JOKER TALK

Measurements of inclusive and differential cross-sections of $t\bar{t}\gamma$ production in leptonic final states in a fiducial volume at $\sqrt{s}$ = 13 TeV

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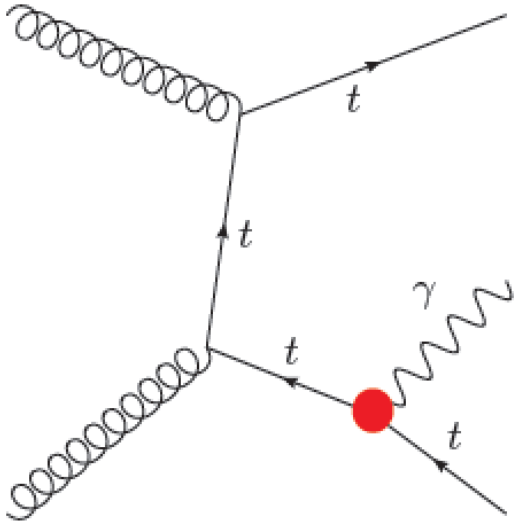
on behalf of the ATLAS Collaboration



Motivation
Event selection
Analysis strategy
Backgrounds estimation
Results (fiducial cross-section measurements)

ATLAS-CONF-2018-048

$tt\gamma$ production

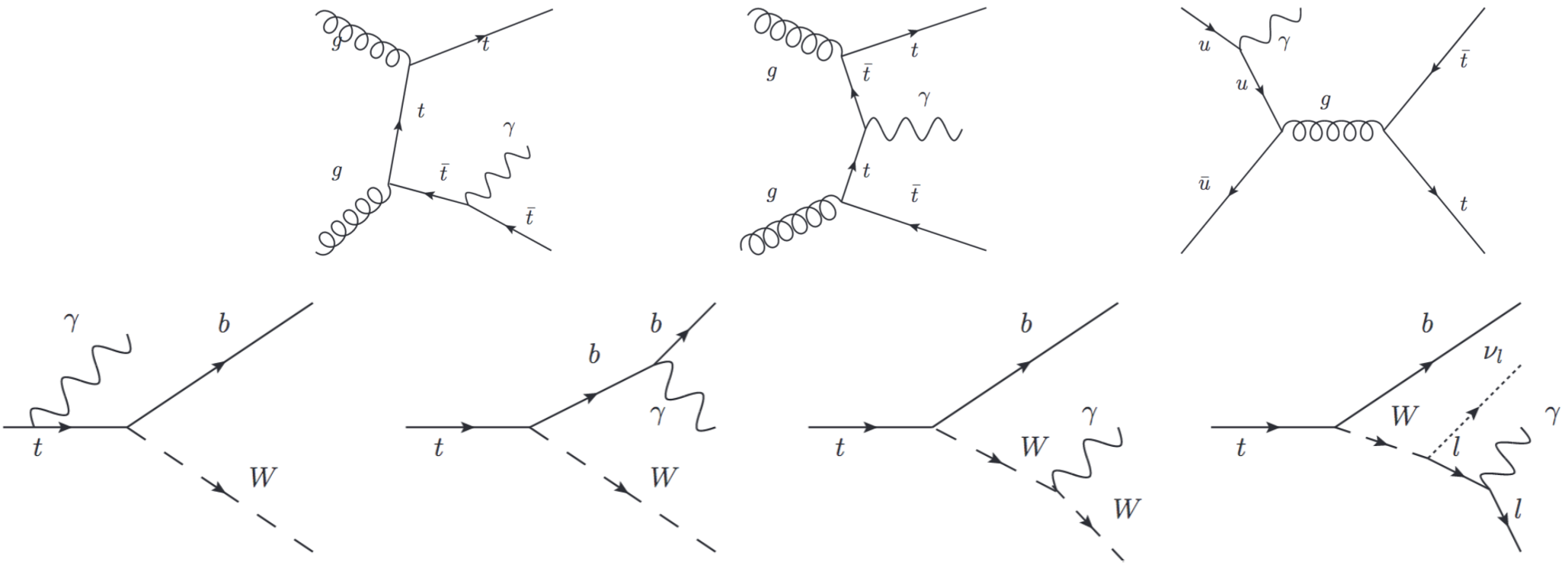
- direct probe of electromagnetic coupling (top electric charge)
- *gg & qq* initiated: potential charge asymmetry measurement (enhanced compared to *tt*)
- can constrain some of the Wilson coefficients in top-quark effective field theories

Photon can be emitted from

A) Production (emission before top goes on-shell): ISR+off-shell tops

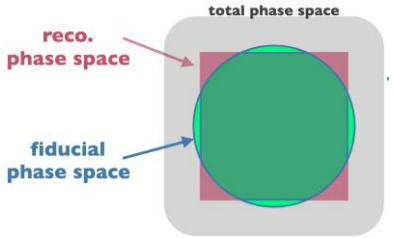
B) Decay: on-shell top quarks and its decay products

→ selection suppresses FSR photons from top decay products



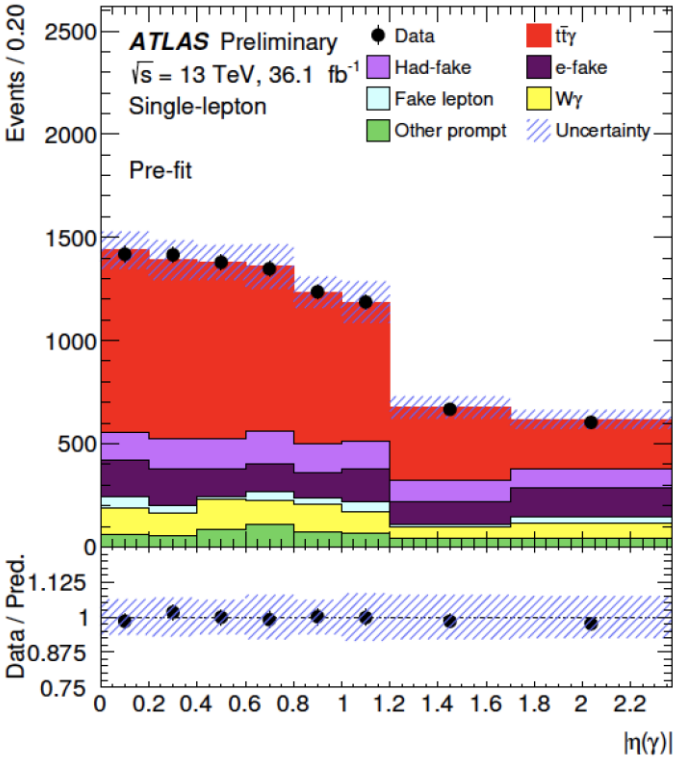
Event selection

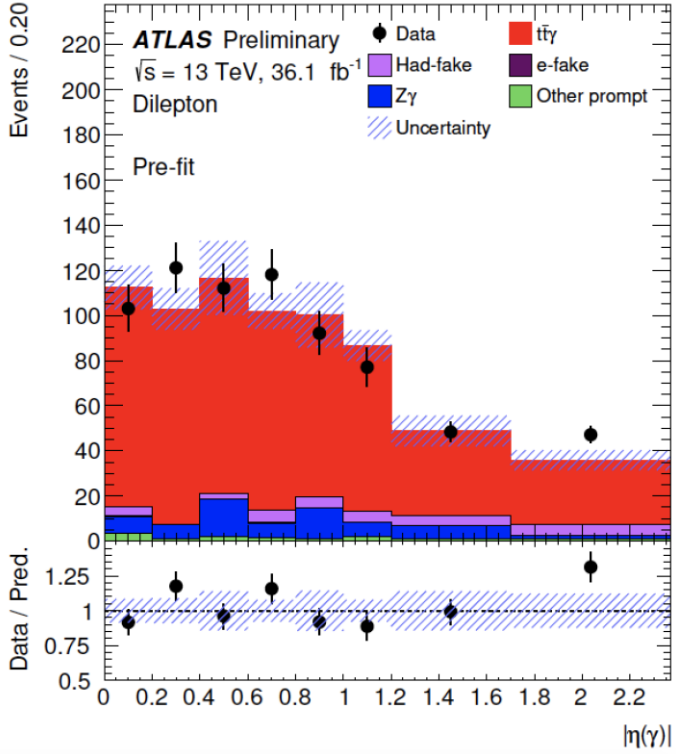
- 1 or 2 OS leptons (≥ 25 GeV)
- ≥4 or ≥2 jets, ≥1 b-jet (≥ 25 GeV)
- =1 photon (≥ 20 GeV)
- ΔR(ℓ,γ)>1.0



	Single-lepton channel	Dilepton channel
$t\bar{t}\gamma$	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

