $e\mu$ from W boson decays considered as signal

[1] See talk by Y. Li, LHCTopWG May

Event selection, signal and background composition

- Selection: exactly one μ and electron with opposite sign, $\geq$2 jets and $\geq$1 b-tagged jet (all with $p_T > 25$ GeV), exactly one photon with $p_T > 20$ GeV

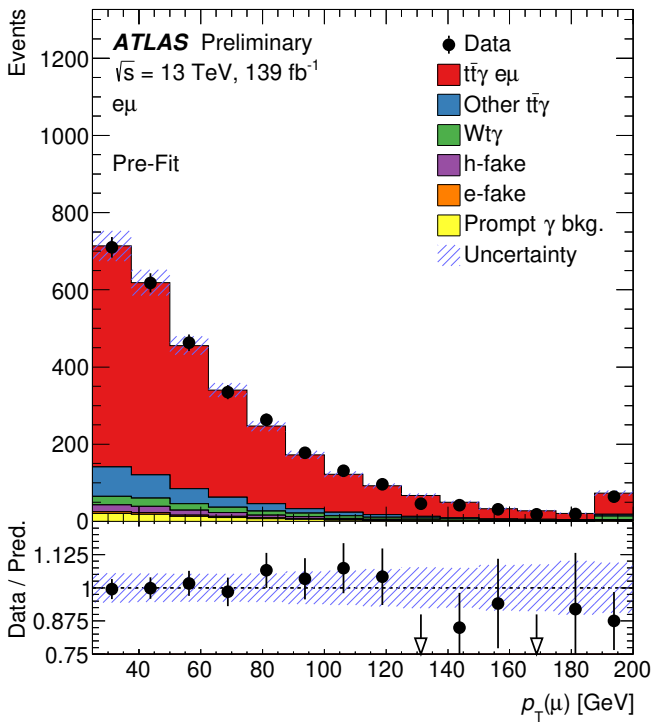
- Signal events: $e\mu$ $t\bar{t}\gamma$ events ~80%
  (LO MadGraph5_aMC@NLO, full 2→7 process, doubly-resonant)
- Other $t\bar{t}\gamma$: non-$e\mu$ $t\bar{t}\gamma$ events
  (mostly leptonic τ decays)
- Single top tW+photon
  (LO MadGraph5_aMC@NLO, 5FS)
- Prompt-photon background: $W\gamma/Z\gamma$+jets, diboson and $t\bar{t} + V$ with prompt photon from shower

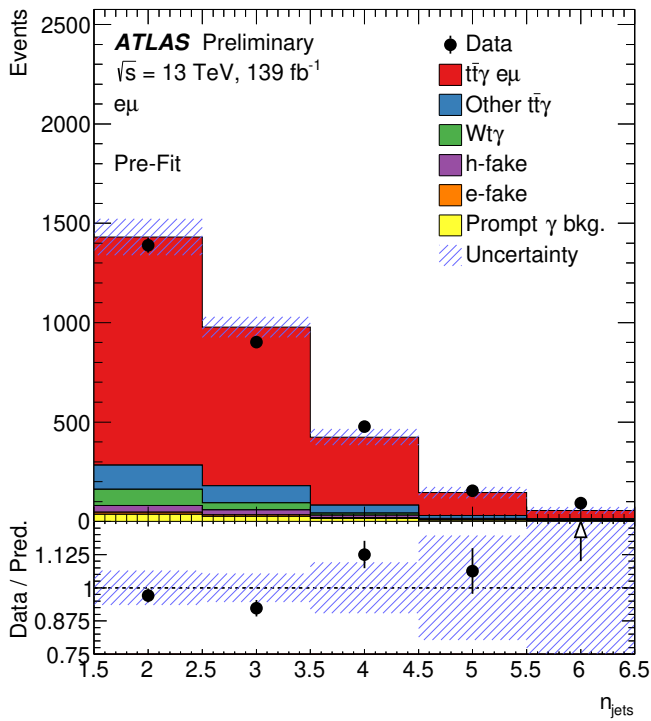


- Fake-photon background:
  - "Hadronic fakes", i.e. j → γ, non-prompt photons from jets (mostly from $t\bar{t}$ and W/Z+jets)
  - "Electronic fakes", i.e. e → γ

Event yields and control distributions

	full data set
$t\bar{t}\gamma\ e\mu$	2450 ± 120
Other $t\bar{t}\gamma$	266 ± 13
$Wt\gamma$	131 ± 22
h-fake	80 ± 40
e-fake	24 ± 12
Prompt γ bkg.	90 ± 40
Total	3030 ± 150
Data	3014





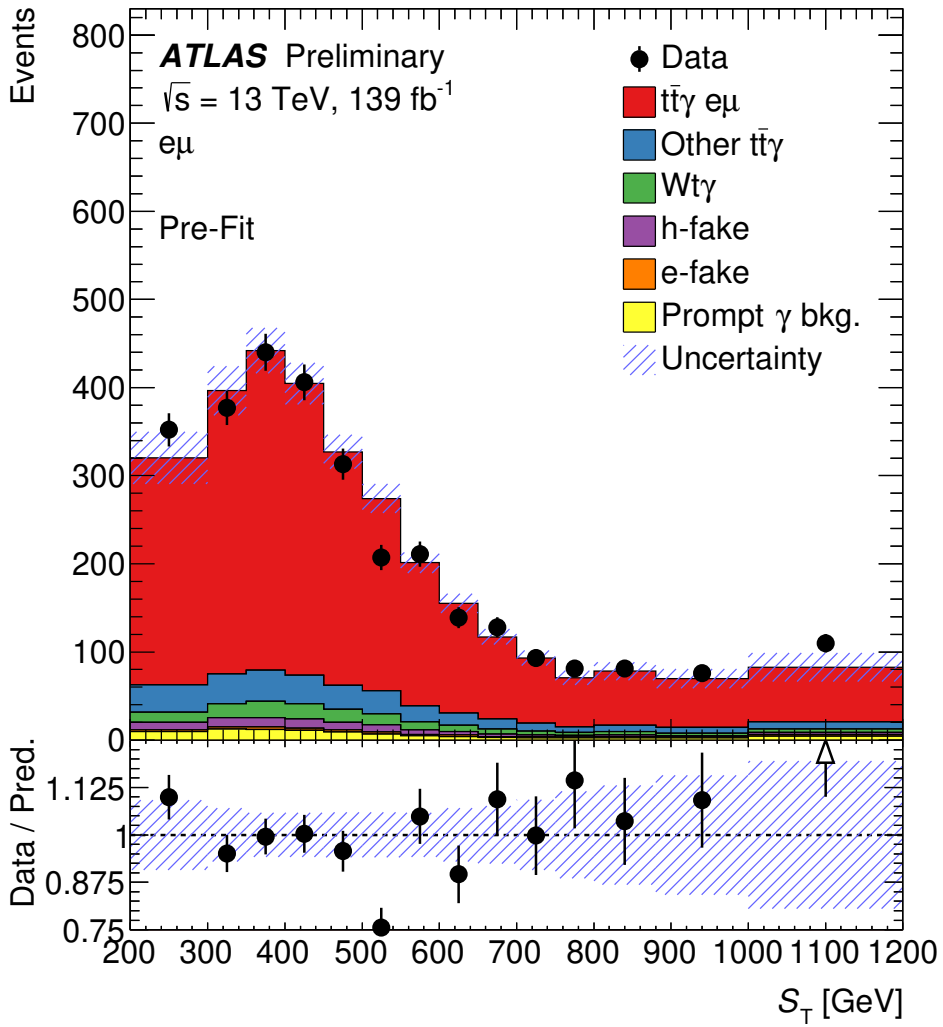
Signal definition and fiducial phase space

