Observation of associated production of top quarks with the ATLAS experiment

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Top quark and EW Physics

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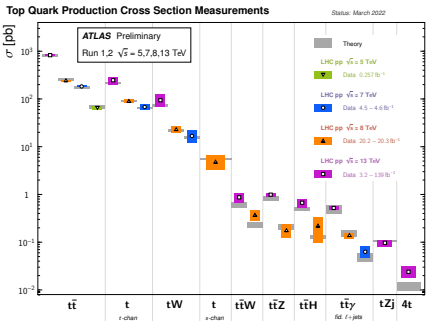
Introduction to Top+X processes

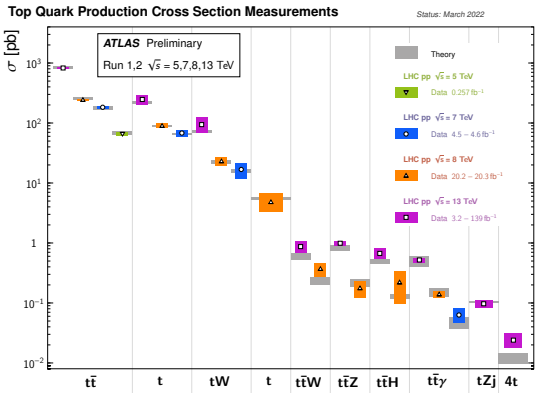
- Stand-out role in the standard model due to high mass (173 GeV)
  - Decays before hadronisation ($\tau \sim 10^{-25}$ s)
    $\rightarrow$ direct probing through decay products
  - Yukawa coupling-strength close to unity
- Probing $t\bar{t}V$ and tVq means probing the fundamental properties of the top quark
- Z-coupling sensitive to EW parameters: (hypercharge, weak isospin)
- Small tensor-like contributions with higher order loop corrections
- Coupling accessible through $t\bar{t}V$ and tVq processes $\rightarrow$ probing theory predictions by measuring these rare processes
- In Run 2 we moved from discoveries to precision measurements
- Here:
  $t\bar{t}\gamma$: **JHEP 09(2020) 049**, $t\bar{t}Z$: **Eur. Phys. J. C. 81 (2021) 737**, tZq: **JHEP 07(2020) 124**, $t\gamma q$: **ATLAS-CONF-2022-013**, $t\bar{t}t\bar{t}$ **JHEP 11 (2021) 118**



Top cross section summary plot

Run 2 - Observations and precision measurements with ATLAS

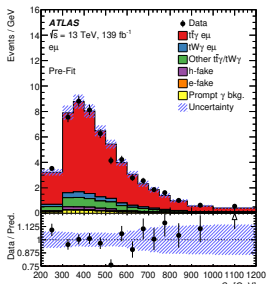
- Large Run 2 dataset allows for many precision analyses in the top-sector
- We are now able to increasingly probe rare SM processes such as $t\bar{t}Z$, $t\bar{t}\gamma$, $t\gamma q$, tZq and even 4-tops
- $t\gamma q$ observed for the first time in ATLAS
- Able to measure inclusive **and** differential distributions
- Improved analyses techniques such as deployment of MVA techniques improve performance of several analyses

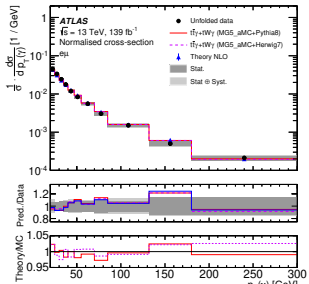


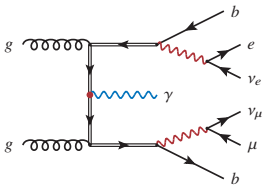
Top cross section summary plot

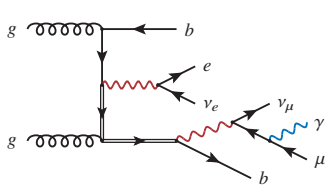
$t\bar{t}\gamma$-production - inclusive & differential

- $e\mu$ final state with single photon, two jets, at least one tagged
- Includes **both** $t\bar{t}\gamma$ and $tW\gamma \rightarrow$ check full off-shell calculations
- Measurement is performed in a fiducial volume defined at parton level
- Fiducial cross section:
  $\sigma^{\text{fid.}}_{t\bar{t}\gamma} = 39.6 \pm 0.8(\text{stat.})^{+2.6}_{-2.2}(\text{syst.})\,\text{fb}$,
  $\sigma^{\text{SM, fid.}}_{t\bar{t}\gamma} = 38.50^{+0.56}_{-2.18}(\text{scale})^{+1.04}_{-1.18}(\text{PDF})\,\text{fb}$
  meas. syst. limited ($t\bar{t}\gamma/Wt\gamma$ modelling)
- Diff. cross-sections of several variables are compared with state-of-the-art MC simulations and NLO calculations
- All meas. in agreement with SM
- New $t\bar{t}\gamma$ charge-asymmetry measurement $\rightarrow$ Nellos talk







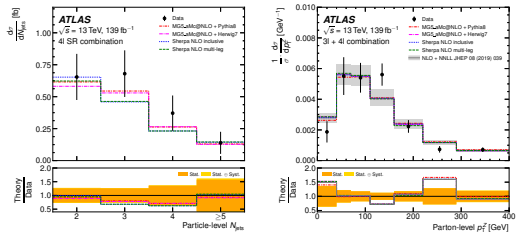


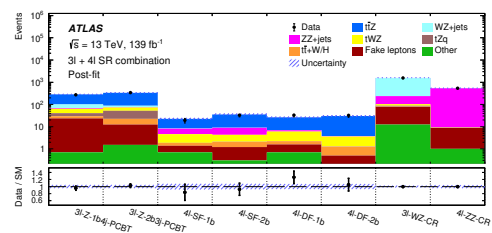
JHEP 09(2020) 049

Theory pred.: JHEP01(2019)188, JHEP10(2018)158

$t\bar{t}Z$-production - Inclusive & differential

- Measurements targets 3ℓ and 4ℓ final states
- Trileptonic regions split by (b-)jet multiplicities. Tetraleptonic regions split into same-flavour/different-flavour non-Z leptons + b-jet multiplicity
- CRs to control WZ (3ℓ) and ZZ (4ℓ)
- $\sigma^{\text{Incl.}}_{t\bar{t}Z} = 0.99 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})\,\text{pb}$
  $\sigma^{\text{NLO+NNLL}}_{t\bar{t}Z} = 863^{+8.5\%}_{-9.9\%}(\text{scale})^{+3.2\%}_{-3.2\%}(\text{PDF}+\alpha_s)\,\text{fb}$
  $\rightarrow$ relative unc. of 10%, syst. limited ($t\bar{t}Z$ parton shower), in agreement with SM
- Diff. measurements of several variables in agreement with SM

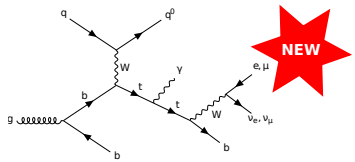


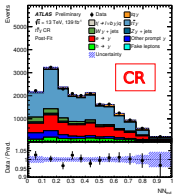


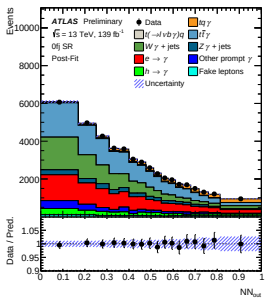
Eur. Phys. J. C. 81 (2021) 737
Theory pred.: **Eur. Phys. J. C 79 (2019) 249**

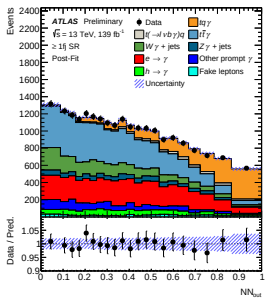
Observation $t\gamma q$-production

- Rare SM process sensitive to top-$\gamma/W^{\pm}$ interaction & electric/magnetic dipole moments of top quark
- 2 SRs, requiring the presence of 1 photon, 1 e/μ, 1 b-tagged jet and 1 or 0 forward jets
- Using NN to separate signal from background
- Performing profile-likelihood fit in the SRs & $t\bar{t}\gamma$ CR with $\mu_{t\gamma q}$, $\mathcal{N}_{t\bar{t}\gamma}$, and $\mathcal{N}_{W+\text{jets}}$
- Observed (expected) significance is 9.1σ (6.7σ)
- $\sigma^{\text{fid.}}_{t\gamma q} = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})$ fb, syst. limited ($t\bar{t}\gamma$ modelling)
  $\sigma^{\text{SM, fid.}}_{t\gamma q} = 406^{+25}_{-32}$ fb. (compatible within 2.5σ)
  $\sim$40% higher than SM, consistent with CMS