Had-fake
Fake lepton
e-fake
Wγ

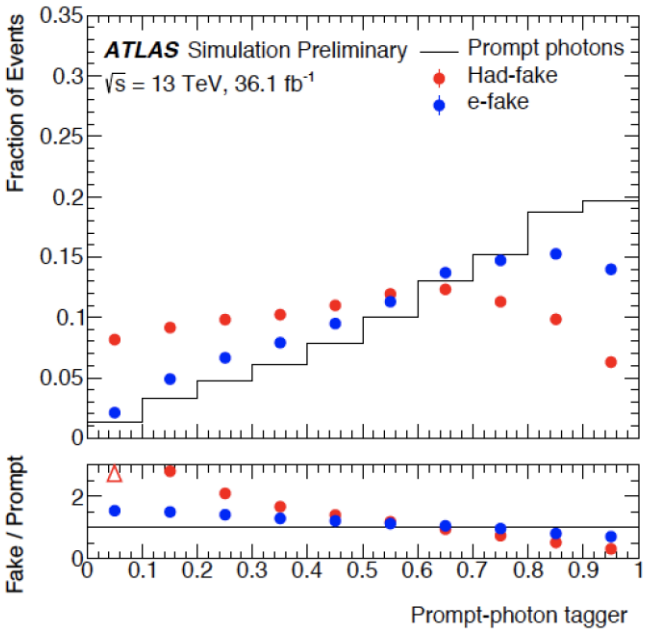




Analysis strategy

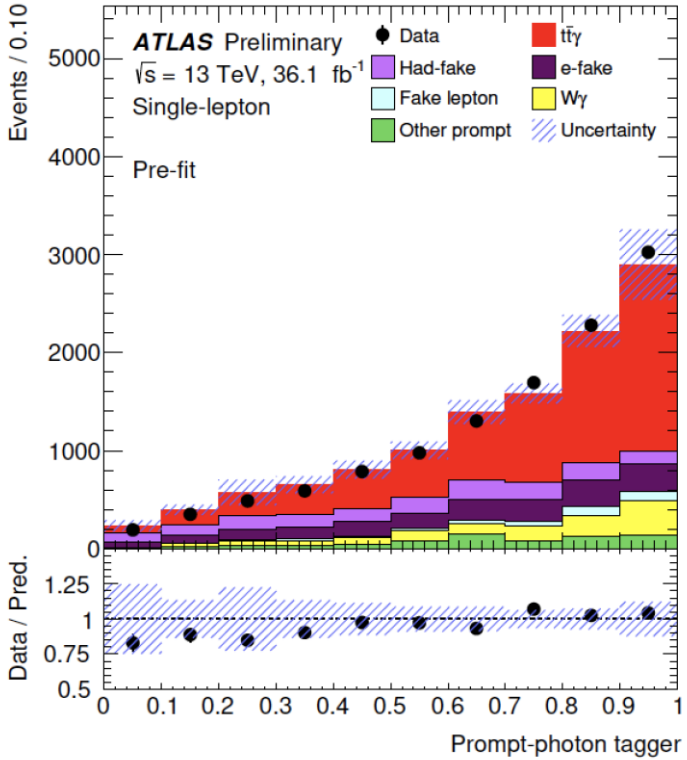
Object-level MVA to reject hadronic fakes: prompt photon tagger

- only for single-lepton channel
- analysis independent
- shower-shape variables as inputs: R_{had}, R_{η}, R_{ϕ}, w_2, w_1, f_{side}



Event-level MVA to reject background:
event level discriminator (ELD)

- 15 (7) variables for single-lepton (di-lepton)
- most-discriminant variables:
  single-lepton: b-tagging score, PPT and jets p_T
  di-lepton: b-tagging score, m(ll), $E_{T,\,miss}$ and jets p_T



Cross-section measurements

- Fiducial inclusive cross-section: profile likelihood fit to ELD
- Normalised fiducial differential cross-sections: unfolding

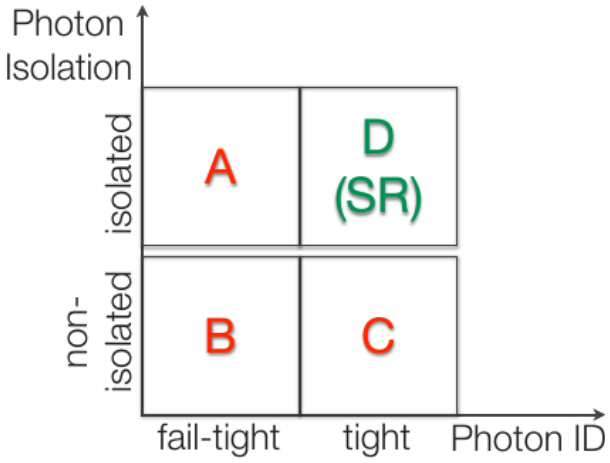
Background estimation

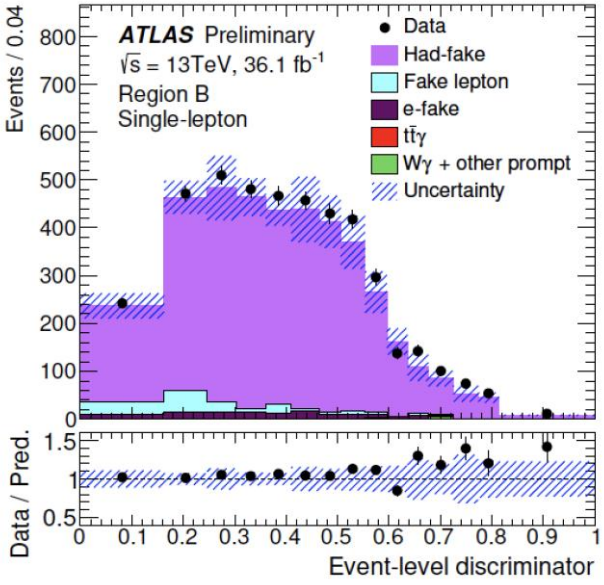
processes with a prompt photon: Wγ+jets, Zγ+jets, others	From MC (VRs defined to check their modelling) Wγ normalisation free floating in single-lepton ch.
hadronic-fakes (from tt and W/Z+jets)	ABCD method and SF (3D p_T/η/conv-unconverted, *from 0.8 to 3.2 typical value ~1.5±0.5)*
electron-fakes (from tt and Z→ee)	From MC corrected with the fake-rate SF (2D p_T/η, *from 0.8 to 2.1*) + overall data-over-MC SFs
fake leptons	Matrix method (2D $m_{T,W}$/η for el, $m_{T,W}/p_T$ for mu)

hadronic-fakes

$$N^{\text{h-fake}}_{\text{D, est.}} = \frac{N^{\text{h-fake}}_{\text{A, data}} \times N^{\text{h-fake}}_{\text{C, data}}}{N^{\text{h-fake}}_{\text{B, data}}} \times \theta_{\text{MC}}$$

$$\theta_{\text{MC}} = \frac{N^{\text{h-fake}}_{\text{D, MC}} / N^{\text{h-fake}}_{\text{C, MC}}}{N^{\text{h-fake}}_{\text{A, MC}} / N^{\text{h-fake}}_{\text{B, MC}}}$$

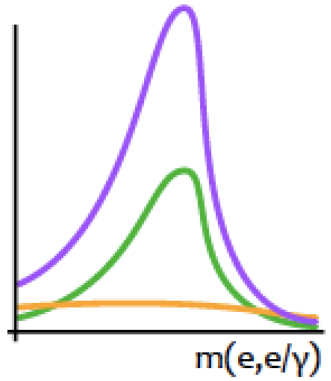




electron-fakes

$$\text{FR} \equiv \frac{N_{e,\gamma}}{N_{e,e}} = p_{e\to\gamma} \times \frac{\epsilon_\gamma(F)}{\epsilon^{reco}_{e2} \cdot \epsilon^{\text{others}}_{e2}} = p_{e\to\gamma} \times C$$

$$\text{FR}_{dd} = \frac{N^{\text{data}}_{e,\gamma} - N^{non\text{-}Z}_{e,\gamma}}{N^{\text{data}}_{e,e} - N^{non\text{-}Z}_{e,e}}$$



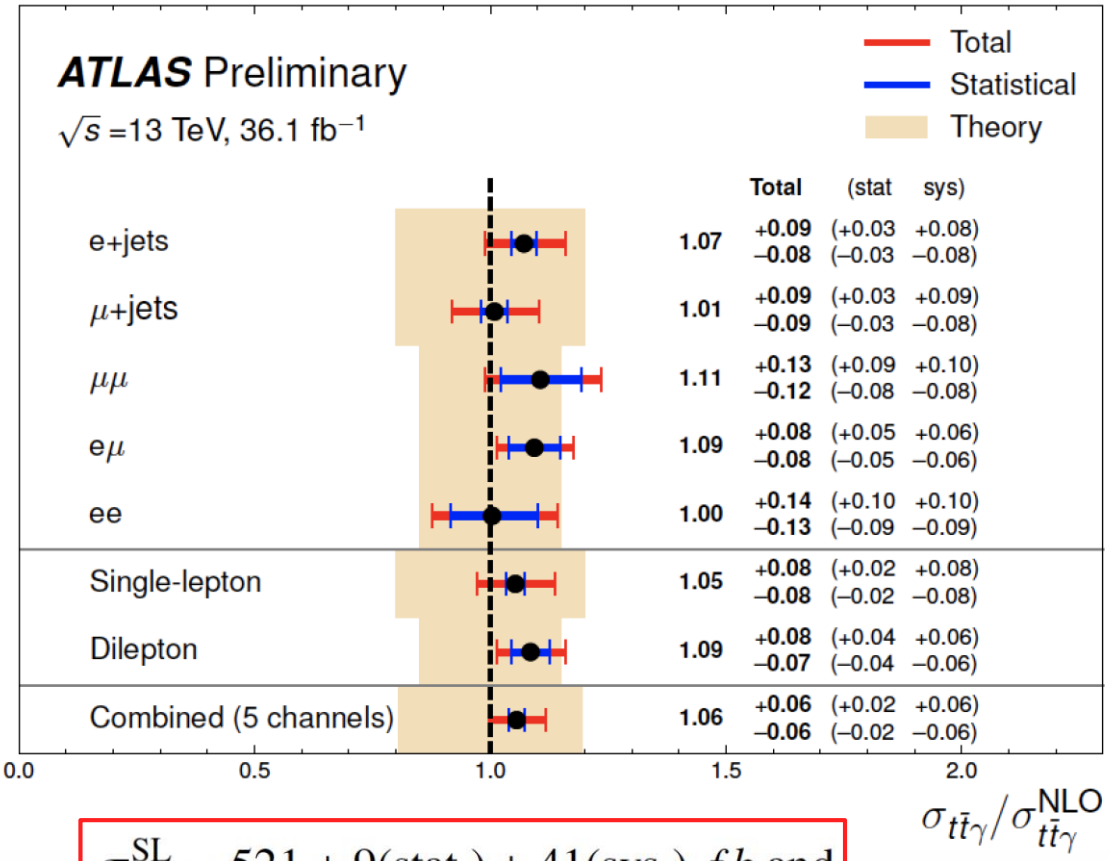
Z→ee (ee CR) shows the usual Z mass peak