- Measurement done at parton level to compare with NLO ME calculation
- Leptons from W boson decays, after parton shower dressed with close-by photons with ΔR <0.1
- Photon: after PS
- b-jets [2]
  - Parton-level jets defined via jet clustering of all partons (ISR and FSR) including b-quarks (anti-kt with R=0.4)
  - Required to include a b-quark from the decay of a top quark
- Fiducial phase space:
  - Exactly one electron and muon with p_{T} >25 GeV, $|\eta| < 2.5$ (from prompt W decays)
  - Exactly one photon with p_{T} >20 GeV, $|\eta| < 2.37$
  - Exactly one b- and one $\bar{b}$-jet with p_{T} >25 GeV, $|\eta| < 2.5$
  - $\Delta R(l, \gamma) > 0.4$, $\Delta R(e, \mu) > 0.4$, $\Delta R(b, \bar{b}) > 0.4$, $\Delta R(l, b) > 0.4$

[2] Calculation: anti-kt with R=0.4 to cluster b-quarks and NLO emissions to b-jets

Inclusive cross section

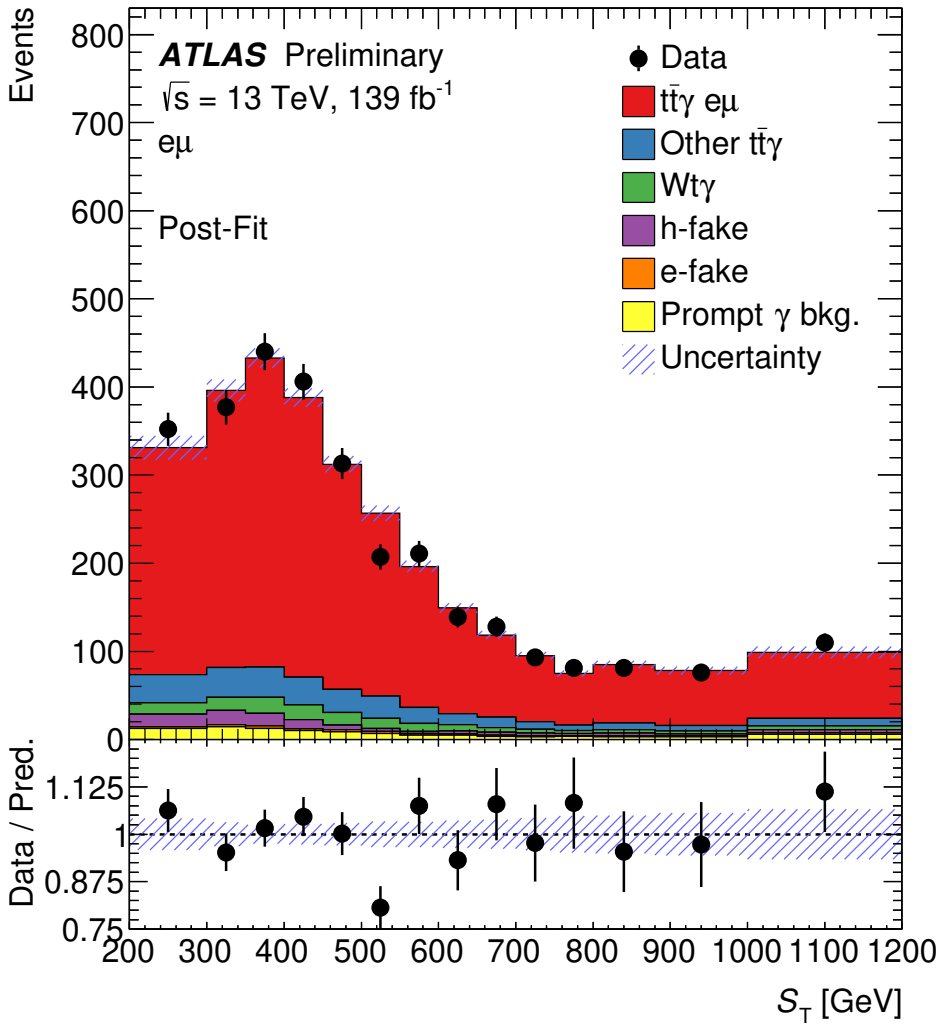
- Inclusive σ obtained with a profile likelihood fit to S_T distribution (sum of all particle momenta)
- Dominant sources of uncertainty considered
  - $t\bar{t}\gamma$, $tW\gamma$ modelling uncertainties: alternative showering Pythia/Herwig, Ren./factorisation scales, ISR variation
  - Additional 50% BG normalisation (h-fake/e-fake/prompt-photon)



Results: inclusive cross section

Table: Categories of systematic uncertainties and their relative impact on the result.

Category	Uncertainty
Signal modelling	3.4%
Background modelling	2.2%
Photons	2.0%
Luminosity	1.9%
Jets	1.8%
Flavour-tagging	1.1%
MC statistics	0.5%
Others	1.7%
Total syst.	5.5%



Results: inclusive cross section

- Measured cross section in fiducial phase space:

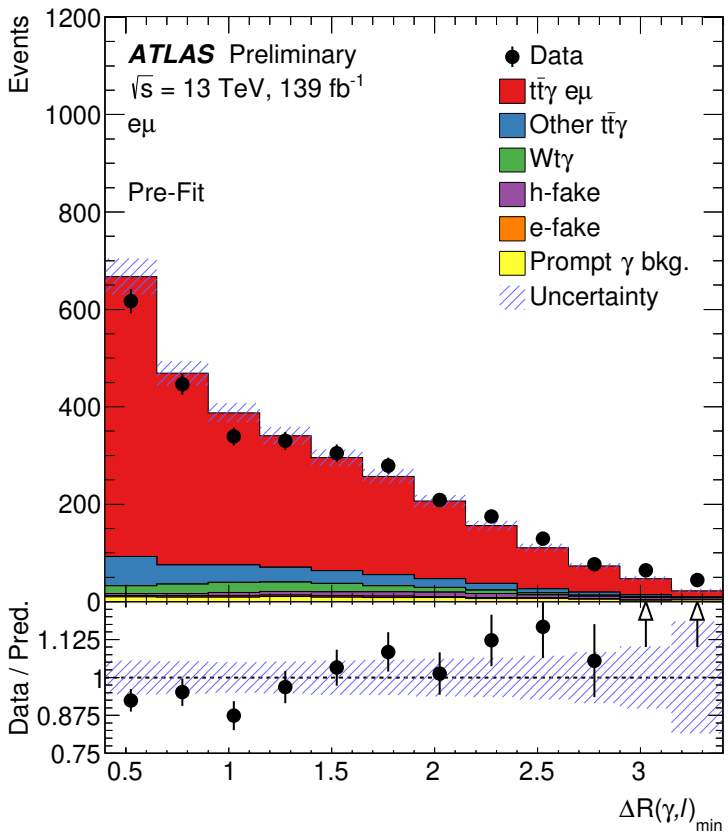
$$\sigma_{\text{fid}}(t\bar{t}\gamma \to e\mu) = \frac{N_{\text{reco}}^{\text{data}} - N_{\text{reco}}^{\text{bkg}}}{\mathcal{L}} \cdot \frac{N_{\text{reco}}^{e\mu}}{N_{\text{reco}}^{\text{all } t\bar{t}\gamma}} \cdot \frac{1}{C_{e\mu}} = 44.2^{+0.9}_{-0.9}(\text{stat})^{+2.6}_{-2.4}(\text{syst})\,\text{fb}$$