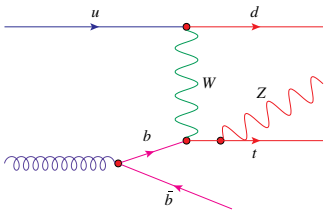


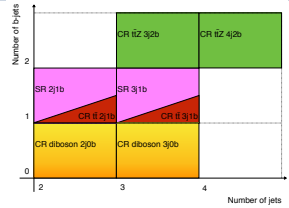


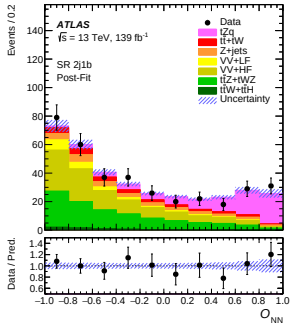
ATLAS-CONF-2022-013, Theory pred. ($\sigma^{\text{SM, fid.}}_{t\gamma q}$) calculated @ NLO in QCD

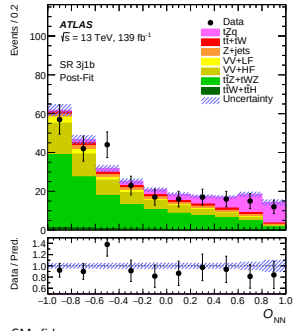
Observation of tZq-production

- Measured in 3ℓ channel with $139\,\text{fb}^{-1}$
- 3ℓ selections and 2 or 3 jets, one b-tagged, and one untagged
- 8 non-overlapping regions: 2 SRs, 6 CRs (constrain $t\bar{t}Z$, $t\bar{t}$, diboson)
- NN for sig./bkg. separation
- Binned maximum-likelihood fit using SRs and CRs
- Incl. $\sigma_{tZq}^{\text{fid.}} = 97 \pm 13(\text{stat.}) \pm 7(\text{syst.})$ rel. uncertainty $\sim 14\,\%$ (stat. limited)
- Agrees with SM prediction: $\sigma_{tZq}^{\text{SM, fid.}} = 102^{+5}_{-2}$ fb (calculated @ NLO in QCD including non-resonant contributions with $m_{\ell\ell} > 30$ GeV)





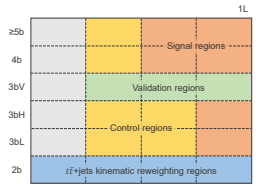


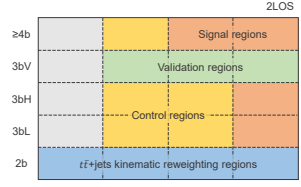


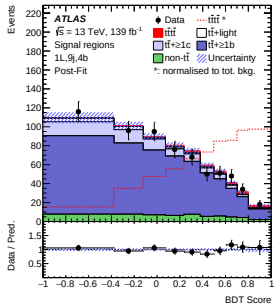
JHEP 07 (2020) 124, Theory pred. ($\sigma_{tZq}^{\text{SM, fid.}}$) calculated @ NLO in QCD

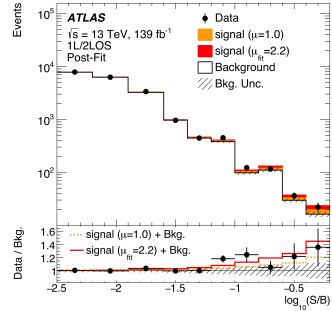
Evidence for four-tops-production

- Measuring 4-tops Xsec in single-lepton or opposite sign lepton pairs
- Events in 1ℓ and 2LOS are split into 10 SRs, 11 CRs, 6 VRs
- Combining results with prev. ATLAS measurement in multi-lepton final states.
- ATLAS reports significance of 4.7σ (2.6 expected)
- $\sigma_{t\bar{t}t\bar{t}} = 26 \pm 8(\text{stat.})^{+15}_{-13}(\text{syst.})\,\text{fb}$
  $\sigma^{SM}_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4\,\text{fb}$
  agrees with SM within 2σ
- Meas. dominated by syst. uncertainties: $t\bar{t}t\bar{t}$ & $t\bar{t}+\geq 1b$ modelling









JHEP 11 (2021) 118 , Theory pred.:JHEP 02 (2018) 031

Summary & Outlook

- Full Run 2 dataset allows for precision measurements in $t\bar{t}V$ and tVq sector
- Presented today:
  - $t\bar{t}Z$ incl. and diff. measurements in 3ℓ and 4ℓ
  - $t\bar{t}\gamma$ incl. and diff measurements in $e\mu$ channel
  - tZq incl. measurement
  - $t\gamma q$ incl. (brand new) measurement
  - Evidence for 4 tops production

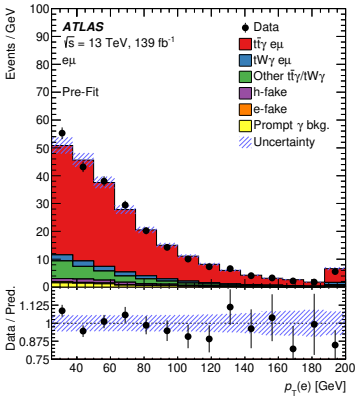
- Presented measurements show good agreement for inclusive and differential results with SM predictions
  - Measurements are compared with state-of-the-art fixed-order computations as well as NLO+PS Monte Carlo simulations

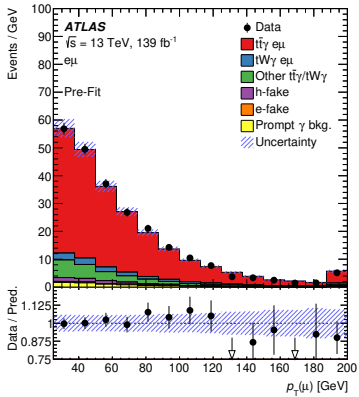
- These analyses are the first round of ATLAS full Run 2 measurements $\rightarrow$ stringent tests of SM predictions
- Presented results are only glimpse of rich ATLAS **top-quark analysis program**
- With Run 2 measurements we have moved from discoveries to precision measurements in the $t\bar{t}V$ and tVq sector! $\rightarrow$ Looking forward to Run 3.

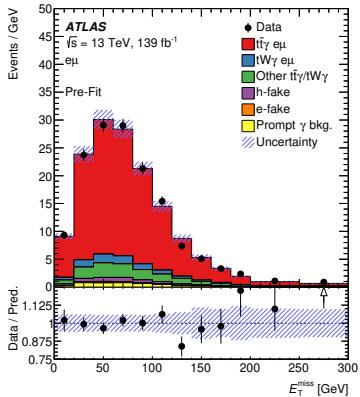
- $t\bar{t}\gamma$: **JHEP 09(2020) 049**, $t\bar{t}Z$: **Eur. Phys. J. C. 81 (2021) 737**, tZq: **JHEP 07(2020) 124**, $t\gamma q$: **ATLAS-CONF-2022-013** $t\bar{t}t\bar{t}$ **JHEP 11 (2021) 118**

Backup

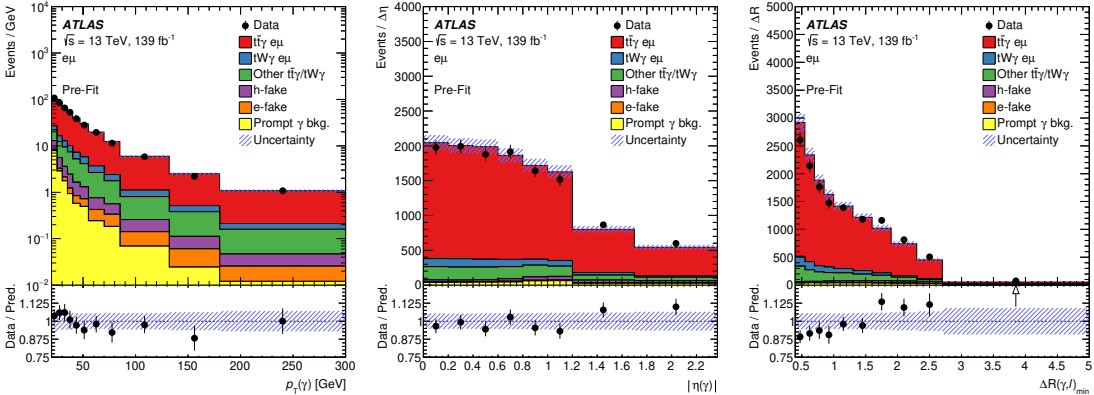
$t\bar{t}\gamma$ — pre-fit control plots