Z→eγ (eγ CR) shows a peak for e faking a γ

non-Z contributions can be subtracted

Fiducial inclusive cross-section

Fiducial inclusive cross-section: profile likelihood fit to ELD



$$\sigma^{\mathrm{SL}}_{\mathrm{fid}} = 521 \pm 9(\mathrm{stat.}) \pm 41(\mathrm{sys.})\ fb \text{ and}$$
$$\sigma^{\mathrm{DL}}_{\mathrm{fid}} = 69 \pm 3(\mathrm{stat.}) \pm 4(\mathrm{sys.})\ fb,$$

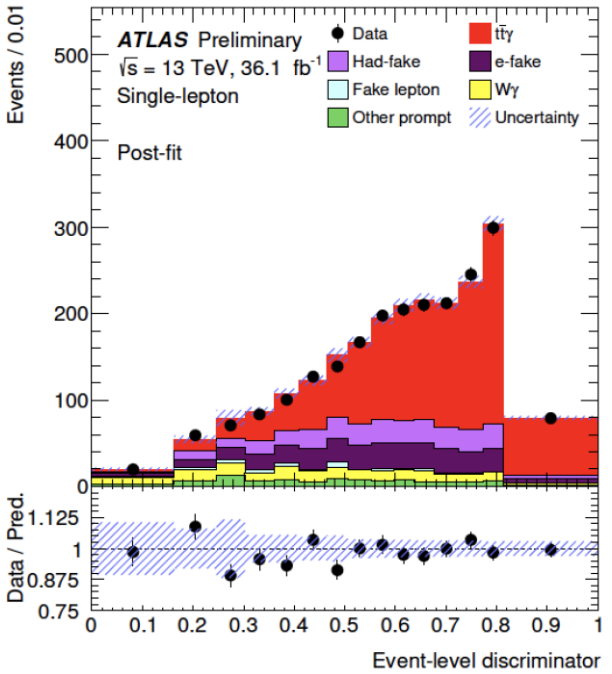
theory prediction:

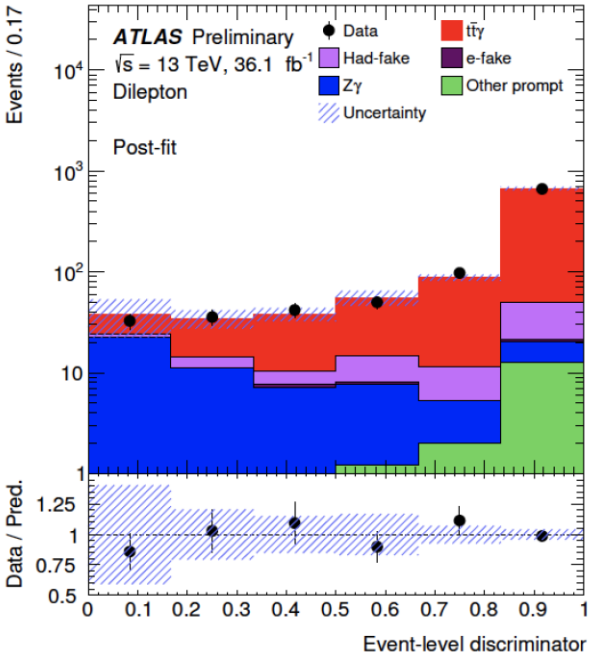
$$\sigma_{\mathrm{fid}}{}^{\mathrm{SL}} = 495 \pm 99 \text{ fb}$$
$$\sigma_{\mathrm{fid}}{}^{\mathrm{DL}} = 63 \pm 9 \text{ fb}$$

In agreement with the NLO QCD+LO EW prediction

Main uncertainties

- Single-lepton: jet-related, background modelling and PPT systematics
- Dilepton: data statistics, followed by signal and background modelling



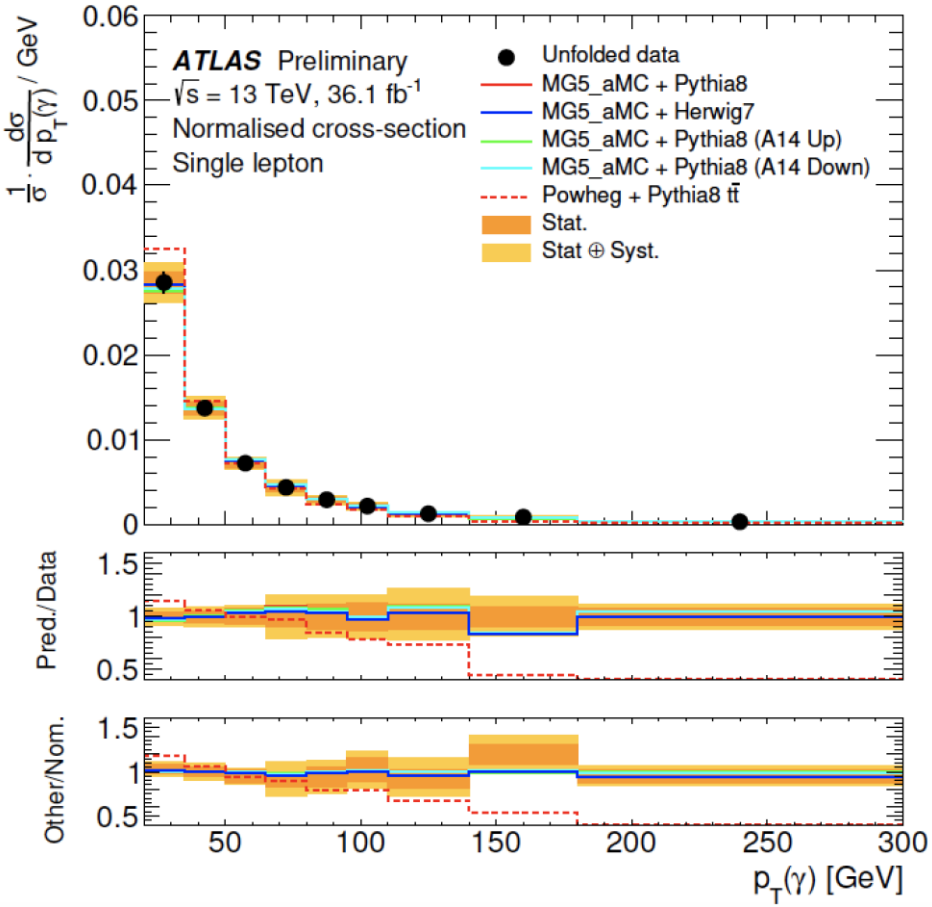


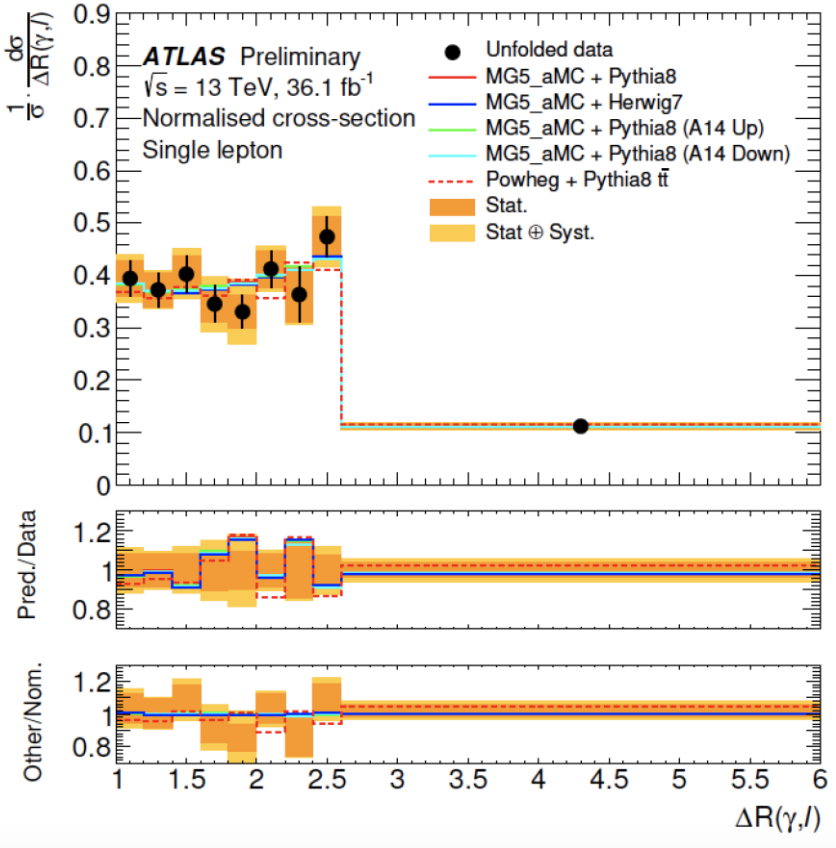
Normalised fiducial differential distributions