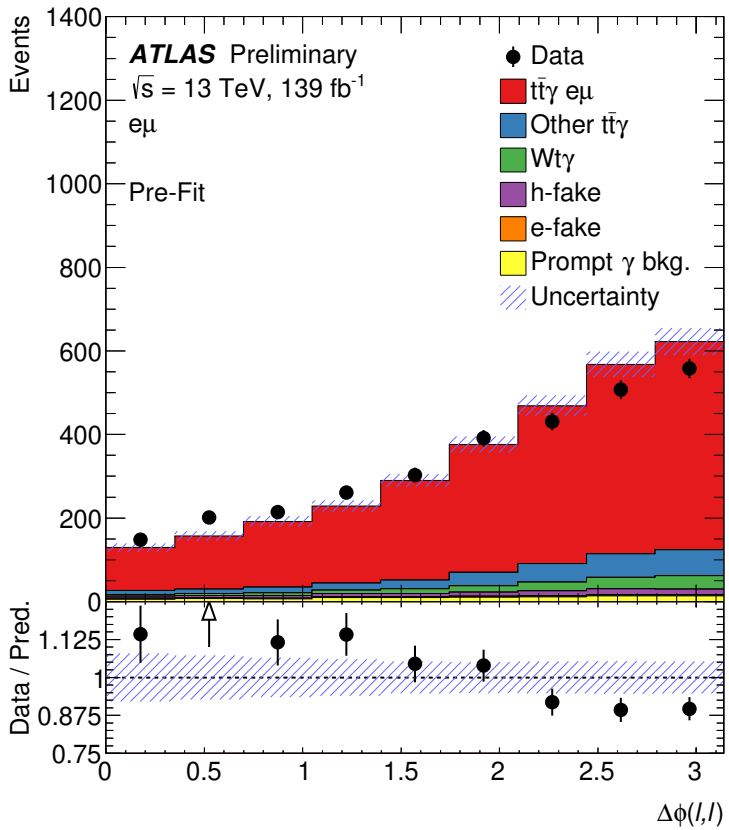
  with $C_{e\mu} = \frac{N_{\text{reco}}}{N_{\text{MC}}^{\text{fid}}} = 0.393 \pm 0.013$

- Compared to theory value: $\sigma = 39.50^{+0.56}_{-2.18}(\text{scale})^{+1.04}_{-1.18}(\text{PDF})$ fb
  - Assumed top mass: 173.2 GeV
  - CT14 PDF set
  - Dynamic scale $H_T/4$
  - theory includes $tW\gamma$, non-resonant diagrams, while measurement only $t\bar{t}\gamma$ emission

Differential cross section

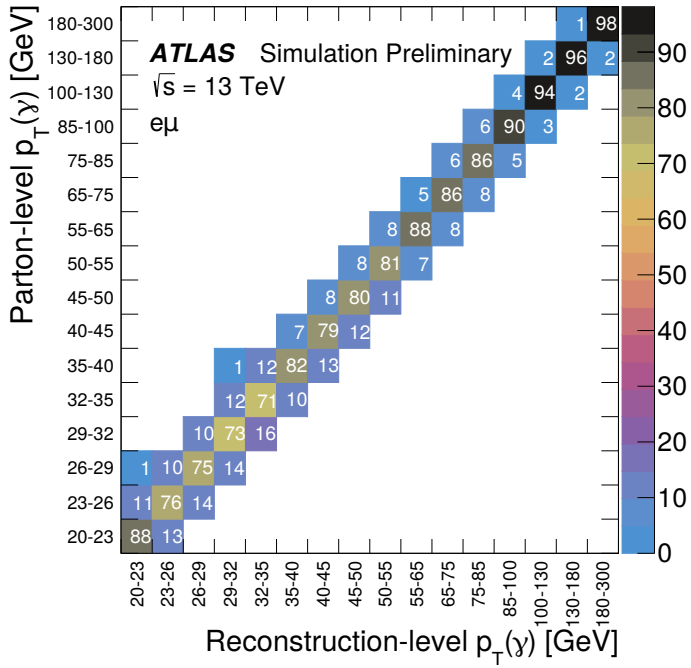
- Absolute and normalised differential cross-sections measured at parton level
- Compared to NLO QCD theory prediction and $t\bar{t}\gamma$ LO MC predictions (only normalised cross sections)
- Variables: photon p_{T} and $|\eta|$, $\Delta R(\gamma,\ell)_{\mathrm{min}}$, $\Delta\phi(\ell,\ell)$ and $|\Delta\eta(\ell,\ell)|$