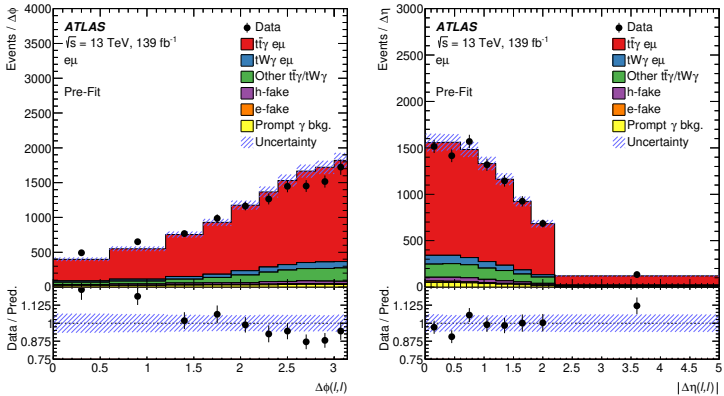




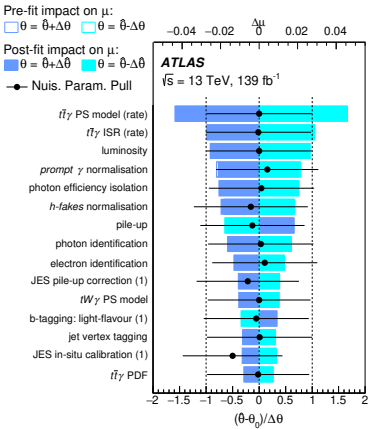
$t\bar{t}\gamma$ — unfolded variables pre-fit



$t\bar{t}\gamma$ — unfolded variables pre-fit



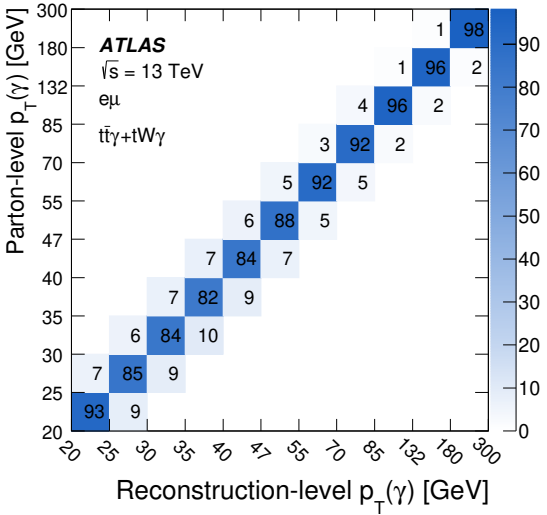
$t\bar{t}\gamma$ - Uncertainties

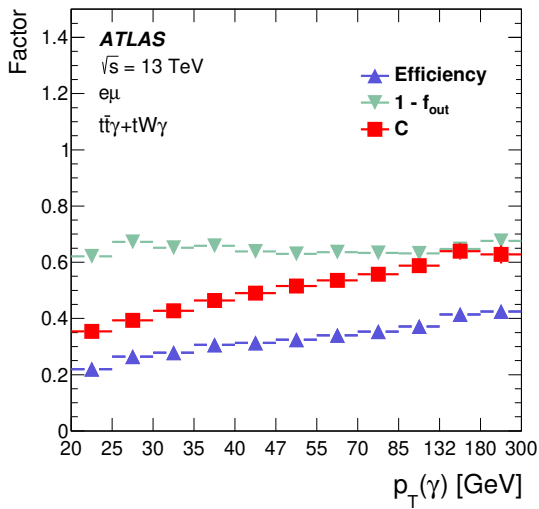


	Events
$t\bar{t}\gamma\ e\mu$	2391 ± 130
$tW\gamma\ e\mu$	156 ± 15
Other $t\bar{t}\gamma/tW\gamma$	279 ± 15
h-fake	78 ± 40
e-fake	23 ± 12
Prompt γ bkg.	87 ± 40
Total	3014 ± 160
Data	3014

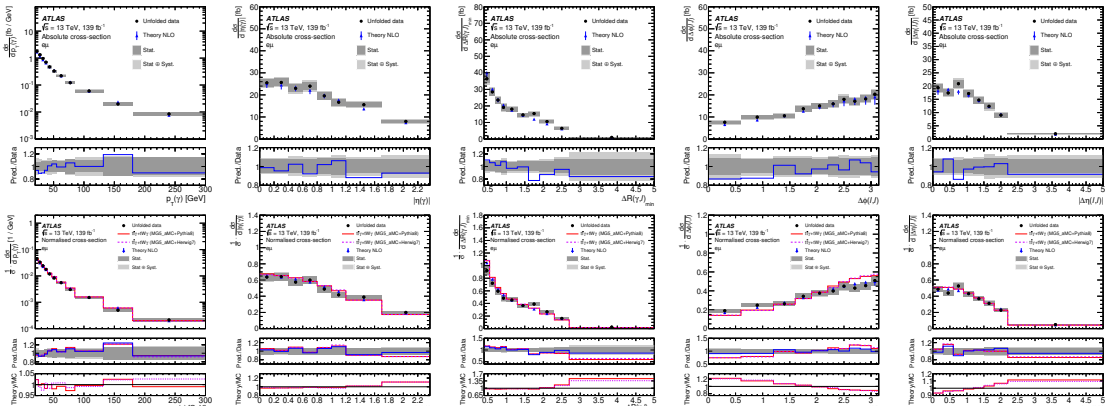
Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%
MC statistics	0.4%
Soft term $E_{\mathrm{T}}^{\mathrm{miss}}$	0.2%
$tW\gamma$ parton definition	2.8%
Total syst.	6.3%

$t\bar{t}\gamma$ - migration matrix and efficiencies





$t\bar{t}\gamma$ — absolute and normalised diff. cross sections

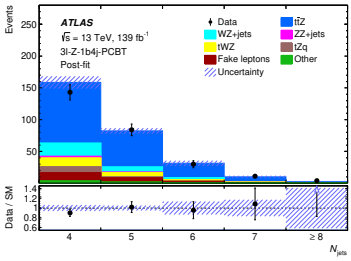


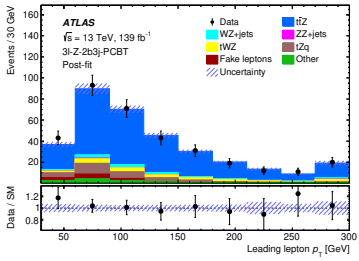
$t\bar{t}\gamma$ - NLO calculations: χ^2 & p-values

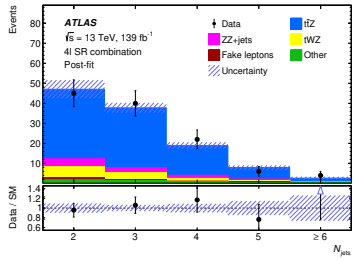
Predictions	$p_{\mathrm{T}}(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)_{\mathrm{min}}$		$\Delta\phi(\ell,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
Theory NLO	6.1/11	0.87	4.5/8	0.81	11.7/10	0.31	5.8/10	0.83	6.2/8	0.62

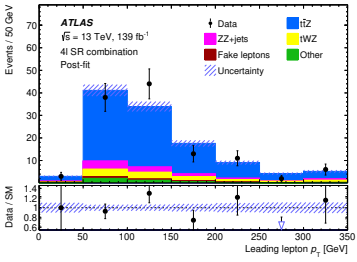
Predictions	$p_{\mathrm{T}}(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)_{\mathrm{min}}$		$\Delta\phi(\ell,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Pythia8)	6.3/10	0.79	7.3/7	0.40	20.1/9	0.02	30.8/9	<0.01	6.5/7	0.48
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Herwig7)	5.3/10	0.87	7.7/7	0.36	18.9/9	0.03	31.6/9	<0.01	6.8/7	0.45
Theory NLO	6.0/10	0.82	4.5/7	0.72	13.5/9	0.14	5.8/9	0.76	5.6/7	0.59