Normalised fiducial differential cross-sections: unfolding (iterative bayesian method)

$$\sigma_k^{\text{diff}} = \frac{1}{L} \times \frac{1}{\epsilon_k} \times \sum_j M_{jk}^{-1} \times (N_{\text{data},j} - N_{\text{bkgs},j}) \times (1 - f_{\text{mig},j}) \qquad \sigma_k^{\text{norm}} = \frac{\sigma_k}{\int_k \sigma_k}$$

Single-lepton distributions: $\mathbf{p_T(\gamma)}$, $|\eta(\gamma)|$, $\mathbf{\Delta R(\gamma,\ell)}$

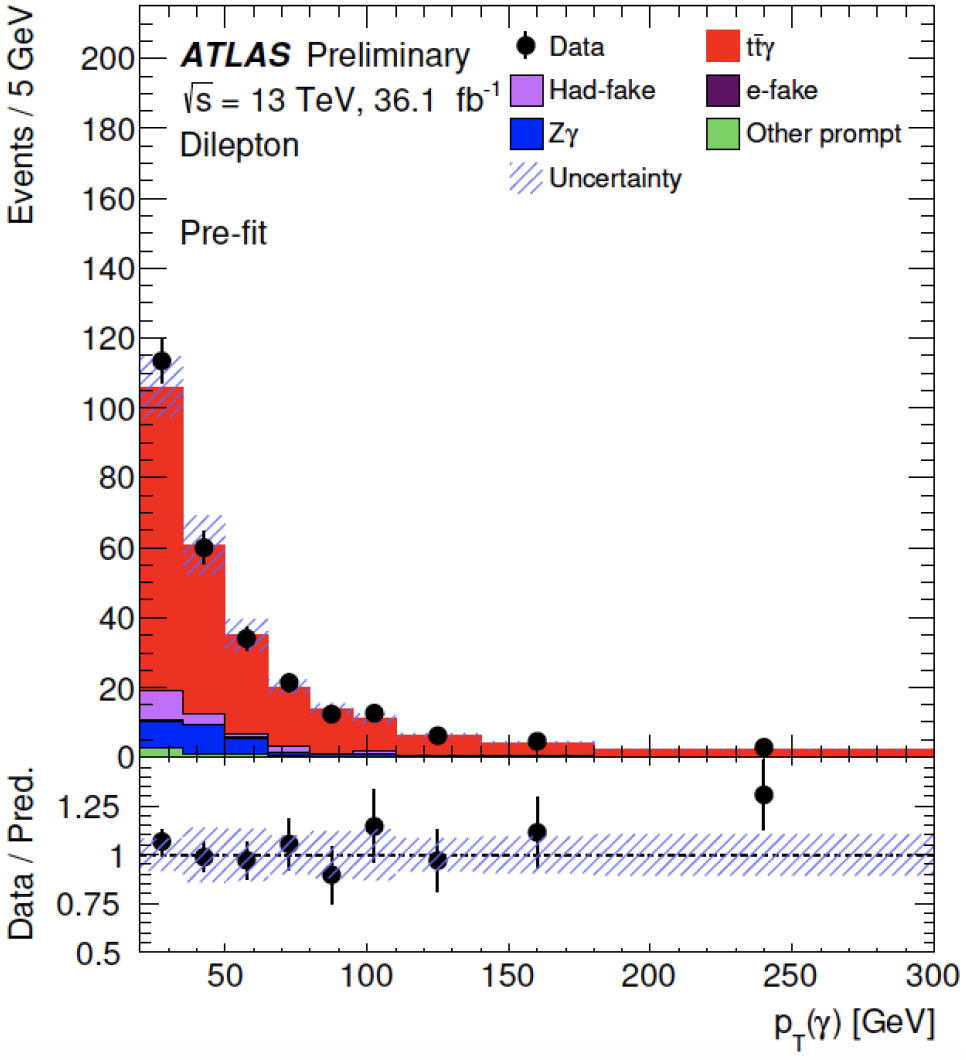


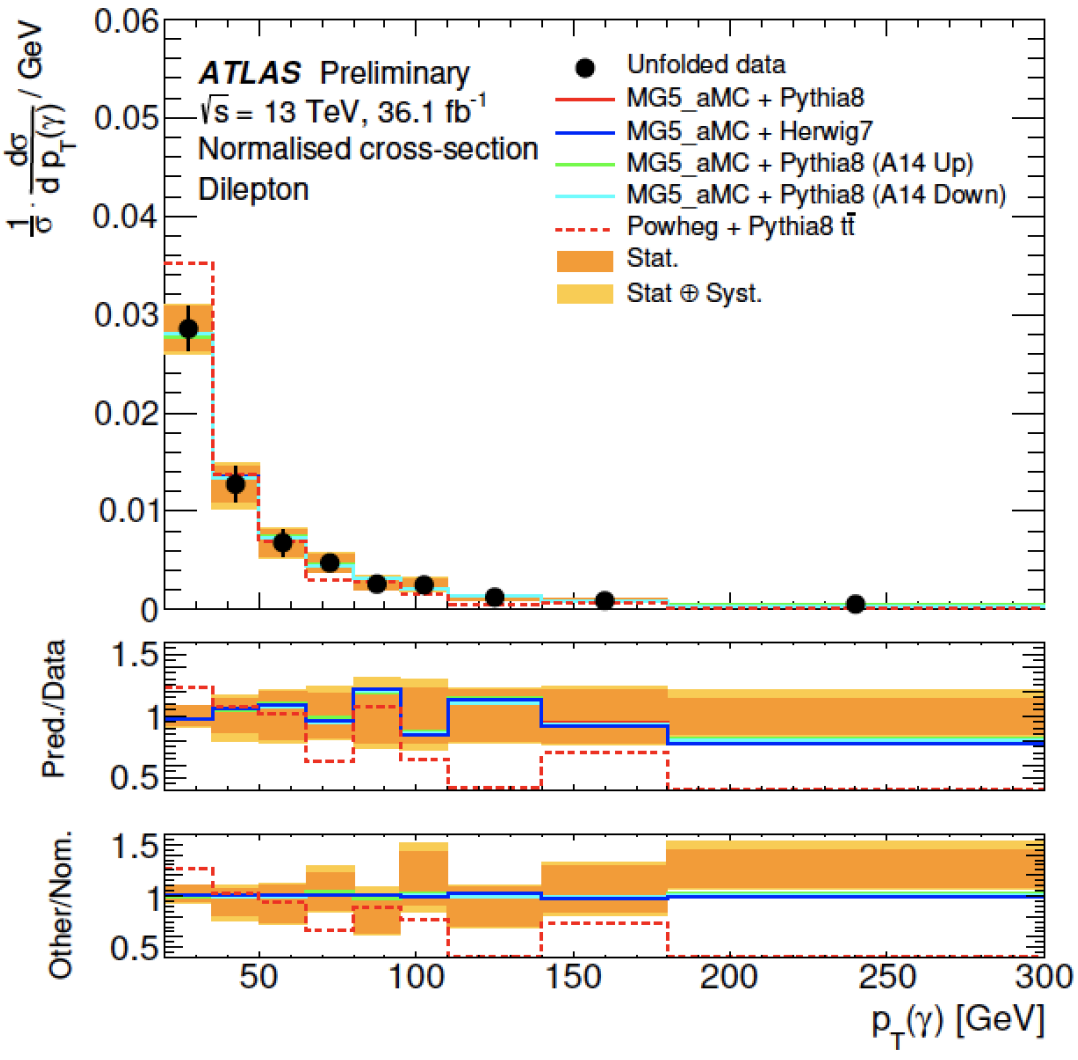


The measured normalised diff.cross-sections agree well with a few LO $tt\gamma$ MadGraph5_aMC@NLO predictions. Data/NLO *tt* Powheg+Py8: some slopes for p_T .