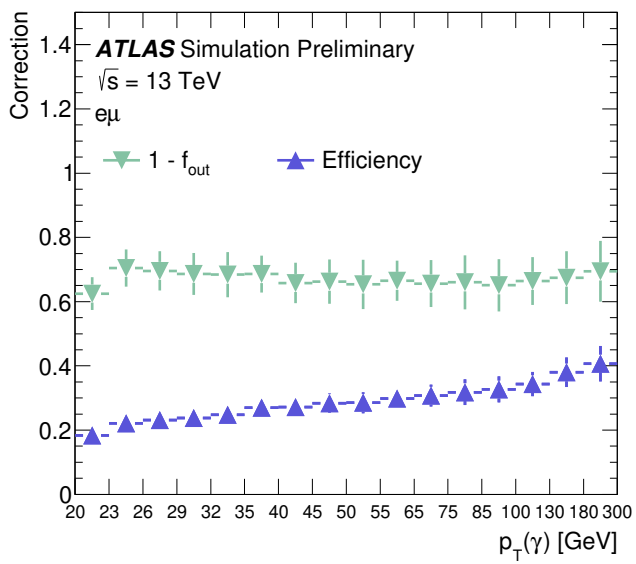




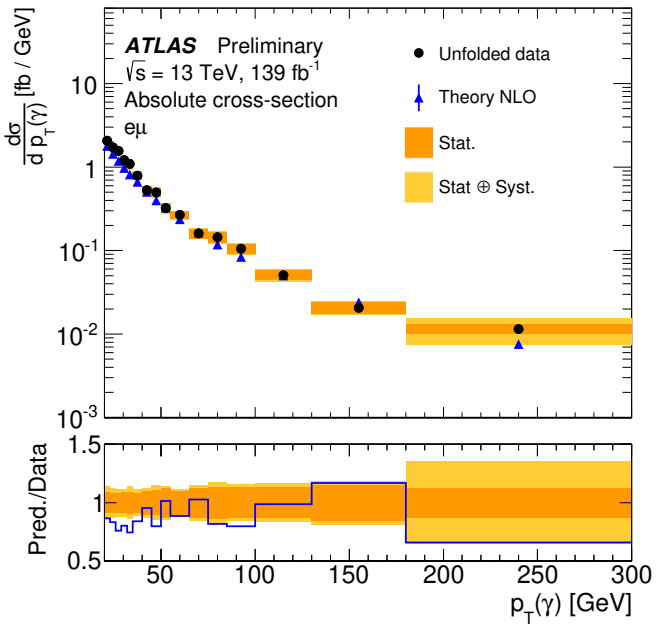
Unfolding: binning, migration matrix

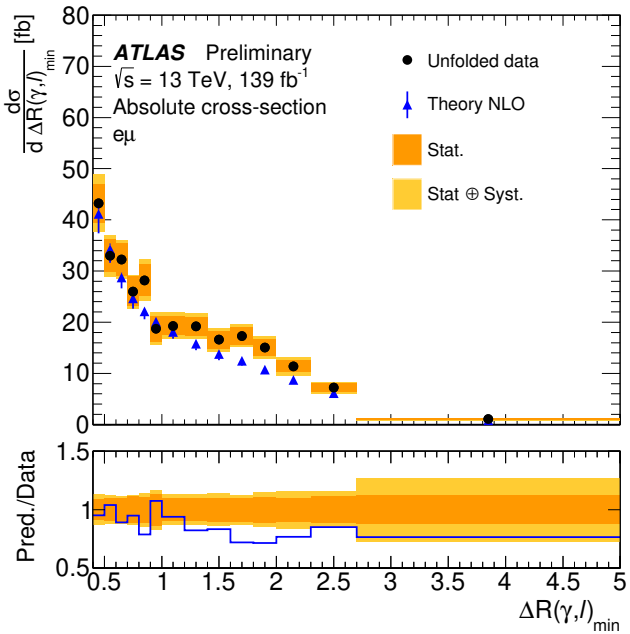
- Use Iterative Bayesian Unfolding
- Binning optimised with respect to:
  - 10% uncertainty per bin
  - bin width $>$ 2·resolution
- Observables have very good resolution. Bin width limited by stat. uncertainty
- Small bin-by-bin migrations, purity close to 100% for leptonic observables