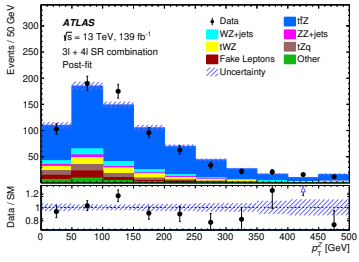
$t\bar{t}Z$ - post fit distributions

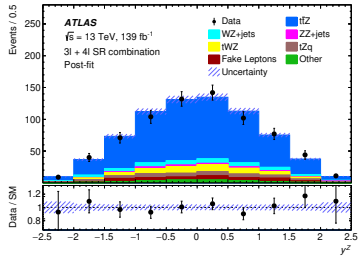




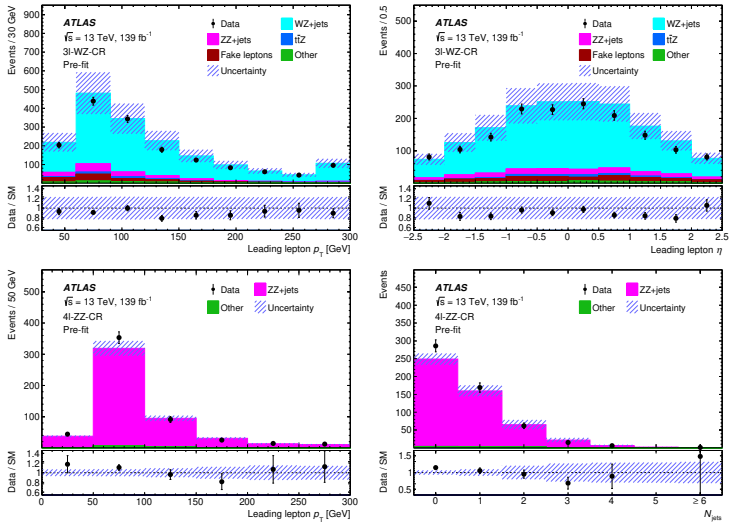




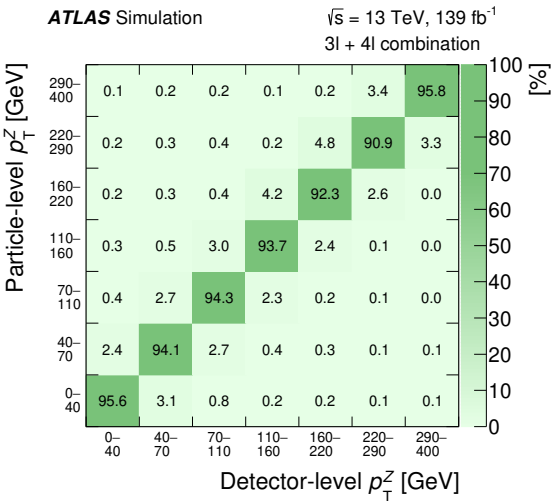


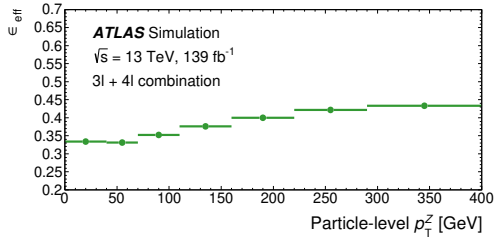


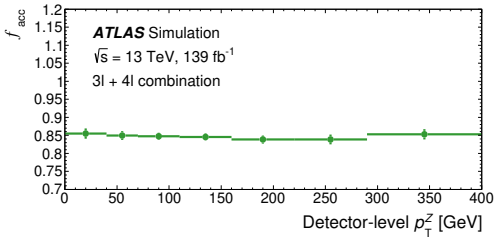
$t\bar{t}Z$ - pre-fit CR distributions



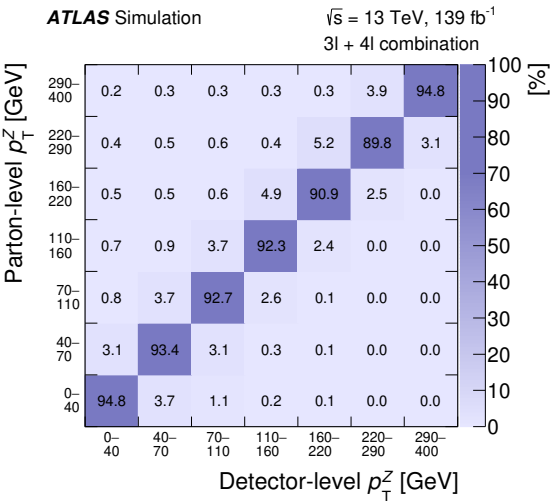
$t\bar{t}Z$ - Particle level migration matrix and efficiency

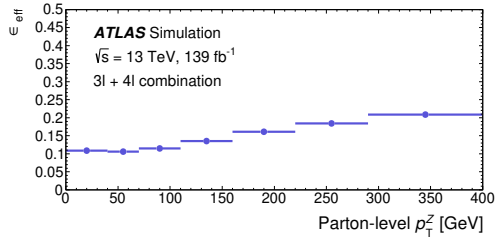


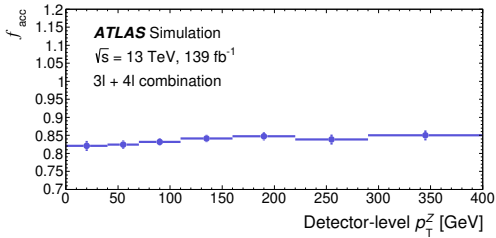




$t\bar{t}Z$ - Parton level migration matrix and efficiency







$t\bar{t}Z$ - Region definitions and $\mu_{t\bar{t}Z}$ results

Variable	3ℓ-Z-$1b4j$-PCBT inclusive	3ℓ-Z-$2b3j$-PCBT inclusive	3ℓ-Z-$2b3j$ differential
N_ℓ ($\ell = e, \mu$)	= 3		
	≥1 OSSF lepton pair with $\lvert m^Z_{\ell\ell} - m_Z \rvert < 10\,\text{GeV}$		
	for all OSSF combinations: $m_{\text{OSSF}} > 10\,\text{GeV}$		
p_{T} (ℓ_1, ℓ_2, ℓ_3)	> 27, 20, 20 GeV		
N_{jets}	≥ 4	≥ 3	≥ 3
$N_{b\text{-jets}}$	= 1@60%	≥ 2@70%	≥ 2@85%
	veto add. b-jets@70%		

Variable	3ℓ-WZ-CR	4ℓ-ZZ-CR
N_ℓ ($\ell = e, \mu$)	= 3	= 4
	1 OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 10\,\text{GeV}$	2 OSSF lepton pairs with $\lvert m_{\ell\ell} - m_Z \rvert < 10\,\text{GeV}$
$p_{\text{T}}(\ell_1, \ell_2, \ell_3, \ell_4)$	> 27, 20, 20 GeV	> 27, 20, 10, 7 GeV
N_{jets}	≥ 3	–
$N_{b\text{-jets}}$@85%	= 0	–
$E_{\text{T}}^{\text{miss}}$	–	20 GeV < $E_{\text{T}}^{\text{miss}}$ < 40 GeV

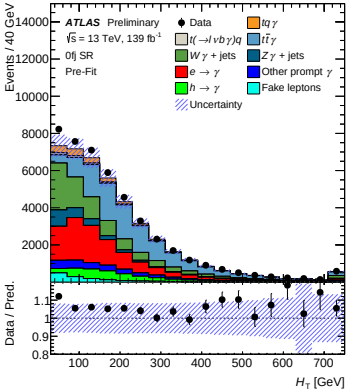
Variable	4ℓ-SF-$1b$	4ℓ-SF-$2b$	4ℓ-DF-$1b$	4ℓ-DF-$2b$
N_ℓ ($\ell = e, \mu$)	= 4			
	≥1 OSSF lepton pair with $\lvert m^Z_{\ell\ell} - m_Z \rvert < 10\,\text{GeV}$ for all OSSF combinations: $m_{\text{OSSF}} > 10\,\text{GeV}$			
p_{T} (ℓ_1, ℓ_2, ℓ_3, ℓ_4)	> 27, 20, 10, 7 GeV			
$\ell\ell^{\text{non-}Z}$	e^+e^- or $\mu^+\mu^-$	e^+e^- or $\mu^+\mu^-$	$e^\pm\mu^\mp$	$e^\pm\mu^\mp$
$E_{\text{T}}^{\text{miss}}$	> 100 GeV, if $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z \rvert \leq 10$ GeV > 50 GeV, if $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z \rvert > 10$ GeV	> 50 GeV, if $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z \rvert \leq 10$ GeV –	–	–
N_{jets}	≥ 2	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$@85%	= 1	≥ 2	= 1	≥ 2

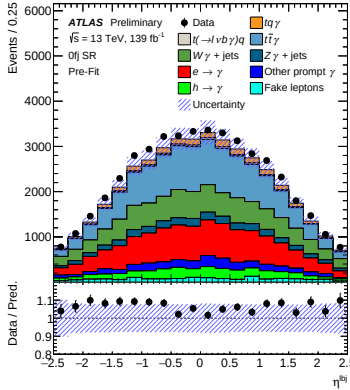
Channel	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combination ($3\ell + 4\ell$)	$1.19 \pm 0.06\,(\text{stat.}) \pm 0.10\,(\text{syst.})$