Normalised fiducial differential distributions

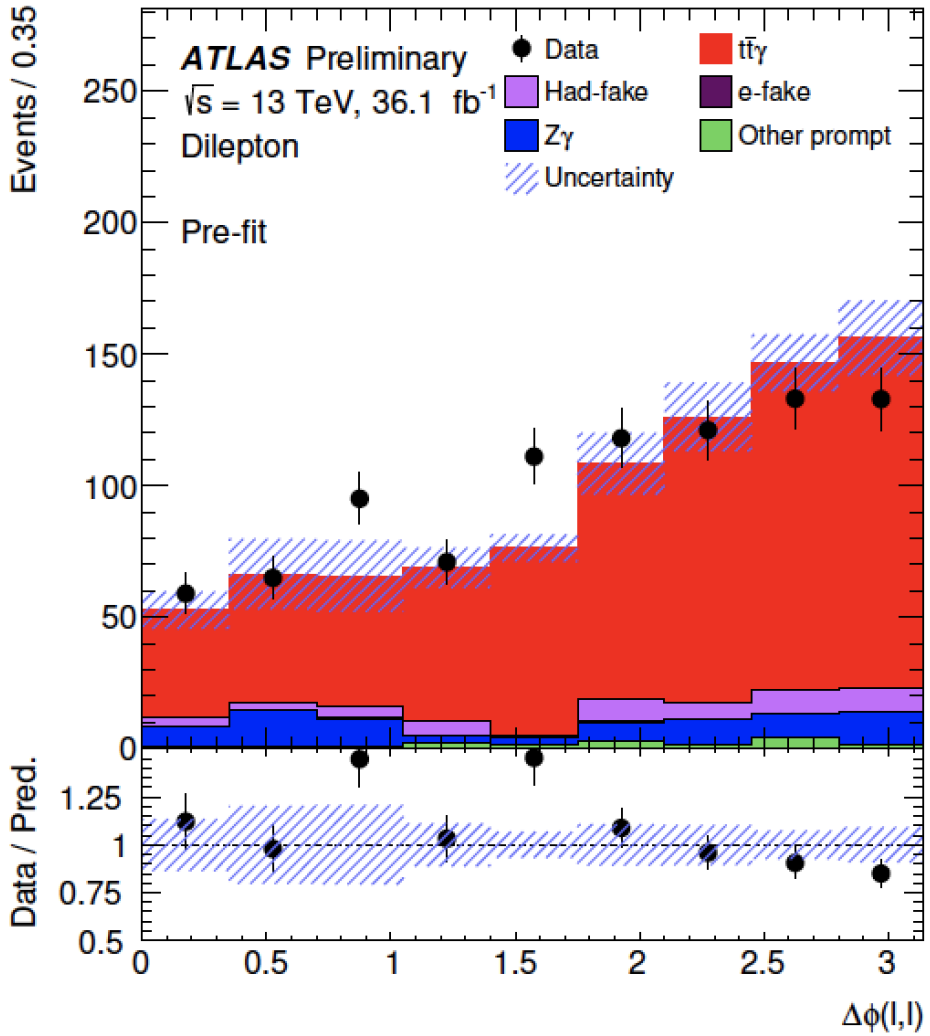
Dilepton distributions: $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)_{min}$, $\Delta\eta(\ell,\ell)$, $\Delta\Phi(\ell,\ell)$

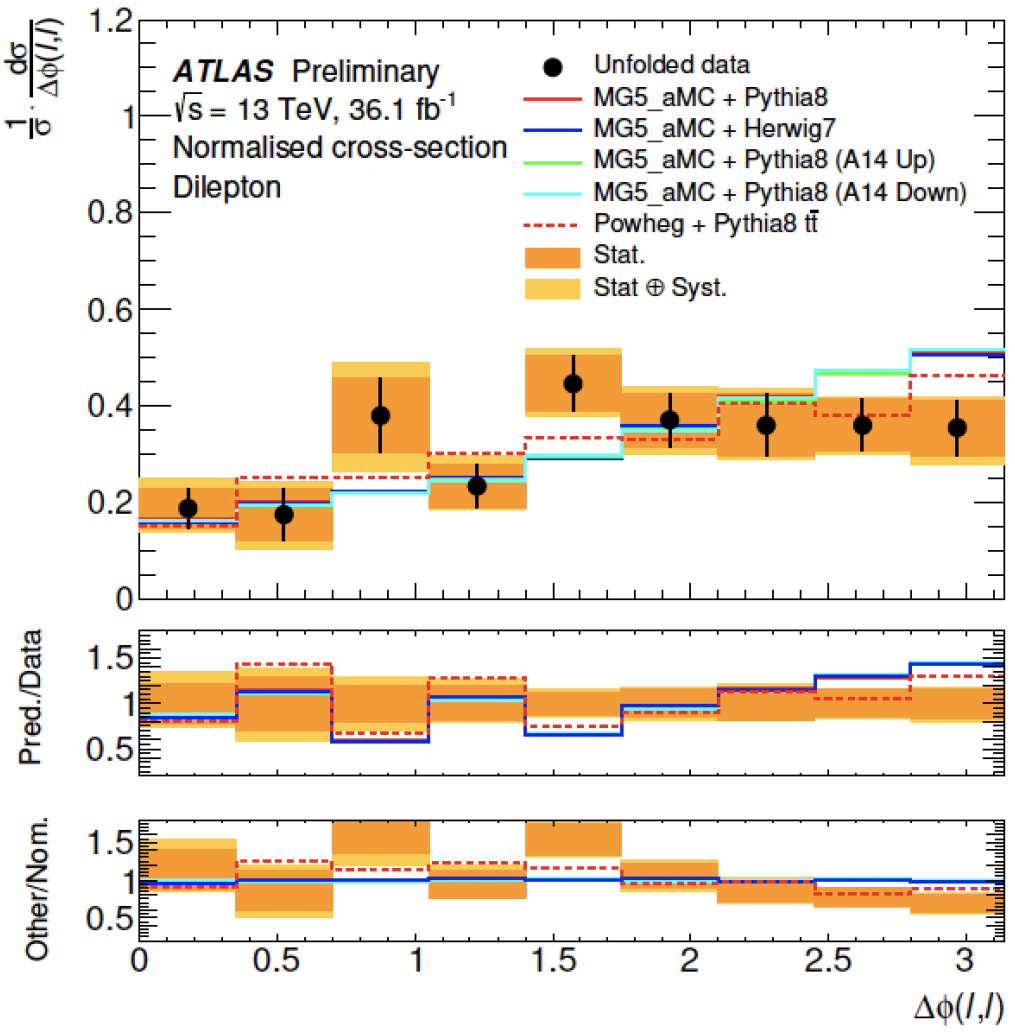




Normalised fiducial differential distributions

Dilepton distributions: $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)_{min}$, $\Delta\eta(\ell,\ell)$, **$\Delta\Phi(\ell,\ell)$**





Hints of small deviation in $\Delta\Phi(\ell,\ell)$ with same trend as reported in *tt* events.

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NEW ttγ fiducial inclusive and normalised differential cross-sections measured by ATLAS

- $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)_{min}$, $\Delta\eta(\ell,\ell)$, $\Delta\Phi(\ell,\ell)$
- quite good agreement with few LO $tt\gamma$ and NLO tt Powheg+Pythia8 predictions
- the largest disagreement between data and LO tt prediction is observed $\Delta\Phi(\ell,\ell)$, while NLO tt sample provides a good agreement (better than for tt events)
- A new regime to explore with full Run-2 dataset !!!!

Predictions	$p_T(\gamma)$ χ^2/NDF	$p_T(\gamma)$ p-value	$\lvert\eta(\gamma)\rvert$ χ^2/NDF	$\lvert\eta(\gamma)\rvert$ p-value	$\Delta R(\gamma,\ell)$ χ^2/NDF	$\Delta R(\gamma,\ell)$ p-value
MG5_aMC + Pythia8	3.2/8	0.92	0.7/7	1.0	5.0/8	0.76
MG5_aMC + Herwig7	2.3/8	0.97	0.9/7	1.0	4.8/8	0.78
MG5_aMC + Pythia8 (A14 Up)	3.3/8	0.91	0.8/7	1.0	4.9/8	0.77
MG5_aMC + Pythia8 (A14 Down)	2.6/8	0.96	0.9/7	1.0	4.6/8	0.8
POWHEG + Pythia8 $t\bar{t}$	25.4/8	<0.01	2.8/7	0.9	8.7/8	0.37