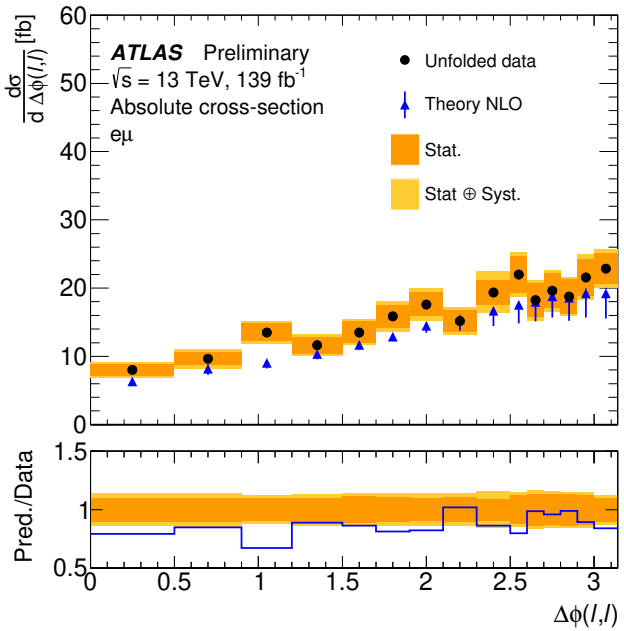




Absolute cross sections

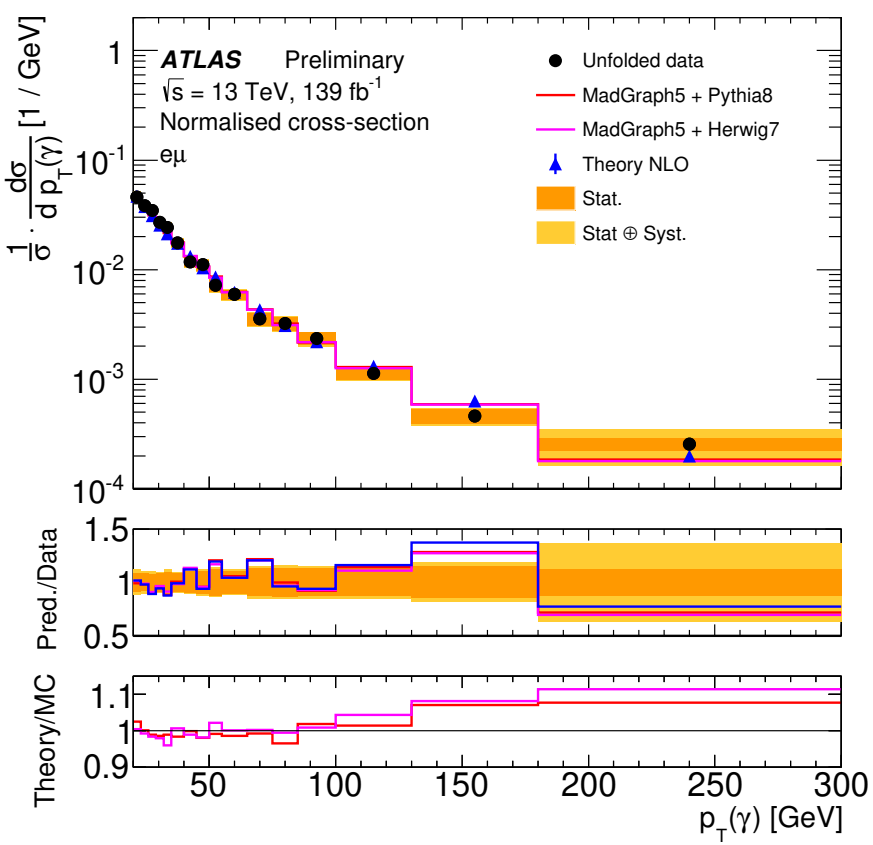


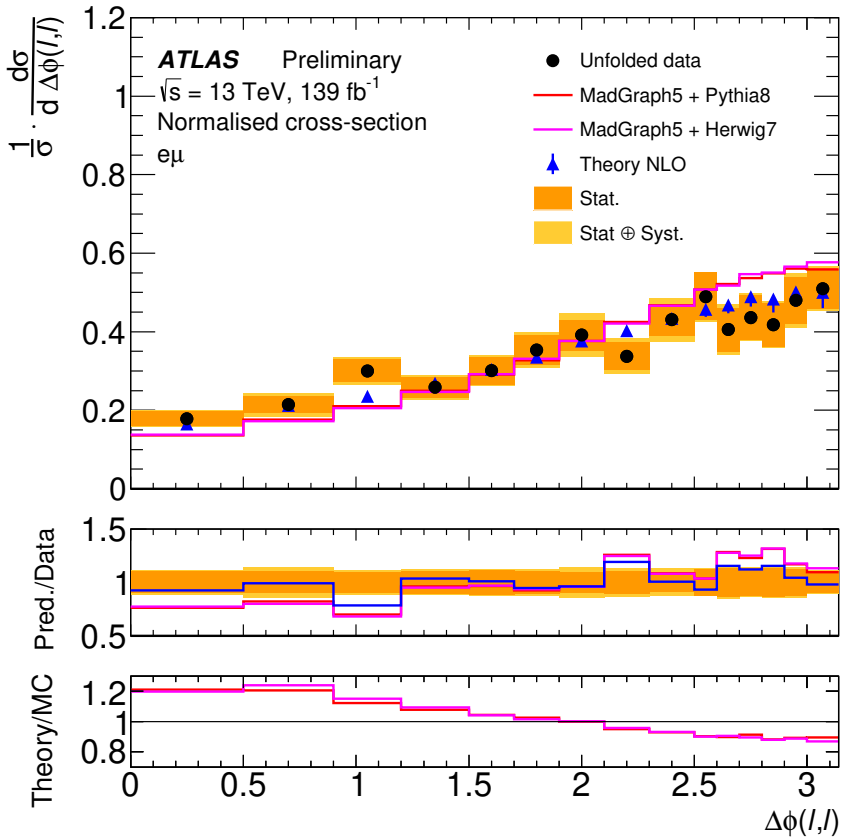




Predictions	$p_T(\gamma)$		$\Delta R(\ell,\gamma)$		$\Delta\phi(\ell,\ell)$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
Theory NLO	16.0/16	0.45	12.8/14	0.54	16.3/15	0.36

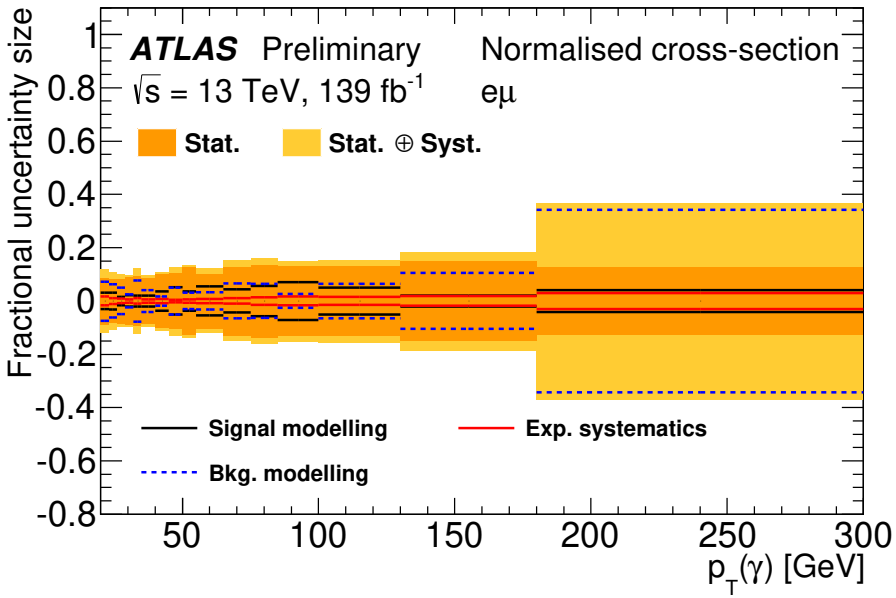
Normalised cross sections

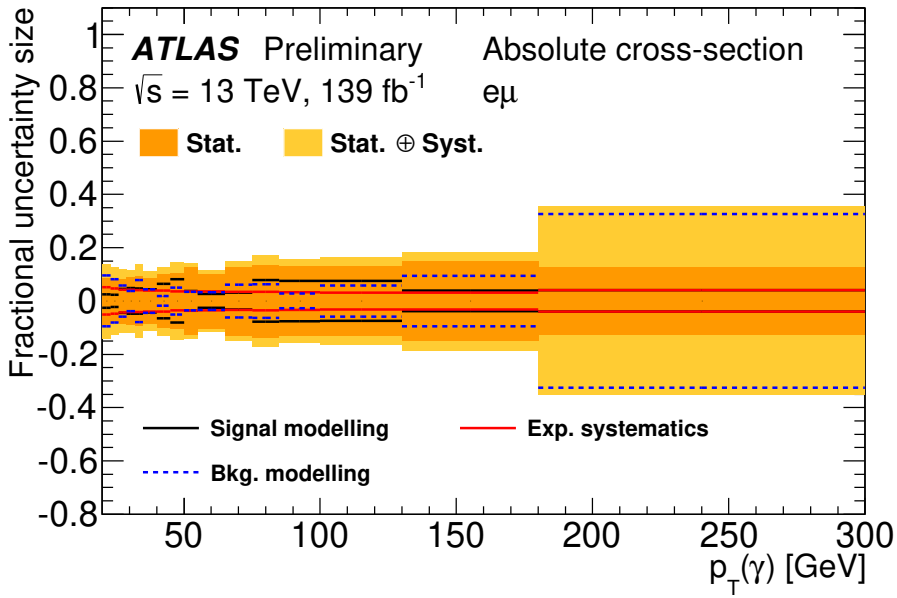




Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value
MadGraph+Pythia8	14.0/15	0.53	35.2/14	<0.01
MadGraph+Herwig7	11.9/15	0.69	36.8/14	<0.01
Theory NLO	16.9/15	0.32	12.0/14	0.61

Uncertainties (photon p_T)





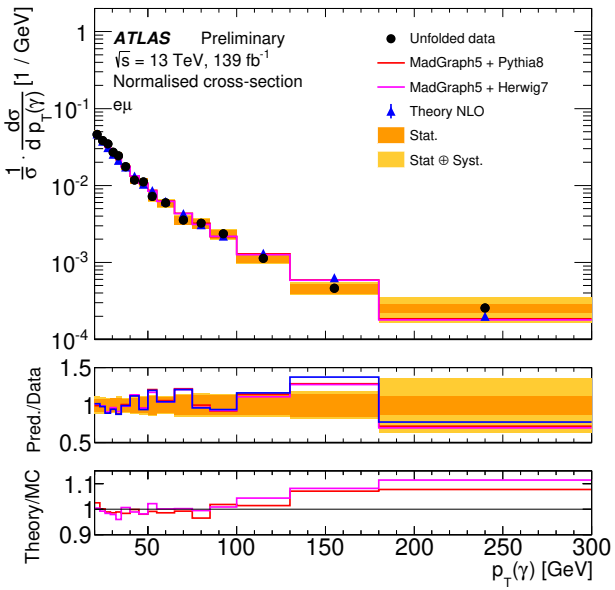
- Dominated by statistical uncertainties (∼10%)
- Dominant systematic uncertainties: $t\bar{t}\gamma$ and background modelling
- Experimental uncertainties in normalised cross sections: negligible impact