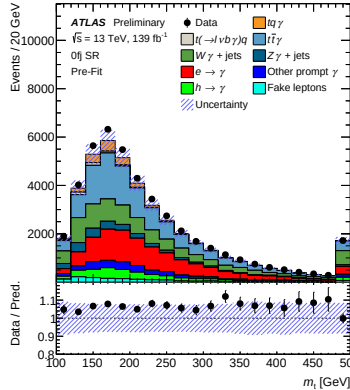
$t\bar{t}Z$ - Yields

Region	3ℓ-Z-1b4j -PCBT	3ℓ-Z-2b3j -PCBT	4ℓ-SF-1b	4ℓ-SF-2b	4ℓ-DF-1b	4ℓ-DF-2b	3ℓ-WZ-CR	4ℓ-ZZ-CR
$t\bar{t}Z$	185 ± 16	247 ± 20	14.5 ± 1.7	26.9 ± 2.5	19.3 ± 1.8	26.7 ± 2.3	45 ± 11	0.8 ± 0.1
$WZ + l$	2.4 ± 1.8	0.2 ± 0.3	–	–	–	–	1068 ± 110	–
$WZ + b$	20 ± 11	10.8 ± 6.1	–	–	–	–	11.2 ± 6.3	–
$WZ + c$	10.8 ± 4.8	1.8 ± 0.8	–	–	–	–	207 ± 87	–
$ZZ + l$	0.3 ± 0.2	0.02 ± 0.02	1.7 ± 0.7	0.9 ± 0.5	0.5 ± 0.1	0.02 ± 0.01	121 ± 15	496 ± 26
$ZZ + b$	3.0 ± 1.6	2.0 ± 1.0	0.9 ± 0.6	2.5 ± 1.5	0.2 ± 0.1	0.07 ± 0.07	1.8 ± 0.9	12.9 ± 7.1
$ZZ + c$	0.7 ± 0.2	0.1 ± 0.1	0.9 ± 0.5	1.1 ± 0.6	0.2 ± 0.1	0.02 ± 0.01	13.0 ± 4.1	19.8 ± 7.1
tWZ	23.8 ± 4.0	20.5 ± 7.0	2.7 ± 0.4	2.2 ± 0.8	3.8 ± 1.1	2.3 ± 0.9	13.2 ± 1.2	0.2 ± 0.1
tZq	10.8 ± 4.5	29.7 ± 9.0	–	–	–	–	8.6 ± 3.2	–
$t\bar{t}$+W/H	5.8 ± 0.9	10.1 ± 2.2	0.5 ± 0.1	0.9 ± 0.1	0.6 ± 0.1	0.8 ± 0.1	1.8 ± 0.4	0.01 ± 0.01
Fake leptons	23 ± 11	11.0 ± 5.3	0.7 ± 0.3	0.9 ± 0.4	0.9 ± 0.5	0.3 ± 0.1	65 ± 31	7.9 ± 3.1
Other	0.7 ± 0.4	1.5 ± 0.7	0.7 ± 0.3	0.2 ± 0.1	0.7 ± 0.4	0.2 ± 0.1	12.4 ± 6.3	1.0 ± 0.5
SM total	286 ± 13	334 ± 15	22.5 ± 1.8	35.6 ± 2.7	26.1 ± 1.9	30.3 ± 2.2	1569 ± 43	539 ± 23
Data	272	343	19	33	33	32	1569	539

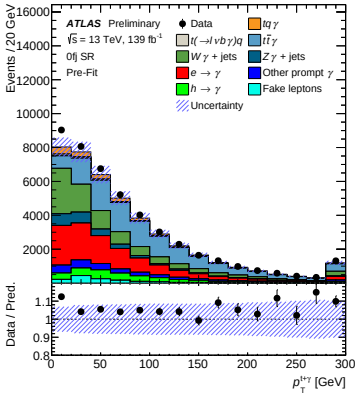
$t\gamma q$ - pre-fit event yields (0fj SR)

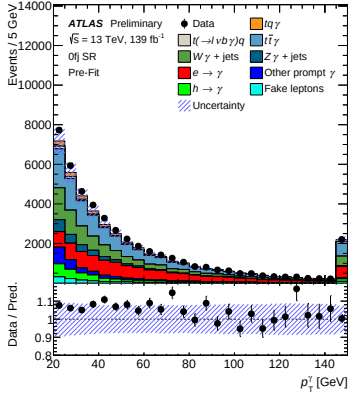


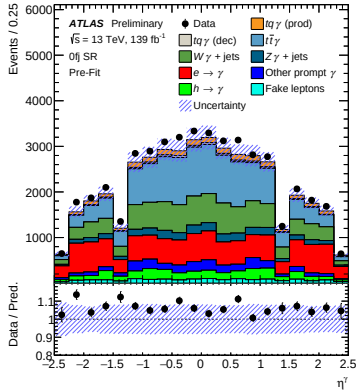




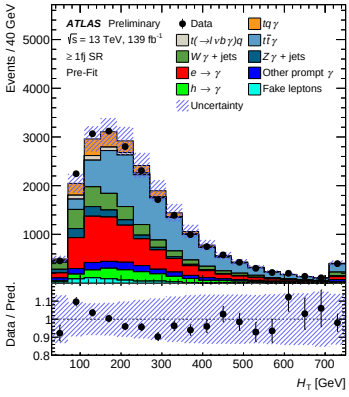
$t\gamma q$ - pre-fit event yields (0fj SR)

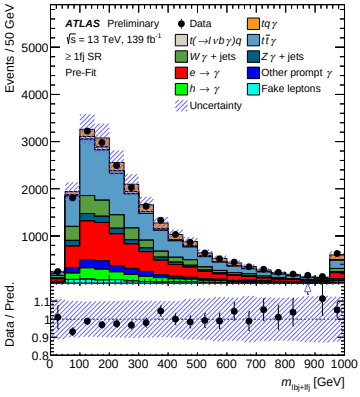


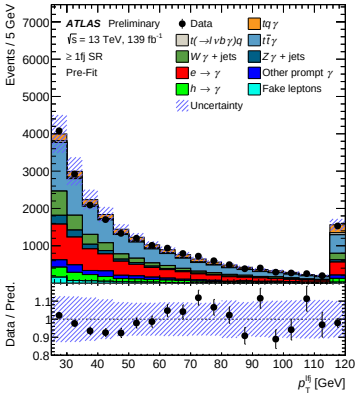




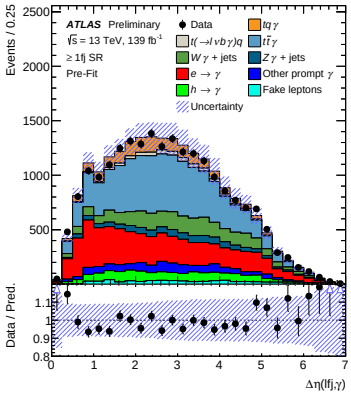
$t\gamma q$ - pre-fit event yields ($\geq$1fj SR)

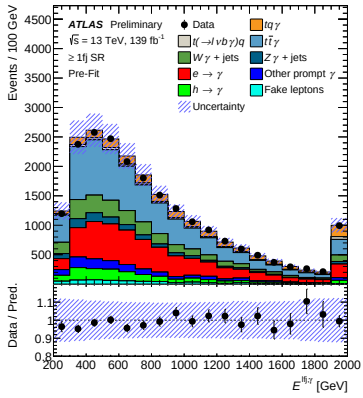


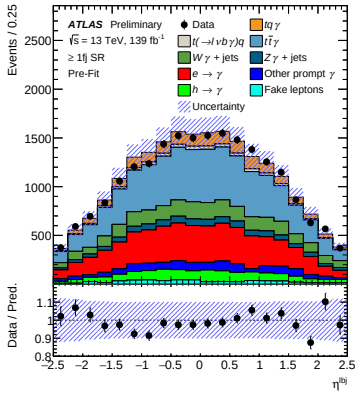




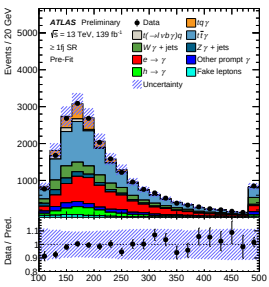
$t\gamma q$ - pre-fit event yields ($\geq$1fj SR)

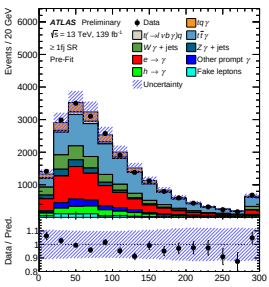


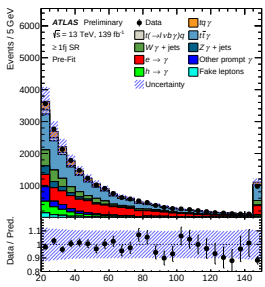


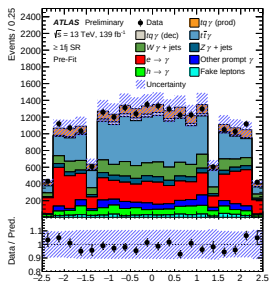


$t\gamma q$ - pre-fit event yields ($\geq$1fj SR)