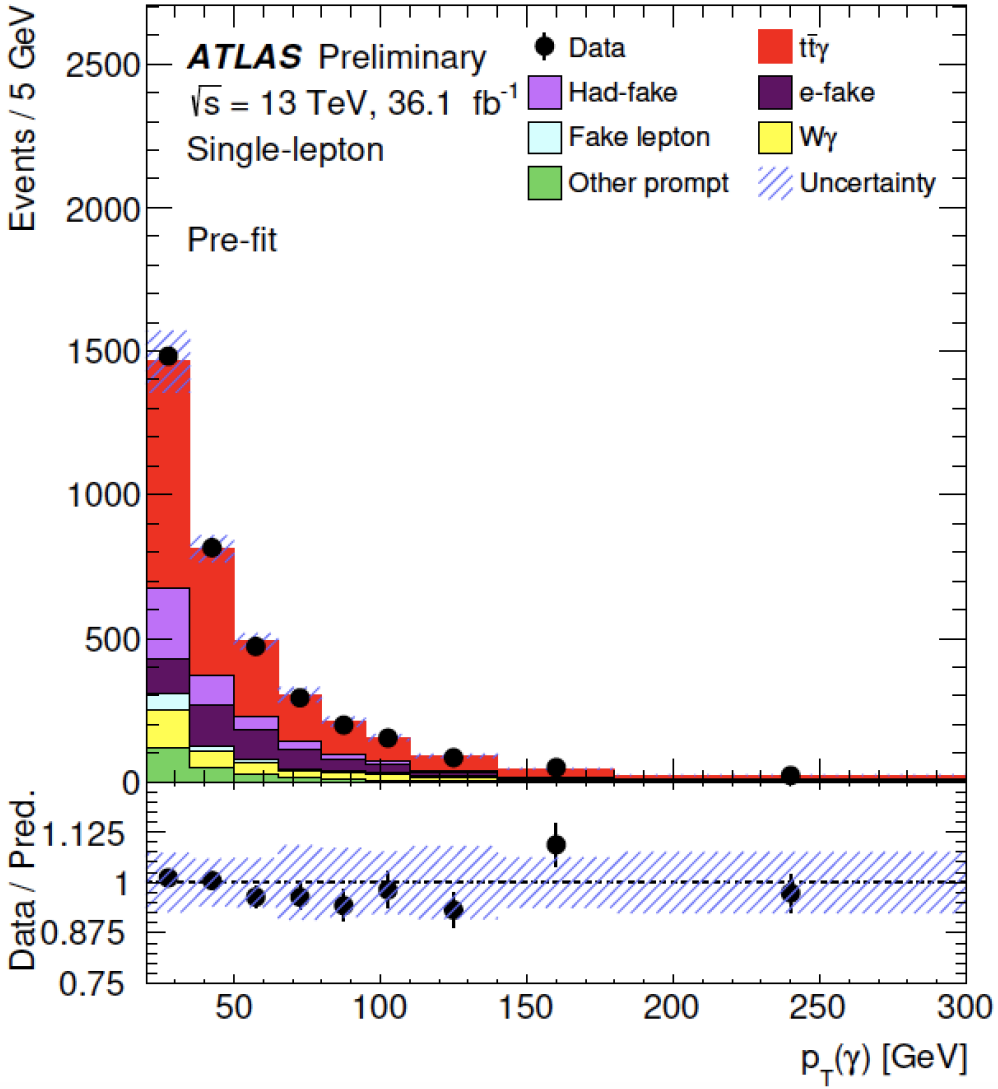
BACK-UP

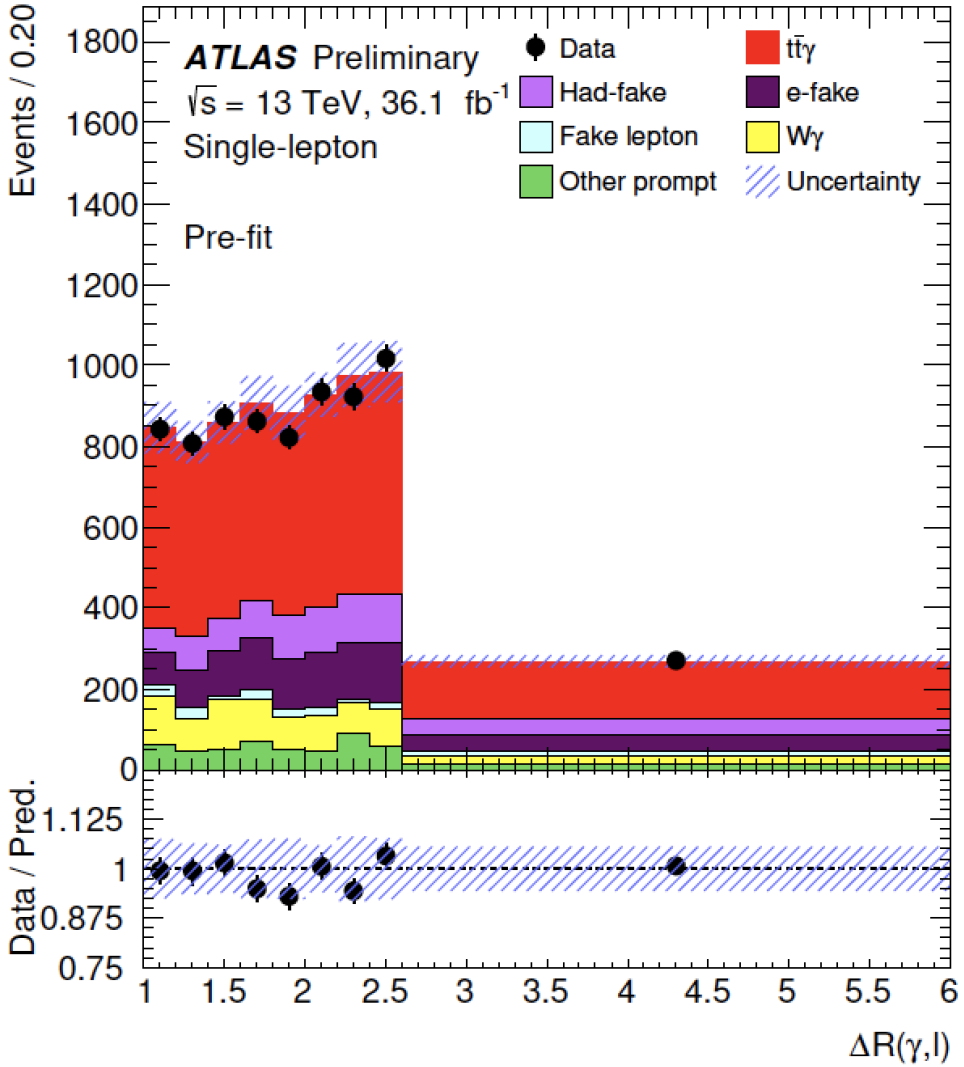
e+jets	μ+jets	ee	$\mu\mu$	$e\mu$	
Primary vertex					
1 e	1 μ	2 e, OS	2 μ, OS	1 e + 1 μ, OS	e/μ p_T>25GeV
Trigger match					
$\geq$ 4 jets		$\geq$ 2 jets			jets p_T>25GeV
$\geq$ 1 b-jet					
1 γ					photon p_T>20GeV
$m(e,\gamma) \notin [m(Z)\text{-}5, m(Z)\text{+}5]$ GeV	-				
-	$m(\ell,\ell) \notin$ [85,95] GeV			-	
-	$m(\ell,\ell,\gamma) \notin$ [85,95] GeV			-	
-	$E_T^{miss} > 30$ GeV			-	
-	$m(\ell,\ell) > 15$ GeV				
$\Delta R(\gamma,\ell) > 1.0$					

Variable	Description	Single-lepton	Dilepton
PPT	Prompt-photon tagger output	5	
H_{T}	Scalar sum of the p_{T} of the leptons and jets	7	
$m(\gamma, \ell)$	Invariant mass of the system of the photon and the lepton	15	
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse energy	13	3
m_W^{T}	Reconstructed transverse mass of the leptonically decaying W-boson $= \sqrt{2 \times p_{\mathrm{T}}(\ell) \times E_{\mathrm{T}}^{\mathrm{miss}} \times (1 - \cos(\Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}})))}$	12	
N_{jets}	Jet multiplicity	14	
$p_{\mathrm{T}}(j_1)$	p_{T} of the leading jet (ordered in p_{T})	6	4
$p_{\mathrm{T}}(j_2)$	p_{T} of the sub-leading jet	8	7
$p_{\mathrm{T}}(j_3)$	p_{T} of the third jet	9	
$p_{\mathrm{T}}(j_4)$	p_{T} of the fourth jet	10	
$p_{\mathrm{T}}(j_5)$	p_{T} of the fifth jet	11	
$N_{b\text{-jets}}$	b-jet multiplicity	4	5
$b_1(j)$	highest b-tagging score of all jets	1	6
$b_2(j)$	second highest b-tagging score of all jets	2	1
$b_3(j)$	third highest b-tagging score of all jets	3	
$m(\ell, \ell)$	Invariant mass of the system of the two leptons		2

Single-lepton distributions (reconstructed level)

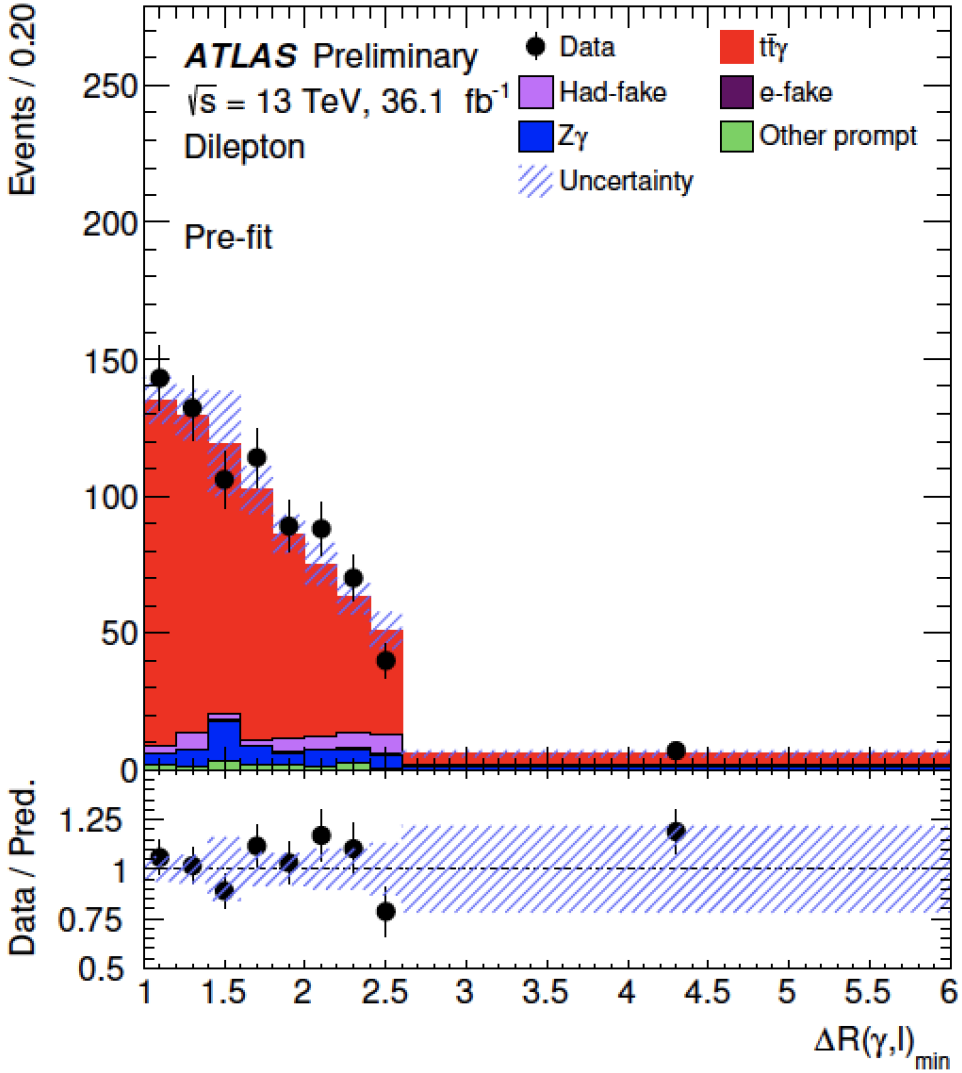
Single-lepton distributions: $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)$