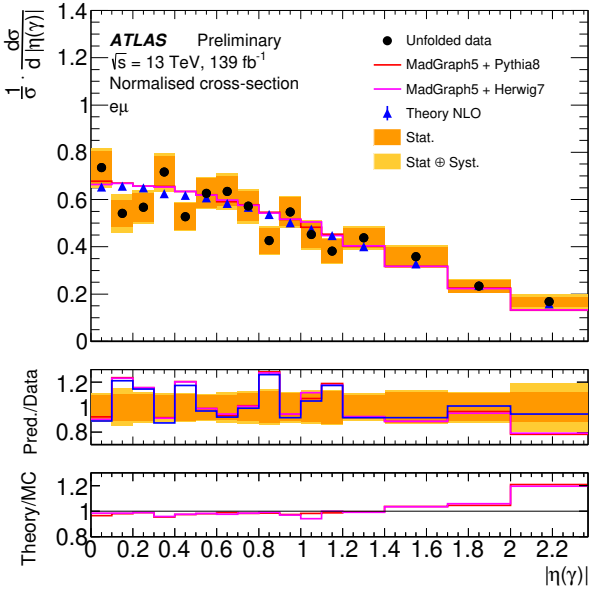
Summary

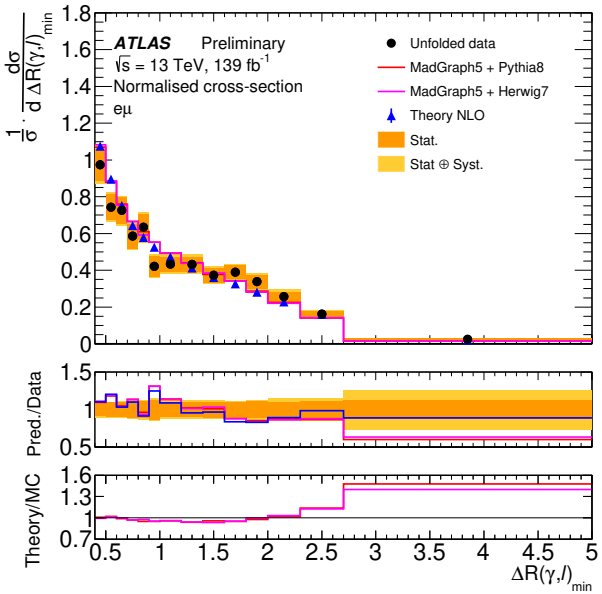
- Presented $t\bar{t}\gamma$ analysis in the $e\mu$ channel with full Run 2 data (ATLAS-CONF-2019-042)
  - Inclusive and differential measurements in fiducial phase space (absolute and normalised)
  - Results compared with latest NLO theory prediction: results compatible within uncertainties
  - Precision of inclusive measurement around 6%, similar as the theory
  - Normalised differential cross-sections also compared to $t\bar{t}\gamma$ LO MC (2→7), MG5+P8/H7: reasonable agreement with data, NLO calculation tends to describe data better
- Not the end of the story: many more interesting measurements/interpretations exploiting top quark + photon topologies as anomalous couplings, EFT, charge asymmetry, etc.