$t\gamma q$ - Parton level post-fit event yields

	$\geq$ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2390 ± 260	2480 ± 320	890 ± 120	1280 ± 150
$t\,(\to \ell\nu b\gamma)\,q$	360 ± 150	460 ± 240	120 ± 50	230 ± 110
$t\bar{t}\gamma$ (production)	3100 ± 400	4800 ± 700	4300 ± 600	2720 ± 350
$t\bar{t}\gamma$ (radiative decay)	3800 ± 600	9300 ± 1400	5700 ± 600	4300 ± 900
$W\gamma$+jets	2500 ± 400	9300 ± 1300	1050 ± 190	31 900 ± 3000
$Z\gamma$+jets	990 ± 310	2800 ± 800	440 ± 150	7900 ± 2400
$e \to \gamma$ fake photons	5200 ± 500	10 300 ± 800	4800 ± 400	5400 ± 500
$h \to \gamma$ fake photons	1100 ± 400	2700 ± 800	1300 ± 500	2500 ± 800
Other prompt γ	1360 ± 350	2600 ± 900	1400 ± 400	4100 ± 500
Fake leptons	350 ± 170	900 ± 400	100 ± 50	3300 ± 1600
Total	21 250 ± 150	45 720 ± 240	20 180 ± 140	63 590 ± 310
Data	21 227	45 723	20 194	63 592

$t\gamma q$ - Particle level post-fit event yields

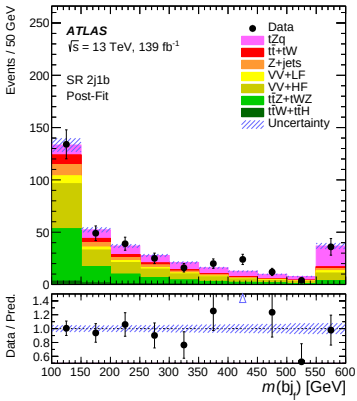
	$\geq$ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2340 ± 250	2430 ± 310	880 ± 120	1250 ± 140
$t\,(\to \ell\nu b\gamma)\,q$	480 ± 160	660 ± 210	170 ± 60	320 ± 120
$t\bar{t}\gamma$ (production)	3100 ± 400	4700 ± 700	4200 ± 600	2670 ± 350
$t\bar{t}\gamma$ (radiative decay)	3700 ± 600	9100 ± 1300	5600 ± 600	4200 ± 900
$W\gamma$+jets	2500 ± 400	9400 ± 1300	1060 ± 190	31 800 ± 3000
$Z\gamma$+jets	990 ± 310	2800 ± 800	440 ± 150	7900 ± 2400
$e \to \gamma$ fake photons	5200 ± 500	10 400 ± 800	4900 ± 400	5500 ± 500
$h \to \gamma$ fake photons	1200 ± 400	2700 ± 800	1400 ± 500	2600 ± 800
Other prompt γ	1380 ± 350	2600 ± 900	1400 ± 400	4100 ± 500
Fake leptons	350 ± 170	900 ± 500	100 ± 50	3300 ± 1600
Total	21 250 ± 150	45 720 ± 240	20 180 ± 150	63 590 ± 320
Data	21 227	45 723	20 194	63 592

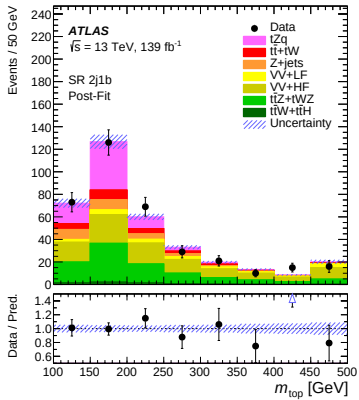
$t\gamma q$ - Systematic uncertainties for particle and parton level measurement

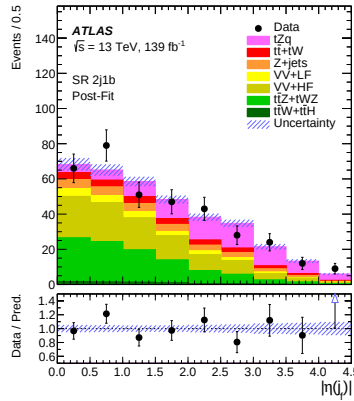
Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	±5.6%
Background MC statistics	±3.5%
$t\bar{t}$ modelling	±3.4%
$tq\gamma$ MC statistics	±3.4%
$t\,(\to \ell\nu b\gamma)\,q$ modelling	±1.9%
Additional background uncertainties	±1.9%
$tq\gamma$ modelling	±1.8%
$t\,(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \to \gamma$ photon fakes	±2.2%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±4.0%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.8%
Total systematic uncertainty	±10.9%

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	±5.7%
Background MC statistics	±3.5%
$t\bar{t}$ modelling	±3.1%
$tq\gamma$ MC statistics	±3.1%
$t\,(\to \ell\nu b\gamma)\,q$ modelling	±2.2%
$tq\gamma$ modelling	±2.0%
Additional background uncertainties	±1.9%
$t\,(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.4%
$h \to \gamma$ photon fakes	±2.2%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.3%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.9%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.6%
Total systematic uncertainty	±11.0%