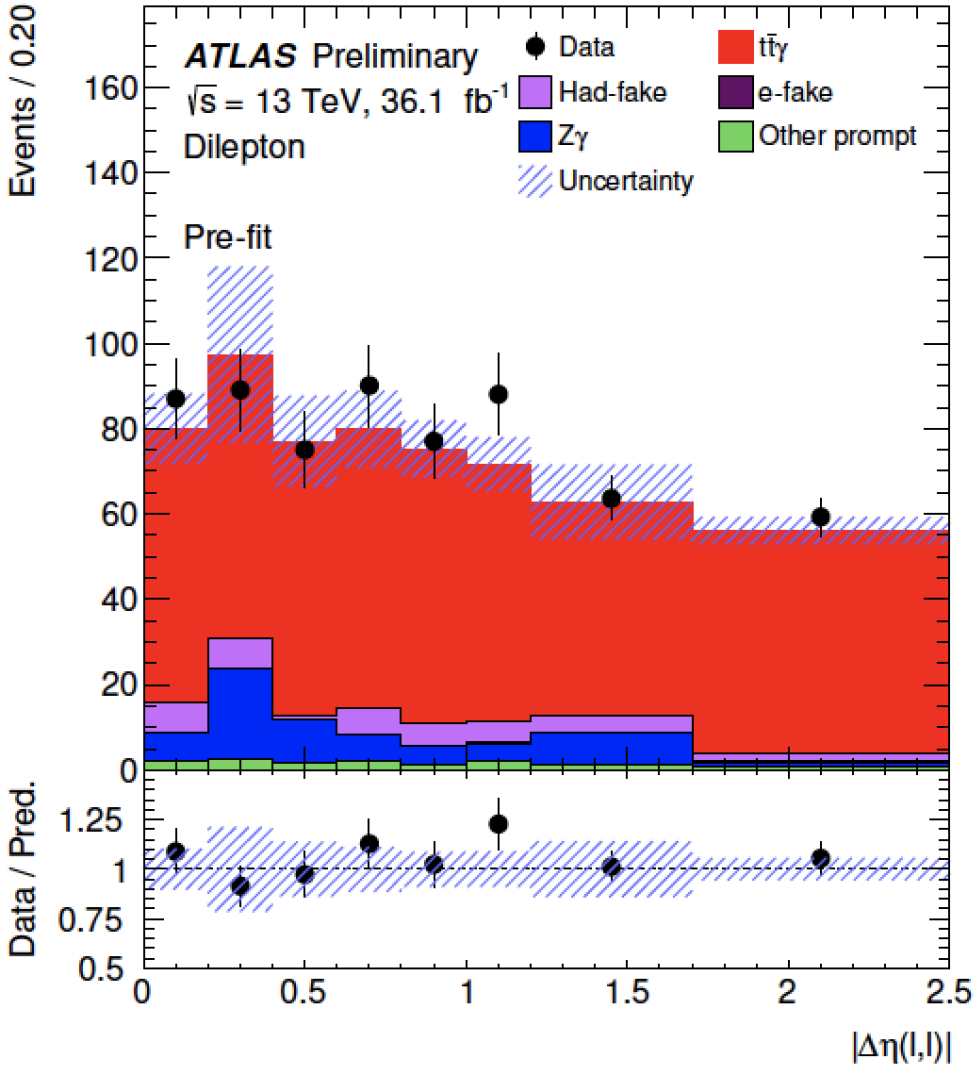




Di-lepton distributions (reconstructed level)

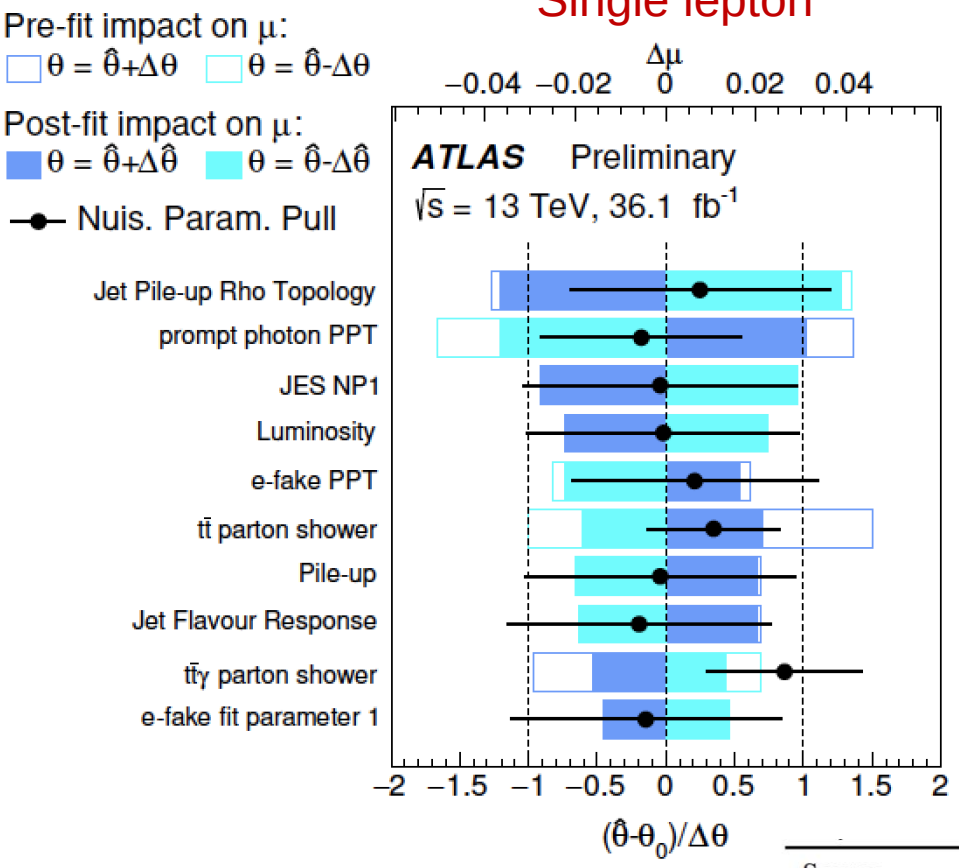
Di-lepton distributions: $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)_{min}$, $\Delta\eta(\ell,\ell)$, $\Delta\Phi(\ell,\ell)$