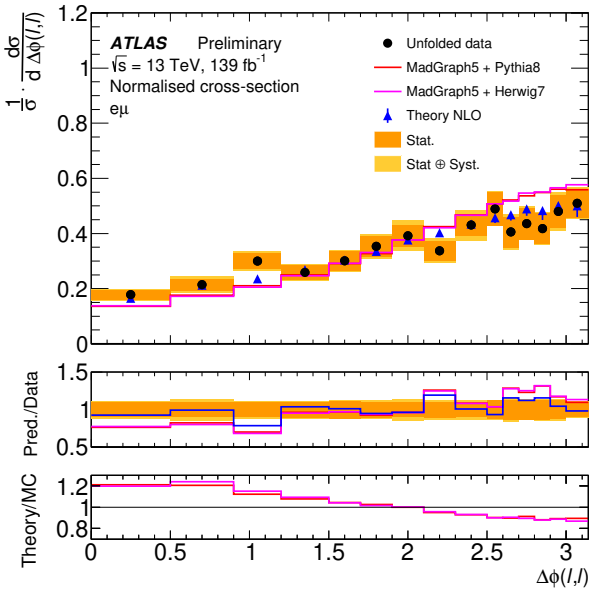
BACK UP

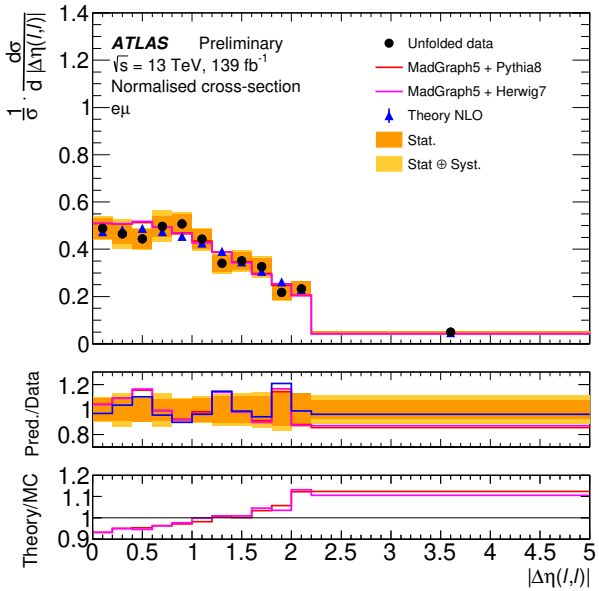
Normalised cross sections



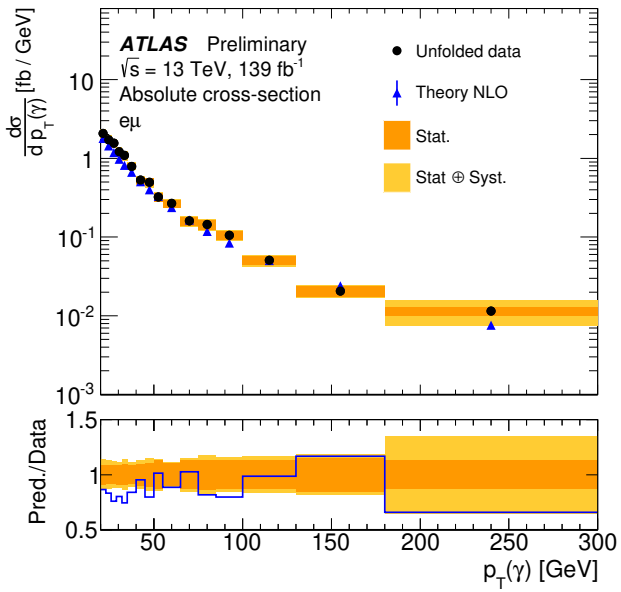


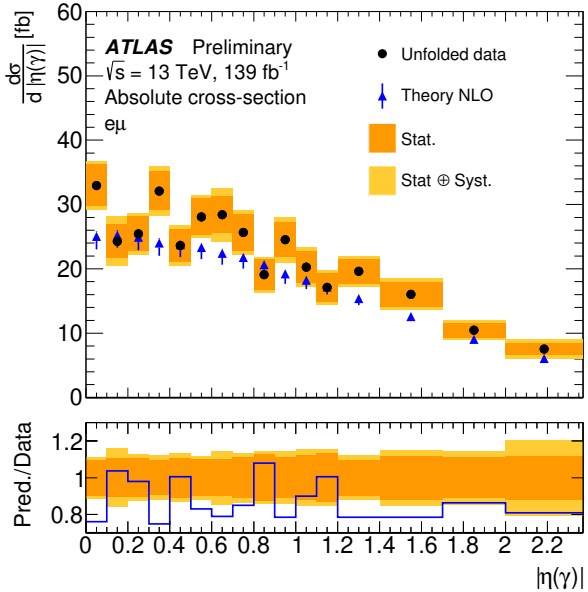


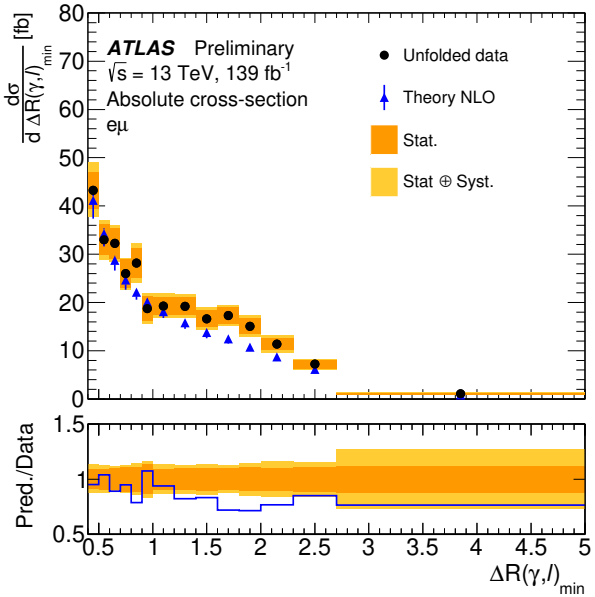


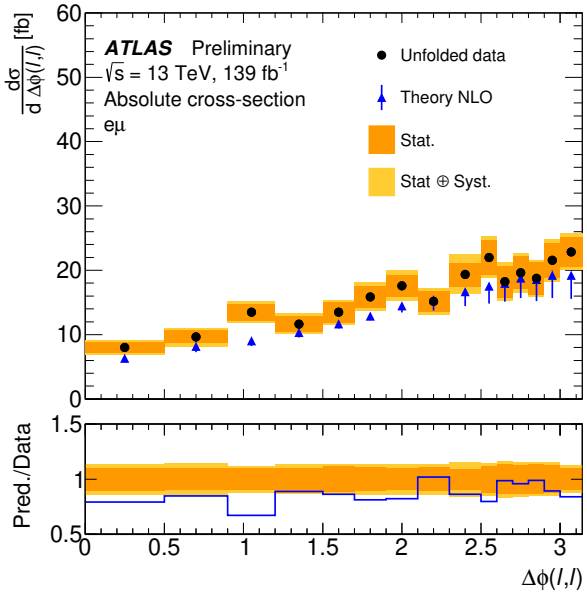


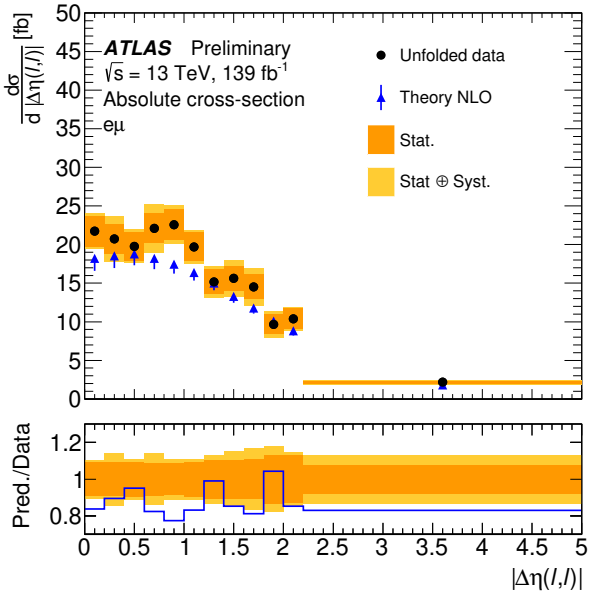
Absolute cross sections



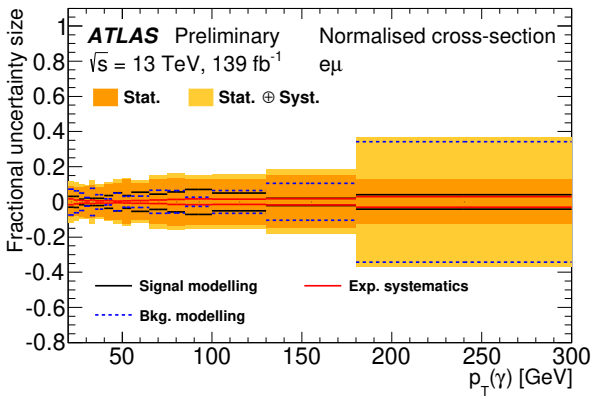


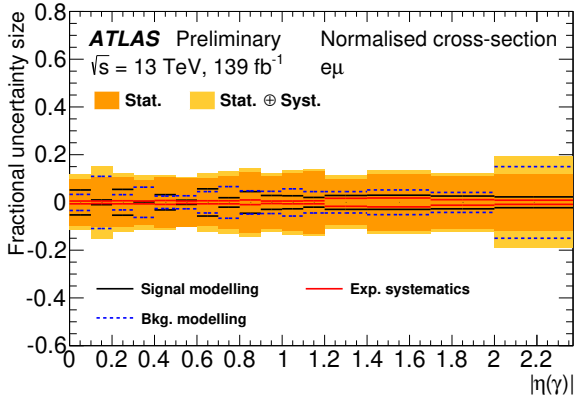


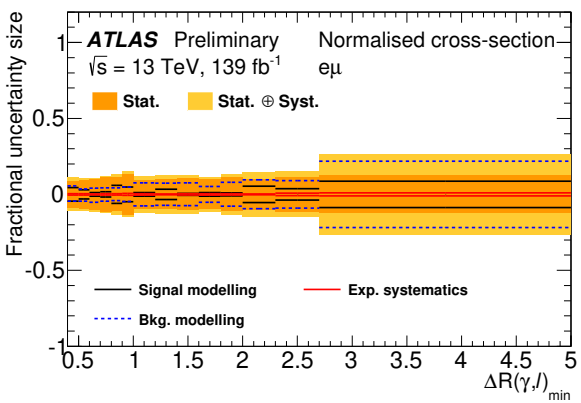


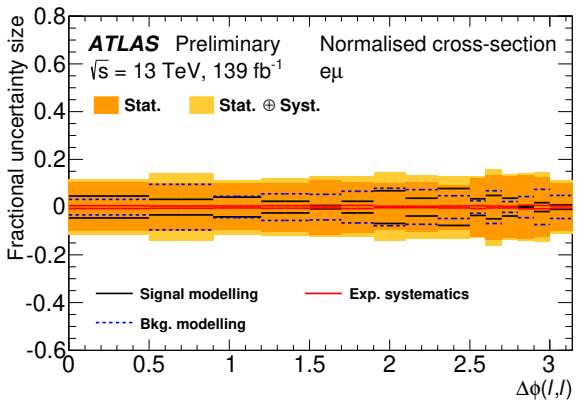


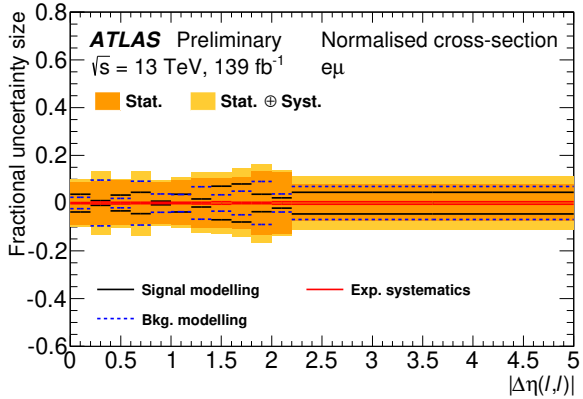
Uncertainties: Normalised cross sections