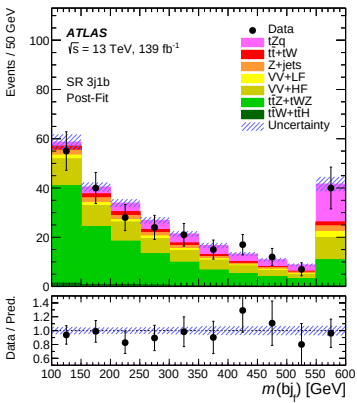
tZq - post-fit distributions

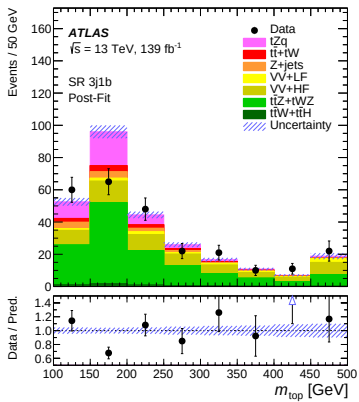


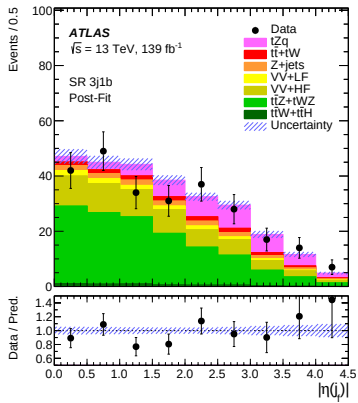




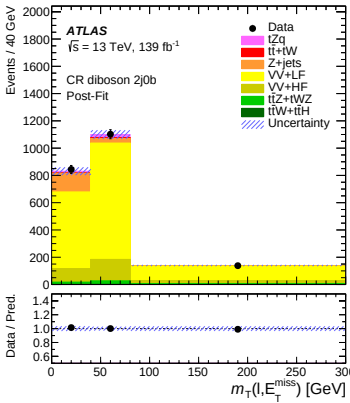
tZq - post-fit distributions

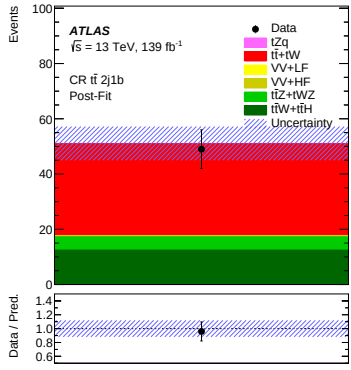


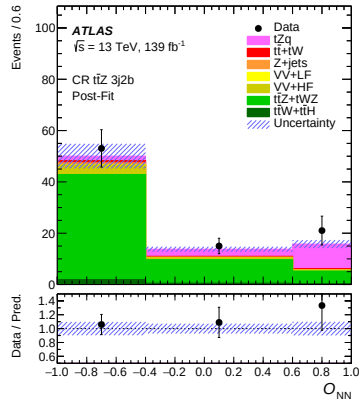




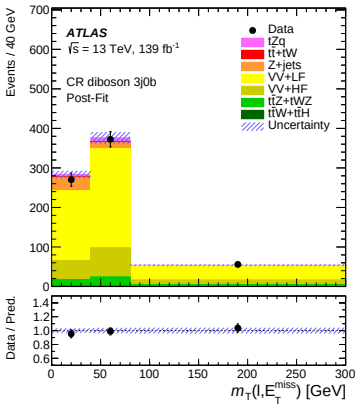
tZq - CR post-fit distributions

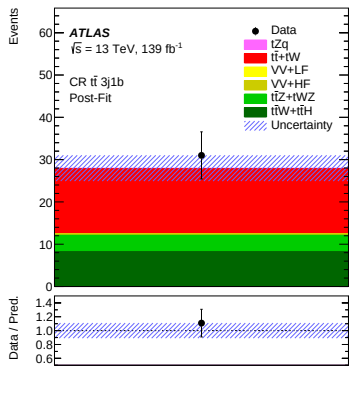


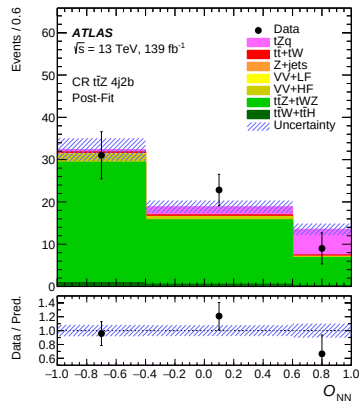




tZq - CR post-fit distributions







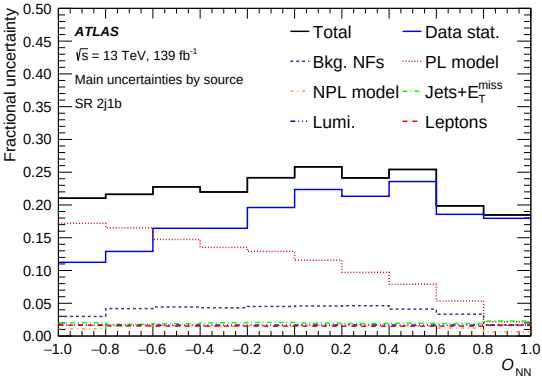
tZq - Yields and systematic uncertainties

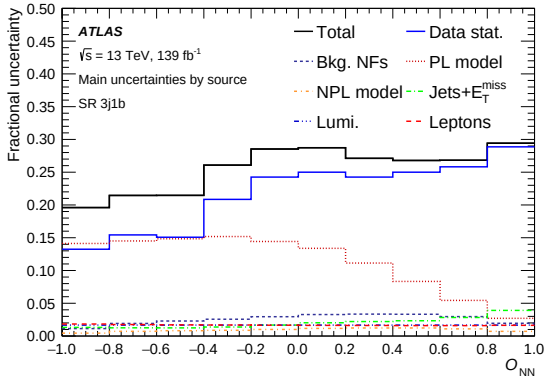
	SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
tZq	79 ± 11	53.1 ± 7.5	0.2 ± 0.1	12.9 ± 2.0
$t\bar{t}+tW$	23.8 ± 4.8	13.7 ± 2.7	33.3 ± 6.3	1.7 ± 0.3
Z + jets	28 ± 13	181 ± 82	< 0.1	1.4 ± 0.6
VV + LF	19.7 ± 7.9	2000 ± 100	< 0.1	0.1 ± 0.1
VV + HF	101 ± 22	383 ± 78	0.4 ± 0.1	5.2 ± 1.7
$t\bar{t}Z+tWZ$	96 ± 11	63.2 ± 7.0	4.8 ± 0.5	59.3 ± 7.1
$t\bar{t}H+t\bar{t}W$	6.5 ± 1.0	3.0 ± 0.5	12.4 ± 1.9	2.8 ± 0.5
Total	354 ± 16	2697 ± 56	51.1 ± 6.1	83.5 ± 6.4
Data	359	2703	49	92

	SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
tZq	43.4 ± 6.2	21.2 ± 3.3	0.2 ± 0.1	8.0 ± 1.3
$t\bar{t}+tW$	11.0 ± 2.2	6.9 ± 1.3	15.4 ± 3.1	1.0 ± 0.2
Z + jets	12.8 ± 6.0	53 ± 23	< 0.1	0.4 ± 0.2
VV + LF	10.1 ± 4.2	624 ± 53	< 0.1	0.1 ± 0.1
VV + HF	58 ± 17	186 ± 51	0.3 ± 0.1	3.4 ± 1.0
$t\bar{t}Z+tWZ$	132 ± 12	61.9 ± 6.2	3.9 ± 0.5	58.1 ± 5.3
$t\bar{t}H+t\bar{t}W$	4.7 ± 0.7	1.7 ± 0.3	8.2 ± 1.3	2.0 ± 0.3
Total	272 ± 12	955 ± 29	28.0 ± 3.0	72.8 ± 5.0
Data	259	949	31	75

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistics	12.6
$t\bar{t}+tW$ and Z + jets normalisation	2.1
Total statistical uncertainty	12.9

tZq - Breakdown of uncertainties

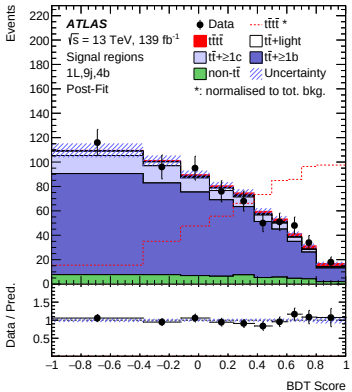


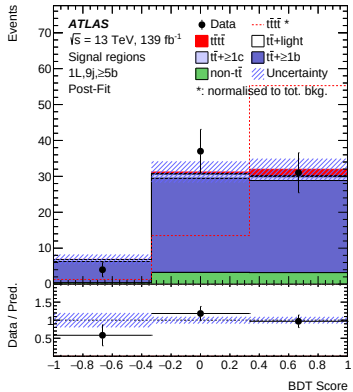


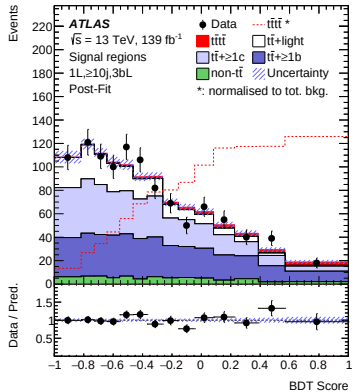
tZq - Neural network inputs

Variable	Rank		Definition
	SR 2j1b	SR 3j1b	
$m_{b\mathrm{j_f}}$	1	1	(Largest) invariant mass of the b-jet and the untagged jet(s)
m_{top}	2	2	Reconstructed top-quark mass
$\lvert\eta(\mathrm{j_f})\rvert$	3	3	Absolute value of the η of the $\mathrm{j_f}$ jet
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	4	4	Transverse mass of the W boson
b-tagging score	5	11	b-tagging score of the b-jet
H_{T}	6	–	Scalar sum of the p_{T} of the leptons and jets in the event
$q(\ell_W)$	7	8	Electric charge of the lepton from the W-boson decay
$\lvert\eta(\ell_W)\rvert$	8	12	Absolute value of the η of the lepton from the W-boson decay
$p_{\mathrm{T}}(W)$	9	15	p_{T} of the reconstructed W boson
$p_{\mathrm{T}}(\ell_W)$	10	14	p_{T} of the lepton from the W-boson decay
$m(\ell\ell)$	11	–	Mass of the reconstructed Z boson
$\lvert\eta(Z)\rvert$	12	13	Absolute value of the η of the reconstructed Z boson
$\Delta R(\mathrm{j_f}, Z)$	13	7	ΔR between the $\mathrm{j_f}$ jet and the reconstructed Z boson
$E_{\mathrm{T}}^{\mathrm{miss}}$	14	–	Missing transverse momentum
$p_{\mathrm{T}}(\mathrm{j_f})$	15	10	p_{T} of the $\mathrm{j_f}$ jet
$\lvert\eta(\mathrm{j_r})\rvert$	–	5	Absolute value of the η of the $\mathrm{j_r}$ jet
$p_{\mathrm{T}}(Z)$	–	6	p_{T} of the reconstructed Z boson
$p_{\mathrm{T}}(\mathrm{j_r})$	–	9	p_{T} of the $\mathrm{j_r}$ jet