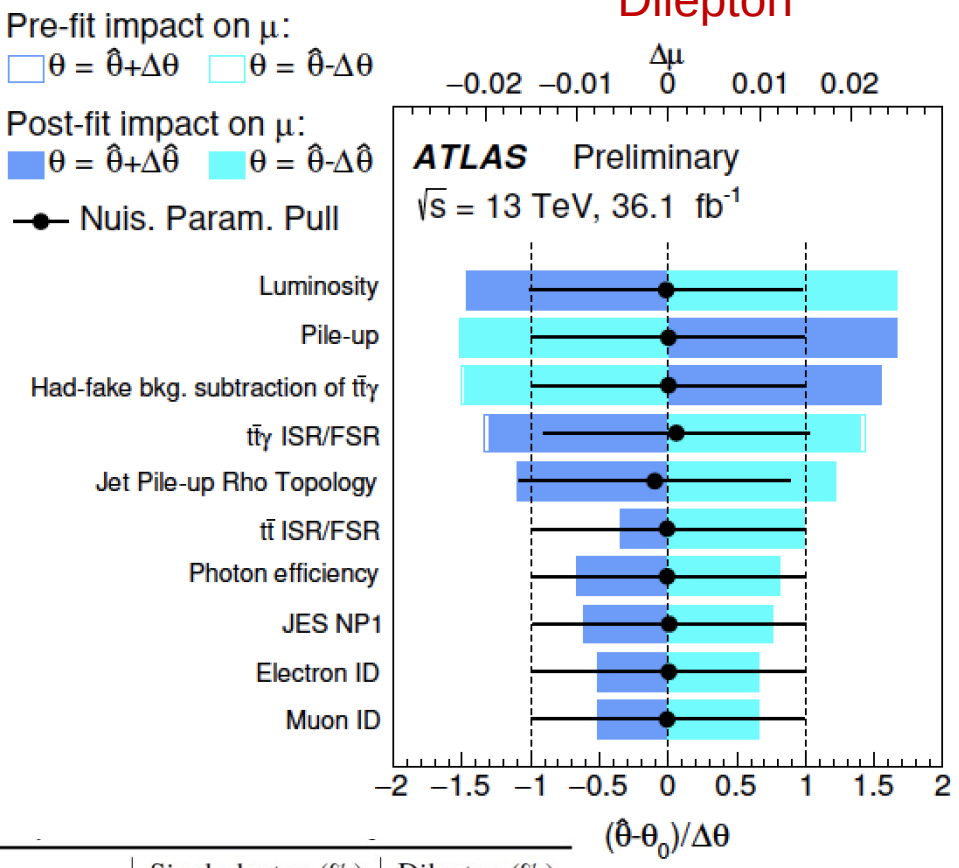


Ranking of systematic uncertainties

Single lepton



Dilepton



Source	Single-lepton (%)	Dilepton (%)
Signal modelling	± 1.6	± 2.9
Background modelling	± 4.8	± 2.9
Photon	± 1.1	± 1.1
Prompt-photon tagger	± 4.0	-
Leptons	± 0.3	± 1.3
Jets	± 5.4	± 2.0
B-Tagging	± 0.9	± 0.4
Pileup	± 2.0	± 2.3
Luminosity	± 2.3	± 2.3
MC sample size	± 1.9	± 1.7
Total systematic uncertainty	± 7.9	± 5.8
Data sample size	± 1.5	± 3.8
Total uncertainty	± 8.1	± 7.0

χ^2/n.d.f. values and their corresponding p-values

Predictions	$p_T(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)$	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
MG5_aMC + Pythia8	3.2/8	0.92	0.7/7	1.0	5.0/8	0.76
MG5_aMC + Herwig7	2.3/8	0.97	0.9/7	1.0	4.8/8	0.78
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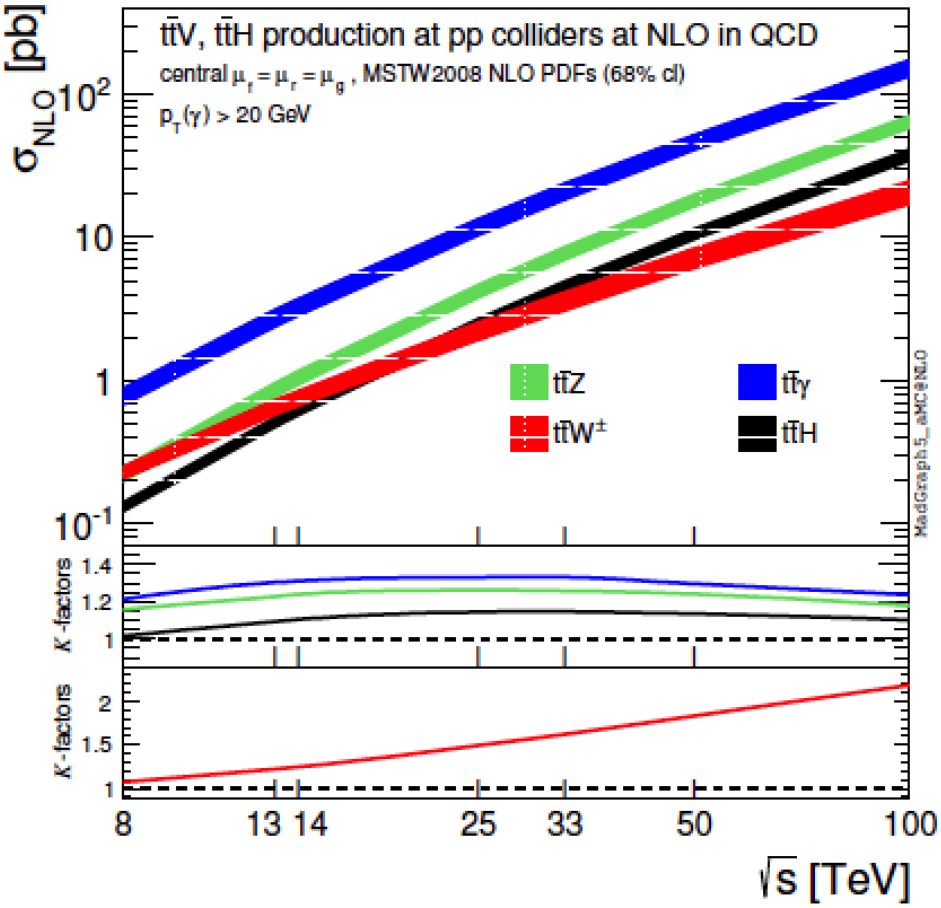
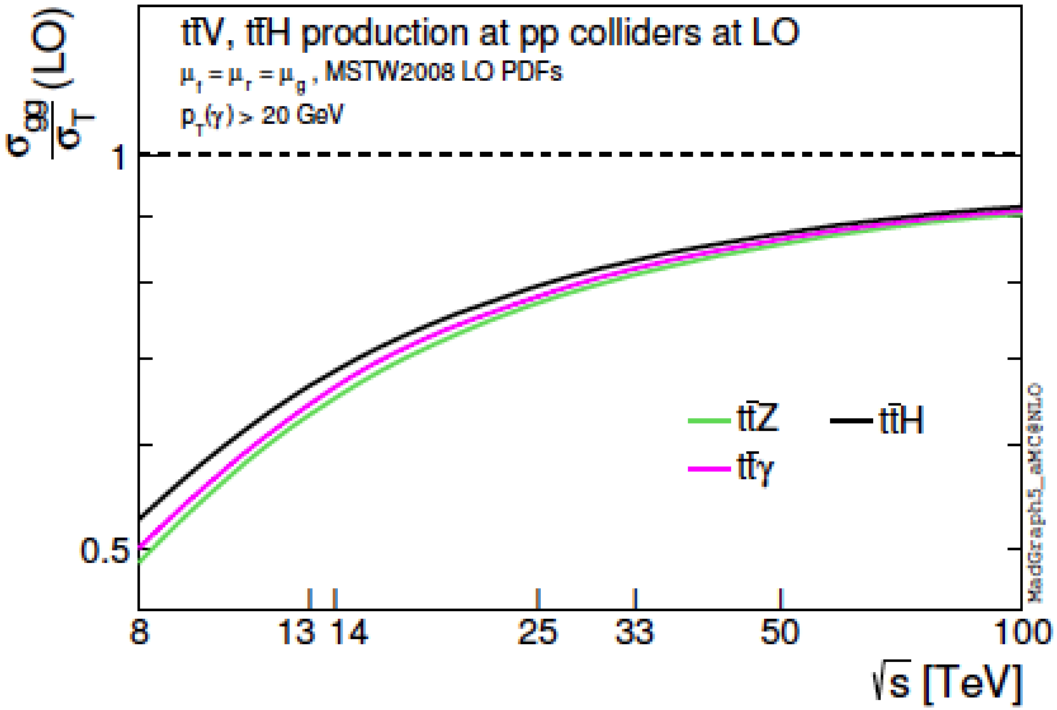
MG5_aMC + Pythia8 (A14 Down)	2.6/8	0.96	0.9/7	1.0	4.6/8	0.8
POWHEG + Pythia8 $t\bar{t}$	25.4/8	<0.01	2.8/7	0.9	8.7/8	0.37

Predictions	$p_T(\gamma)$		$\eta(\gamma)$		$\Delta R(\gamma,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$		$\Delta\phi(\ell,\ell)$	
	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
MG5_aMC + Pythia8	1.7/8	0.99	7.4/7	0.39	6.9/8	0.55	3.0/7	0.89	14.4/8	0.07
MG5_aMC + Herwig7	2.0/8	0.98	7.4/7	0.39	6.6/8	0.58	3.1/7	0.88	14.4/8	0.07
MG5_aMC + Pythia8 (A14 Up)	1.6/8	0.99	8.4/7	0.3	7.4/8	0.49	3.4/7	0.85	14.0/8	0.08
MG5_aMC + Pythia8 (A14 Down)	1.6/8	0.99	7.9/7	0.34	7.5/8	0.48	3.2/7	0.87	14.4/8	0.07
POWHEG + Pythia8 $t\bar{t}$	20.1/8	0.01	10.8/7	0.15	8.6/8	0.38	4.5/7	0.72	9.8/8	0.28


tt̄V, tt̄H production at pp colliders at NLO in QCD
central μ_f = μ_r = μ_g, MSTW2008 NLO PDFs (68% cl)
p_T(γ) > 20 GeV
σ_NLO [pb]
tt̄Z
tt̄W±
tt̄γ
tt̄H
K-factors
K-factors
MadGraph5_aMC@NLO
√s [TeV]


tt̄V, tt̄H production at pp colliders at LO
μ_f = μ_r = μ_g, MSTW2008 LO PDFs
p_T(γ) > 20 GeV
σ_gg (LO) / σ_T
tt̄Z
tt̄H
tt̄γ
MadGraph5_aMC@NLO
√s [TeV]