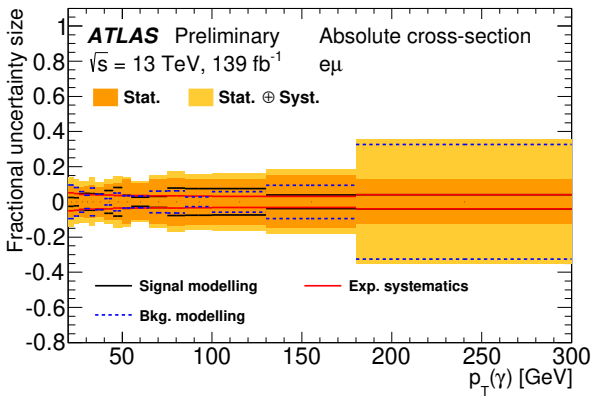


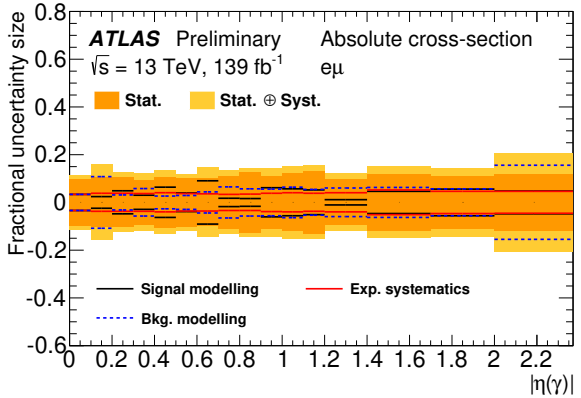


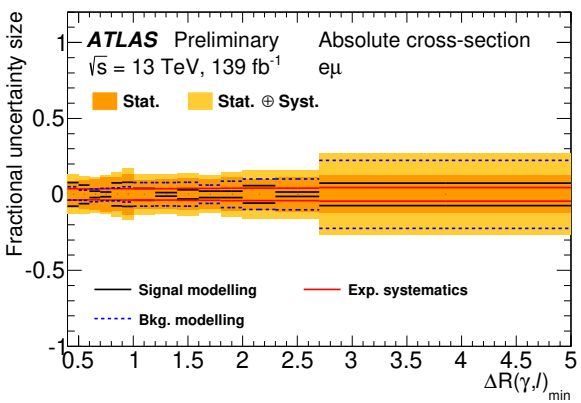


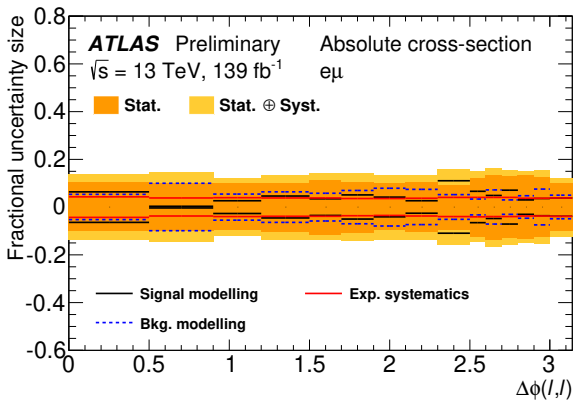


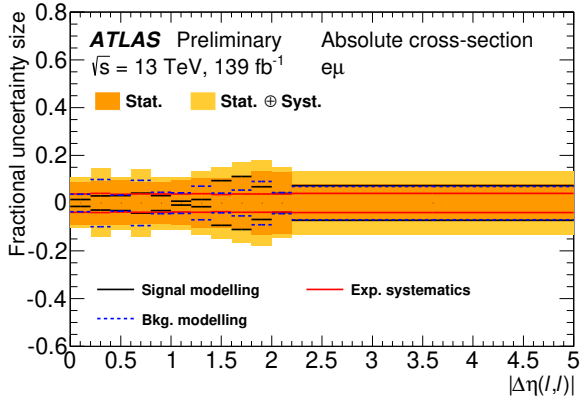
Uncertainties: Absolute cross sections











χ^2/ndof cross sections

Predictions	$p_T(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\ell,\gamma)$		$\Delta\eta(\ell,\ell)$		$\Delta\phi(\ell,\ell)$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
MadGraph+Pythia8	14.0/15	0.53	20.7/15	0.15	17.3/13	0.19	8.3/11	0.69	35.2/14	<0.01
MadGraph+Herwig7	11.9/15	0.69	20.8/15	0.14	18.5/13	0.14	9.4/11	0.59	36.8/14	<0.01
Theory NLO	16.9/15	0.32	20.1/15	0.17	14.7/13	0.33	7.2/11	0.78	12.0/14	0.61

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	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
Theory NLO	16.0/16	0.45	20.7/16	0.19	12.8/14	0.54	11.4/12	0.49	16.3/15	0.36

Systematic uncertainties

- $t\bar{t}\gamma$ modelling systematics included:
  - Ren./factorisation scale variations, shower radiation, alternative showering with Herwig7, PDF uncertainties
- $t\bar{t}$ modelling fully included: ren./fact. scales, hdamp, radiation, ME
- $Wt\gamma$ modelling: Ren./factorisation scale, alternative showering: Herwig7, reweighting uncertainty, 15% normalisation
- Additional 50% BG normalisation uncertainties h-fake/e-fake/prompt-photon
- Experimental uncertainties: lepton, photon, jet , b-tagging, MET, pileup and luminosity

Signal and background composition

- $t\bar{t}\gamma$ events: LO Madgraph5, full 2→7 process, doubly-resonant

  $\sigma = 4.6$ pb with cuts: isolated photon with $p_T > 15$ GeV, $\Delta R(\gamma, l/q) > 0.2$
- Dedicated single top tW+photon: LO MadGraph_aMCNLO), 2→3 process pp→ $Wt\gamma$, 5F scheme
- Minor background samples:
  - Dedicated $W\gamma/Z\gamma$+jets samples (Sherpa 2.2.2/2.2.4) and inclusive W/Z+jets samples (Sherpa 2.2.1), overlap removed
  - Diboson with prompt photon from shower (Sherpa 2.2.1 and 2.2.2)
  - $t\bar{t} + V$ with prompt photon from shower (MadGraph_aMCNLO)

Object and event selection

	Definition, Isolation	p_T	$\|\eta\|$
Electrons	TightLH, Gradient	> 25 GeV	< 2.47, crack excluded
Muons	Medium, FCTight_FixedRad	> 25 GeV	< 2.5
Photons	Tight, fixed-cut tight	> 20 GeV	< 2.37, crack excluded
Jets	Anti-k_t EM-topo jets with R=0.4	> 25 GeV	< 2.5
b-tagging	MV2c10 tagger at 85% WP		
Triggers	single-e OR single-mu trigger		

	SR definition
Common	Primary vertex, event cleaning etc.
Photons	= 1 with p_T > 20 GeV
Leptons	>= 1 e/μ with trigger match and p_T > 25, 27, 28, 28 GeV
	= 1e with p_T > 25 GeV
	= 1μ with p_T > 25 GeV
	opposite sign
ΔR	ΔR(γ, l) > 0.4
Jets	>= 2 with p_T > 25 GeV
b-tags	>= 1