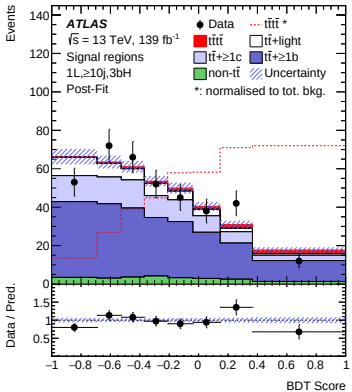
tZq - post-fit distributions

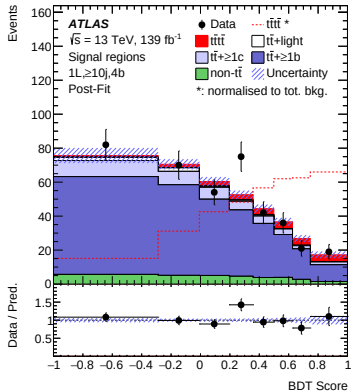


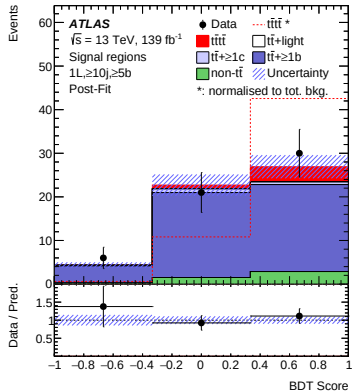




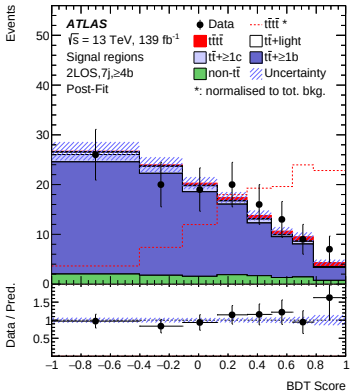
tZq - post-fit distributions

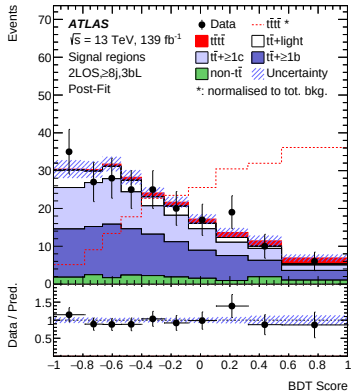


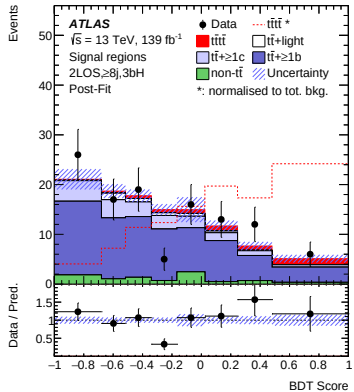




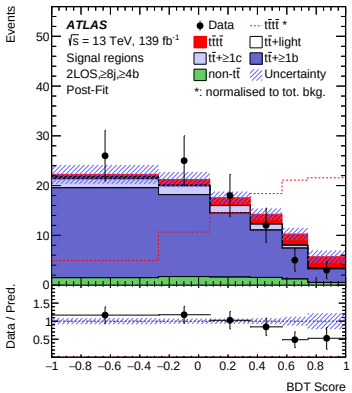
tZq - post-fit distributions

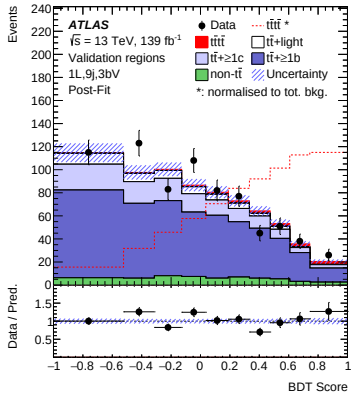


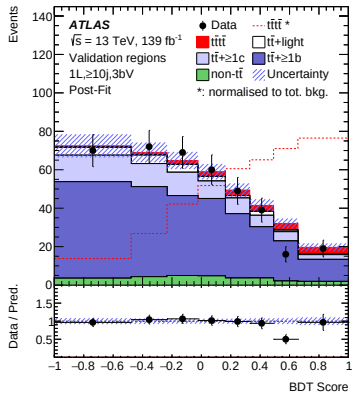




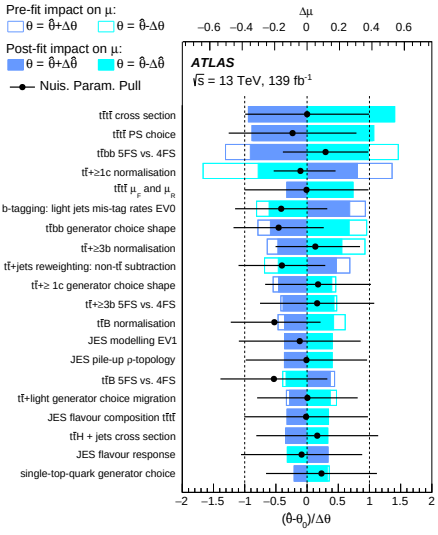
tZq - post-fit distributions





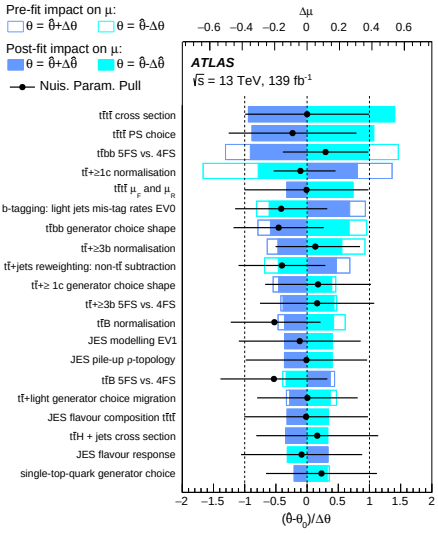


4 tops - Ranking and uncertainties



Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	−3
Background Modelling		
$t\bar{t}$+≥1b modelling	+8	−7
$t\bar{t}$+≥1c modelling	+5	−4
$t\bar{t}$+jets reweighting	+4	−3
Other background modelling	+4	−3
$t\bar{t}$+light modelling	+2	−2
Experimental		
Jet energy scale and resolution	+6	−4
b-tagging efficiency and mis-tag rates	+4	−3
MC statistical uncertainties	+2	−2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	−12
Statistical uncertainty	+8	−8
Total uncertainty	+17	−15

4 tops - Ranking and uncertainties



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MC statistical uncertainties	+2	−2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	−12
Statistical uncertainty	+8	−8
Total uncertainty	+17	−15

4 tops - *b*-tagging requirements

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	$= 2$	-
3bL	≤ 2	$= 3$	-
3bH	$= 3$	$= 3$	$= 3$
3bV	$= 3$	$= 3$	≥ 4
$\geq$4b (2LOS)	-	≥ 4	-
4b (1L)	-	$= 4$	-
$\geq$5b (1L)	-	≥ 5	-

4 tops - $t\bar{t}$+jets modelling

Uncertainty source	Description	Components (number)
$t\bar{t}$+≥1b normalisation	±50%	$t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b (4)
$t\bar{t}$+≥1c normalisation	±50%	$t\bar{t}$+≥1c (1)
Generator choice	Powheg vs MadGraph5_aMC@NLO	($t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b) ⊗ (shape, migration) (12)
PS choice	Pythia 8 vs Herwig 7	($t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b) ⊗ (shape, migration) (12)
Renormalisation scale	Varying μ_r in Powheg	$t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b (3)
Factorisation scale	Varying μ_f in Powheg	$t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b (3)
ISR	Varying α_S^{ISR}(PS) in Pythia 8	$t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b (3)
FSR	Varying μ_f (PS) in Pythia 8	$t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b (3)
5FS vs 4FS	PowhegBoxRes (4FS) vs PowhegBox (5FS)	$t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b (4)

4 tops - BDT inputs

Name	Description
$\sum b$-tag	Sum of pseudo-continuous b-tagging score over the six jets with the highest score
N_{jets}	Number of jets
$\Delta R_{bb}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets
$H_{\text{T}}^{\text{all}}$	Scalar sum of all jet and lepton transverse momenta
C^{all}	Centrality ($\sum_i p_{\text{T}i} / \sum_i E_i$) of the leptons and jets
$p_{\text{T}}^{\text{lead}}$	Transverse momentum of the leading jet
$\Delta R_{b\ell}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets and leptons
$\Delta R_{jj}^{\text{avg}}$	Average ΔR between all pairs of jets
m_{jjj}	Invariant mass of the closest triplet of jets
$E_{\text{T}}^{\text{miss}}$	Missing transverse momentum
m_{T}^{W}	W reconstructed transverse mass $m_T(\ell, E_{\text{T}}^{\text{miss}})$ (1L)
$N_{\text{LR-jets}}$	Number of large-R jets with a mass above 100 GeV
$\sum d_{12}$	Sum of the first k_t splitting scale d_{12} of all large-R jets
$\sum d_{23}$	Sum of the second k_t splitting scale d_{23} of all large-R jets